GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

Course Tittle: Sensors & Transducers

Following documents are available in Course File.

S.No.	Points	Yes	No
1	Institute and Department Vision and Mission Statements	✓	
2	PEO & PO Mapping	✓	
3	Academic Calendar	✓	
4	Subject Allocation Sheet	✓	
5	Class Time Table, Individual Timetable (Single Sheet)	✓	
6	Syllabus Copy	✓	
7	Course Handout	✓	
8	CO-PO Mapping	✓	
9	CO-Cognitive Level Mapping	✓	
10	Lecture Notes	✓	
11	Tutorial Sheets With Solution	✓	
12	Soft Copy of Notes/Ppt/Slides	✓	
13	Sessional Question Paper and Scheme of Evaluation	✓	
14	Best, Average and Weak Answer Scripts for Each Sessional Exam. (Photocopies)	✓	
15	Assignment Questions and Solutions	✓	
16	Previous University Question Papers	✓	
17	Result Analysis		
18	Feedback From Students	✓	
19	Course Exit Survey		
20	CO Attainment for All Mids.	✓	
21	Remedial Action.		

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

Course Instructor / Course Coordinator **Course Instructor / Course Coordinator**

(Name) **(Signature)**

Vision of the Institute

To be among the best of the institutions for engineers and technologists with attitudes, skills and knowledge and to become an epicenter of creative solutions.

Mission of the Institute

To achieve and impart quality education with an emphasis on practical skills and social relevance.

Vision of the Department

To impart technical knowledge and skills required to succeed in life, career and help society to achieve self sufficiency.

Mission of the Department

- To become an internationally leading department for higher learning.
- To build upon the culture and values of universal science and contemporary education.
- To be a center of research and education generating knowledge and technologies which lay groundwork in shaping the future in the fields of electrical and electronics engineering.
- To develop partnership with industrial, R&D and government agencies and actively participate in conferences, technical and community activities.

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

Programme Educational Objectives (B.Tech. – EEE)

This programme is meant to prepare our students to professionally thrive and to lead.

During their progression:

Graduates will be able to

PEO 1: Have a successful technical or professional careers, including supportive and leadership roles on multidisciplinary teams.
PEO 2: Acquire, use and develop skills as required for effective professional practices.
PEO 3: Able to attain holistic education that is an essential prerequisite for being a responsible member of society.
PEO 4: Engage in life-long learning, to remain abreast in their profession and be leaders in our technologically vibrant society.

Programme Outcomes (B.Tech. – EEE)

At the end of the Programme, a graduate will have the ability to

PO 1: Apply knowledge of mathematics, science, and engineering.
PO 2: Design and conduct experiments, as well as to analyze and interpret data.
PO 3: Design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability.
PO 4: Function on multi-disciplinary teams.
PO 5: Identify, formulates, and solves engineering problems.
PO 6: Understanding of professional and ethical responsibility.
PO 7: Communicate effectively.
PO 8: Broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context.
PO 9: Recognition of the need for, and an ability to engage in life-long learning.
PO 10: Knowledge of contemporary issues.
PO 11: Utilize experimental, statistical and computational methods and tools necessary for engineering practice.
PO 12: Demonstrate an ability to design electrical and electronic circuits, power electronics, power systems; electrical machines analyze and interpret data and also an ability to design digital and analog systems and programming them.

PEOs & POs Mapping

Programme Educational Objectives (PEOs)	**Programme Outcomes (POs)**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	M	M	-	-	H	-	-	H	H	-	H	H
2	-	-	M	M	H	H	H	-	-	-	-	H
3	-	-	-	-	H	H	M	M	M	M	H	H
4	-	-	-	M	M	H	M	H	H	-	M	H

* H: Strongly Correlating (3); M: Moderately Correlating (2)& L: Weakly Correlating (1)

HOD-EEE

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

GRIET/DAA/1H/G/18-19 05 May 2018

ACADEMIC CALENDAR
Academic Year 2018-19

III&IV B.TECH – FIRST SEMESTER

S. No.	EVENT	PERIOD	DURATION
1	1st Spell of Instructions	02-07-2018 to 01-09-2018	9 Weeks
2	1st Mid-term Examinations	03-09-2018 to 05-09-2018	3 Days
3	2nd Spell of Instructions	06-09-2018 to 24-10-2018	7 Weeks
4	2nd Mid-term Examinations	25-10-2018 to 27-10-2018	3 Days
5	Preparation	29-10-2018 to 06-11-2018	1 Week3 Days
6	**End Semester Examinations (Theory/ Practicals) Regular/Supplementary**	**08-11-2018 to 08-12-2018**	**4 Weeks 3 Days**
7	Commencement of Second Semester, A.Y 2018-19	10-12-2018	

III&IV B.TECH – SECOND SEMESTER

S. No.	EVENT	PERIOD	DURATION
1	1st Spell of Instruction	10-12-2018 to 02-02-2019	8 Weeks
2	1st Mid-term Examinations	04-02-2019 to 06-02-2019	3 Days
3	2nd Spell of Instruction	07-02-2019 to 06-04-2019	**8 Weeks 3 Days**
4	2nd Mid-term Examinations	08-04-2019to 10-04-2019	3 Days
5	Preparation	11-04-2019 to 17-04-2019	1 Week
6	**End Semester Examinations(Theory/ Practicals) Regular**	18-04-2019 to 08-05-2019	3 Weeks
7	**Supplementary and Summer Vacation**	**09-05-2019 to 22-06-2019**	**6 Weeks 3 Days**
8	Commencement of First Semester, A.Y 2019-20	24-06-2019	

Copy to Director, Principal, Vice Principal, DOA, DOE, Balaji Kumar, DCGC, All HODs

(Dr. K. Anuradha)
Dean of Academic Affairs

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

2018-19 II sem Subject Allocation sheet

GRIET/EEE/05B/G/18-19 **30.10.18**

II YEAR(GR17)	Section-A	Section-B
Managerial Economics and Financial Analysis		
Power Generation and Distrubution	SN	SN
AC Machines	VVSM	VVSM
Control Systems	Dr DGP	MS
Princeples of Digital Electronics	PRK	PRK
AC Machines Lab	PPK/DSR	PPK/DSR
Control Systems Lab	MS/PSVD	MS/PSVD
Analog and Digital Electronics Lab	RAK/DKK	RAK/DKK
Value Education and Ethics		
Gender Sensitization Lab	MS/PSVD	MS/PSVD
III YEAR (GR15)		
Computer Methods in Power systems	VVRR/MP	VVRR/MP
Switch Gear & Protection	PSVD	Dr JSD
Management Science		
Utilization of Electrical Energy	MRE	MRE
Non Conventional Sources of Energy		
Neural and Fuzzy Systems		
Sensors&Transducers	UVL	UVL
Power Systems Lab	GSR/YSV	GSR/YSV
Advanced English Communications Skills Lab		
Industry Oriented Mini Project Lab	PPK/AVK/Dr JP	MP/Dr JP
IV YEAR (GR15)		
Programmable Logic Controllers	PK	
Flexible AC Transmission Systems	Dr TSK	
EHV AC Transmission		
Power System Automation		
Modern Power Electronics	AVK	
DSP Based Electromechanical Systems		
Advaced Control Systems		
Programmable Logic Controllers-Lab	VVSM	PK

Main Projects	RAK/Dr SVJK	PK/VVRR
M.Tech PE		
Modeling and Analysis of Electrical Machines	Dr BPB	
Digital control of power Electronics and Drive Systems	Dr DGP	
FACTS and Custom power Devices	Dr TSK	
Smart Grids	VVRR	
Audit Course -2	YSV/UVL	
Power Quality Lab	Dr BPB	
Digital Signal Processing Lab	AVK	
MINI Projects	Dr JP/GSR	
M.Tech PS		
Digital Protection of Power System	Dr JSD	
Power System Dynamics -II	Dr SVJK	
FACTS and Custom power Devices	Dr TSK	
Smart Grids	VVRR	
Audit Course -2	YSV/UVL	
Power Quality Lab	Dr BPB	
Power System Protection Lab	VUR	
MINI Projects	Dr JP/GSR	
Other Dept.		
BEE (I YEAR) CSE (6)	MNSR,MK,MVK,	
BEE Lab	MNSR,MK,MVK,YSV,VUR,PS,UVL,MRE,GBR	
EET (II YEAR) Mech (2)	KS	KS
EET LAB (II TEAR) Mech (2)	KS,DKK,PPK,	

HOD,EEE

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

GRIET/PRIN/06/G/01/18-19

Wef : 10 Dec 2018

BTech - EEE - A

III year - II Semester

DAY/ HOUR	9:00 - 9:45	9:45 - 10:30	10:30 - 11:15	11:15-12:00	12:00- 12:30	12:30 - 1:20	1:20 - 2:10	2:10 - 3:00
MONDAY	SGP		CMPS		BREAK	S&T		UEE
TUESDAY	SGP		S&T			UEE		CMPS
WEDNESDAY	MS		UEE			SGP		S&T
THURSDAY	IOMP Lab(A1) / AECS Lab(A2)					CMPS		S&T
FRIDAY	PS Lab(A2) /AECS Lab(A1)					MS		UEE
SATURDAY	IOMP Lab(A2) / PS Lab (A1)					CMPS		SGP

Room No	
Theory	4501
Lab	4504/4407/

Class Incharge :	M Rekha

Subject Code	Subject Name	Faculty Code	Faculty name	Almanac	
CMPS	Computer Methods in Power systems	VVRR/MP	V Vijaya Rama Raju/M Prashanth	1st Spell of Instructions	10-12-2018 to 06-02-2019
SGP	Switch Gear & Protection	PSVD	P Srividya Devi	1st Mid-term Examinations	07-02-2019 to 09-02-2019
MS	Management Science	Dr MSRS	Dr M S R Sesha giri	2nd Spell of Instructions	11-02-2019 to 03-04-2019
UEE	Utilization of Electrical Energy	MRE	M Rekha	2nd Mid-term Examinations	04-04-2019 to 06-04-2019
S&T	Sensors&Transducers	UVL	U Vijaya Lakshmi	Preparation	08-04-2019 to 17-04-2019
PS Lab	Power Systems Lab	GSR/YSV	G Sandhya Rani/Y Satyavani	End Semester Examinations (Theory/ Practicals) Regular	18-04-2019 to 08-05-2019
AECS Lab	Advanced English Communications Skills Lab	ES	E Sailaja		
IOMP Lab	Industry Oriented Mini Project Lab	AVK/PPK/Dr JP	A Vinay Kumar/P Praveen Kumar/ Dr J Praveen	Supplementary and Summer Vacation	09-05-2019-to 22-06-2019
				Commencement of Second Semester , AY	24-06-2019

HOD **Co-ordinator** **DAA**

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

GRIET/PRIN/06/G/01/18-19 **Wef : 10 Dec 2018**

BTech - EEE - B **III year - II Semester**

DAY/ HOUR	**9:00 - 9:45**	**9:45 - 10:30**	**10:30 - 11:15**	**11:15-12:00**	**12:00-12:30**	**12:30 - 1:20**	**1:20 - 2:10**	**2:10 - 3:00**
MONDAY	PS Lab(B1) /AECS Lab(B2)				BREAK	UEE	CMPS	
TUESDAY	PS Lab(B2) /IOMP Lab(B1)					CMPS	S&T	
WEDNESDAY	IOMP Lab(B2) / AECS Lab(B1)					SGP	CMPS	
THURSDAY	SGP		UEE			S&T	MS	
FRIDAY	UEE		CMPS			S&T	SGP	
SATURDAY	MS		SGP			UEE	S&T	

Room No	
Theory	4404
Lab	4504/4407/

Class Incharge :	M Rekha

Subject Code	**Subject Name**	**Faculty Code**	**Faculty name**	**Almanac**	
CMPS	Computer Methods in Power systems	VVRR/MP	V Vijaya Rama Raju/M Prashanth	1st Spell of Instructions	10-12-2018 to 06-02-2019
SGP	Switch Gear & Protection	DrJSD	Dr J Sridevi	1st Mid-term Examinations	07-02-2019 to 09-02-2019
MS	Management Science	Dr MSRS	Dr M S R Sesha giri	2nd Spell of Instructions	11-02-2019 to 03-04-2019
UEE	Utilization of Electrical Energy	MRE	M Rekha	2nd Mid-term Examinations	04-04-2019 to 06-04-2019
S&T	Sensors&Transducers	UVL	U Vijaya Lakshmi	Preparation	08-04-2019 to 17-04-2019
PS Lab	Power Systems Lab	GSR/YSV	G Sandhya Rani/Y Satyavani	End Semester Examinations (Theory/ Practicals) Regular	18-04-2019 to 08-05-2019
AECS Lab	Advanced English Communications Skills Lab	ES	E Sailaja		
IOMP Lab	Industry Oriented Mini Project Lab	MP/Dr JP	M Prashanth/ Dr J Praveen	Supplementary and Summer Vacation	09-05-2019-to 22-06-2019
				Commencement of Second Semester , AY	24-06-2019

HoD **Co-ordinator** **DAA**

Syllabus:

SENSORS AND TRANSDUCERS (Open Elective – II)

Course Code: GR17A3152 **III Year II Sem**

UNIT I: Introduction: Sensors / Transducers, principles, classification, parameters, Characterizations.

UNIT II: Introduction to mechanical & Electro Mechanical Sensors: Resistive Potentiometer, Inductive sensors, Capacitive Sensors, Ultrasonic Sensors.

UNIT III: Basics of Thermal and Magnetic Sensors: Gas thermometric sensors, Thermal expansion type thermometric sensors, acoustic temperature sensors, dielectric constant and refractive index thermo sensors. Sensors and principles: Yoke coil sensor, coaxial type sensor, Force and displacement sensor.

UNIT IV: SMART Sensors: Introduction, Primary sensors, Excitation, Amplification, Filters, Converters, Compensation, Information coding / processing, Data Communication, The Automation.

UNIT V : Sensors their Applications: Flow - rate sensors, Pressure Sensors, Temperature Sensors, Torque & Position Sensors, Home Appliance Sensors – Distance Sensing Medical Diagnostic sensors, Sensors for Environmental Monitoring

TEXT BOOKS: 1. Sensors & Transducers By D. Patranabis , PHI Publications

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

COURSE OBJECTIVES

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

On completion of this Subject/Course the student shall be able to:

S.No	Course Objectives
1.	Describe and interpret important physical principles applied in sensors and transducer
2.	Design and fabricate sensors and transducer with desired physical and chemical properties.
3.	Describe the various types of sensors including thermal, mechanical, electrical and electromechanical sensors.
4.	Use these sensors for various applications.

Signature of HOD

Signature of faculty

Date:

Date:

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

COURSE OUTCOMES

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

The expected outcomes of the Course/Subject are:

S.No	Course Outcomes
1.	Understand the principles involved in sensors and transducers
2.	Analyze various characterizations of sensors
3.	Identify working of mechanical and electromechanical sensors
4.	Discuss various Thermal and magnetic sensors
5.	Understand the principles involved in Smart sensors
6.	Know the various applications of sensors and transducers
7.	Design various types of sensors

Signature of HOD

Signature of faculty

Date:

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

GUIDELINES TO STUDY THE COURSE/SUBJECT

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Guidelines to study the Course/ Subject:

Course Design and Delivery System (CDD):

- The Course syllabus is written into number of learning objectives and outcomes.
- These learning objectives and outcomes will be achieved through lectures, assessments, assignments, experiments in the laboratory, projects, seminars, presentations, etc.
- Every student will be given an assessment plan, criteria for assessment, scheme of evaluation and grading method.
- The Learning Process will be carried out through assessments of Knowledge, Skills and Attitude by various methods and the students will be given guidance to refer to the text books, reference books, journals, etc.

The faculty be able to –

- Understand the principles of Learning
- Understand the psychology of students
- Develop instructional objectives for a given topic
- Prepare course, unit and lesson plans
- Understand different methods of teaching and learning
- Use appropriate teaching and learning aids
- Plan and deliver lectures effectively
- Provide feedback to students using various methods of Assessments and tools of Evaluation
- Act as a guide, advisor, counselor, facilitator, motivator and not just as a teacher alone

Signature of HOD Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

COURSE SCHEDULE

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

The Schedule for the whole Course / Subject is:

S. No.	Description	Total No of Periods
1.	Introduction: Sensors / Transducers, principles, classification, parameters, Characterizations.	7
2.	Introduction to mechanical & Electro Mechanical Sensors: Resistive Potentiometer, Inductive sensors, Capacitive Sensors, Ultrasonic Sensors.	15
3.	Basics of Thermal and Magnetic Sensors: Gas thermometric sensors, Thermal expansion type thermometric sensors, acoustic temperature sensors, dielectric constant and refractive index thermo sensors. Sensors and principles: Yoke coil sensor, coaxial type sensor, Force and displacement sensor.	13
4.	SMART Sensors: Introduction, Primary sensors, Excitation, Amplification, Filters, Converters, Compensation, Information coding / processing, Data Communication, The Automation.	10
5.	Sensors their Applications: Flow - rate sensors, Pressure Sensors, Temperature Sensors, Torque & Position Sensors, Home Appliance Sensors – Distance Sensing Medical Diagnostic sensors, Sensors for Environmental Monitoring	12

Total No. of Instructional periods available for the course: …. 57…….Hours / Periods

Signature of HOD	Signature of faculty
Date:	Date:

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering
SCHEDULE OF INSTRUCTIONS
COURSEPLAN

Academic Year : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Unit No.	**Lesson No.**	**No. of Periods**	**Topics / Sub-Topics**	**Objectives & Outcomes Nos.**	**References (Text Book, Journal…) Page Nos.: ____to ____**
1	1	1	Introduction of Sensors & Transducers	1,3&1	1
	2	1	Principles involved in Sensors & Transducers	1&1	1 to 2
	3	1	Classification , Parameters	2,3&1,2	3 to 5
	4	1	Static Characteristics	1&1,2	5 to 9
	5	1	Dynamic Characteristics	1&1,2	9
	6	1	Environmental Characteristics	1&1,2	9
	7	1	Electrical, Mechanical and Thermal characteristics	1,3&1,2	10 to 13
2	8	1	Introduction to mechanical and electromechanical sensors	3&3	14
	9	1	Resistive potentiometers	3&3	15 to 18
	10	1	Strain gauges types	3&3	19 to 29
	11	1	Inductive Sensors	3&1,3	29 to 36
	12	4	Inductive Sensors Types	3&1,3	36 to 47
	13	3	Capacitive Sensors Types	3&1,3	47 to 62
	14	1	Problems on Inductive sensors	3&3	65 to 67
	15	2	Problems on Capacitive Sensors	3&1	65 to 67

Department of Electrical & Electronics Engineering

	16	1	Ultrasonic sensors	3&1	64 to 65
3	17	1	Basics of Thermal and Magnetic sensors	3&4	68 to 69
	18	1	Gas thermometric sensors	3&4	69 to 72
	19	3	Thermal expansion type, acoustic temperature sensors	3&4	72 to 76
	20	2	Dielectric constant and refractive index thermo sensors	3&4	77 to 78
	21	2	Yoke coil sensors, coaxial type sensors	3&4	142 to 146
	22	1	Force & Displacement sensors	3&4	146 to 148
	23	2	Problems on Thermal Sensors	3,4&4	133 to 135
	24	1	Problems on Magnetic Sensors	3,4&4	181 to 182
4	25	1	Introduction to Smart Sensors	2&5	262 to 264
	26	1	Primary Sensors	2&5	264 to 267
	27	2	Excitation, amplification, filters, converters	2,4&5,6	267 to 269
	28	1	Compensation & Defects	4&5	269 to 277
	29	2	Information coding/processing, Data communication& automation	3,4&6,7	277 to 281
	30	3	Problems on Primary Sensors	3,4&6,7	281
5	31	1	Flow rate sensors	3&5,6	300 to 301
	32	1	Pressure sensors-Types	3&5,6	301 to 302
	33	1	Flow rate sensors-Types	3&5,6	300 to 301
	34	2	Temperature sensors-Types	3&5,6	302 to 303
	35	1	Torque & position sensors-Types	3&5,6	305 to 306
	36	1	Home appliance sensors-Types	3&5,6	306 to 309
	37	1	Distance sensing-Types	3&5,6	316 to 319
	38	1	Medical Diagnostic sensors	3&5,6	319 to 321
	39	1	Environmental monitoring sensors	3&5,6	321 to 324
	40	1	Pressure sensors-Types	3&5,6	301 to 302
	41	1	Problems on Pressure sensors	3&5,6	324 to 325

Signature of HOD　　　　Signature of faculty

Date:　　　　Date:

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

CO'S AND PO'S MAPPINGS

Academic Year : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…GR17A3152

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Course Code	**Course Title**	**Course Outcomes**	**Program Outcomes**											
			a	**b**	**c**	**d**	**e**	**f**	**g**	**h**	**i**	**j**	**k**	**l**
GR15A3162	SENSORS AND TRANSDUCERS	Understand the principles involved in sensors and transducers	H	M	M	H	M	-	-	M	-	-	H	H
		Analyze various characterizations of sensors	H	M	M	H	M	-	-	M	-	-	H	H
		Identify working of mechanical and electomechanical sensors	H	H	M	H	M	-	-	H	-	-	M	M

		Discuss various Thermal and magnetic sensors	H	H	M	H	M	-	-	M	-	-	M	M
		Understand the principles involved in Smart sensors	H	H	H	H	M	-	-	H	-	-	H	H
		Know the various applications of sensors and transducers	M	-	-	M	-	-	-	M	-	-	M	-
		Design various types of sensors	M	H	H	H	-	-	-	M	-	-	H	H

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic **Y**ear : 2018-2019

Semester : II UNIT NO.: ………**1**…………

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Lesson No	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Introduction of Sensors & Transducers	1,3	1	1
2	1	Principles involved in Sensors & Transducers	1	1	1 to 2
3	1	Classification , Parameters	2,3	1,2	3 to 5
4	1	Static Characteristics	1	1,2	5 to 9
5	1	Dynamic Characteristics	1	1,2	9
6	1	Environmental Characteristics	1	1,2	9
7	1	Electrical, Mechanical and Thermal characteristics	1,3	1,2	10 to 13

Signature of HOD

Date:

Signature of faculty

Date:

Department of Electrical & Electronics Engineering

Note: 1. ENSURE THAT ALL TOPICS SPECIFIED IN THE COURSE ARE MENTIONED.
2. ADDITIONAL TOPICS COVERED, IF ANY, MAY ALSO BE SPECIFIED IN BOLD
3. MENTION THE CORRESPONDING COURSE OBJECTIVE AND OUT COME NUMBERS AGAINST EACH TOPIC.

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic **Y**ear : 2018-2019

Semester : II UNIT NO.: ………**2**…………

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Introduction to mechanical and electromechanical sensors	3	3	14
2	1	Resistive potentiometers	3	3	15 to 18
3	1	Strain gauges types	3	3	19 to 29
4	1	Inductive Sensors	3	1,3	29 to 36
5	4	Inductive Sensors Types	3	1,3	36 to 47
6	3	Capacitive Sensors Types	3	1,3	47 to 62
7	1	Problems on Inductive sensors	3	3	65 to 67
8	2	Problems on Capacitive Sensors	3	1	65 to 67
9	1	Ultrasonic sensors	3	1	64 to 65

Signature of HOD Signature of faculty

Date: Date:

Note: 1. ENSURE THAT ALL TOPICS SPECIFIED IN THE COURSE ARE MENTIONED.
2. ADDITIONAL TOPICS COVERED, IF ANY, MAY ALSO BE SPECIFIED IN BOLD
3. MENTION THE CORRESPONDING COURSE OBJECTIVE AND OUT COME NUMBERS AGAINST EACH TOPIC.

Department of Electrical & Electronics Engineering

SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic **Y**ear : 2018-2019

Semester : II UNIT NO.: ………**3**…………

Name of the Program: EEE……… B.Tech**…….**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Basics of Thermal and Magnetic sensors	3	4	68 to 69
2	1	Gas thermometric sensors	3	4	69 to 72
3	3	Thermal expansion type, acoustic temperature sensors	3	4	72 to 76
4	2	Dielectric constant and refractive index thermo sensors	3	4	77 to 78
5	2	Yoke coil sensors, coaxial type sensors	3	4	142 to 146
6	1	Force & Displacement sensors	3	4	146 to 148
7	2	Problems on Thermal Sensors	3,4	4	133 to 135
8	1	Problems on Magnetic Sensors	3,4	4	181 to 182

Signature of HOD Signature of faculty

Date: Date:

Note: 1. ENSURE THAT ALL TOPICS SPECIFIED IN THE COURSE ARE MENTIONED.
2. ADDITIONAL TOPICS COVERED, IF ANY, MAY ALSO BE SPECIFIED IN BOLD
3. MENTION THE CORRESPONDING COURSE OBJECTIVE AND OUT COME NUMBERS AGAINST EACH TOPIC.

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic **Y**ear : 2018-2019

Semester : II UNIT NO.: ………**4**…………

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Introduction to Smart Sensors	2	2	262 to 264
2	1	Primary Sensors	2	2	264 to 267
3	2	Excitation, amplification, filters, converters	2,4	2,4	267 to 269
4	1	Compensation & Defects	4	4	269 to 277
5	2	Information coding/processing, Data communication& automation	3,4	3,4	277 to 281
6	3	Problems on Primary Sensors	3,4	3,4	281

Signature of HOD Signature of faculty

Date: Date:

Note: 1. ENSURE THAT ALL TOPICS SPECIFIED IN THE COURSE ARE MENTIONED.
2. ADDITIONAL TOPICS COVERED, IF ANY, MAY ALSO BE SPECIFIED IN BOLD
3. MENTION THE CORRESPONDING COURSE OBJECTIVE AND OUT COME NUMBERS AGAINST EACH TOPIC.

Department of Electrical & Electronics Engineering

SCHEDULE OF INSTRUCTIONS
UNIT PLAN

Academic **Y**ear : 2018-2019

Semester : II UNIT NO.: ………**5**…………

Name of the Program: EEE……… B.Tech**…….**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Lesson No.	No. of Periods	Topics / Sub - Topics	Objectives	Outcomes	References (Text Book, Journal…) Page Nos.: ____to ____
1	1	Flow rate sensors	3	5,6	300 to 301
2	1	Pressure sensors-Types	3	5,6	301 to 302
3	1	Flow rate sensors-Types	3	5,6	300 to 301
4	2	Temperature sensors-Types	3	5,6	302 to 303
5	1	Torque & position sensors-Types	3	5,6	305 to 306
6	1	Home appliance sensors-Types	3	5,6	306 to 309
7	1	Distance sensing-Types	3	5,6	316 to 319
8	1	Medical Diagnostic sensors	3	5,6	319 to 321
9	1	Environmental monitoring sensors	3	5,6	321 to 324
10	1	Pressure sensors-Types	3	5,6	301 to 302
11	1	Problems on Pressure sensors	3	5,6	324 to 325

Signature of HOD Signature of faculty

Date: Date:

Note: 1. ENSURE THAT ALL TOPICS SPECIFIED IN THE COURSE ARE MENTIONED.
2. ADDITIONAL TOPICS COVERED, IF ANY, MAY ALSO BE SPECIFIED IN BOLD
3. MENTION THE CORRESPONDING COURSE OBJECTIVE AND OUT COME NUMBERS AGAINST EACH TOPIC.

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**…. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….1&2… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Sensors & Transducers and Principles involved in Sensors & Transducers

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about sensor, transducer.

2. Know types of signals.

3. Understand physical and chemical transduction principles.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.

90 min.: Introduction of Sensors & Transducers and Principles involved in Sensors & Transducers

- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss different physical and chemical transduction principles (Obj;-1,3Out;-1)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**…. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….3… Duration of Lesson: …. 90min……

Lesson Title: Classification , Parameters

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about active and passive sensors.
2. Know types of sensors.
3. Understand different parameters.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Classification, Parameters.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss about property based classification. (Obj;- 2,3Out;-1,2)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….4&5… Duration of Lesson: …. 90min……

Lesson Title: Static Characteristics and Dynamic Characteristics

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about different Static Characteristics of sensor, transducer.

2. Know about different Dynamic Characteristics of sensor, transducer.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Static Characteristics and Dynamic Characteristics.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Define selectivity and specificity. (Obj;- 1Out;-1,2)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**…. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….6&7… Duration of Lesson: …. 90min……

Lesson Title: Environmental Characteristics and Electrical, Mechanical and Thermal characteristics

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about Environmental Characteristics

2. Know Electrical, Mechanical Characteristics.

3. Understand Thermal characteristics

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Environmental Characteristics and Electrical, Mechanical and Thermal characteristics.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the equation for Bath tub curve. (Obj;- 1,3Out;-1,2)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….8… Duration of Lesson: …. 90min……

Lesson Title :Introduction to mechanical and electromechanical sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about electromechanical coupling.
2. Know types of mechanical variables.
3. Understand translational or rotational displacements.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to mechanical and electromechanical sensors.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Explain about mechanical sensors (Obj;-3Out;,3)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: …9&10 Duration of Lesson: …. 90min……

Lesson Title: Resistive potentiometers and Strain gauges types

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

2. Know about Resistive potentiometers.

2. Know types of strain gauges.

3. Understand properties of adhesives .

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Resistive potentiometers and Strain gauges types
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the equation for Gauge factor. (Obj;- 3Out;-3)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic Year : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….11&12… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Inductive Sensors and Inductive Sensors Types

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about sensitivity and linearity of sensor.

2. Know types of Inductive Sensors.

3. Understand B-H loops of different materials.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Inductive Sensors Types.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss transformer type transducer. (Obj;- 3Out;-1,3)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2017-2018

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….13… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Capacitive Sensors Types

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about parallel type Capacitive Sensors .

2. Know about variable permittivity types.

3. Understand electrostatic transducer.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Capacitive Sensors Types
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the equation for sensitivity. (Obj;- 3Out;-1,3)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….14&15… Duration of Lesson: …. 90min……

Lesson Title: Problems on Inductive sensors and Capacitive Sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

2. Solve Problems on Inductive sensors
3. Solve Problems on Capacitive Sensors

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
  90 min: Problems on Inductive sensors and Capacitive Sensors
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the equation for sensitivity of Inductive sensors. (Obj;- 3Out;-1,3)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….16… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Ultrasonic sensors
<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

4. Know about sensor, transducer.

2. Know types of signals.

3. Understand principle of working of Ultrasonic sensors .

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Ultrasonic sensors
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss principle of working of Ultrasonic sensors . (Obj;-3Out;-1)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**…. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….17&18… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Basics of Thermal and Magnetic sensors and Gas thermometric sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

5. Know about Thermal sensor, transducer.

2. Know types of Magnetic sensors.

3. Understand principles of Gas thermometric sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.

90 min.: Introduction of Basics of Thermal and Magnetic sensors and Gas thermometric sensors.

- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Explain schematic of gas pressure thermometer. (Obj;- 3Out;-4)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….19… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Thermal expansion type, acoustic temperature sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

6. Know about Thermal expansion type sensors.

2. Know about acoustic temperature sensors .

3. Understand principles of Thermal expansion type, acoustic temperature sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Thermal expansion type, acoustic temperature sensors.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the equation for corrected velocity in acoustic temperature sensors . (Obj;-3Out;-4)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2017-2018

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….20… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Dielectric constant and refractive index thermo sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

7. Know about Dielectric constant sensor, transducer.

2. Know about refractive index thermo sensors .

3. Understand principles of Dielectric constant and refractive index thermo sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Dielectric constant and refractive index thermo sensors.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the equation for gas temperature measurement (Obj;- 3Out;-4)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….21… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Yoke coil sensors, coaxial type sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

8. Know about Yoke coil sensors.

2. Know about coaxial type sensors types .

3. Understand principles of Yoke coil sensors, coaxial type sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Yoke coil sensors, coaxial type sensors.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss about Yoke coil sensors, coaxial type sensors . (Obj;- 3Out;-4)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….22… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Force & Displacement sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

9. Know about force sensor, transducer.

2. Know types of Force & Displacement sensors.

3. Understand transduction principles of Force & Displacement sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Force & Displacement sensors
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss about Displacement sensors.. (Obj;- 3Out;-4)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….23&24… Duration of Lesson: …. 90min……

Lesson Title: Problems on Thermal Sensors and Magnetic Sensors

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

1. Solve Problems on Thermal Sensors .

2. Solve Problems on Magnetic Sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Solve Problems on Thermal Sensors and Magnetic Sensors.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Derive the equation for angular deflection of Thermometric sensor
(Obj;- 3,4Out;-4)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**………** Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: …25&26… Duration of Lesson: …. 90min……

Lesson Title: Introduction to Smart Sensors and Primary Sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

2. Know about Smart Sensors.

2. Know about Primary Sensors.

3. Understand transduction principles of Smart Sensors and Primary Sensors .

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: : Introduction to Smart Sensors and Primary Sensors
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss single chip pressure sensor. (Obj;- 2Out;-5)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**…….**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….27&28… Duration of Lesson: …. 90min……

Lesson Title: Excitation, amplification, filters, converters, Compensation & Defects

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about Excitation, amplification
2. Know about filters, converters
3. Understand about Compensation & Defects.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.

90 min.: Introduction to Excitation, amplification, filters, converters, Compensation & Defects.

- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Explain about Excitation, amplification (Obj;- 2,4Out;-5,6)

Signature of faculty

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….29… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Information coding/processing, Data communication& automation

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

3. Know about Information coding/processing.

2. Know about Data communication

3. Understand principles of automation.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Information coding/processing, Data communication& automation.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss about Information coding/processing, Data communication.
(Obj;- 3,4Out;-6,7)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….30… Duration of Lesson: …. 90min……

Lesson Title: Problems on Primary Sensors

<u>INSTRUCTIONAL/LESSON OBJECTIVES:</u>

On completion of this lesson the student shall be able to:

4. Know about Primary Sensors .

2. Know types of Primary Sensors signals.

3. Solve Problems on Primary Sensors

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Problems on Primary Sensors
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss about Primary Sensors . (Obj;- 3,4Out;-6,7)

Signature of faculty

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**.… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….31,32 ,33… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Flow rate sensors , Pressure sensors-Types

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

5. Know about Flow rate sensor, transducer.

2. Know types of Pressure sensors .

3. Understand transduction principles of Pressure sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Flow rate sensors , Pressure sensors-Types
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss negative pressure sensing silicon chip. (Obj;-3Out;-5,6)

Signature of faculty

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2017-2018

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….34&35… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Temperature sensors-Types, Torque & position sensors-Types

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about Torque & position sensors-Types

2. Know about Temperature sensors.

3. Understand transduction principles of Temperature sensors-Types, Torque & position sensors-Types.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Temperature sensors-Types, Torque & position sensors-Types
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss about Temperature sensors. (Obj;- 3Out;-5,6)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2017-2018

Semester : II

Name of the Program: EEE……… B.Tech………. Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….36&37… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Home appliance sensors-Types and Distance sensing-Types

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

2. Know about Distance sensing-Types.
3. Know types of Home appliance sensors

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.

90 min.: Introduction to Home appliance sensors-Types and Distance sensing-Types

- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss Home appliance sensors-Types (Obj;- 3Out;-5,6)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….38&39… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Medical Diagnostic sensors and Environmental monitoring sensors

INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

1. Know about Medical Diagnostic sensors

2. Know types of Environmental monitoring sensors

3. Understand principles of Environmental monitoring sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.

90 min.: Introduction to Medical Diagnostic sensors and Environmental monitoring sensors .

- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss Environmental monitoring sensors . (Obj;- 3Out;-5,6)

Signature of faculty

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

LESSON PLAN

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**…….**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…**GR17A3152**

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor
Lesson No: ….40&41… Duration of Lesson: …. 90min……

Lesson Title: Introduction of Pressure sensors-Types, problems
INSTRUCTIONAL/LESSON OBJECTIVES:

On completion of this lesson the student shall be able to:

2. Know about Pressure sensors-Types.

2. Solve problems on Pressure sensors.

3. Understand transduction principles of Pressure sensors.

TEACHING AIDS : OHP PROJECTOR, WHITEBOARD, MARKER, DUSTER.
TEACHING POINTS :

- 5 min.: Taking attendance
- 15 min.: Re collecting the contents of previous class.
- 90 min.: Introduction to Pressure sensors-Types.
- 10min.: Doubts clarification and Review of the class.

Assignment / Questions: Discuss the transduction principles of Pressure sensors . (Obj;- 3Out;- 5,6)

Signature of faculty

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(Autonomous)
Department of Electrical and Electronics Engineering

Academic Year: 2018-19 **Year: III** **Semester: I**	**MID Exam - I** **ELCTRICAL MEASUREMENTS & INSTRUMENTATION**	**Date:** **Duration:** **Max Marks: 15**

Note: Answer any three questions. All questions carry equal marks.

1	Calculate the Deflection angle for MI Instruments [CO1]
2	Summarize construction, working and Torque equation for Induction type Energy meter [CO3]
3	Conclude the working of Coordinate type AC Potentiometer[CO3]
4	a. Design a multi-range D.C milli ammeter using a basic movement with an internal resistance R_M= 50 ohms & a full scale deflection current I_M = 1mA. The range required are 0-10mA; 0-50mA; 0-100mA & 0-500mA [CO2] b. The arms of an A.C Maxwell bridge are arranged as follows : AB is an non inductive resistance of 1000 ohms in parallel with a capacitor of capacitance 0.5micro farad, BC is a non-inductive resistance of 600 ohms CD is an inductive impedance (unknown) and DA is a non inductive resistance of 400 ohms. If balance is obtained under these conditions, find the value of the resistance and the inductance of the branch CD [CO4]

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING & TECHNOLOGY
(Autonomous under JNTUH)
Dept. of EEE
ELECTRICAL MEASUREMENTS AND INSTRUMENTATION
III B.Tech- I Sem II Mid Examination

Time: 90 Min Date: Marks: 15

Answer any 3 Questions (All questions carry equal marks)

1)Articulate Ramp type & Stair case Ramp DVM's [CO6]

2)Generalize working of a CRT with a neat diagram. [CO5]

3) Summarize Photoelectric Transducers. [CO7]

4) Illustrate Flow Transducers.[CO7]

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING & TECHNOLOGY
(Autonomous under JNTUH)
Dept. of EEE
ELECTRICAL MEASUREMENTS AND INSTRUMENTATION
III B'Tech- I Sem II Mid Examination

Time: 20 Min Date: Marks: 5 Roll No:

---

1. An inverse transducer is a device which converts ( )
   a) An electrical quantity into a non-electrical quantity
   b) Electrical quantity into mechanical quantity
   c) Electrical energy into thermal energy
   d) Electrical energy into light energy
2. A strain gauge is a passive transducer and is employed for converting ( )
   a) Mechanical displacement into a change of resistance
   b) Pressure into a change of resistance
   c) Force into a displacement
   d) Pressure into displacement
3. S1: Transducer is a device which converts physical into electrical quantity ( )
   S2: Transducer is also called as sensor.
   a) S1 is true & S2 is false
   b) S2 is true & S1 is false
   c) Both S1 & S2 are true
   d) Both S1 & S2 are false
4. The principle of operation of LVDT is based on the variation of ( )
   a) Self-inductance
   b) Mutual inductance
   c) Reluctance
   d) Permanence
5. Materials used for piezo-electric effect are ( )
   a) Quartz
   b) Rochelle Salts
   c) Tourmaline
   d) All
6. Thermistor is used for measurement of ____________________
7. Piezo-electric transducers are________________________ transducers.
8. ____________________________ and _______________________ are analog methods for Angular Velocity
9. The transducers that converts the input signal into the output signal, which is a continuous function of time is known as ___________ transducer
10. LVDT stands for________________________

GOKARAJU RANGARAJU INSTITUTE OF ENGINEERING AND TECHNOLOGY
(Autonomous)
Department of Electrical and Electronics Engineering

Academic Year: 2018-19
Year: III
Semester: I

MID Exam – I (Objective)

Electrical Measurements & Instrumentation

Date:
Max Marks: 5

1. The following is not essential for the working of an indicating instrument

(a) Deflecting torque (b) Braking torque (c) Damping torque (d) Controlling torque [ ]

2. In a single-phase power factor meter, controlling torque is

(a) Provided by spring control (b) Provided by gravity control

(c) Provided by stiffness of suspension (d) Not required [ ]

3. The dielectric loss of a capacitor can be measured by which one of the following?

(a) Wien bridge (b) Owen bridge (c) Schering bridge (d) Maxwell bridge [ ]

4. Which of the following devices should be used for accurate measurement of low D.C. voltage?

(a) Small range moving coil voltmeter (b) D.C. potentiometer

(c) Small range thermocouple voltmeter (d) None of the above [ ]

5. How can a milli-ammeter be used as a voltmeter?

(a) By connecting a low resistance in parallel with the instrument

(b) By connecting a high resistance in parallel with the instrument

(c) By connecting a low resistance in series with the instrument

(d) By connecting a high resistance in series with the instrument [ ]

6. A moving coil ammeter has full scale deflection of 50 μA and coil of resistance 1000 Ω the value of shunt resistance to extend the range to 1 A is ________________ Ω.

7. An analog ammeter is an ______________________ instrument.

8. A _______________ device prevents the oscillation of the moving system and enables the later to reach its final position quickly.

9. Standardization of AC potentiometers is done by applying _________________ voltages.

10. Electro Dynamometer type PF meter has____________ fixed coils & ______moving coils.

III B. Tech II Semester Regular Examinations, Apr/May 2019

Sensors and Transducers

(Electrical and Electronics Engineering)

Time: 3 hours **Max Marks: 70**

PART – A

Answer ALL questions. All questions carry equal marks.

*****

10 * 2 Marks = 20 Marks

1). a Define Resolution and Threshold. [2]

b Distinguish between Active and Passive Transducers. [2]

c List various types of capacitive Sensors. [2]

d What is the principle of Ultrasonic Sensor? [2]

e What are different types of acoustic temperature Sensors? [2]

f Define dielectric constant and refractive index [2]

g Mention types of filters used in Smart Sensors. [2]

h Define Automation. [2]

i What are the position Sensors used in Automobiles? [2]

j What types of Sensors are used for Environmental Monitoring? [2]

PART – B

Answer any FIVE questions. All questions carry equal marks.

*****

5 * 10 Marks = 50 Marks

2. Discuss the Sensor characterization methods. Explain how a Sensor is electrically characterized? [10]

3. a) Derive Gauge factor for resistive strain gauge. [10]

b) Explain how the Capacitive Transducer is used for measurement of liquid level.

4. a) Discuss in detail about Thermal expansion type thermometric Sensors with necessary diagrams [10]

b) Describe the working principle of Yoke Coil Sensor with neat sketch.

5. What is basically the concept of Smart Sensors? What are the essential elements in such a unit? Show with the help of a diagram the arrangement of these elements. [10]

6. Sketch and explain about the Semiconductor flow and Pressure Sensors used in Automobiles. How and where are they installed and how do they function? [10]

7. a) Define the terms: [10]
   i) Sensitivity
   ii) Selectivity
   iii) Accuracy
   iv) Precision
   v) Non linearity

   b) Write short notes on Inductive Sensors.

8. a) Discuss about Data Communication used in Smart Transmitters. [10]

   b) Write about Sensors used in Medical Diagnostics.

*****

CODE: GR15A3162 **GR 15** **SET - 1**

III B. Tech II Semester Regular Examinations, May/June 2018
Sensors And Transducers

(Electrical and Electronics Engineering**)**

Time: 3 hours **Max Marks: 70**

PART-A

Answer ALL questions. All questions carry equal marks

****

10*2 Marks = 20 Marks

1)	a	Define Sensitivity.	[2]
	b	If m units of produced items have been checked n times and the average failure ratre at an instant of time t, is found to be 1%, what is the value of reliability function?	[2]
	c	List two examples of mechanical to electrical conversion sensors	[2]
	d	Define the Coil dissipation factor.	[2]
	e	What is Villari effect. Explain with an example.	[2]
	f	What are the commonly used liquids for vapour pressure thermometers.	[2]
	g	What is basically the concept of Smart sensor	[2]
	h	List the limitations of cubic spline interpolation method.	[2]
	i	Describe, on what principles do the microsensors work in biomedical systems.	[2]
	j	List different on-board automobile sensors	[2]

PART-B

Answer any FIVE questions. All questions carry equal marks

****

10*5 Marks = 50 Marks

2.	a	List the primary and secondary signals in sensor classification? Give examples of some magnetic-electric sensors and chemical-electrical sensors.	[6]
	b	If the input noise of a sensor is sinusoidal with a peak-peak value of 0.1mV, what would be the MDS?	[4]
3.	a	Derive Gauge factor for resistive strain gauge.	[5]
	b	Estimate the Quality factor for equivalent circuit of a Ferro magnetic coil	[5]
4.	a	How does the acoustic temperature work? What are the different types of acoustic sensors? Describe a pulse echo transit time technique of measuring temperature with requisite diagrams.	[5]
	b	What are the different types of magnetic sensors? On what principles do they work? Outline briefly.	[5]
5.	a	What are the different deviations that need be compensated in sensor systems. How is non-linearity taken care of in a present day smart sensor.	[5]
	b	Define the following terms: (i) Excitation, (ii) Amplification and (iii) Converters	[5]
6.	a	Draw a block diagram to show how sensors interact with the automated manufacturing process. Describe distance sensing in this context.	[5]
	b	Draw the sketch of a laser beam operated system of distance sensing and explain its operation. What types of detectors are used here?	[5]
7.	a	Demonstrate how a bath tub curve is associated with failures of transducer? What	[5]

		are the screening steps taken in standard silicon integrated sensors?	
	b	If the diaphragm diameter is 2.8cm (in a diaphragm type capacitive sensor), separation between the fixed and movable plate is 0.4cm in normal condition and the diaphragm is kept taut with a tension of 2kg/cm, what is the change in capacitance for an input differential pressure of 1kg/cm^2.	[5]
8.	a	What is ΔY effect? How is it used in practice for magnetic field sensing? What materials are specifically suitable for the purpose?	[5]
	b	Draw the sketch of a pyroelectric IR sensor as used in microwave oven. What is the material used for developing this sensor?	[5]

*****

Chapter 1

Getting Started!

1.1 WHAT ARE SENSORS/TRANSDUCERS?

Instrument Society of America defines a sensor or transducer as *a device which provides a usable* **output** *in response to a specified* **measurand**. Here, the output is defined as an 'electrical quantity' and measurand as a 'physical quantity, property, or condition which is measured.'

This definition can now be generalized by extending 'electrical quantity' to any type of signal such as mechanical and optical and extending 'physical quantity, property, or condition being measured' to those of nature—chemical and biochemical and so on.

1.2 PRINCIPLES

Different views exist over a common definition of both sensors and transducers. As a result, different definitions have been adopted for an easy distinction. One set of definitions holds as—an element that senses a variation in input energy to produce a variation in another or same form of energy is called a *sensor* whereas a *transducer* uses transduction principle to convert a specified measurand into usable output. Thus, a properly cut piezoelectric crystal can be called a sensor whereas it becomes a transducer with appropriate electrodes and input/output mechanisms attached to it.

In general, however, the sensing principles are physical or chemical in nature and the associated gadgets are only secondary and hence, the distinction is gradually being ignored. The principles can be grouped according to the form of energy in which the signals are received and generated. A matrix-like arrangement can thus be obtained for elaborating the principles. Signals can be divided into six categories on the basis of energies generated or received, namely (i) mechanical, (ii) thermal, (iii) electrical, (iv) magnetic, (v) radiant, and (vi) chemical.

Table 1.1 enlists physical and chemical transduction principles alongwith some elaborations.

Table 1.1 Physical and chemical transduction principles

Output Input	*Mechanical*	*Thermal*	*Electrical*	*Magnetic*	*Radiant*	*Chemical*
Mechanical	Mechanical including acoustic effects. eg: diaphragm.	Friction effects, cooling effects. eg: thermal flowmeter.	Piezoelectricity, piezoresistivity, resistive, inductive, and capacitive changes.	Piezomagnetic effects.	Photoelasticity, interferometry, Doppler effect.	—
Thermal	Thermal expansion. eg: expansion thermometry.	—	Seebeck effect, pyroelectricity, thermoresistance. eg: Johnson noise.	—	Thermo-optical effects. eg: liquid crystals, thermo-radiant emission.	Thermal dissociation, thermally induced reaction.
Electrical	Electrokinetic effects. eg: inverse piezoelectricity.	Peltier effect, Joule heating.	Charge controlled devices, Langmuir probe.	Biot-Savart's electromagnetic law.	Electroluminescence, Kerr effect.	Electrolysis, electrically induced reaction. eg: electromigration.
Magnetic	Magnetostriction, magnetometers.	Magnetothermal effects (Righi-Leduc effect).	Ettinghaussen-Nernst effect, Galvanomagnetic effect. eg: Hall effect, magnetoresistance.	—	Magneto-optical effects. eg: Faraday effect, Cotton-Mouton effect.	—
Radiant	Radiation pressure.	Bolometer, thermopile.	Photoelectric effects. eg: photovoltaic cell, LDR's.	—	Photorefractivity, photon induced light emission.	Photodissociation, photosynthesis.
Chemical	Photoacoustic effect, hygrometry.	Thermal conductivity cell, calorimetry.	Conductimetry, potentiometry, voltametry, flame-ionization, chem FET.	Nuclear magnetic resonance.	Spectroscopy. eg: emission and absorption types, Chemiluminescence.	—

Table 1.1 produces a matrix of 6 × 6 entries, each of which can be another submatrix whose rows and columns are designated by the signal types within each major domain as shown in Table 1.2. There are some entries that are involved with more than one input or output as in the case of the thermomagnetic or galvanomagnetic effects, both of which have two inputs. Thus, Hall effect has electrical and magnetic inputs. They can, therefore, go to a different location in the matrix. In such a situation, application aspect is given more importance which fixes the entry position. However, the above classification is only to provide an illustration to represent the physical and chemical effects that form a variety of sensors.

Table 1.2 Energy types and corresponding measurands

Energy	*Measurands*
Mechanical	Length, area, volume, force, pressure, acceleration, torque, mass flow, acoustic intensity, and so on.
Thermal	Temperature, heat flow, entropy, state of matter.
Electrical	Charge, current, voltage, resistance, inductance, capacitance, dielectric constant, polarization, frequency, electric field, dipole moment, and so on.
Magnetic	Field intensity, flux density, permeability, magnetic moment, and so forth.
Radiant	Intensity, phase, refractive index, reflectance, transmittance, absorbance, wavelength, polarization, and so on.
Chemical	Concentration, composition, oxidation/reduction potential, reaction rate, pH, and the like.

1.3 CLASSIFICATION

It is very difficult to classify sensors under one criterion and hence, different criteria may be adopted for the purpose. Some of these include:

1. transduction principles using physical or chemical effects,
2. primary input quantity, that is, the measurand,
3. material and technology, that have acquired more importance lately,
4. application, and
5. property.

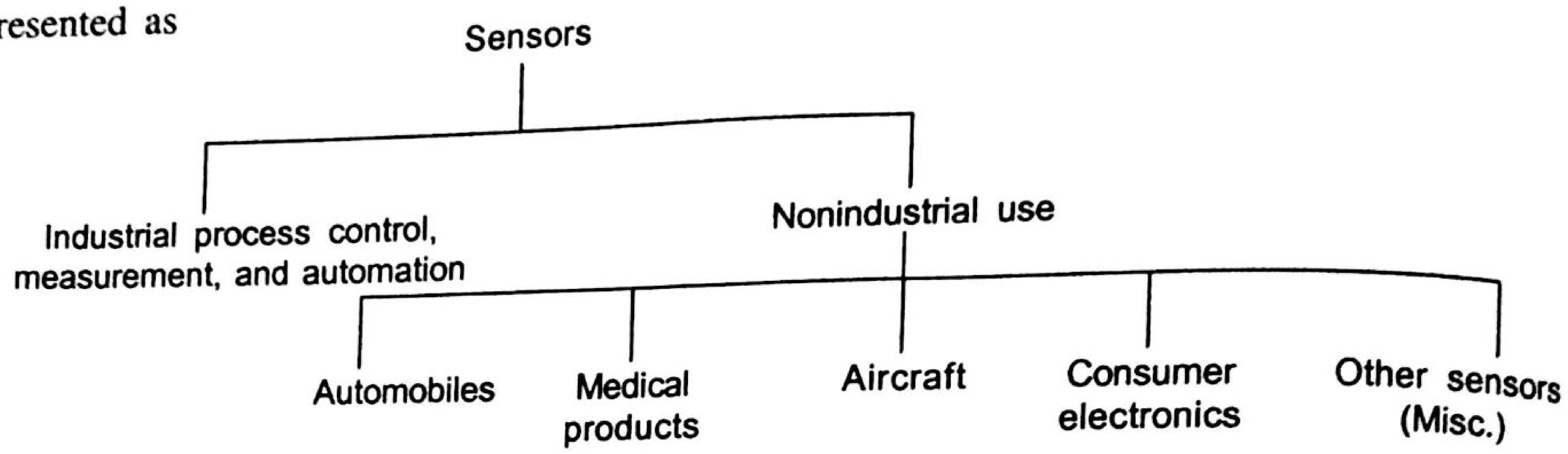
Others of consequence are cost and accuracy.

People would choose their own criterion to suit their areas of activity. For example, development engineering groups prefer material and technology as the basis. However, the *transduction principle* is the basic criterion which should be followed for a systematic approach. Table 1.1 presents such a grouping.

Another very preliminary classification or subclassification as it may be, is based on the energy or power supply requirements of the sensors. This means that some sensors require power supply and there are some that do not. As a result, the sensors are called *active* and *passive* respectively. Sometimes, terms such as *self-generating* and *modulating* are used to qualify these.

Conventional sensors are now aptly supported by technologies which have yielded Micro Electro Mechanical Sensors (MEMS), CMOS image sensors, displacement and motion detectors and biosensors. Similarly, Coriolis, magnetic and ultrasonic flowmeters, photoelectric, proximity, Hall effect, infrared, integrated circuit (IC), temperature, radar-based level sensors are also relatively modern.

Application based classification is another very convenient way to show the segmentation in a very broad manner. But new technologies coupled with the existing ones can display a good segmentation when classified based on some property. Application based classification is represented as



Property based classification is much more elaborate and to a certain extent exhaustive. Here, the subdivision is in technology scale. A brief presentation of this segmentation is given in Table 1.3.

Table 1.3 Property based classification

	Property				
	Flow	*Level*	*Temperature*	*Pressure*	*Proximity and displacement*
Technology	Differential pressure, positional displacement, vortex, thermal mass, electromagnetic, Coriolis, ultrasonic, anemometer, open channel.	Mechanical, magnetic, differential pressure, thermal displacement, vibrating rod, magnetostrictive, ultrasonic, radio frequency, capacitance type, microwave/radar, nuclear.	Filled-in systems, RTDs, thermistors, IC, thermocouples, inductively coupled, radiation (IR).	Elastic, liquid-based manometers, inductive/LVDT, piezoelectric, electronic, fibre optic, MEMS, vacuum.	Potentiometric, inductive/LVDT, capacitive, magnetic, photoelectric, magnetostrictive, ultrasonic.

Table 1.3 *(cont.)*

	Property				
	Acceleration	*Image*	*Gas and chemical*	*Biosensors*	*Others*
Technology	Accelerometers, gyroscopes.	CMOS, CCDs (charge coupled devices).	Chemical bead, electrochemical, thermal conductance, paramagnetic, ionization, infrared, semiconductor.	Electrochemical, light-addressable potentiometric (LAP), surface plasmon resonance (SPR), resonant mirror	Mass, force, load, humidity, moisture, viscosity.

CMOS image sensors have low resolution compared to earlier developed charge coupled devices but their small size, less cost, and low power consumption are considered better substitutes for CCDs as camera-on-a-chip sensors.

In biosensors group, SPR and LAP are relatively new optical technology-based sensors. Accelerometers are separately grouped mainly because of their role in the development of future automobiles, aircrafts, in industrial sector and in lesser developed areas of toys, videograms, physical therapy and so on, which is increasing sharply specially when the micromachining processes are decreasing the size considerably retaining the usual level of performance. Table 1.4 shows the emerging sensor technologies with current and future application schedules as a chart.

Table 1.4 Emerging sensor technologies

Sensors

	Image sensors	*Motion detectors*	*Biosensors*	*Accelerometers*
	Technology: CMOS-based	*Technology: IR, ultrasonic, microwave/radar*	*Technology: electrochemical*	*Technology: MEMS-based*
Applications	Traffic and security surveillance, blind-spot detection as autosensors (robots etc.), video conferencing, consumer electronics, biometrics, PC imaging	Obstruction detection (robots, auto), security detection (intrusion), toilet activation, kiosks videograms and simulations, light activation	Water testing, food testing (contamination detection), medical care device, biological warfare agent detection	Vehicle dynamic system (auto), patient monitoring (including pace makers etc.)

1.4 PARAMETERS

The normal environmental conditions from where the data are made available through sensors are noisy and keep changing. The high fidelity mapping of such a varying reality requires extensive studies of 'fidelity' of the sensors themselves. Or, in other words, sensors are required to be appropriately characterized. These are done in terms of certain parameters and characteristics of the sensors.

1.4.1 Characteristics

Sensors like measurement systems have two general characteristics, namely 1. static, and 2. dynamic.

Static characteristics

(a) *Accuracy specified by inaccuracy* or *usually error:* which is given by

$$\varepsilon_a\% = \frac{x_m - x_t}{x_t} \times 100 \tag{1.1}$$

where

t stands for true value,
m for measured value, and
x stands for measurand.

This is often expressed for the full scale output (fso) and is given by

$$\varepsilon_{\text{fso}}\% = \frac{x_m - x_t}{x_{\text{fso}}} \times 100 \tag{1.2}$$

Obviously,

$$|\varepsilon_{\text{fso}}| \le |\varepsilon_a|$$

For multi-error systems, the overall performance in terms of error can be assessed either through (i) the worst case approach which assumes that all errors add up in the same direction so that the overall error is very high, being the linear sum of all the performance errors, or through (ii) the root mean square approach which is optimistic as well as practical, when the total performance error is assessed as

$$\varepsilon_0 = \left[\sum_i (\varepsilon_i)^2\right]^{1/2} \tag{1.3}$$

(b) *Precision:* describes how far a measured quantity is reproducible as also how close it is to the true value.

The term 'repeatability' is close to precision which is the difference in output y at a given value of the input x when obtained in two consecutive measurements. It may be expressed as % FSO. Figure 1.1 shows the plot of repeatability.

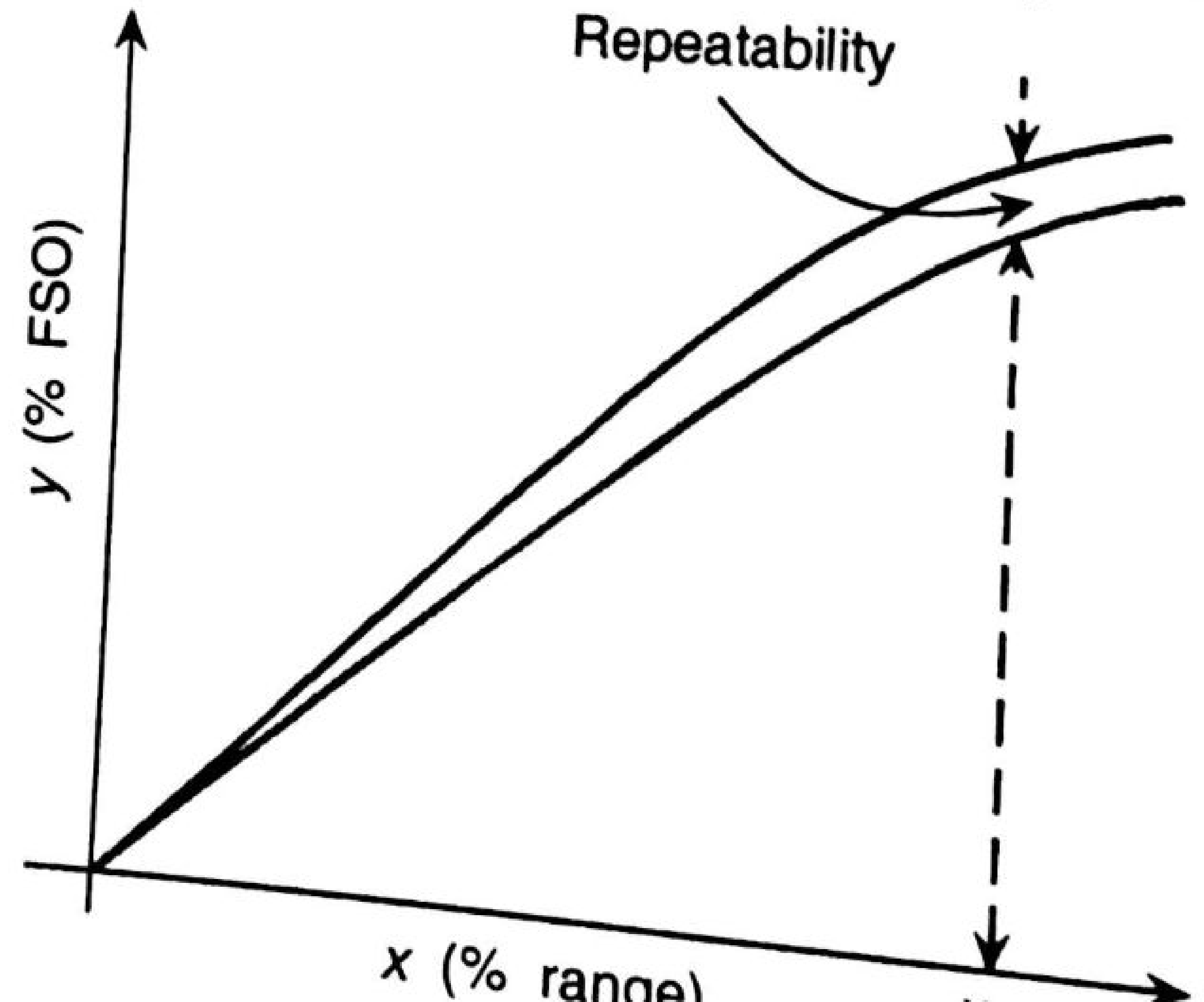


Fig. 1.1 Repeatability in y–x coordinates.

(c) *Resolution:* is defined as the smallest incremental change in the input that would produce a detectable change in the output. This is often expressed as percentage of the measured range, *MR*. The measured range is defined as the difference of the maximum input and the minimum input, that is, $MR = x_{\max} - x_{\min}$. For a detectable output Δy, if the minimum change in x is $(\Delta x)_{\min}$, then the maximum resolution is

$$R_{\max}(\%) = \frac{100(\Delta x)_{\min}}{MR} \tag{1.4}$$

Over the range of operation, an average resolution has also been defined as

$$R_{\text{av}}(\%) = 100 \frac{\sum_{1}^{n} \Delta x_i}{n \cdot MR} \tag{1.5}$$

(d) *Minimum Detectable Signal (MDS):* Noise in a sensor occurs because of many reasons—internal sources or fluctuations due to externally generated mechanical and electromagnetic influences. Noise is considered in detail, on individual merits and often an equivalent noise source is considered for test purposes.

If the input does not contain any noise, the minimum signal level that produces a detectable output from the sensor is determined by its noise performance or noise characteristics. For this, the equivalent noise source is connected to the input side of the ideal noiseless sensor to yield an output which is the actual output level of the sensor. The MDS is then taken as the RMS equivalent input noise. When signal exceeds this value, it is called a detectable signal.

(e) *Threshold:* At the zero value condition of the measurand, the smallest input change that produces a detectable output is called the threshold.

(f) *Sensitivity:* It is the ratio of the incremental output to incremental input, that is

$$S = \frac{\Delta y}{\Delta x} \tag{1.6}$$

In normalized form, this can be written as

$$S_n = \frac{\Delta y/\Delta x}{y/x} \tag{1.7}$$

If sensitivity or the output level changes with time, temperature and/or any other parameters without any change in input level, drift is said to occur in the system which often leads to instability.

(g) *Selectivity and specificity:* The output of a sensor may change when afflicted by environmental parameters or other variables and this may appear as an unwanted signal. The sensor is then said to be *non-selective*. It is customary to define selectivity or specificity by considering a system of n sensors each with output $y_k (k = 1, 2, \ldots, n)$. The partial sensitivity S_{jk} is defined as the measure of sensitivity of the kth sensor to these other interfering quantities or variables x_j as

$$S_{jk} = \frac{\Delta y_k}{\Delta x_j} \tag{1.8}$$

A selectivity matrix would thus be obtained with S_{jk} as the jkth entry. Obviously, an ideally selective system will have only diagonal entries S_{jj} in the selectivity matrix. An ideally specific system is characterized by having a matrix with a single entry in the diagonal. Following relationship describes selectivity, λ;

$$\lambda = \min \left[\frac{S_{jj}}{\sum_{k=1}^{n} |S_{jk}| - |S_{jj}|} \right] \qquad j = 1, 2, \ldots, n \tag{1.9}$$

Thus, for a selective group, denominator tends to zero and $\lambda \to \infty$. Also, specificity is a special case of selectivity.

(h) *Nonlinearity:* Deviation from linearity, which itself is defined in terms of superposition principles, is expressed as a percentage of the full scale output at a given value of the input. Nonlinearity can, however, be specified in two different ways, namely (i) deviation from best fit straight line obtained by regression analysis, and (ii) deviation from a straight line joining the end points of the scale. These are shown in Figs. 1.2(a) and (b). The maximum nonlinearity in the first method is always less than the maximum nonlinearity in the second one. The figure is actually half.

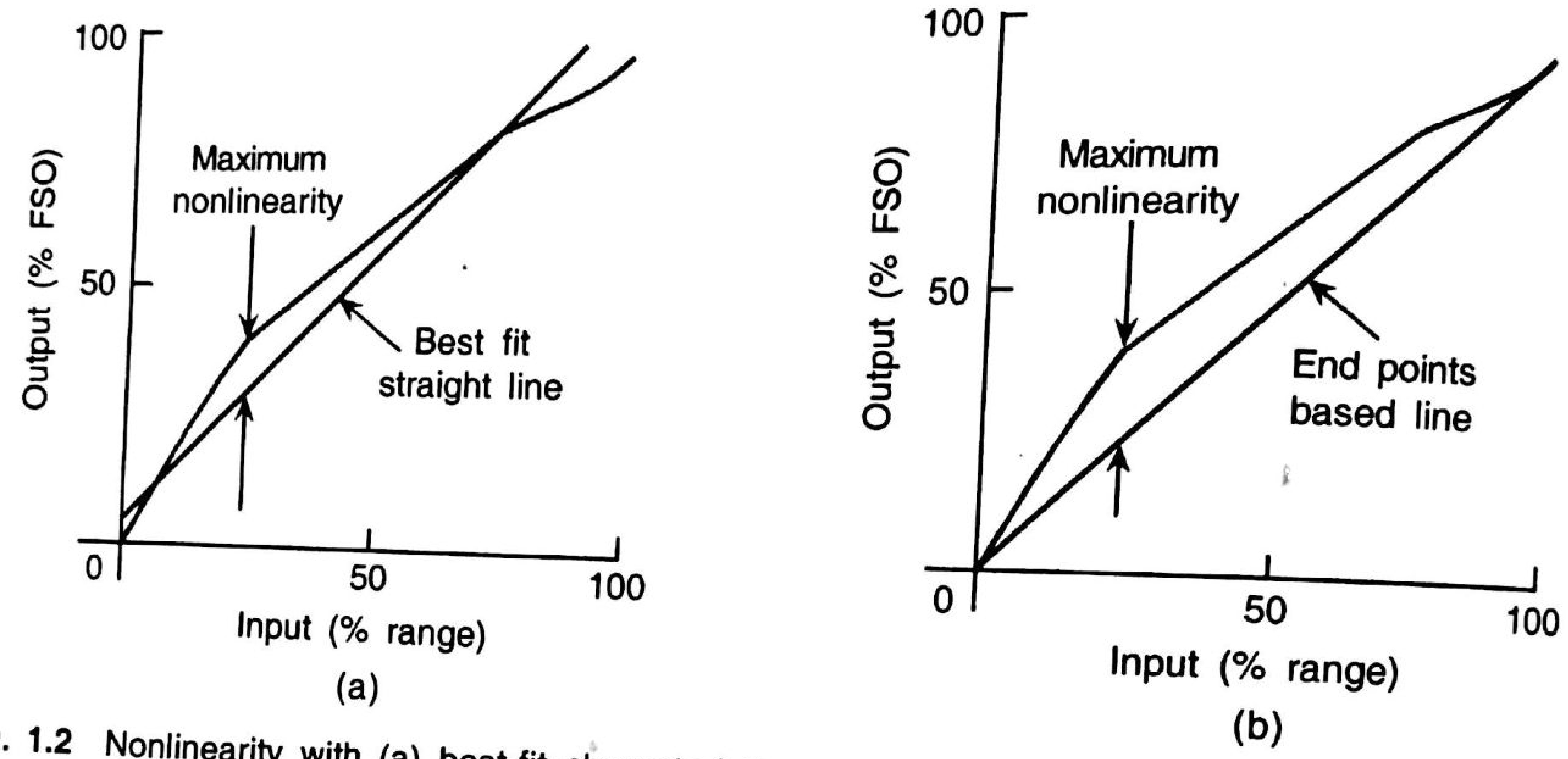


Fig. 1.2 Nonlinearity with (a) best-fit characteristics and (b) terminal-based characteristics.

A consequence of nonlinearity is *distortion* which is defined as the deviation from an expected output of the sensor or transducer. It also occurs due to presence of additional input components. If deviation at each point of the experimental curve is negligibly small from the corresponding point in the theoretical curve or from a curve made by using least square or other standard fits, the sensor is said to have *conformance* which is quantitatively expressed in % FSO at any given value of the input.

(i) *Hysteresis:* It is the difference in the output y of the sensor for a given input x when x reaches this value in upscale and downscale directions as shown in Fig. 1.3. The causes

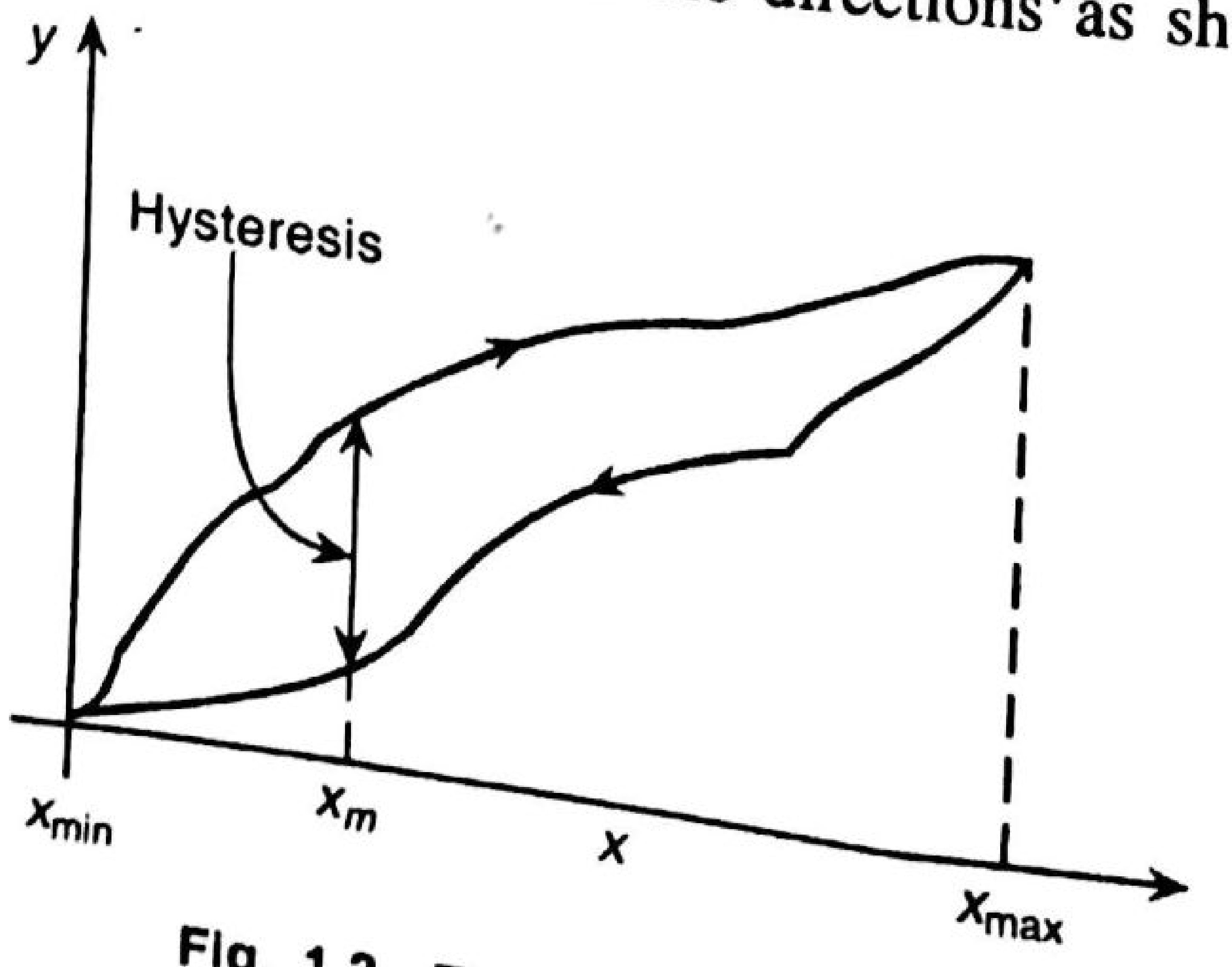


Fig. 1.3 The hysteresis curve.

are different for different types of sensors. In magnetic types, for example, it is the lag in alignment of the dipoles, in semiconductor types it is the injection type slow traps producing the effect, and so on.

(j) *Output impedance:* It is a characteristic to be considered on individual merit. It causes great restriction in interfacing, specifically in the choice of the succeeding stage.

(k) *Isolation and grounding:* Isolation is necessary to eliminate or at least reduce undesirable electrical, magnetic, electromagnetic, and mechanical coupling among various parts of the system and between the system and the environment. Similarly, grounding is necessary to establish a common node among different parts of the system with respect to which potential of any point in the system remains constant.

Dynamic caracteristics

These involve determination of transfer function, frequency response, impulse response as also step response and then evaluation of the time-dependent outputs. The two important parameters in this connection are (a) fidelity determined by dynamic error and (b) speed of response determined by lag.

For determining the dynamic characteristics, different specified inputs are given to the sensor and the response characteristics are studied. With step input, the specifications in terms of the time constant of the sensor are made. Generally, the sensor is a single time constant device and if this time constant is τ, then one has the specifications as given in Table 1.5.

Table 1.5 % Response time of the sensors

% Response time	*Value in terms of τ*
$t_{0.1}$ or 10	0.104τ
$t_{0.5}$ or 50	0.693τ
$t_{0.9}$ or 90	2.303τ

This gives $t_{0.9}/t_{0.5} = 3.32$ which is taken as a quick check relation.

Impulse response as well as its Fourier transform are also considered for time domain as well as frequency domain studies.

1.5 ENVIRONMENTAL PARAMETERS (EP)

These are the external variables such as temperature, pressure, humidity, vibration, and the like which affect the performance of the sensor. These parameters are not the ones that are to be sensed.

For non-temperature transducers, temperature is the most important environmental parameter (EP). For any EP, the performance of the transducer can be studied in terms of its effect on the static and dynamic characteristics of the sensor as has already been discussed. For this study, one EP at a time is considered variable while others are held constant.

1.6 CHARACTERIZATION

Characterization of the sensors can be done in many ways depending on the types of sensors, specifically microsensors. These are electrical, mechanical, optical, thermal, chemical, biological and so on.

Electrical characterization

It consists of evaluation of electrical parameters like (a) impedances, voltage and currents, (b) breakdown voltages and fields, (c) leakage currents, (d) noise, (e) cross talk, and so on.

The knowledge of the sensor 'output impedance' is very important for coupling the measuring equipment to it. For voltage sensitive sensors, the ratio of the input impedance of the measuring equipment to the output impedance of the transducer/sensor should be very high while for current sensitive sensors, reverse is true.

'Breakdown' of the insulating parts of the sensor is very critical as the health of the system depends on it. For metal-insulator-metal (MIM) or for metal-insulator-semiconductor (MIS) structures, the breakdown of the insulating film is studied by the system of Fig. 1.4. Three different types of breakdown are of interest for such a film: (i) dielectric strength, (ii) wear out, and (iii) current induced breakdown. Tests are also different and are performed with a particular independent parameter for a particular case. The three case studies are illustrated in Figs. 1.5(a), (b), and (c).

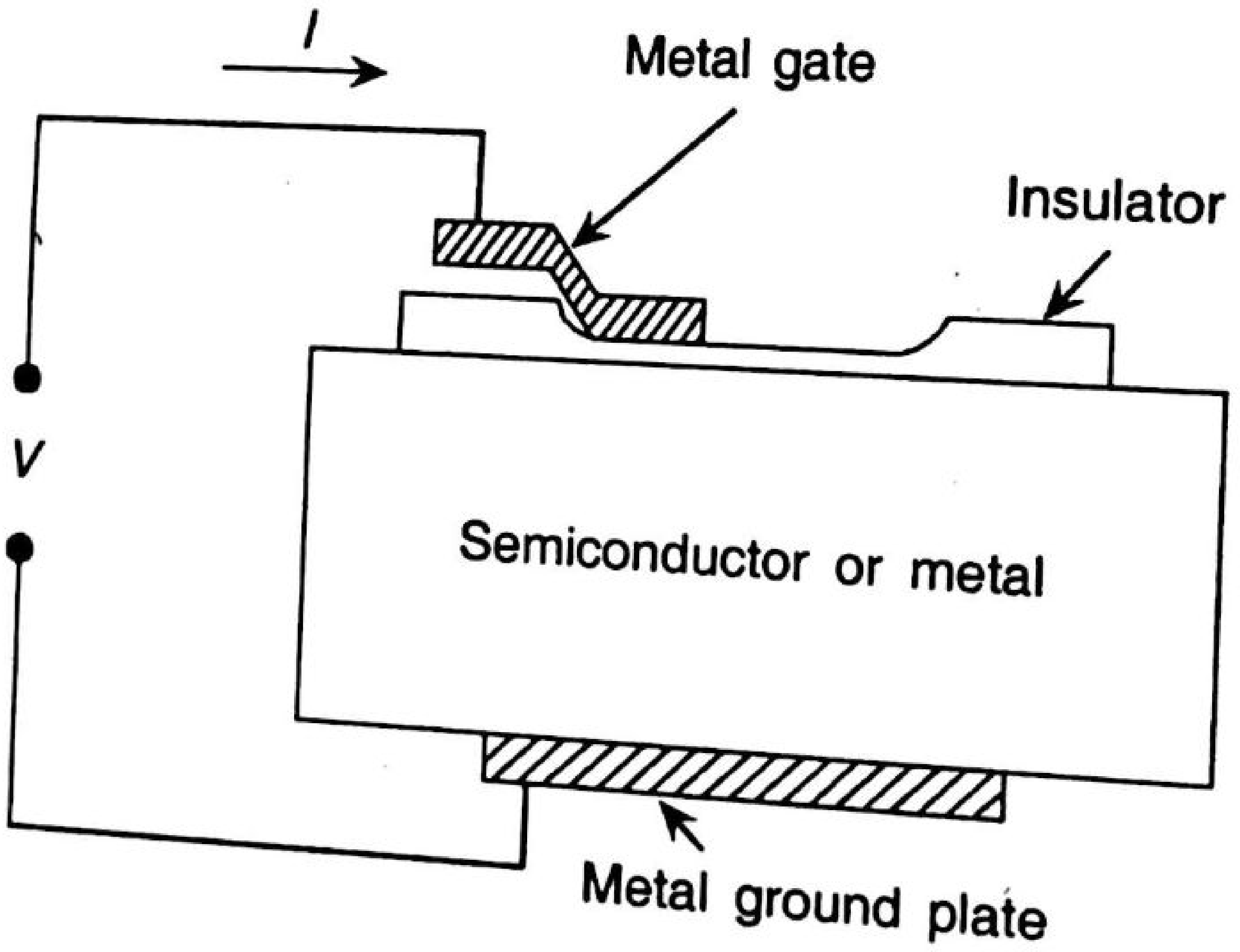
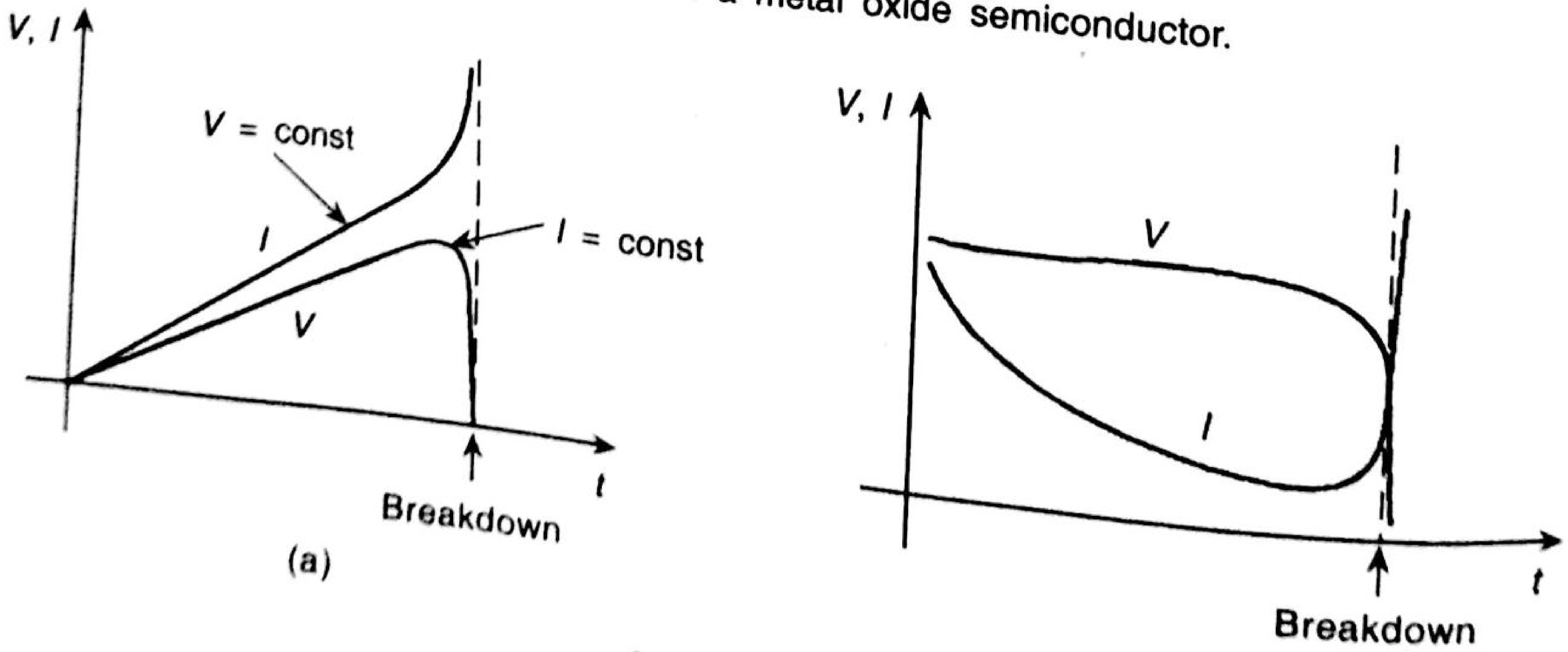


Fig. 1.4 Structure of a metal oxide semiconductor.



(a)

(b)

Fig. 1.5 Cont.

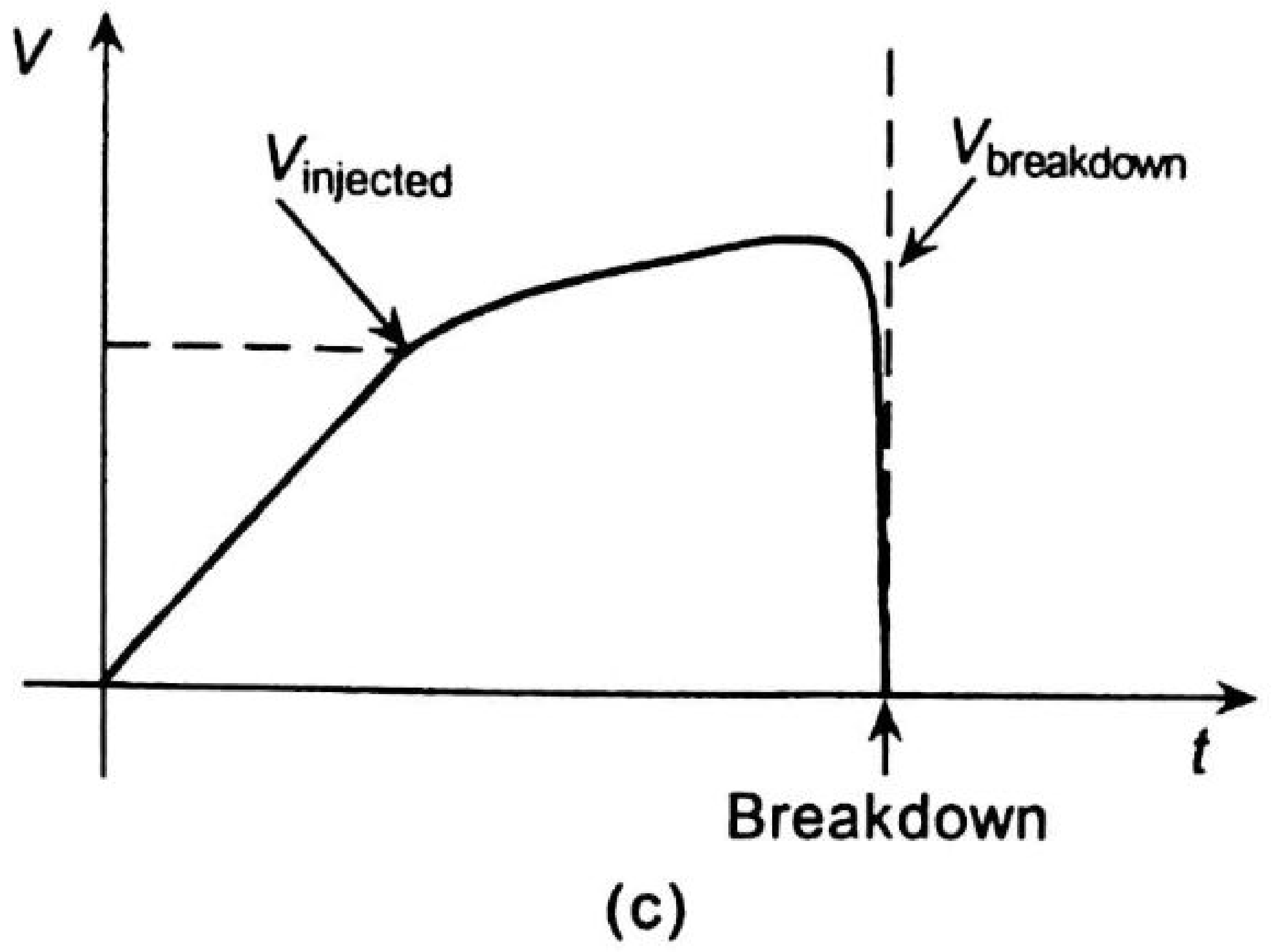


Fig. 1.5 Breakdown characteristics: (a) dielectric strength, (b) wear out, (c) current induced type.

Breakdown generally implies a sudden or 'avalanche' change in the voltage or current—voltage dropping to a negligible value and current rising to a very high value. Breakdown may be extrinsic or intrinsic though the mechanism in either case is basically the same. There occurs a high local field in the material which may be defect-induced which then is called *extrinsic*. However, if this is high field-induced, it is called *intrinsic* type. In the latter case, the high field induces microvoids to generate defects leading it to behave as the extrinsic type.

'Leakage current' measurement specifies the sensor quality, specifically its insulating quality as also the quality of p–n junctions wherever it exists.

'Noise' comes from electromagnetic interference, ac magnetic fluctuation, 50Hz supply pick up, mechanical or acoustical vibration, or photon-induced output. Sensors are to be characterized for noise testing for immunity to such noise. For testing purposes, different noise sources are developed.

In multichannel or array sensors, 'crosstalk' may occur due to overlapping of signals between the two adjacent transducer elements. It may, however, occur in a single transducer system because of inductive or capacitive coupling or coupling through the common voltage source during transduction inside the element. It is measured using correlation techniques.

Mechanical and thermal characterization

It involves mechanical and thermal properties related to the overall reliability and integrity of the transducer, as well as relevant transduction process. Reliability is an important aspect of characterization. By means of testing, the functional and reliable portion of a batch of sensors or transducers is identified. Basically, failure analysis is performed and the mechanism of failure is attempted to be eliminated and thereby reduce the subsequent failures. In fact, the above two approaches are supplementary to each other.

Failure of transducers can be divided into three different categories:

(i) Catastrophic early life failures, often called infant mortality,
(ii) Short term drifts in the sensor parameters, and
(iii) Long term drifts and failures.

Catastrophic failure of the sensors is the complete failure in the normal operation. It is called *wear out* if it occurs in later life.

Short term and long term drifts are, in effect, changes in sensor parameters and are, therefore, to be studied more intensely for the sensor characterization.

The reliability of an item is given by what is known as reliability function, $R(x)$ which is the probability that the item would survive for a stated interval, say, between 0 and x. If $F(x)$ is the probability of failure, then

$$R(x) = 1 - F(x) = \int_{x}^{+\infty} f(t)\,dt \tag{1.10}$$

$$= \frac{\text{No. of 'sound' components at instant } x}{\text{Total no. of components at } x = 0} \tag{1.11}$$

The probability of failure $F(x)$ is actually a cumulative distribution function and in reliability statistics, the distribution functions that are used may have the following characteristics: (i) normal, (ii) exponential, (iii) log-normal, (iv) gamma, and (v) Weibull, depending on the usage.

In general, the failure rate has a time dependency as shown in Fig. 1.6. The curve between failure rate and time appears like a bath tub which can be divided into three distinct zones— Zone 1 is the infant mortality zone, Zone 2 is the working zone with a constant failure rate, and Zone 3 is the wear out zone. As the normal working life is usually very long, estimating failure is tested by 'accelerated ageing test'. Before this ageing test, screening steps are taken to isolate the defective transducers. These steps vary depending on the types of the transducers. For standard silicon integrated type sensors (SITS), the typical tests that are performed are briefly discussed here.

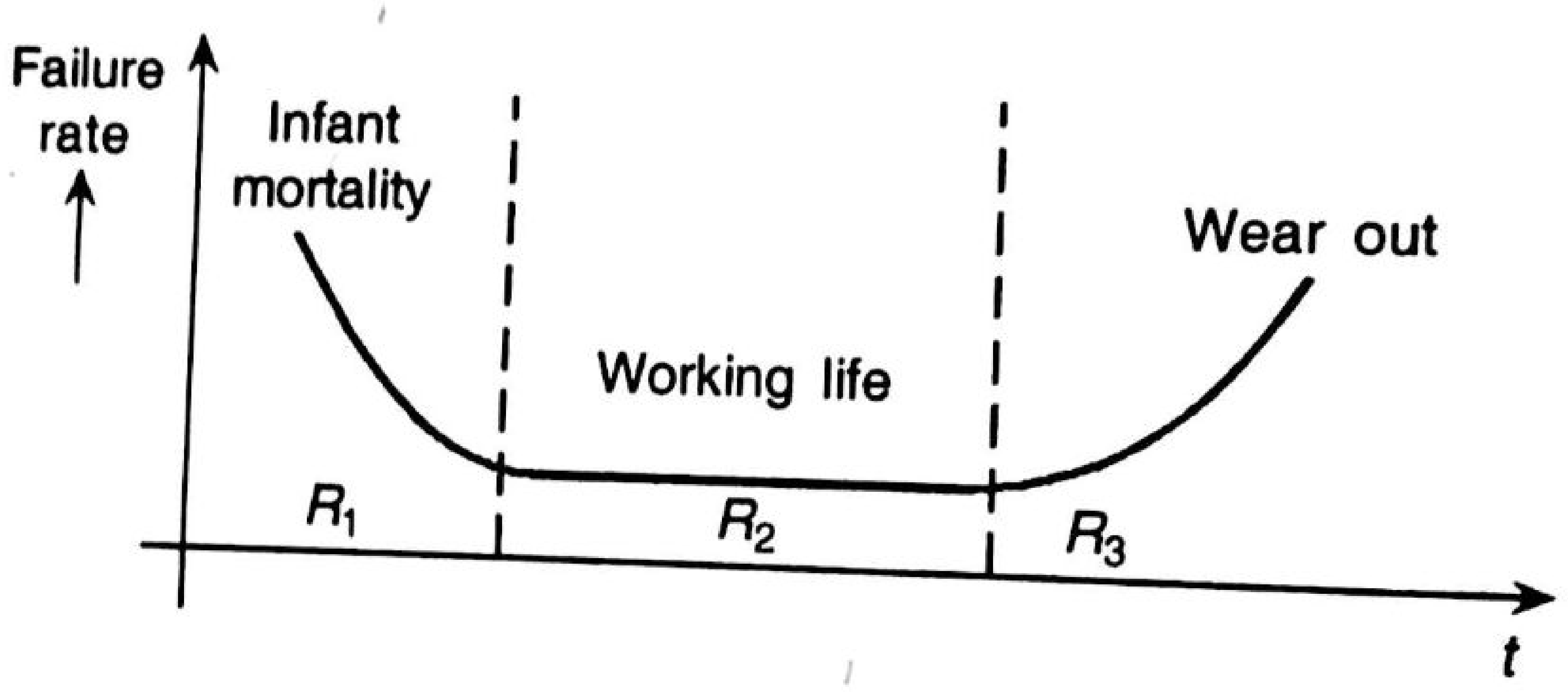


Fig. 1.6 The bath-tub curve.

High temperature burn in: The sensors are subjected to a high temperature over a stipulated period, usually at 125°C for 48 hours for SITS, when the defective units are burnt out and the remaining ones are expected to run for the expected life.

High temperature storage bake: The units are baked at a high temperature, usually at 250°C for SITS, for several hours when the instability mechanisms such as contamination, bulk defects, and metallization problems are enhanced in some units which were initially defective. These units are then screened out.

Electrical overstress test: Where progressively larger voltages upto 50% in excess of specification are applied over different intervals of time so that failures due to insulation, interconnection or oxide formation can occur in some units which were originally defective and are screened out.

Thermal shock test: Mainly done for packaging defects where the units are subjected to a temperature between −65° and 125°C for about 10 seconds for every temperature. The time is gradually increased to 10 minutes and the cycle is repeated 10 times. The failed units are rejected.

Mechanical shock test: Also for packaging, this test is performed by dropping the units from a specified height that varies from 3 to 10 m. Alternately, the unit is shaken by attaching it to a shaking table for a specified period of time.

As has already been mentioned, real-time operational test for reliability is difficult to perform so that accelerated ageing test has been proposed. The test should simulate the real ageing process in a much shorter time. High stress is imposed on the sensor and results from such a test are used to predict the performance in the normally stressed condition. The results should be interpreted for (i) true accelerated ageing, (ii) valid extrapolation to obtain expected performance under normal conditions, and (iii) determining the acceleration factor for the scaling, that is, how many hours of normal operation correspond to 1 hour of accelerated operation.

Appropriate models have been developed for the purpose and failures with respect to specified parameters such as leakage current, temperature, and so forth are predicted.

Optical characterization

It is usually done by ascertaining absorption coefficient, refractive index, reflectivity and the like. Here, again the consideration of the individual merit comes in.

Chemical/biological characterization

This is basically a test of the sensor with respect to its resistance to chemicals or corrosion in industrial as well as biological environment. Safety is an important aspect here particularly in case of biomedical sensors which should be tested against toxic or harmful effects in the prescribed environment.

REVIEW QUESTIONS

1. What are primary and secondary signals in sensor or transducer classification? Give examples of some magnetic-electric sensors and chemical-electrical sensors.
2. (a) What do you mean by minimum detectable signal? If the input noise of a sensor is sinusoidal in nature with a peak-to-peak value of 0.1 mV, what would be the MDS? [*Hint:* The rms value of the noise is the MDS which is $0.05/(2)^{1/2} = 0.035$ mV]

   (b) Define selectivity and specificity. How are they related?
3. Discuss the sensor characterization methods. How is a sensor electrically characterized? Support your answer with diagrams.
4. What are the different types of failures possible in a sensor? How do you define reliability function? If m units of produced items have been checked n times and the average failure at an instant of time, t, is found to be 1%, what is the value of the reliability function?
   [*Hint:* As per definition $R(t) = 1 - 0.01 = 0.99$]
5. How is a 'bath tub' curve associated with failures of transducers? What are the screening steps taken in standard silicon integrated sensors?

Chapter 2

Mechanical and Electromechanical Sensors

2.1 INTRODUCTION

The controversy associated with formal definitions of sensors and transducers has apparently been resolved but not as yet the one with the classification perhaps, although, a generalized concept has been introduced in Chapter 1 in terms of input-output or primary and secondary signals.

Mechanical sensors, are those which have a mechanical quantity as the input and the output may be a quantity such as an electrical, magnetic, optical, thermal, and so on. In such a case, motion, displacement, speed, velocity, force, acceleration, torque and other such quantities should be measured by mechanical sensors. Process variables like pressure, flow, and level should also be considered as mechanical inputs and sensors for measurement of such variables should also be considered as mechanical sensors.

In many such sensors 'electromechanical coupling' is involved. As such, the primary objective is to convert the input form into an electrical output form for convenience of processing and display. In this respect, mechanical sensors are also termed as electromechanical or mechano-electrical sensors. It would, however, be seen that many sensors may be categorized under more than one category without being inappropriate. In the proceedings, appropriate references may be made for such multiplacement.

Further, same sensor is often used for measuring different variables by appropriate adaptation. In this way, it is not always possible to uniquely identify a sensor for a specific function. It is, therefore, perhaps more appropriate to discuss the sensors in the way they are formed and developed and not in the way a specific variable is measured.

Many mechanical variables are secondary in nature such as the 'motion' of the tip of a bimetallic element (thermal sensor) which is the result of the temperature variation of the element. Temperature, here, is the primary variable or input. The tip motion is angular or rotational. Similarly, a diaphragm actuated by pressure has a linear motion in its central part, or a bellows element actuated by pressure has a linear displacement of its free end. In contrast, a shaft under a torque with one end rigidly held has its free end in rotation.

Such rotational or translational displacements are measurable by various means. But direct measurement by using a pointer attached to the 'moving' end often leads to poor accuracy because of small movement and/or low resolution. Instead, resistive potentiometers, LVDT's, capacitive sensors, and so forth are used, not only for displacements alone but also for various other related variables, as has already been mentioned.

2.2 RESISTIVE POTENTIOMETERS

Resistive potentiometer is a kind of variable resistance transducer. Others in this category are strain gauges, RTD, thermistor, wire anemometer, piezoresistor and many more. A typical scheme of the potentiometer is shown in Fig. 2.1. This is a precision wire-wound potentiometer which is used as a sensor. A major advantage with this type is its large output. Resolution and noise are important aspects to be discussed in connection with it. For the former, the cross-section of the n-turn winding is shown in Fig. 2.2(a) with the wiper in two different possible positions: (i) touching only one wire and (ii) touching two turns is important as is obvious. In case (i) for a voltage supply V to the potentiometer, the voltage resolution would be

$$\Delta V = \frac{V}{n} \tag{2.1}$$

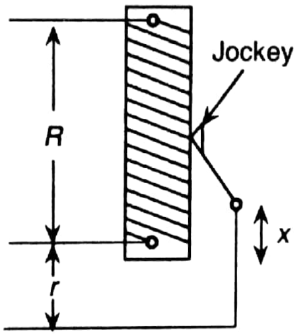
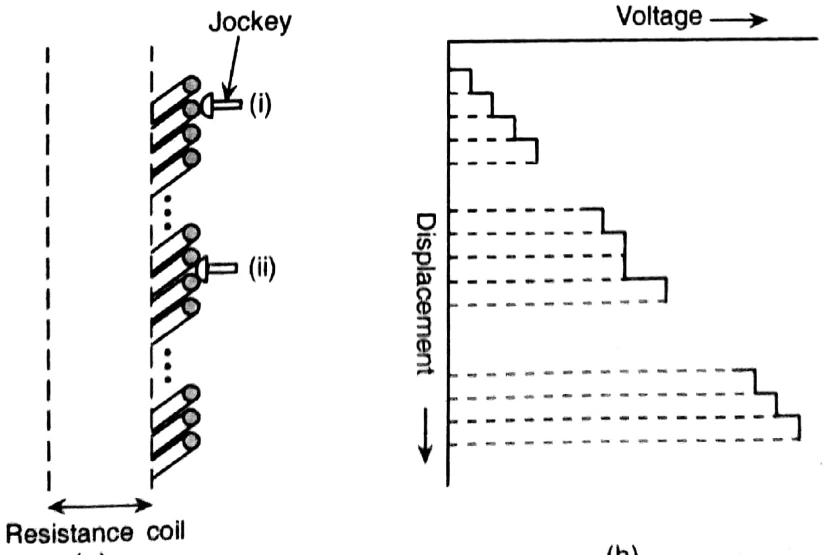


Fig. 2.1 Wire-wound potentiometer.



(a)

(b)

Fig. 2.2 (a) Jockey contact schemes: (i) single wire contact, (ii) two-wire shorting, (b) corresponding voltage levels.

In Fig. 2.2(b), the solid line stairs show the output voltage steps each of which is equivalent to a value V/n. But during transit, two adjacent wires are likely to be shorted as shown in (ii) of Fig. 2.2(a) and a minor resolution pulse of magnitude

$$\Delta V_m = V_p\left[\frac{1}{n-1} - \frac{1}{n}\right] \tag{2.2}$$

is obtained, where pth and $(p + 1)$th wires are shorted. This shows that with increasing value of p, minor pulse magnitude also increases and the loss in resolution due to this shorting leads to an actual resolution value

$$\Delta V - \Delta V_m = \frac{V}{n} - V_p\left[\frac{1}{n-1} - \frac{1}{n}\right] \tag{2.3}$$

The jockey shape/profile or the ratio of jockey radius to wire radius and geometry of wire winding should be considered for reducing ΔV_m. If jockey radius is small, with the jockey in use for some time with pressure, the wire gets its round surface worn out to develop a flat surface and finally gets torn. With a large radius of wire and close winding, this effect is small but may short more than two wires during the movement of the jockey and hence, precision of measurement is affected. For circular wire and circular jockey, it is recommended that the ratio of their radii be around 10, that is, $r_{\text{jockey}}/r_{\text{wire}} \approx 10$.

Also, materials of resistance wire and jockey are equally important, particularly from the wearing point of view and 'noise'. For noise, among other things, the jockey construction is to be considered seriously. A few types of the jockeys are shown in Figs. 2.3(a), (b), (c), and (d). The pressure at contact with the wire is provided by giving an adequate flexibility to the arm in relation to its mass. However, the required pressure is dependent on the materials, jockey to wire radius ratio, and the proposed lifespan of the potentiometer. A value of 10–50 mN is quite common.

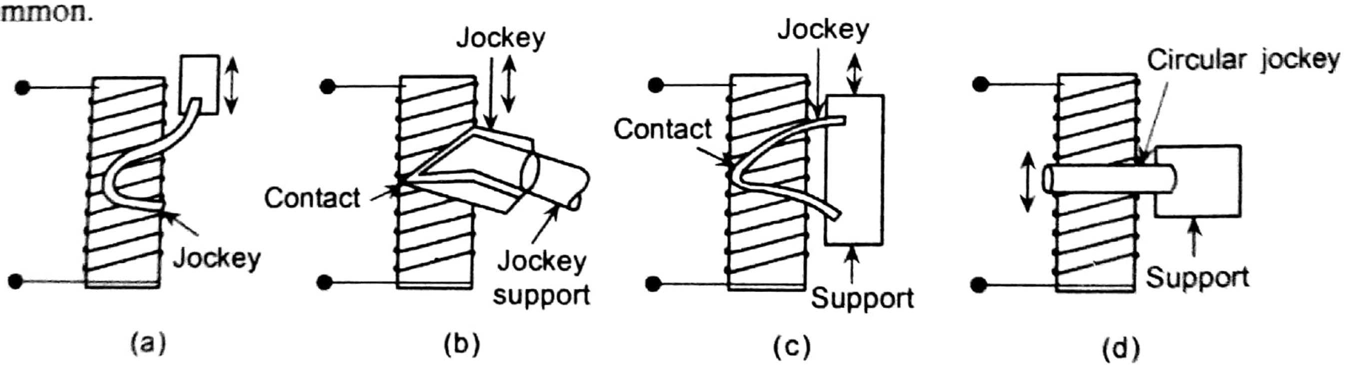


Fig. 2.3 Different designs of jockeys.

Noise is contributed by

1. irregularities in resolution—a random type noise,
2. thermal motions of molecules that come in equilibrium with random motions of electrons giving rise to white/Johnson noise with equivalent voltage output as $\{\langle V^2\rangle\}^{1/2} = \sqrt{4kTR\Delta f}$,
3. contact non-uniformity mainly produced due to changing contact area and hence, contact resistance—aggravated by the presence of foreign particles in the area of

contact (contact area changes with use, also contamination and oxidation change the resistance and hence, noise),

4. rubbing action between the jockey and the wire—an equivalent of 100–300 μV is easily obtained with this rubbing action, and
5. thermoelectric action specifically at high temperatures and dc operations.

Sensitivity, under ideal unloaded condition of the potentiometer is the output voltage per unit travel of the jockey. Irregularities occur (i) at the potentiometer ends and (ii) due to power dissipation and corresponding rise in resistance of the potentiometer. Adequate corrections are to be made for these. A proper choice of the wire material with safety limit extended in current carrying capacity can minimize these errors to a certain extent.

As discussed earlier, with *n*% resolution of full scale (FS), the linearity of measurement in the scale is limited and the error on this count is smaller than ±(*n*/2%) FS. Other factors that contribute to nonlinearity are (i) irregularities in winding pitch, (ii) mechanical uncertainties in jockey's movements, and (iii) tolerance/variation in wire and former dimensions and diameters. Linearity, better than the apparently calculated value can be obtained by using more number of turns than the theoretically calculated value.

The performance of the potentiometer changes in the loaded condition. Specifically, linearity is badly affected. Considering the circuit of Fig. 2.4, if R_L is the load resistance, V_i and V_o are input and output voltages respectively, R_i is the instantaneous tapped resistance across which V_o is obtained, and if the jockey begins movement from the bottom end, so that minimum $R_i = 0$ and maximum $R_i = R$, then

$$\frac{V_o}{V_i} = \frac{R_i/R}{1 + \dfrac{R_i}{R_L}\left(1 - \dfrac{R_i}{R}\right)} \tag{2.4}$$

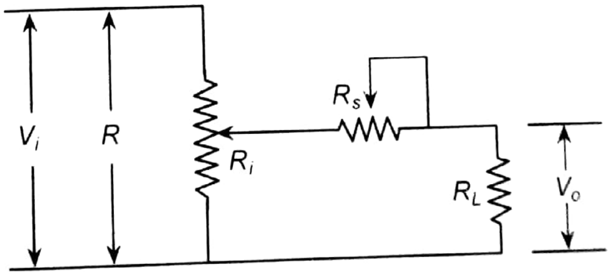


Fig. 2.4 Circuital method of drawing output from the potentiometer (for better linearity).

The figure also shows a variable series resistance R_s which is, in fact, optional and Eq. (2.4) has been obtained with $R_s = 0$. Generally, for ideal condition, $V_{oi}/V_i = R_i/R$. Representing R_i/R by ρ and R/R_L by λ, the percentage error in output–input voltage ratio is given as

$$\varepsilon = \frac{(V_{oi}/V_i - V_o/V_i)}{(V_{oi}/V_i)} \times 100$$

$$= \left(1 - \frac{1}{(1 + \lambda\rho(1-\rho))}\right) \times 100 \tag{2.5}$$

Plots of ε versus ρ can be drawn with λ as a parameter, using Eq. (2.5), to show that the percentage deviation from linearity may be as high as 20% at $R_i = R/2$ for $R_L = R$. However, this is kept to within 1% by making $R_L \geq 20R$.

Alternate methods make use of

(i) a potentiometer which itself has nonlinear characteristics or
(ii) a nonlinear variable resistance R_s in series with the load.

The first method, in effect, proposes a design of the former, on which the winding is made, to have a nonlinear profile on the side the jockey moves. This nonlinear profile is such that the resistance ratio R_i/R curve drawn against the jockey movement (travel) is complementary to that of V_o/V_i.

In the second method, since R_s is also variable, a double jockey system—one for R and the other for R_s with equal lengths to move should be used. It can be shown that a resistance $R_s = R/4$ with parabolic resistance characteristics about an axis of symmetry at $x = 0.5$ are necessary for the purpose, where x is the normalized movement from 0 to 1.

As has already been mentioned, materials, both of the wire and the jockey are equally important. Table 2.1 shows a list of materials for the wire and the jockey which can be used in correspondence.

Table 2.1 Materials for wire and jockey

Wire	*Jockey*
1. Copper–nickel alloys like constantan (Cu 55–Ni 45), advance, ferry alloy, eureka and so on.	(a) Gold, gold–silver, (b) Ni 40–Ag 60, 10% graphite in Cu or 2–5% graphite in Ag.
2. Nickel–chromium alloys such as nichrome (Ni 80, Cr 20), Karma and so forth.	Group (b) above, and/or Rh or Rh-plated metals, gold–silver, osmium–iridium, Cu 40–Pd, ruthenium 10–Pt, Gold.
3. Silver–palladium alloys	Pt–iridium, Au 10–Cu 13–Ag 30–Pd 47.
4. Platinum–iridium	Pt–iridium

The wire is precision-drawn and annealed in a reducing atmosphere. The resistance per unit length varies from 0.25–1.5 μΩ. The temperature coefficient of resistance is material-dependent and lies between 2×10^{-5}/°C and 10^{-4}/°C. Wire diameter tolerance is prescribed to be less than 5% at 0.025 mm.

2.3 STRAIN GAUGE

Although the basic principle of change in resistance of a metallic wire in response to strain produced in it was known as early as the mid-nineteenth century, its application in areas of commercial importance for measurement started becoming popular only about ninety years after that. Presently, the literature in strain gauges and their applications is so vast that it is difficult to prepare even a gist of all these in the folds of a section as proposed here. Strain gauges are of two types, namely the resistance type and the semiconductor type—the latter being of more recent origin.

2.3.1 Resistance Strain Gauge

Resistance strain gauges can be divided into two categories—(a) unbonded and (b) bonded—the former, being of limited use has received less attention than the latter. Unbonded strain gauge consists of a piece of wire stretched in multiple folds between a pair or more of insulated pins fixed to movable members of a 'body' or even a single flexible member whose strain is to be measured. There occurs a relative motion between the two members on strain and the wire gets strained as well with a corresponding change in its resistance value. The scheme of such a system is shown in Fig. 2.5.

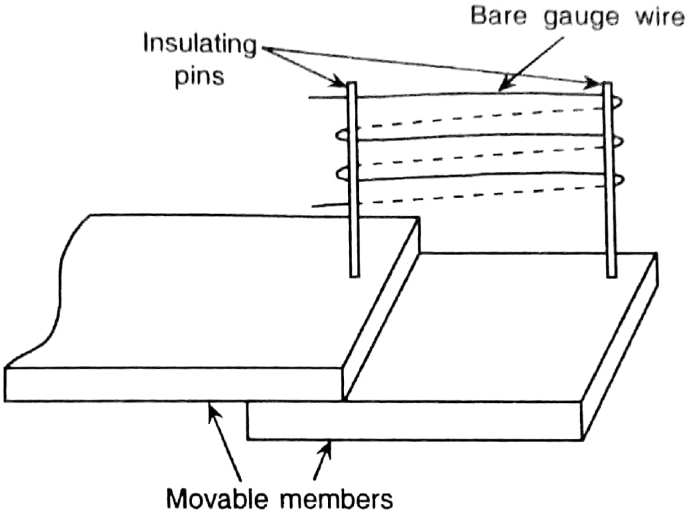


Fig. 2.5 Mounting an unbonded strain gauge.

The bonded type is more common and in its simplest form consists of wire/strip of resistance material arranged usually in the form of a grid for larger length and resistance value. The grid is bonded to the test specimen with an insulation layer between the gauge material and the specimen as shown in Fig. 2.6. If the insulation and the bonding material thickness is h which also is the height of the wire above the specimen surface and H is the distance of the neutral axis of the specimen from its surface, then the actual strain ε, in terms of measured strain ε_m, is given by

$$\varepsilon = \varepsilon_m \frac{H}{h+H} \tag{2.6}$$

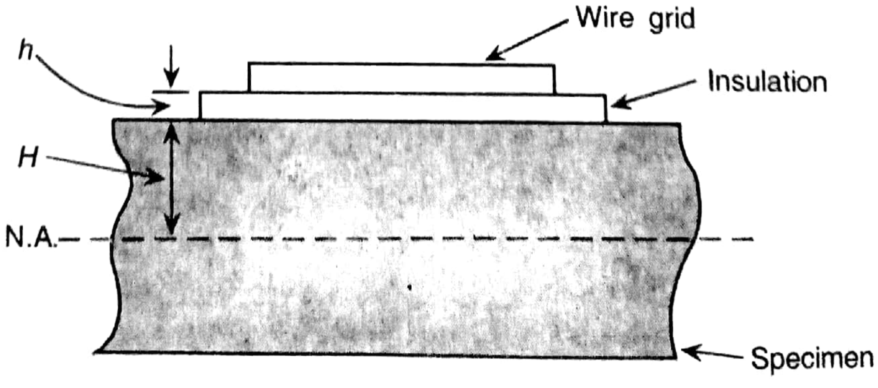


Fig. 2.6 Mounting a bonded strain gauge.

Depending upon the implementation, the resistance gauges can be classified as:

(a) Unbonded metal wire,
(b) Bonded metal wire,
(c) Bonded metal foil,
(d) Thin metal film by vacuum deposition, and
(e) Thin metal film by sputter deposition.

Considering a circular cross-section metal resistance wire of length l and cross-sectional area A with resistivity ρ of the material, the unstrained resistance of the wire is given by

$$R = \frac{\rho l}{A} \tag{2.7}$$

If the wire is uniformly stressed along its length (Fig. 2.7) and if the stress is given by σ, then

$$\frac{dR}{d\sigma} = \frac{d}{d\sigma}\left(\rho\frac{l}{A}\right) \tag{2.8}$$

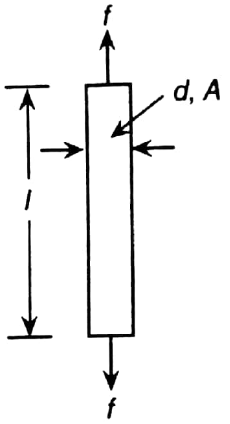


Fig. 2.7 Straining of an elastic member.

which gives

$$\left(\frac{1}{R}\right)\frac{dR}{d\sigma} = \left(\frac{1}{l}\right)\left(\frac{\partial l}{\partial\sigma}\right) - \left(\frac{1}{A}\right)\left(\frac{\partial A}{\partial\sigma}\right) + \left(\frac{1}{\rho}\right)\left(\frac{\partial\rho}{\partial\sigma}\right)$$

Eliminating all σ terms, we get

$$\frac{dR}{R} = \frac{\partial l}{l} - \frac{\partial A}{A} + \frac{\partial\rho}{\rho} \tag{2.9}$$

If the wire has a diameter d then the lateral contraction of the wire, $\Delta d/d = (1/2)\,(dA/A)$, is related to the fractional extension of the length, $\varepsilon = \Delta l/l$ by the Poisson's ratio μ as

$$\frac{\Delta d}{d} = -\frac{\mu\Delta l}{l} \tag{2.10}$$

so that Eq. (2.9) changes to

$$\frac{\Delta R}{R} = (1 + 2\mu)\frac{\Delta l}{l} + \frac{\Delta\rho}{\rho} \tag{2.11}$$

The strain sensitivity or the gauge factor λ is now defined as the ratio $(\Delta R/R)/(\Delta l/l)$ and is given by

$$\lambda = \frac{\Delta R/R}{\Delta l/l} = 1 + 2\mu + \frac{\Delta\rho/\rho}{\Delta l/l} \tag{2.12}$$

It is generally assumed that resistivity of a metallic material is usually constant implying that the gauge factor λ is constant at 1.6 as most metal has a Poisson ratio of 0.3. It can have a maximum value of 0.5. But it is known that λ varies from metal to metal and under elastic strain its value is, in general, different from 1.6 meaning thereby that the resistivity also changes with strain. The last term on the right hand side of Eq. (2.12) is due to piezoresistance effect or Bridgeman effect and is often expressed as

$$\frac{\Delta\rho/\rho}{\Delta l/l} = \psi E \tag{2.13}$$

where ψ is the Bridgeman or longitudinal piezoresistance coefficient and E is the modulus of elasticity.

As mentioned, μ has a maximum value of 0.5 which occurs in the plastic constant volume case so that when the change from essentially elastic to essentially plastic strain occurs, strain sensitivity also changes as shown in Figs. 2.8(a), (b), and (c). In Fig. 2.8(d), there is no change in strain sensitivity and the constant value is around 2 indicating that $(\partial\rho/\rho)/(\partial l/l)$ compensates for the gauge factor in the elastic strain region. Hard drawn nickel shows that its gauge factor is initially negative changing gradually to positive value. Minalpha has a slow and smooth transition and the change is not sharp. Obviously, the curve of Fig. 2.8(d) (i) is the most suitable one.

(a) Fe, hard Cu, Ag, Pt, 10% Ir + Pt, 10% Rh + Pt (b) Ag (40%), Pd

(c) Minalpha (d) (i) Annealed Cu/Ni, (ii) Hard drawn Ni

Fig. 2.8 Strain sensitivity for different materials.

Unbonded strain gauges are used in preloaded conditions not to allow the 'strings' to go slack. The wires are nickel alloys such as Cu–Ni, Cr–Ni, or Ni–Fe with gauge factor between 2 and 4 and diameters varying from 0.02–0.03 mm.

The bonded strain gauges are of a few types. When wire is used, the possibilities are (i) flat grid type, (ii) wrap around type, and (iii) woven type, although the flat grid type is more popular of all the three. Etched foil type resistance strain gauge is one variety that, in recent years, has most extensively been used.

A gauge consists of the resistance element of proper design/shape, the gauge backing, cement, connection leads, and often protective coating or other protective means.

The construction of the flat grid bonded strain gauge is shown in Fig. 2.9. Such a construction has the advantage of better strain transmission from the member to the wire grid, small hysteresis and creep, and is more accurate when the strain member is thin.

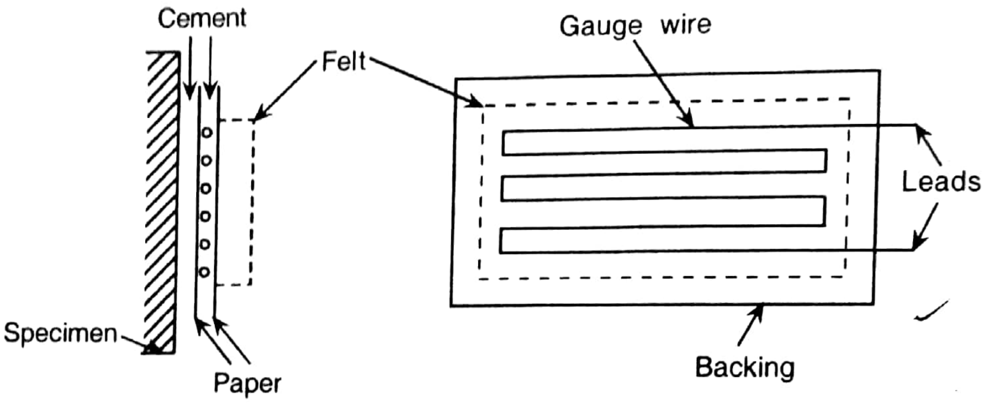


Fig. 2.9 Grid type gauge.

The foil gauges are etched out from deposited films or sheets and have higher surface area to cross-section ratio than wire gauges, and hence, have better heat transfer property so that they can handle higher current.

For wire gauges, the wires are usually drawn and often annealed, while bonded foil gauges consist of sensing elements which are formed from sheets of thickness less than 5×10^{-4} cm by photoetching processes so that any arbitrary shape can be given to these elements.

Because the wire grid in the grid type structure has a finite width, the gauge has a sensitivity to transverse strain which may be as large as 2% of the longitudinal sensitivity. In foil grid structure, the end turns can be made wider or fat enough so that the transverse strain sensitivity is lesser. A typical grid structure foil gauge is shown in Fig. 2.10.

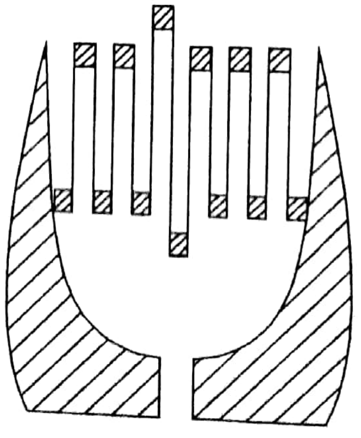


Fig. 2.10 Grid structure gauge with reduced transverse strain sensitivity.

Vacuum deposition and sputter deposition thin film gauges are produced where cement between the elastic element and the gauge is not necessary for bonding. In the former case, a suitable elastic metal element which can be adapted for strain generation such as a diaphragm for pressure measurement, is placed in a vacuum chamber with a suitable dielectric material of much lower vapour point than the metal. With application of requisite amount of heat, this dielectric material vapourizes and then condenses and finally forms a thin layer on the metallic member. A template of a suitable shape is now placed over it and the evaporation-deposition process is repeated with the gauge material. Thus, the gauge is formed over the insulator substrate.

In the sputtering-deposition process, the first step is nearly the same to form an insulating layer on the strain member. In the second step, without using a template, the metallic gauge material is sputtered over the entire substrate and the gauge pattern is defined by using micro-imaging techniques and photosensitive masking materials from outside the chamber and finally sputter-etching is used to remove all unmasked layers inside the vacuum chamber.

If strain members are not available or bonded metal foil gauges are required to be produced for 'general purpose' uses, the gauges are produced on flexible insulating carrier films such as polyimide and glass-reinforced phenolic having a thickness of about 0.002 cm.

One important aspect of resistance gauges is its temperature coefficient of resistance. The temperature at which the strain is measured may be different from the temperature when the strain member is bonded. This gives rise to a differential expansion between the strain member and the gauge resulting in error in strain measurement. Table 2.2 shows the list of resistance type strain gauge materials with corresponding gauge factors and temperature coefficient of resistance along-with the resistivity values.

Table 2.2 Strain gauge materials and their properties

Material	*Approx. nominal composition (%)*	*Gauge factor*	*Thermal coefficient of resistance (%/°C)*	*Nominal resistivity ($\mu\Omega$ cm)*
Constantan, Advance, Ferry	Ni 45, Cu 55	2.1–2.2	2×10^{-3}	0.45–0.48
Karma	Ni 74, Cr 20, Fe 3 Cu 3	2.1	2×10^{-3}	1.25
Nichrome V	Ni 80, Cr 20	2.2–2.6	10^{-2}	1.00
Isoelastic	Ni 36, Cr 8, Fe 52, Mn–Si–Mo 4	3.5–3.6	1.75×10^{-2}	1.05
Pt–W alloy	Pt 92, W 8	3.6–4.5	2.4×10^{-2}	0.62
Nickel	Ni 100	12	0.68	0.65
Manganin	Cu 84, Mn 12, Ni 4	0.3–0.48	2×10^{-3}	—
Platinum	Pt 100	4.8	0.4	0.1

The adhesives used to bond the gauge (backings) to the elastic member to be strained should be carefully selected. They must

(a) transmit the strain fully from the member surface to the gauge,
(b) have high insulation property,
(c) have high mechanical strength,
(d) have low thermal insulation,
(e) be as thin as possible yet provide strong bonding, and
(f) be suited to the environment, specifically the metal–paper and metal–dielectric interfacing.

Table 2.3 gives the properties of a few adhesives specially made for bonding strain gauges.

Table 2.3 Properties of adhesives

Material-base	*Temperature range (°C)*	*Cure-time (hrs)*	*Cure pressure* kg/cm^2	*Max. strain at room temp.* (%)	*Recommended lifetime* (yrs)
Acrylic	−75–65	1/12	Normal	10–15	1/2
Nitrocellulose	−75–65	24–48	1/2–1	10–15	2
Epoxy	0–200	12–24	1–3	6	1
Epoxy-phenolic	0–220	2	2–3	3–4	1
Polyimide	0–400	2–3	2.5–3	2–3	1/3
Ceramic	0–700	1	—	1/2	1

Acrylic has long term instability, nitrocellulose is a general purpose adhesive. Epoxy is resistant to moisture and has long term stability while epoxy-phenolic can be used in a thinner layer than the others. Polyimide and ceramic-base cements can be used at high temperatures though the latter is not very commonly used.

The recommended value of electrical insulation is of the order of 10^9 ohm at 50 V dc. If this value is not complied with, the gauge is likely to be 'shorted' and reading is susceptible to error. Most of the adhesives are vulnerable to high temperature and moisture/humidity which deteriorate their insulating as well as mechanical properties. Epoxy-base adhesives have been produced in various combinations with resins and hardeners for improving their properties.

Other than the adhesives given in Table 2.3, flame-spray and welding techniques have also been developed and are specifically used in some cases of free filament wire gauges. In the flame-spray, a solid rod is atomized to produce a ceramic spray which solidifies on the wires of the strain gauge making a bond without damaging the gauge or the strain member. This can be used upto about 800°C from near absolute zero while in the welding technique, the gauge is first epoxied to a thin metal shim. With low energy spot welder, the shim is then attached to the specimen. The foil gauges are specifically suitable with shim of thickness varying between 0.1–0.12 mm.

Gauges are made available in combinations often called 'rosettes' and these are designed in various configurations for specific stress–strain analysis and/or for transducer applications. A number of gauges are given relative orientations following certain pattern for the purpose. Thus, a three-gauge rosette used in stress analysis solves problems of a surface stress in magnitude and direction. Since the stress/strain is necessary to be measured at a point, it is best to stack these three gauges to form a rosette on that point. In fact, this sandwich pattern rosette is available from the manufacturers under the name 'stacked rosette'. Figure 2.11(a) shows such a three element rosette stacked at 45° to each other. In this, the topmost gauge is farthest from the specimen and all the gauges are insulated from each other, the topmost gauge gets heated up more compared to the bottommost which use the specimen as the heat sink. Two element stack type design is also commercially available. Such a design has an advantage that the strain/stress at the same point is sensed by all the gauges.

The alternative to the stack type design is the planar design which covers a small area rather than a point. Rosettes with such a design are available in two element 90° planar—usual and shear, three element 45°, 60° planar. They can be generated on the specimen as well. Figures 2.11(b), (c), and (d) show some of the types.

In fact, the technology of generating gauges on the specimen itself or on substrate as mentioned earlier by vacuum process has lead to wide scope of gauge pattern variation. It can be of any type depending on the specific requirements. The number of gauges at a location can also be changed as per this practice. Figure 2.11(e) shows a gauge pattern variation for measurement of strain in a diaphragm. Gauges 1 and 3 are subjected to tensile tangential stress while gauges 2 and 4 are subjected to compressive radial stress. 1′, 2′, 3′, and 4′ are contact terminals.

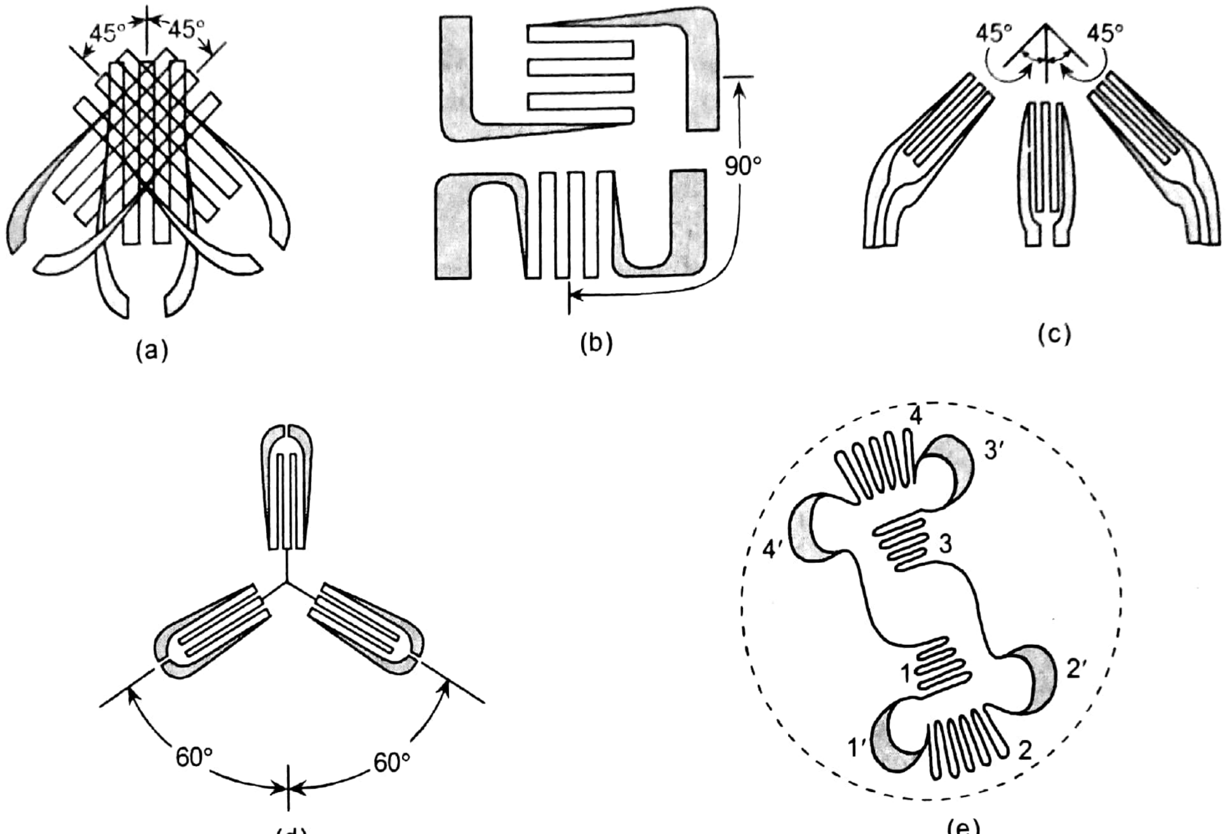


Fig. 2.11 Rosetted strain gauges: (a) three-element stacked type, (b) two-element right-angled, (c) three elements at 45° to each other, (d) three elements at 120° to each other, (e) gauge pattern on a diaphragm.

2.3.2 Semiconductor Strain Gauges

First lot of semiconductor strain gauges were produced early in mid-thirties from single crystal silicon or germanium by cutting thin strips. Lot of work has since been done and is still being done on the improvement of their performance and manufacturing ease because it has been known that although the semiconductor gauges have higher gauge factors, they are much inferior to the resistance types in so far as linearity and temperature stability are concerned (specifically the latter). But the discovery of semiconductor strain gauges has cleared the path of smart sensors, including production of strain sensitive cantilevers and diaphragms by doping selected small areas of monolithic silicon slice. Semiconductor strain gauges can be divided into two classes—(i) bonded semiconductor and (ii) diffused semiconductor—depending on their implementation.

Strain sensitivity of semiconductor material depends, among other things, on the crystal material such as Si or Ge, doping levels (if any), type of doping materials, crystal cut-axis orientation, and so on. Because the bandgaps both in intrinsic and extrinsic semiconductors are affected by temperature variation, semiconductor gauges are more prone to temperature variations. For intrinsic semiconductors, gauge factors are larger decreasing with increasing degrees of doping, the thermal coefficients of resistivity also decrease correspondingly.

As has been shown, the gauge factor of strain gauge is given by the relation

$$\lambda = 1 + 2\mu + \psi E \tag{2.14}$$

The strain sensitivity of a semiconductor gauge is high and the large value is due to the large value of ψE, that is, $(\Delta\rho/\rho)/(\Delta l/l)$, specifically ψ. The value of Poisson's ratio for semiconductors is less than that of metals although it is more in Si than Ge. Table 2.4 shows different values of Young's moduli (E), μ's, ρ's, and λ's for different Si and Ge crystals.

There are a number of piezoresistive coefficients in a semiconductor material, they are called 'fundamental'. The longitudinal piezoresistive coefficients, in which the stress and current are in the same direction and the transverse piezoresistive coefficients, in which the stress and current are perpendicular to each other, are computed from these fundamental coefficients and the direction cosines of the current with respect to the crystallographic axes.

Table 2.4 Properties of semiconductor gauges

Material with crystal orientation	μ	E (10^{10}N/m^2)	ρ $(10^{-3}\,\Omega\text{m})$	λ *(longitudinal)*	*Thermal coefficient of resistance* β $(10^{-5}/°\text{C})$
p-Si (111)	0.180	18.7	78	175	$70 \le \beta \le 700$
n-Si (100)	0.275	13.0	118	–135	$70 \le \beta \le 700$
p-Ge (111)	0.155	15.5	150	105	$70 \le \beta \le 700$
n-Ge (111)	0.156	15.5	160	–155	$70 \le \beta \le 700$

Practical aspect of using a semiconductor strain gauge is governed by λ, R, gauge length, encapsulation/backing, bonding, leads geometry, and means of temperature compensation. Size and shape of the gauge are equally important. Some possible and useful shapes are given in Figs. 2.12(a), (b), (c), and (d). Sizes are determined by the specimen size as also resistance value R.

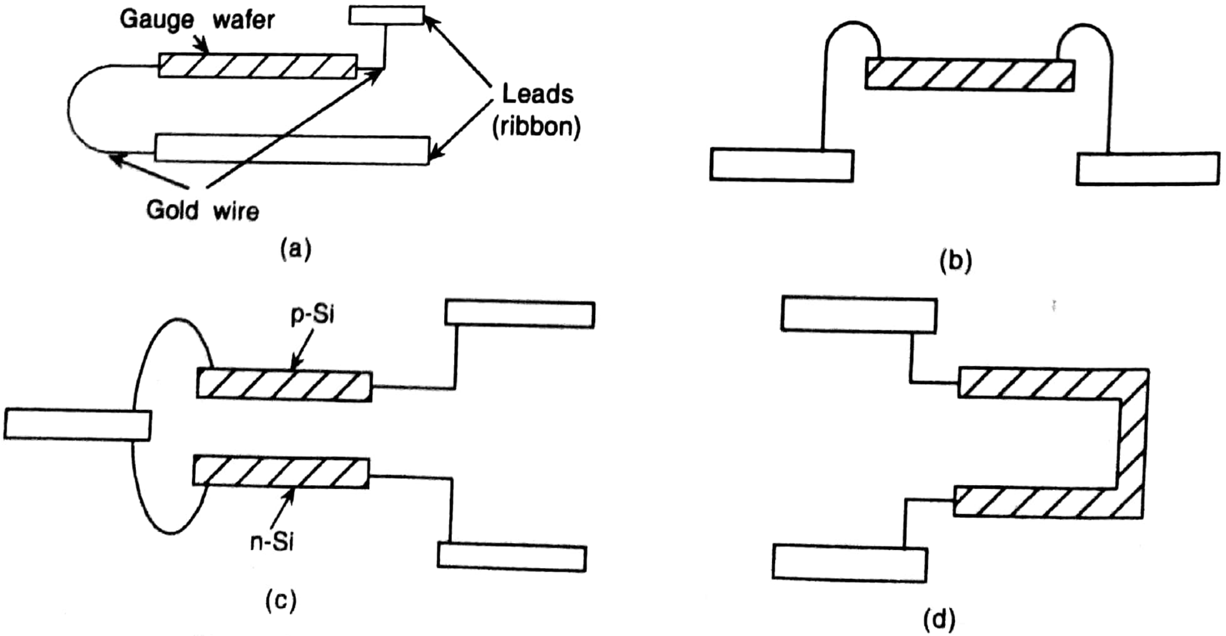


Fig. 2.12 Semiconductor gauges of different shapes and mountings.

Semiconductor gauges with/without backing are bonded to the specimen with epoxy-based adhesives, or for better, diffused semiconductor gauges are attached to the specimen by semiconductor diffusion process. The gauge is diffused directly on to the surface of the specimen such as a diaphragm, using photolithographic masking technique and an impurity such as boron is diffused into it. No separate bonding is necessary here. In recent times, the specimen, that is the strained member such as a cantilever or a diaphragm itself is also made from Si and the whole unit is developed into a smart sensor. A diaphragm of 2.5–25 mm diameter or cantilever of appropriate size is obtained in the main substrate of Si which is 50–750 mm in diameter. The four arm bridge is developed on this diaphragm as also the circuit of measurement by diffusion process.

The semiconductor strain gauge is basically nonlinear and an empirical relation between $\Delta R/R$ and ε

$$\frac{\Delta R}{R} = \sum_{j=1}^{n} k_j \varepsilon^j \tag{2.15}$$

is suggested, where k_j's are constants that depend on the materials and doping levels. Also, at high stress conditions temperature dependence of these coefficients are observed. Nonlinearity has been found to be improved by heavily doping the basic material of lower resistivity but then strain sensitivity is less. Often approximation by truncating the series upto $j = 2$ is good enough for practical use. Thus, an n-Si gauge of $\rho = 3.1 \times 10^{-4}$ ohm m would have

$$\lambda = -110 + 10^5 \varepsilon$$

and a p-Si with $\rho = 0.2 \times 10^{-3}$ ohm m would have

$$\lambda = 120 + 4 \times 10^4 \varepsilon$$

However, with higher resistivity such as $\rho = 78 \times 10^{-3}$ ohm m, a p-Si has a gauge factor (see Table 2.4)

$$\lambda = 175 + 7.26 \times 10^4 \varepsilon$$

As has been mentioned already, increasing doping decreases sensitivity towards temperature as well. Figure 2.13 shows the temperature–gauge factor curves for varying degrees of doping of a semiconductor gauge.

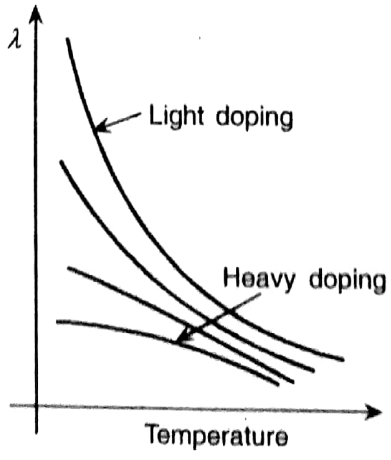


Fig. 2.13 Gauge factor versus temperature plots for different doping levels.

In fact, doping changes the gauge resistance as well, decreasing it with high doping level. Figure 2.14 shows the ρ–T characteristics with doping as a parameter. Figure shows that higher doping gives high value of ρ and β, the temperature coefficient of resistance—positive as well as high. But this occurs only upto a certain temperature above which the material behaves as in intrinsic conduction mode with negative temperature coefficient also of a very high value. However, with heavy doping, ρ is moderate and β quite small, and this condition persists over a wider temperature range.

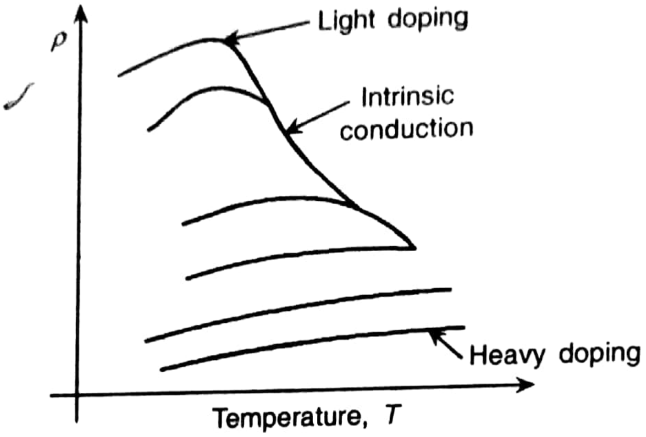


Fig. 2.14 Resistivity versus temperature for doping level variations.

As has been discussed already, semiconductors under strain show piezoresistive effect which is so predominant over other effects related to Poisson's ratio and so on that based only on this dominant effect, pressure transducers have been produced and within the elastic limits of silicon, electrical output is found proportional to mechanical strain or stress. The scheme consists of a cantilever beam of silicon about 0.1 mm thick on to both sides of which planar resistors are produced by diffusion. Figure 2.15 shows the scheme with the header with connecting terminals. With the beam under stress, the resistors on the two sides of the beam undergo different changes because of compression on one side and extension on the other. The difference is measured by a bridge. The length l can be inserted in a pressure cell where a diaphragm actuated by the inlet pressure is so mounted and attached to the cantilever that the deformation of the diaphragm is transmitted to the cantilever and hence, to the diffused resistance gauges.

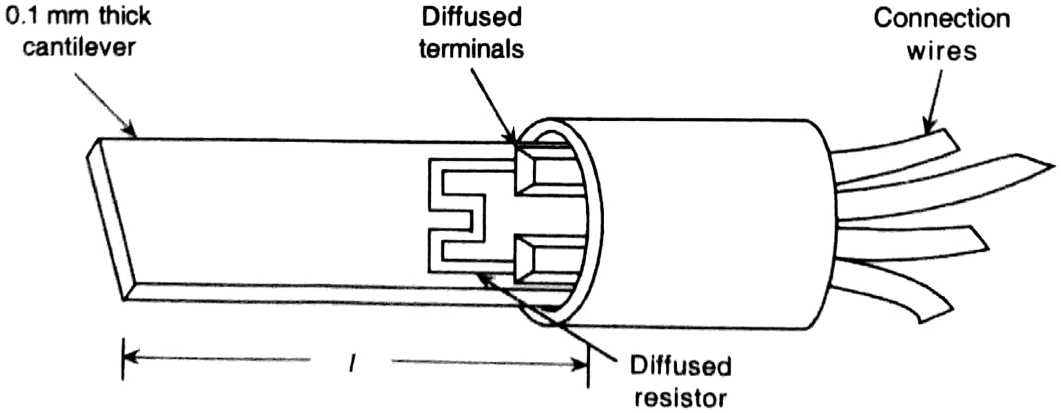


Fig. 2.15 Sensor using semiconductor piezoresistive effect.

For pressure measurement, thin silicon diaphragms with diffused resistors have been developed. A typical scheme is shown in Fig. 2.16. The piezoresistors are usually embedded in the diaphragm so that they get the strain of the diaphragm unabated.

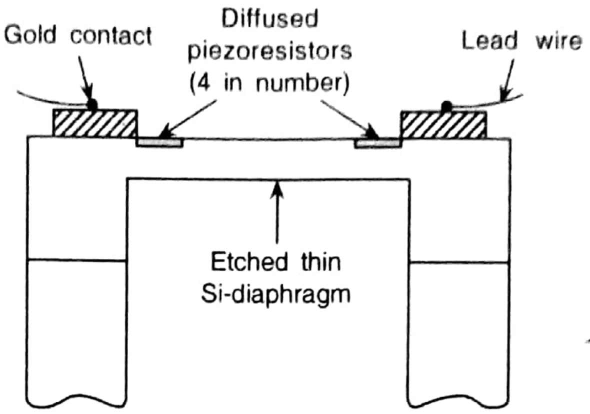


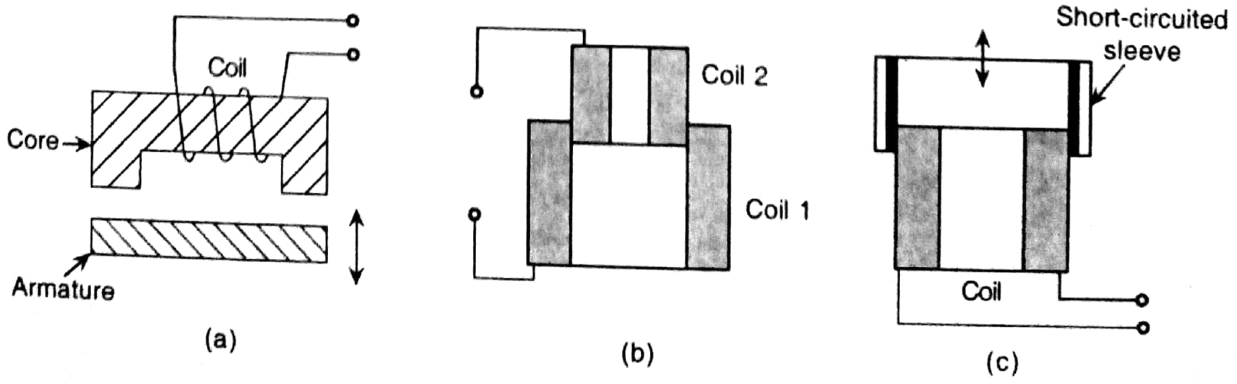
Fig. 2.16 Pressure measurement scheme using semiconductor diaphragm.

2.4 INDUCTIVE SENSORS

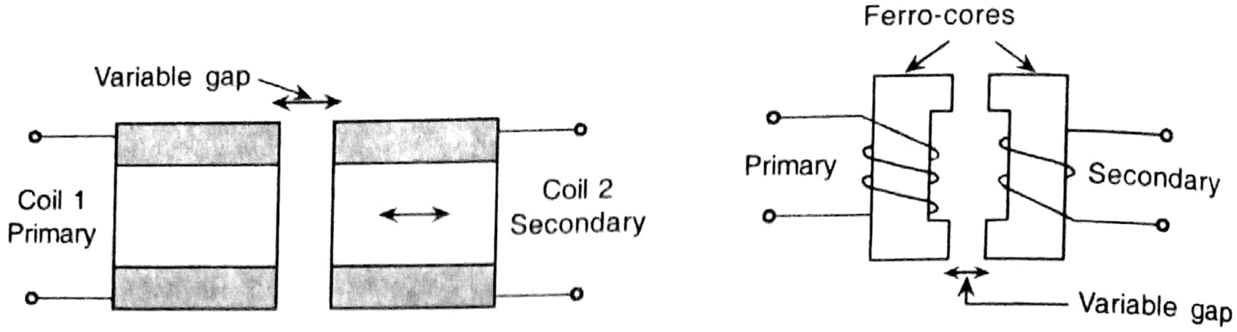
Although specific cases of inductive technique of sensing and/or transducing have been dealt in detail in Chapter 4 on magnetic sensors, a generalized discussion on inductive sensing is given in this section.

The inductive transducer utilizes the simple principle that the physical quantity, such as motion, to be measured can be made to vary the inductance of a coil, maintaining a relation between the two. This variation of inductance can often be measured by ac bridge circuits, or can be made to produce a voltage if it is magnetically coupled to another coil carrying a flux or voltage. If a magnetostrictive core material is used, force or pressure can change the permeability which can be measured as a change in inductance of a coil around the core.

The two most common methods of achieving variation in inductance are (i) by changing the reluctance of the magnetic path and (ii) by coupling two or more elements. The latter technique works by (a) change of mutual inductance, (b) change of eddy current when one element is just a short-circuited sleeve, and (c) transformer action. These are shown schematically in Figs. 2.17(a), (b), (c), and (d) respectively.



(a) (b) (c)



(d) (i) (d) (ii)

Fig. 2.17 Inductive sensors using (a) change of reluctance of magnetic path, (b) change of mutual inductance between two coils, (c) change of mutual inductance between a coil and a sleeve, and (d) (i) and (ii) transformer action.

Then there are inductive sensors of (i) the electromagnetic type which are bilateral in operation with electrical and mechanical input/output relationship and (ii) the magnetostrictive type. A sensor that uses a magnetostrictive core material is shown in Fig. 2.18.

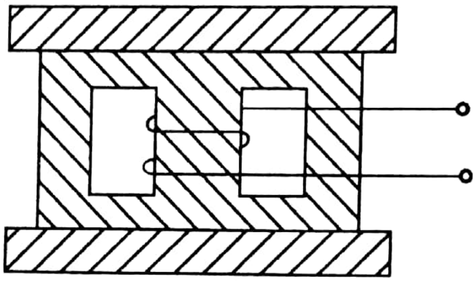


Fig. 2.18 Sensor using a magnetostrictive effect.

Inductance variation can also be achieved by variation of coil geometry such as coil length but such a procedure is not very convenient to be adopted in practice.

It is observed that a coil is an essential part of inductive transducers and the coil may be wound on a metal (iron) core or an air core. In the variable reluctance type, the core is a ferromagnetic material as also the armature. This type of sensors are, perhaps, the most extensively used because it (i) is the most sensitive one, (ii) is least affected by external fields as the air gap is least, and (iii) requires less number of turns than in air core design for same value of inductance so that interwinding or self-capacitance and stray effects are less. The copper coil on a ferromagnetic core has an equivalent circuit that consists of an inductance L in series with copper loss resistance R_c and a resistance R_e, representing eddy loss resistance in the core in parallel with L. Interwinding or self-capacitance, important specially at high frequencies, is in parallel to the coil resistance R_c and inductance L. The equivalent circuit is shown in Fig. 2.19.

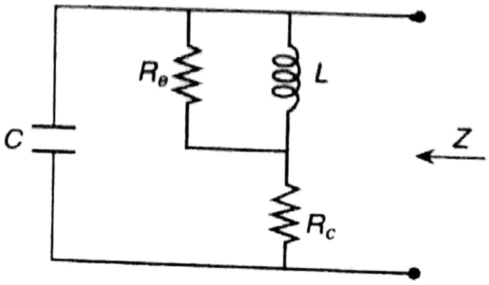


Fig. 2.19 Equivalent circuit of a ferromagnetic coil.

If a coil has n turns, a current I, and the core length l, the field strength H is given by

$$H = \frac{nI}{l} \text{ (A/m)} \tag{2.16}$$

For a core material of permeability μ, which often is expressed as the product of its relative permeability and the permeability of the free space or vacuum ($\mu_0 = 4\pi \times 10^{-7}$ H/m), and core cross-section area a, the self inductance L of the coil is the flux linkage per unit current so that

$$L = \frac{n\phi}{I} = n\frac{Ba}{I} = n\frac{\mu Ha}{I} \tag{2.17}$$

where B is in Tesla or Wb/m^2 and ϕ is in Wb.

Using Eq. (2.16), one derives

$$L = \frac{\mu n^2 a}{l} \text{ (Henries)} \tag{2.18}$$

The copper resistance R_c is also easily calculated if the coil wire diameter d and the copper resistivity ρ are known, so that

$$R_c = \frac{4\rho n l_t}{\pi d^2} \tag{2.19}$$

where l_t is the average length per turn of the coil. The coil dissipation factor D_c is usually defined as

$$D_c = \frac{R_c}{\omega L} \tag{2.20}$$

which decreases with increasing frequency.

For reducing eddy loss or core loss as it is called (the core is usually made of laminations of certain thickness, say t_l), the depth of penetration of eddy current, d_p is given by

$$d_p = \sqrt{\frac{\rho_e}{\pi \mu f}} \tag{2.21}$$

where ρ_e is the resistivity of the core material and $f = \omega/(2\pi)$ is the frequency. The eddy loss resistance is then given by

$$R_e = \left(\frac{2d_p\omega L}{t_l}\right)\left[\frac{\cosh\left(\frac{t_l}{d_p}\right) - \cos\left(\frac{t_l}{d_p}\right)}{\sinh\left(\frac{t_l}{d_p}\right) - \sin\left(\frac{t_l}{d_p}\right)}\right] \tag{2.22}$$

Equations (2.21) and (2.22) are valid only for low frequencies when $\rho_t = (t_l/d_p) \leq 2$. The frequency range, however, varies depending on the core material as well as lamination thickness. Figure 2.20 shows the plots of f versus t for different materials of commercial importance for $\rho_t \approx 2$, so that within this range of frequency Eq. (2.22) can be simplified using Eqs. (2.18) and (2.21) as

$$R_e \approx \frac{6\omega L}{(t_l/d_p)^2} = \frac{12\rho_e a n^2}{(l t_l)^2} \tag{2.23}$$

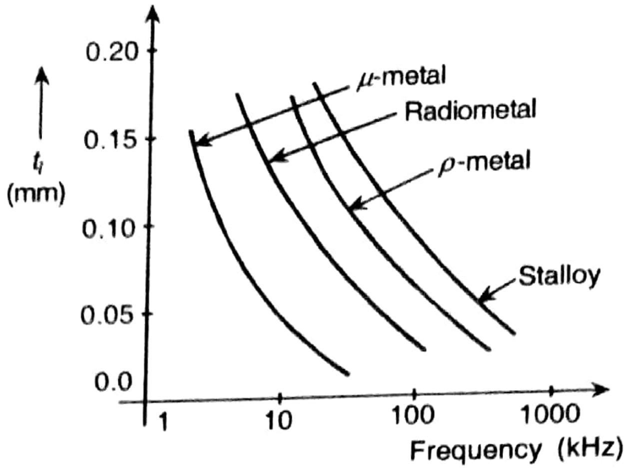


Fig. 2.20 Sheet thickness versus frequency plots for different magnetic materials.

This figure (Fig. 2.20) shows what frequency range can be covered by a specific material with specified thicknesses.

The eddy loss dissipation factor is defined by

$$D_e = \frac{\omega L}{R_e} \tag{2.24}$$

and is directly proportional to frequency.

Magnetic material undergoes hysteresis and this causes dissipation or loss. The area within the hysteresis curve is given by

$$A_h = \int B \cdot dH \tag{2.25}$$

where H is the magnetic field strength and B is the magnetic induction.

The B–H loop for a ferromagnetic material is schematically shown in Fig. 2.21. Following Rayleigh's procedure, the area A_h has been computed and hence, the energy dissipated per unit volume. For a core of cross-sectional area a, and length l, total hysteresis loss, in this way, is obtained as

$$P_h = \left(\frac{16\pi}{3}\right) al\alpha_r H_l^3 f \times 10^{-7} \quad \text{(watts)} \tag{2.26}$$

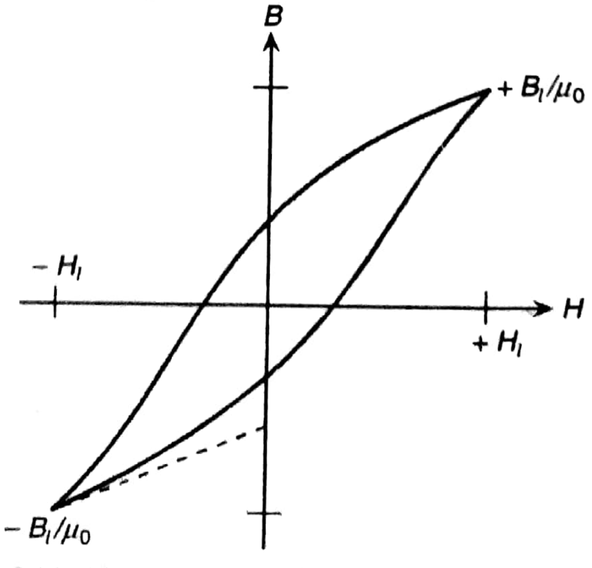


Fig. 2.21 The B–H loop for a magnetic material.

where α_r is the Rayleigh's constant which may be defined by the equation

$$\alpha_r = 2\frac{\left(\dfrac{\Delta B}{\mu_0} - \mu_i H\right)}{(\Delta H)^2} \tag{2.27}$$

where μ_i is the initial permeability, that is, permeability at $H = 0$. With change from zero values of B and H, Eq. (2.27) is written as

$$\alpha_r = \frac{2(B/\mu_0 - \mu_i H)}{H^2} \tag{2.28}$$

Using $P_h = E^2/R_h$, R_h, being the equivalent hysteresis loss resistance, is

$$R_h = \frac{\omega^2 L^2 I^2}{P_h} \tag{2.29}$$

which is proportional to the square of the frequency. However, the hysteresis dissipation factor D_h is given by

$$D_h = \frac{\omega L}{R_h} = \frac{2\alpha_r H_l}{(3\pi \mu_i)} \tag{2.30}$$

which is independent of frequency.

A sensor or a transducer involves the movement of an armature, that is, the situation demands that the core has an air gap, the length of which varies with the value of the measured quantity such as a motion. This is taken into consideration by determining the effective permeability of the core when the sample permeability μ_s is known and a relation between L and the gap length l_g can be found. Thus, for a torroidal ring sample of total path length l, gap length l_g, cross-sectional area a, the effective permeability μ, we obtain

$$\frac{\left(\dfrac{(l - l_g)}{\mu_s} + l_g\right)}{a} = \frac{l}{\mu a} \tag{2.31}$$

yielding

$$\mu = \frac{\mu_s}{\left\{1 + \left(\dfrac{l_g}{l}\right)(\mu_s - 1)\right\}} \tag{2.32a}$$

Since $\mu_s >> 1$,

$$\mu \approx \frac{\mu_s}{\left\{1 + \left(\dfrac{l_g}{l}\right)\mu_s\right\}} \tag{2.32b}$$

Substituting this in Eq. (2.18),

$$L = \left[\frac{\mu_s}{\left\{1 + \left(\dfrac{l_g}{l}\right)\mu_s\right\}}\right]\left(\frac{n^2 a}{l}\right) \quad \text{(Henries)} \tag{2.33}$$

Before moving on to the analysis of change of inductance with air gap and its nature, the effect of the capacitor C of Fig. 2.19 is considered. This capacitance arises, as already mentioned, due to the coil self-capacitance, that is, interwinding capacitance as also due to the connecting cable capacitance. The effect of parallel resistance R_e can be considered in series with the inductance so that the total series resistance R, is then used to calculate the impedance Z as

$$Z = \frac{R + j\omega L}{(1 - \omega^2 LC) + j\omega RC} \tag{2.34}$$

which, on rationalization, can be written as

$$Z = \frac{R}{(1 - \omega^2 LC)^2 + (\omega^2 LC/Q)^2} + j\omega L \frac{(1 - \omega^2 LC) - (\omega^2 LC/Q^2)}{(1 - \omega^2 LC)^2 + (\omega^2 LC/Q)^2} \tag{2.35}$$

where $Q = L/R$.

For a good inductor with $Q^2 >> 1$, we get

$$Z = \frac{R}{(1 - \omega^2 LC)^2} + \frac{j\omega L}{(1 - \omega^2 LC)} = R_{\text{eq}} + j\omega L_{\text{eq}} \tag{2.36}$$

indicating that both R_{eq} and L_{eq} increase but the effective Q, Q_{eq} decreases

$$Q_{\text{eq}} = \frac{\omega L (1 - \omega^2 LC)}{R} \tag{2.37}$$

2.4.1 Sensitivity and Linearity of the Sensor

For a small air gap l_g and effective permeability of the core μ, the inductance is given by Eq. (2.33). Now since n and a are constants, using

$$K_l = 4\pi \times 10^{-7} n^2 a \tag{2.38}$$

Equation (2.33) can be written as

$$L = \frac{K_l}{\left(l_g + \dfrac{l}{\mu_s}\right)} \tag{2.39}$$

from which assuming $l >> l_g$, for small increase or decrease in gap l_g and ∂l_g,

$$\frac{\partial L}{L} = \frac{\partial l_g}{\left(l_g \pm \partial l_g + \dfrac{l}{\mu_s}\right)}$$

$$= \frac{\partial l_g / l_g}{1 + \dfrac{l}{l_g \mu_s}} \cdot \frac{1}{1 \pm \dfrac{(\partial l_g / l_g)}{\{1 + l/(l_g \mu_s)\}}} \tag{2.40a}$$

and for $(\partial l_g/l_g)/(1 + l/(l_g\mu_s)) << 1$.

$$\frac{\partial L}{L} = \frac{\partial l_g / l_g}{1 + \dfrac{l}{l_g \mu_s}} \left[1 \mp \frac{\partial l_g / l_g}{1 + \dfrac{l}{l_g \mu_s}} + \left(\frac{\partial l_g / l_g}{1 + \dfrac{l}{l_g \mu_s}} \right)^2 \mp \cdots \right] \tag{2.40b}$$

If only the first term is accepted for ∂l_g being very small, there appears to be a linear variation between L and l_g, and the sensitivity $S_{l_g}^{L} = (\partial L/L)/(\partial l_g/l_g)$ is given as

$$S_{l_g}^{L} = \frac{1}{1 + l/(l_g \mu_s)} \tag{2.41}$$

However, presence of higher order term increases nonlinearity. Figure 2.22 shows the nature of L versus l_g curve. It is possible to have two coils in the variable inductance transducer such that inductance in one coil increases and that in the other decreases. This can be adapted in the plunger type design, discussed later, where a push–pull arrangement of the coils and their connections would produce an output which is the sum of the fractional changes in the values of inductances in the two coils. This would make the even order terms in Eq. (2.40b) disappear and result in improvement of linearity over a wider gap range as shown in Figs. 2.23(a) and (b).

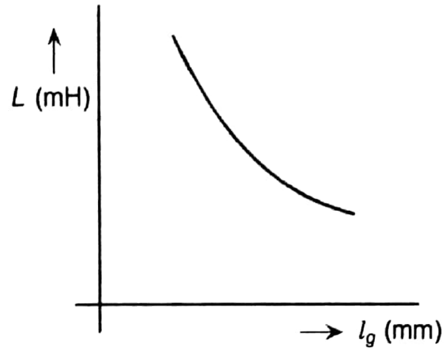
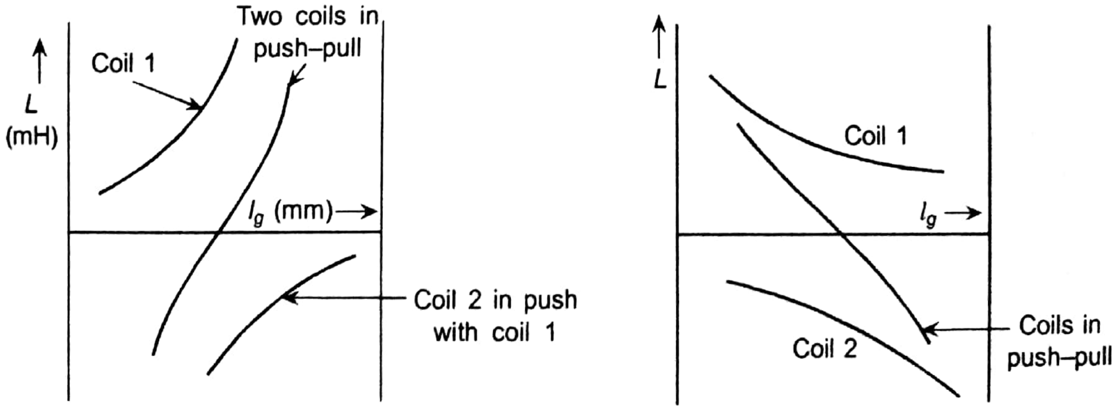


Fig. 2.22 Variation of inductance with air gap.



(a) (b)

Fig. 2.23 Linearity improvement by using two coils in push–pull.

It must be remembered that air gap is likely to vary because of the eddy loss effect that is assumed parallel to the inductance which when transferred to series path, is given by

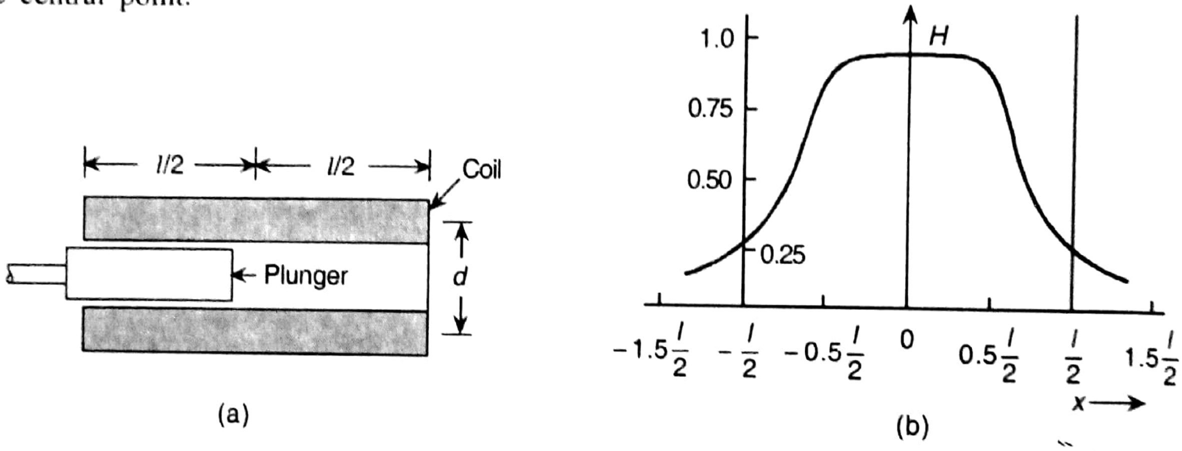
$$R_{es} = R_e(1 + Q^2)^{-1} \approx \frac{R_e}{Q^2} \tag{2.42}$$

As Q contains L as well as frequency f and L being a functions of μ, the resistance R_{es} changes with change in μ or in air gap. The values can actually be computed by using the equations that have been discussed here.

2.4.2 Ferromagnetic Plunger Type Transducers

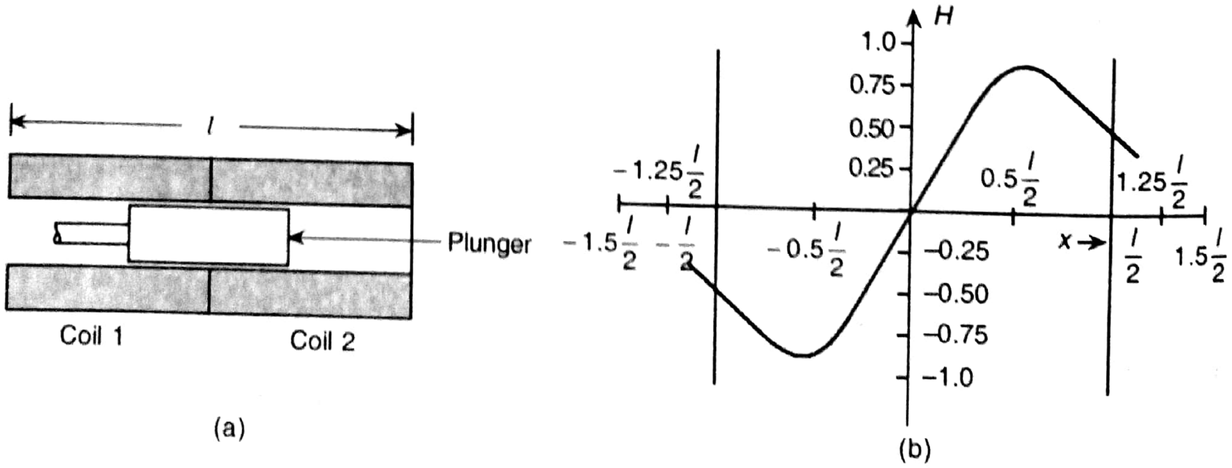
A variation of the variable air gap core type design is the one in which usually a solid ferromagnetic plunger moves inside a helical coil wound on a ferromagnetic sleeve, such that the inductance of the coil depends on the partial core length inside the coil. Such a design can also be analyzed with an equivalent air gap which is now large. The coil itself can be split up into two equal parts such that in their push–pull operation, the field is constant and the inductance has a linear range over wider range of movement of the core. In this case, the sensitivity is also larger.

Figures 2.24(a) and (b) show a single coil with its magnetic field distribution and Figs. 2.25(a) and (b) show a double coil design with field distribution on both sides with respect to the central point.



(a) (b)

Fig. 2.24 (a) Single coil plunger type transducer design, (b) field versus length plot for the system.



(a) (b)

Fig. 2.25 (a) Double coil transducer, (b) the response plot.

For a current I in the coil of Fig. 2.24(a) with the coil length l, diameter d, and number of turns n, the field strength along the axis is given by

$$H = \frac{nI}{2l}\left[\frac{l + 2x}{\sqrt{d^2 + (l + 2x)^2}} + \frac{l - 2x}{\sqrt{d^2 + (l - 2x)^2}}\right] \tag{2.43a}$$

while for push–pull coils 1 and 2 design of Fig. 2.25(a), the field strength is given by the relation

$$H = \frac{nI}{2l}\left[\frac{l - 2x}{\sqrt{d^2 + (l - 2x)^2}} - \frac{l + 2x}{\sqrt{d^2 + (l + 2x)^2}} + \frac{2x}{\sqrt{(d/2)^2 + x^2}}\right] \tag{2.43b}$$

The corresponding field plot is shown in Fig. 2.25(b).

A coil, theoretically of a very large length l, having n number of single layer turns and radius $d/2$ has an inductance [see Eq. (2.18)]

$$L = \left(\frac{\pi^2 n^2 d^2}{l}\right) \times 10^{-7} \quad \text{(H)} \tag{2.44}$$

A ferromagnetic plunger of diameter d_p, length l_p with $l_p < l$, covering the middle part of the coils-length and having effective permeability μ_p, the inductance increases to

$$L_p = \left(\frac{\pi^2 n^2}{l^2}\right)\left[ld^2 + (\mu_p - 1)l_p d_p^2\right] \times 10^{-7} \quad \text{(H)} \tag{2.45}$$

With the movement of the plunger, there occurs a change in l_p, say ∂l_p, and correspondingly L_p changes by ∂L_p, and if in coil 1 there is increase in a parameter, coil 2 observes a decrease in the same. The change ∂L_p in a coil is given by

$$\partial L_p = \frac{\pi^2 n^2 d_p^2 (\mu_p - 1)\,\partial l_p}{l} \times 10^{-7} \quad \text{(H)} \tag{2.46}$$

so that per unit change in ∂L_p is

$$\frac{\partial L_p}{L_p} = \frac{\partial l_p}{l_p}\left(\frac{1}{1 + \left(\frac{l}{l_p}\right)\left(\frac{d}{d_p}\right)^2\left(\frac{1}{\mu_p - 1}\right)}\right) \tag{2.47}$$

In the other coil, same change occurs with opposite sign. If the length of the plunger is the same as that of the coil sleeve, this change is given by

$$\frac{\partial L_p}{L_p} = \frac{\partial l_p}{l_p}\left(\frac{1}{1 + \left(\frac{d}{d'_p}\right)^2\left(\frac{1}{\mu_p - 1}\right)}\right) \tag{2.48}$$

For very large μ_p, $d_p \to d$ and $l_p \to l$. Therefore,

$$S_{l_p}^{L_p} \approx 1 \tag{2.49}$$

Compared to the performances of the transverse type of design (refer Fig. 2.17(a)), this one has a number of disadvantages, mainly because of large air paths and leakage for which more number of turns per coil would be necessary to achieve same inductance value resulting in larger capacitance and higher rise time. Also plunger gives larger core loss and less Q-factor, external pick up increases and finally, design with split-coil tends to introduce asymmetry and a mutual coupling between the two coils. The mutual coupling increases with the two coils sharing a common magnetic path. The directions of the magnetic field of the coils with respect to the core fields are also important.

Considering ideal coils, the equivalent circuit of two coupled coils is given in Fig. 2.26 where Z_a represents the impedance of the individual coils considered identical, and Z_b represents the coupled impedance which is considered positive for opposing fields and negative when fields are in the same direction. The coupling coefficient k is given by

$$k = \frac{Z_b}{(Z_a + Z_b)} = 1 - \frac{2Z_a}{2(Z_a + Z_b)}$$

$$= 1 - \frac{Z_{11}}{2Z_{12}} \tag{2.50}$$

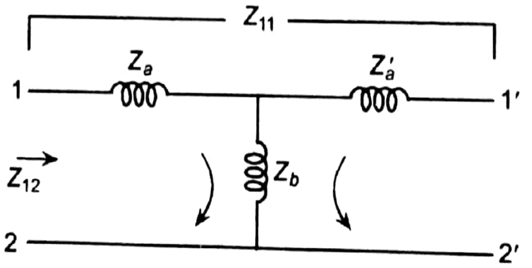


Fig. 2.26 Circuit of a pair of ideal-coupled coils.

As stated already, $k > 0$ for opposing fields and $k < 0$ for fields in the same direction.

Coupling can be eliminated or at least reduced to a greater extent if the magnetic paths for the two coils are independent which is realized to a certain extent by having an E-shaped core as shown in Fig. 2.27.

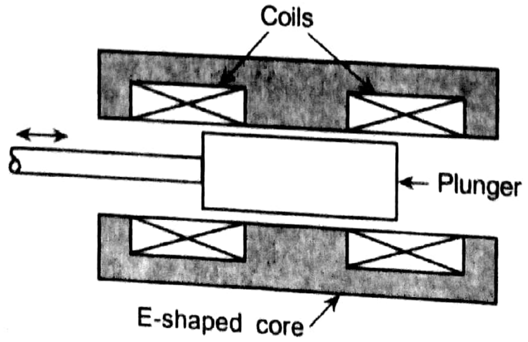


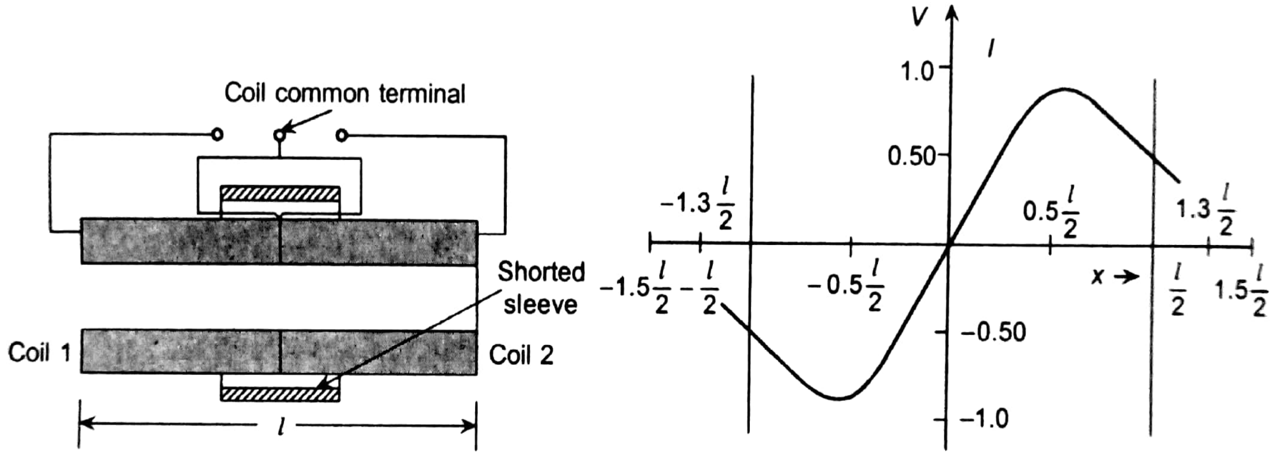
Fig. 2.27 Double coil design with E-shaped coil cores.

2.4.3 Inductance with a Short-circuited Sleeve

A schematic of such a sensor has been given in Fig. 2.17(c) where only a single coil arrangement is given. A double-coil with push–pull arrangement for better sensitivity and linearity is also available in this kind. Figure 2.28(a) shows such a scheme with Fig. 2.28(b) showing the variation of magnetic field with the sleeve position.

Considering, however, the single coil design first with the short-circuited sleeve covering only a part of the 'coil 1' of length, say l_2, (Fig. 2.29) and with coil and sleeve diameters d_1 and d_2, the voltage across the terminals 1 and 2 for a current i_1 in coil 1 would be changed due to presence of the sleeve around the coil (1) as this shorted sleeve acts a secondary of the transformer. If the self-inductance of the sleeve is L_s (its resistance is ignored), the coil inductance and resistance are L_1 and R_1 respectively, and the mutual inductance between the two is M, then the voltage v_1 would be given by

$$v_1 = i_1\left[R_1 + j\omega L_1 + \frac{\omega^2 M^2}{j\omega L_s}\right] \tag{2.51}$$



(a) (b)

Fig. 2.28 (a) Structure of a double coil shorted sleeve transducer, (b) response characteristics of the transducer.

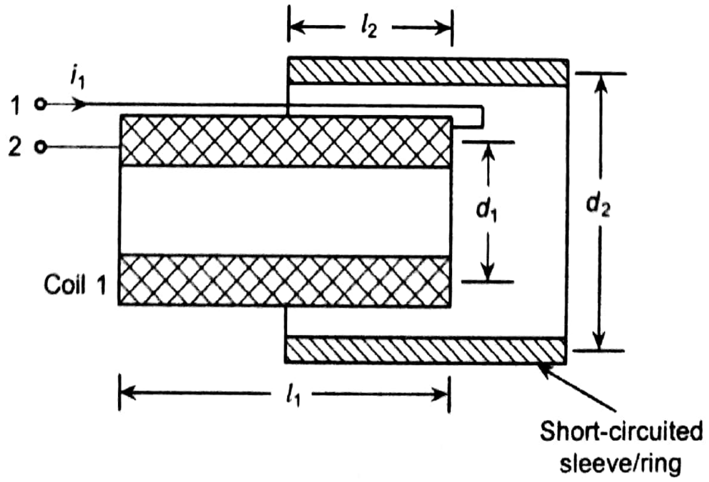


Fig. 2.29 The single coil sleeve type design.

where mutual inductance is produced due the coupling factor

$$k = \frac{M}{\sqrt{(L_1 L_s)}} \tag{2.52}$$

so that.

$$\frac{v_1}{i_1} = Z_{\text{coil1}} = R_1 + j\omega L_1(1 - k^2) \tag{2.53}$$

or in other words, the inductance L_1 is changed by a factor $(1 - k^2)$. In fact, the coupling coefficient can be calculated for a pair of long coils one covering the other. Thus,

$$k = \left(\frac{d_1}{d_2}\right)\left(\frac{l_2}{l_1}\right)^{1/2} \tag{2.54}$$

so that the changed inductance of coil 1 is

$$L_{1c} = L_1\left[1 - \left(\frac{d_1}{d_2}\right)^2\left(\frac{l_2}{l_1}\right)\right] \tag{2.55}$$

From this, the change L_{1c} for the sleeve movement is obtained (sign change ignored) as

$$\partial L_{1c} = \frac{L_1 k^2 \partial l_2}{l_2} \tag{2.56}$$

so that

$$\frac{\partial L_{1c}}{L_{1c}} = \frac{\partial l_2}{l_2}\left(\frac{k^2}{1 - k^2}\right) \tag{2.57}$$

where $k \neq 1$ and sensitivity is never infinitely large. In fact, the normalized sensitivity, given by,

$$S_{l_2}^{L_{1c}} = \frac{k^2}{1 - k^2} \tag{2.58}$$

which becomes unity for $k = \pm\, 1/\sqrt{2}$ and more than unity for $k > 1/\sqrt{2}$. For shorted coils, it is very difficult to make $k \geq 1/\sqrt{2}$, mainly because of fringing effect and non-ideal coupling, so that

$$\frac{\partial L_{1c}}{L_{1c}} < \frac{\partial l_2}{l_2} \tag{2.59}$$

For shorted sleeve or ring type design, the magnetic field changes as shown in Fig. 2.28(b). On the other hand, for a single coil it changes similar to that already shown in Fig. 2.24(b) and the induced voltage and hence, current variation would be similar to variation of H. This, then, is the calibration curve of the transducer.

It would be seen that the nature of this transducer and that of the plunger type are same except that the plunger type transducer has higher iron loss and the shorted sleeve type has lower sensitivity, lower by about 35–40%.

2.4.4 The Transformer Type Transducer

The transformer type transducer can be formed like a transformer with a variable iron core coupling between a pair of coils or more. Figures 2.17(d)(i) and (ii) show two such kinds, of which the latter one can be considered as a typical case where one coil acts as a primary (in which an ac voltage is impressed) and the other acts as the secondary. But for this type, there often occurs a 'no signal' output and this can be compensated by another coil or a compensating current. In this group, the transducer used most is the linear variable differential transformer (LVDT) whose operation has been described in detail later in the book. In LVDT, a plunger type armature moves into a pair of secondary coils and a primary coil, the secondaries being connected in differential mode. The simple plunger type sensor has also been thoroughly discussed in Chapter 4.

While LVDT in the Chapter 4 on Magnetic sensors has been analyzed using an equivalent circuit of a transformer, basic equations are quoted here without the complex deduction process. It takes help of the properties of the magnetic circuit and flux leakages. It has been assumed that the mmf in ferromagnetic/iron is negligible in comparison with that in air paths of the leakage flux. Figure 2.30 is a schematic representation of the differential transformer. For magnetic circuit-based deduction, the gaps and material dimensions are very important.

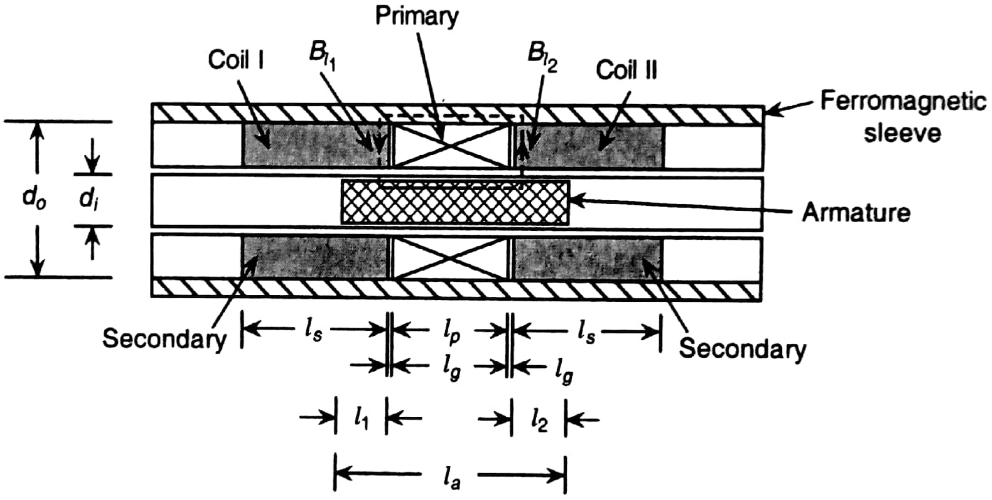


Fig. 2.30 The linear variable differential transformer.

Assuming current in the primary as I_p (rms) and number of turns n_p, if the number of turns in each secondary is n_s, it can be shown that the flux densities around the primary coil linking the secondaries are given as

$$\frac{B_{l_1}}{B_{l_2}} = -\frac{2l_2 + l_g}{2l_1 + l_g} \tag{2.60}$$

The negative sign comes because of direction (see Fig. 2.30).

For a supply frequency ω, the induced emf's in coils I and II are given respectively by

$$e_1 = \frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)} \cdot \frac{2l_2 + l_g}{l_s l_a} \cdot x_1^2 \times 10^{-7} \tag{2.61a}$$

and

$$e_2 = \frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)} \cdot \frac{2l_1 + l_g}{l_s l_a} \cdot x_2^2 \times 10^{-7} \tag{2.61b}$$

where x_1 and x_2 represent penetration of armature from nominal position beyond the primary coil length including the air gap.

Thus, the differential voltage

$$e_o = e_1 - e_2 = \left[\frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)} \times 10^{-7}\right] \frac{l_g}{l_s l_a} \left[\left(\frac{2l_2}{l_g} + 1\right) x_1^2 - \left(\frac{2l_1}{l_g} + 1\right) x_2^2\right] \tag{2.62a}$$

$$= K_1 \left[\left(\frac{2l_2}{l_g} + 1\right) x_1^2 - \left(\frac{2l_1}{l_g} + 1\right) x_2^2\right] \tag{2.62b}$$

$$= K_1 \left[x_1^2 - x_2^2 + \left(\frac{2}{l_g}\right)(l_2 x_1^2 - l_1 x_2^2)\right] \tag{2.62c}$$

where

$$K_1 = \left(\frac{2\pi^2 \omega I_p n_p n_s}{\ln(d_o/d_i)}\right) \frac{l_g}{l_s l_a} \times 10^{-7}$$

In normal condition, if $l_1 = l_2 = l$, then

$$e_o = K_1 \left(1 + \frac{2l}{l_g}\right)\left(x_1^2 - x_2^2\right) \tag{2.63}$$

Approximate linearization is done by making $(1/2)\,(x_1 + x_2) = x_0 =$ constant, and $(1/2)(x_1 - x_2) = x$, the weighted differential movement, then

$$e_o = \left[4K_1 \left(1 + \frac{2l}{l_g}\right) x_o\right] x$$

$$= K_2 x \tag{2.64}$$

A rearrangement of Eq. (2.61) converts e_o in the form

$$e_o = K_3 x\,(1 - K_4 x^2) \tag{2.65}$$

where

$$K_3 = \frac{8\omega I_p n_p n_s (l_p + 2l_g + x_o) x_o \times 10^{-7}}{\ln(d_o/d_i) \cdot l_s l_a} \tag{2.66a}$$

and

$$K_4 = \frac{1}{(l_p + 2l_g + x_o) x_o} \tag{2.66b}$$

In fact, there is a nonlinearity in the output which is given by the relation

$$\eta_l = K_4 x^2 \tag{2.67}$$

Assuming that $2l_g << l_p$ and that even at maximum movement the armature remains within the secondary coils, one can simplify the output relation as

$$e_o = \left(\frac{8\pi^2 \omega I_p n_p n_s}{\ln (d_o/d_i)} \right) \frac{2l_p}{3l_s} \left(1 - \frac{x^2}{2l_p^2} \right) \times 10^{-7} \tag{2.68}$$

The maximum movement of x, $x_{\max}$, l_p, and l_s can now be given for a given nonlinearity.

With iron core, power frequency is usually preferred although a frequency of upto about 5000 Hz can be used with sufficient accuracy. Above this, the core loss rises enormously. This core loss even at lower frequencies creates a different problem—a non-zero output at balance condition mainly because of dissimilar losses due to harmonic contents and varying capacitive effects.

2.4.5 Electromagnetic Transducer

It is a bilateral double-function type transducer, as has already been mentioned, that has 'mechanical input–electrical output' and 'electrical input–mechanical output' construction.

A general name of such systems is *electromechanical energy converters* which are governed simultaneously by (i) Faraday's law of electrodynamics and (ii) piezoelectric effect as postulated by Curie. Such transducers can be used both as 'generators' and 'sensors' often termed as 'senders' and 'receivers' respectively. Only the latter usage is of relevance here and is discussed.

Similar to the reluctance type transducer, such a system consists of an inductance coil wound on a ferromagnetic core and a variable gap provides the variation in the output. For producing unidirectional flux, a magnetizing coil with a bias current may be provided or the core can itself be a permanent magnet. Generally, a permanent magnet is used as a core.

If a coil of n turns wound on the core has a coil flux ϕ and coil inductance L, then as shown earlier

$$L = \frac{\mu_0 a n^2}{d} \quad \text{(H)} \tag{2.69}$$

for coil cross-section a, the effective gap d is given by (refer Fig. 2.31)

$$d = x_1 + \left(\frac{\mu_1}{\mu_2} \right) l_1 \tag{2.70}$$

μ_1 and μ_2 being relative permeabilities of air and core material respectively. Usually μ_1 is unity. Also the magnetic energy stored in the coil is

$$E_m = \frac{1}{2} \frac{(n\phi)^2}{L} \tag{2.71}$$

If a current

$$I = \frac{n\phi}{L} \tag{2.72}$$

flows in the coil, the stored energy is obtained by combining Eqs. (2.69), (2.71) and (2.72) as

$$E_m = \frac{1}{2}\frac{\mu_0 I^2 a n^2}{d} \tag{2.73a}$$

$$= \frac{1}{2} L I^2 \tag{2.73b}$$

This energy leads to development of a force f across the gap d (sign ignored) as

$$f = \frac{\partial E_m}{\partial d} = \frac{1}{2}\frac{LI^2}{d} \quad \text{(N)} \tag{2.74}$$

which would consist of a number of components depending on the 'magnetic condition' of the core. If the bias magnetizing current or its equivalent is given by I_o and a sinusoidal current of amplitude of i and frequency ω with $i << I_o$ energizes the core, then (ignoring the i^2 terms)

$$f = \left(\frac{L}{2d}\right)\left(I_o^2 + 2I_o i\right) \tag{2.75}$$

If the coil resistance is negligible, then

$$i = \frac{V}{j\omega L} \tag{2.76}$$

and the varying force term is

$$f_v = \frac{LI_o}{d} \cdot i \tag{2.77a}$$

and using Eq. (2.76)

$$f_v = \frac{I_o V}{j\omega d} \tag{2.77b}$$

The force f is associated with a velocity v as shown in Fig. 2.31 so that with analogy of electrical parameters, we can write

$$f_m = Z_m v \tag{2.78}$$

where Z_m is the mechanical impedance.

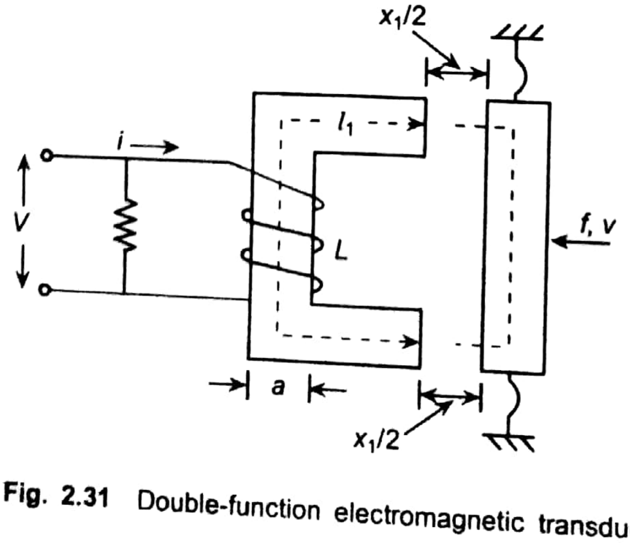


Fig. 2.31 Double-function electromagnetic transducer.

If m, k, and δ represent the mass, stiffness, and damping of the transducer (mechanical), then

$$Z_m = \delta + j\left(\omega_m - \frac{k}{\omega}\right) \tag{2.79}$$

Equations (2.77b) and (2.78) may be combined to give

$$f_t = Z_m v \frac{I_o V}{j\omega d} \tag{2.80}$$

A relation between voltage V, velocity v, and current i can be written as

$$V = \alpha_{vV}\, v + \alpha_{iV} i \tag{2.81}$$

where α_{iV} is the electrical impedance and α_{vV} is complex transducer coefficient. Equation (2.81) can also be used to write, v in terms of V and i.

It can be shown that 'receiver' has a voltage to force ratio

$$\frac{V}{f} = \frac{I_o/(j\omega d)}{\left(\dfrac{I_o^2}{\omega^2 d^2}\right) + \left(\delta + j\left(\omega_m - \dfrac{k}{\omega}\right)\right)\left(\dfrac{1}{R} + \dfrac{1}{R_o} + \dfrac{1}{j\omega L}\right)} \tag{2.82}$$

Where R_o is the load (indicator) resistance and is large, and R is the coil resistance (considered parallel to inductance). The characteristic transfer matrix equation of the transducer can be written as

$$\begin{bmatrix} f \\ v \end{bmatrix} = \begin{bmatrix} \dfrac{I_o}{j\omega d} & 0 \\ \dfrac{-d}{LI_o} & \dfrac{j\omega d}{I_o} \end{bmatrix} \begin{bmatrix} V \\ i \end{bmatrix} \tag{2.83}$$

To this, the mechanical impedance and electrical impedances are superposed so that we get V/f as given by Eq. (2.82).

2.4.6 Magnetostrictive Transducer

Magnetostrictive transducer is not popular as a transducer mainly because of its limitations with respect to materials. Besides the input quantity, its output depends on some other variables also. It is of two different types, namely (i) the variable permeability type and (ii) the variable remanence type.

In general, a magnetostrictive material such as pure nickel has a slope of the hysteresis curve that decreases with increasing tension σ, as shown in Fig. 2.32. This change alters the value of the permeability μ, which also decreases with stress and hence, inductance of a coil wound on it. Also, with increasing tension, the remanence magnetism B_0 decreases. Ni is seen to be a material with negative magnetostriction.

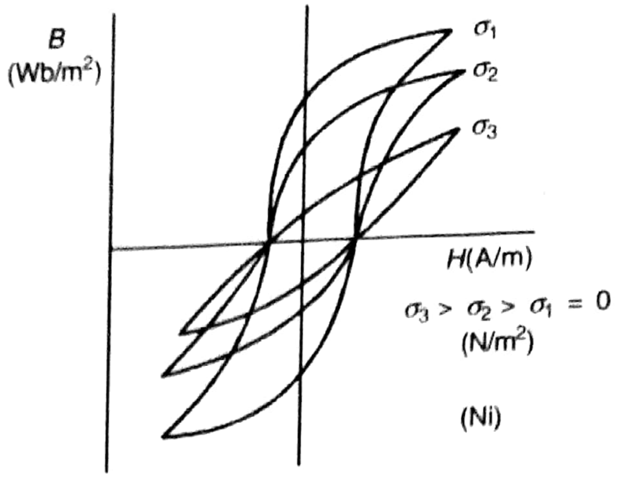


Fig. 2.32 *B–H* loops of magnetostrictive material with changing tension.

However, in case of Ni–Fe alloy known as permalloy such as 68 permalloy (Ni 68), 45 permalloy (Ni 45), the picture is reversed. Increasing tension increases B_0 as also permeability. The shapes of the *B–H* curves for such a situation are depicted in Fig. 2.33.

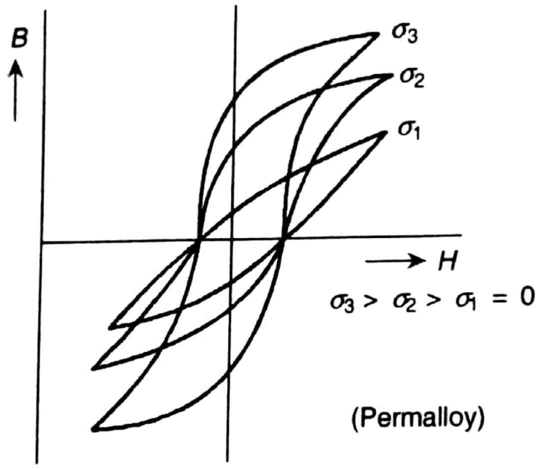
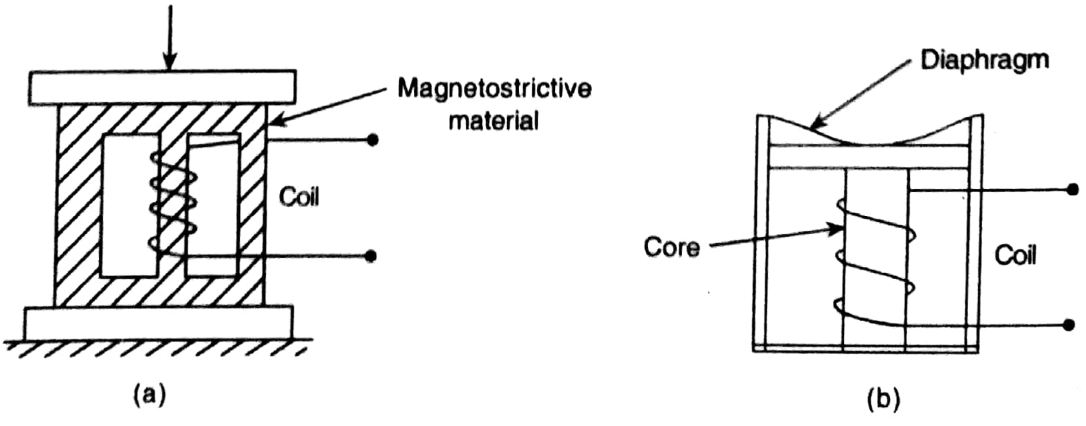


Fig. 2.33 *B–H* loops of another type of material with varying tension.

A typical scheme of the transducer using variable permeability is shown in Fig. 2.34(a). The coil inductance changes with change of force as the latter changes the core permeability. The coil inductance is measured through a bridge with the current and frequency, the coil also changes the inductance. These quantities and temperature have to be kept under strict regulation.



(a) (b)

Fig. 2.34 (a) Scheme of a sensor with magnetostrictive material, (b) transducer operated by a diaphragm usually used in accelerometers.

The variable remanence type transducer is used for specific applications such as an accelerometer where the transducer is designed to receive the stress through a metal diaphragm as shown in Fig. 2.34(b). The open circuit voltage is proportional to the rate of change of the remanence magnetism. In fact, a relation is given as

$$B_0 - B_{0_i} = k_1 \sigma \tag{2.84}$$

and for n turns of coil, the output voltage V is

$$V = nk_2 \frac{dB_0}{dt} \tag{2.85}$$

The k_i's in these equations are constants.

2.4.7 Materials—Some Comments

The core and armature material is essentially ferromagnetic that has high permeability, low loss, high Curie temperature, and low cost. Soft magnetic Ni–Fe alloy is good for the purpose in which there are a few commercial variety such as (i) Mu-metal and (ii) Radiometal (radiometal can further be subdivided into a few types). The permeability in the two cases varies as 60×10^3 to 240×10^3 and 4×10^3 to 65×10^3 respectively. Hysteresis losses are 4 and 40 J/m^3/cycle respectively while Curie temperatures are 350° and 540°C respectively.

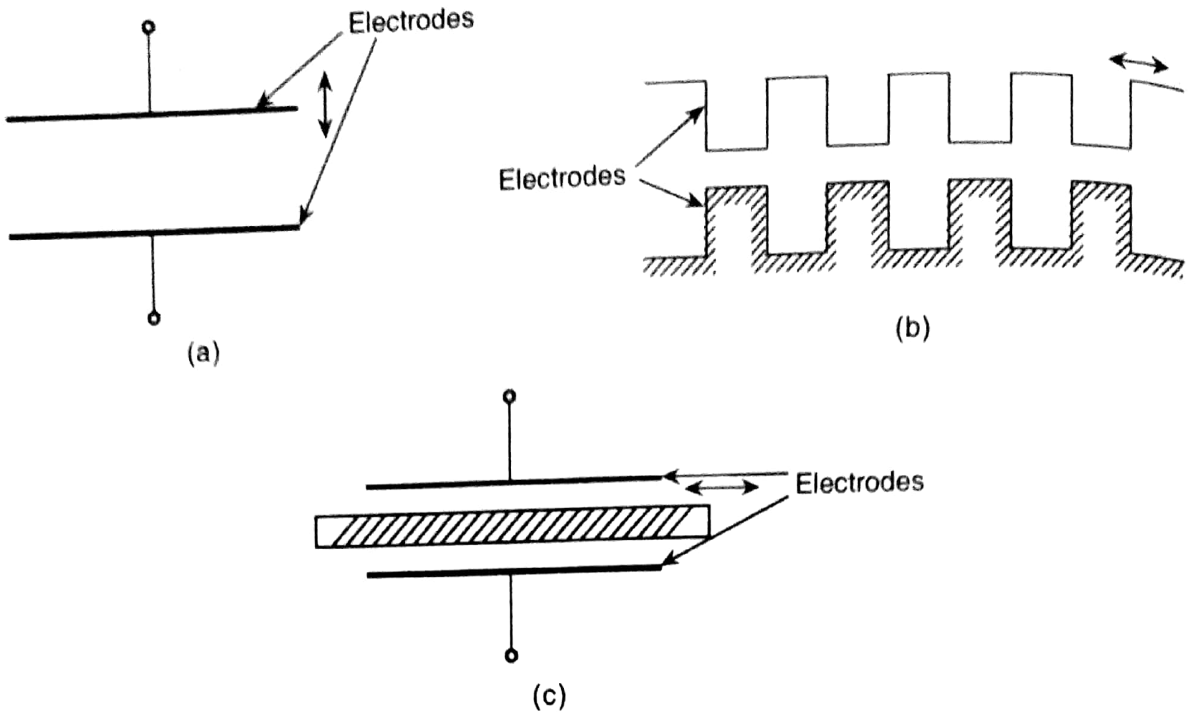
Magnetically soft ferrites consisting of mixed crystals of cubic ferrites are good alternatives, which again have a number of varieties represented by the general formula $M\text{Fe}_2\text{O}_4$ where M is a divalent metal such as manganese–zinc, magnesium–zinc, nickel–zinc, and so on. Such materials have initial permeabilities varying from 0.7×10^3 to 1.8×10^3. One special feature is that ferrites have resistivities about 10^6 times higher than ferromagnetics such that the eddy losses are negligible. Some of such ferrites can be used in high frequency ranges, for example, the Ni–Zn ferrite is particularly suitable for the purpose.

2.5 CAPACITIVE SENSORS

Three types of capacitive sensors can be listed under this category, namely

1. variable capacitance type with varying distance between two or more parallel electrodes (Fig. 2.35(a)).
2. variable capacitance obtained by variable area between the electrodes. An interesting variation of this is obtained by making serrated electrodes or electrodes with teeth, one of which moves (Fig. 2.35(b)), and
3. variable capacitance obtained by having variable dielectric constant of the intervening material. For this the material has to move between the pair of electrodes, and the change in capacitance is obtained and measured (Fig. 2.35(c)).

A fourth variety, the piezoelectric type, depends on the piezoelectric properties of specific kinds of dielectric materials and would be considered later. The movement of the moving electrode of the type shown in Fig. 2.35(b) is restricted to be short, while that of the dielectric material such as an insulation tape is not restricted.

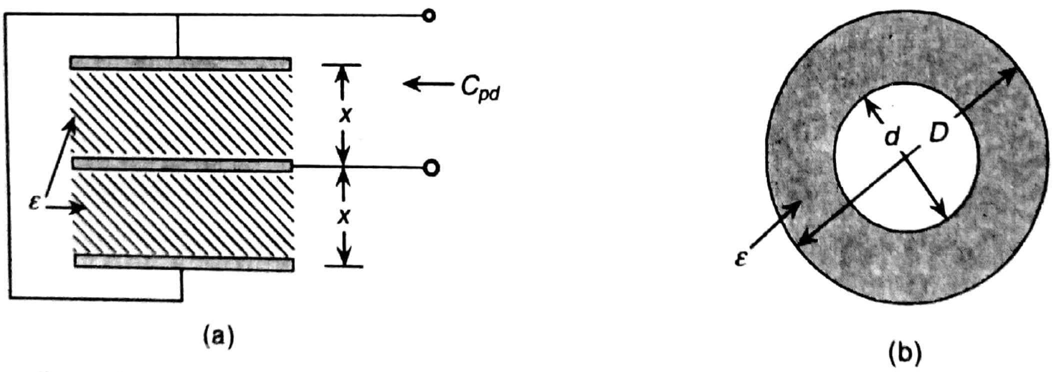


(a) (b) (c)

Fig. 2.35 (a) Parallel plate capacitance type, (b) capacitance type with serrated electrodes, and (c) capacitance type with varying dielectric type material.

A variation in parallel type design is the cylindrical design. Besides, the parallel plate capacitive sensor is often used in a differential form with three plates as shown in a Fig. 2.36(a). For a parallel plate capacitor with dielectric constant or permittivity ε, which is the product of its relative permittivity and the permittivity of the free space (vacuum, often taken as air) of value 8.85×10^{-12} F/m and plate area α, each separated by a distance x from the other, the capacitance is

$$C_p = \frac{\varepsilon\alpha}{x} \tag{2.86}$$



(a) (b)

Fig. 2.36 (a) Parallel plate capacitance sensor, using three plates, (b) cylindrical type capacitance sensor.

A typical three plate capacitor arrangement is shown in Fig. 2.36(a). The capacitance C_{pd} is then given as

$$C_{pd} = \frac{2\varepsilon\alpha}{x} \tag{2.87}$$

For the cylidrical sensor with the electrode thickness negligible as compared to dielectric thickness (Fig. 2.36(b)), the capacitance is

$$C_c = \frac{2\pi \varepsilon l}{\ln(D/d)} \tag{2.88}$$

where l is the cylinder length.

For very thin layer of dielectric material, Eq. (2.88) can be approximated to

$$C_{ca} = \frac{\pi \varepsilon l(D+d)}{(D-d)} \tag{2.89}$$

If in a parallel plate pair the dielectric has a number of layers of dielectric constants with corresponding permittivity ε_i for thickness x_i, the relation (2.86) can be modified to

$$C_{pi} = \frac{\alpha}{\sum x_i/\varepsilon_i} \tag{2.90}$$

The capacitance is, in general, associated with a high resistance, called *leakage*, because the dielectric materials do not have infinite permittivity. This leakage is represented by a parallel resistance R_p, particularly at lower frequencies of measurement. This loss consists of dc conductance, dielectric loss of insulators supporting the electrodes, and the actual dielectric loss. With increasing frequency, the load resistances R_l contribute to loss factors and the complete equivalent circuit is given by the circuit of Fig. 2.37, where the inductance L represents the inductance between the terminals as also the cable inductance whenever such cable is used. Such an equivalent circuit would be taken up at a later stage.

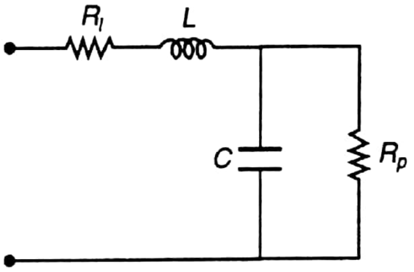


Fig. 2.37 Equivalent circuit of the capacitance transducer.

2.5.1 The Parallel Plate Capacitive Sensor

Considering now a general case of a pair of parallel plates with a solid dielectric of a certain thickness x_s and an air gap x_a as shown in Fig. 2.38, the capacitance C is given by

$$C = \frac{\alpha}{\left(\frac{x_a}{\varepsilon_a}\right) + \left(\frac{x_s}{\varepsilon_s}\right)} \tag{2.91}$$

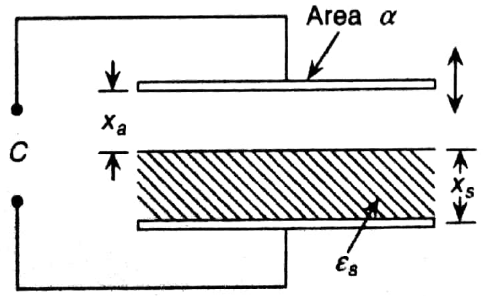


Fig. 2.38 Parallel plate sensor with different dielectric materials.

With the plate moving, a decrease in x_a increases C and vice versa. Thus,

$$C \pm \partial C = \frac{\alpha}{\left(\dfrac{x_a \mp \partial x_a}{\varepsilon_a} + \dfrac{x_s}{\varepsilon_s}\right)} \tag{2.92}$$

Considering, however, $\varepsilon_a \approx 1$, for simplicity, we obtain

$$\mp \frac{\partial C}{C} = \pm\left(\frac{\partial x_a}{x_a + x_s}\right)\left(\frac{1}{\dfrac{1 + \dfrac{x_s}{x_a \varepsilon_s}}{1 + \dfrac{x_s}{x_a}} \mp \dfrac{\partial x_a}{x_a + x_s}}\right) \tag{2.93}$$

In Eq. (2.93), the quantity $(1 + x_s/(x_a\varepsilon_s))/(1 + x_s/x_a)$ is an important factor in determining the value of $+\partial C/C$ as well as its nature. This quantity is represented as $1/\beta$, where β is often referred to as the *sensitivity factor*, but it also is responsible for the nonlinearity. Writing $(\partial x_a/x_a)/(1 + x_s/x_a) = (\partial x_a/x_a)/(1 + \lambda)$, $\pm\partial C/C$ can be expanded as

$$\mp \frac{\partial C}{C} = \pm\left(\frac{\partial x_a}{x_a}\right)\left(\frac{\beta}{1+\lambda}\right)\left[1 \pm \left(\frac{\partial x_a}{x_a}\frac{\beta}{1+\lambda}\right) + \left(\frac{\partial x_a}{x_a}\frac{\beta}{1+\lambda}\right)^2 \pm \ldots\right] \tag{2.94}$$

As β is a function of x_a, x_s, and ε_s, the plots of β versus λ with ε_s as a parameter show that with increasing λ, β increases with ε_s, its minimum value being 1 for $\varepsilon_s = 1$.

It must be stressed here that capacitors have fringing effects which are usually taken care of by providing guard ring which is a ring surrounding a plate of the capacitor, the ring and the plate both being at the same potential.

2.5.2 Serrated Plate Capacitive Sensor

As has been discussed earlier, a pair of flat serrated plates, one of which is fixed in position, the other with a small relative movement show change in capacitance and this principle is utilized in some cases to measure small angular variations. For the measurement to be of any significance, the relative movement has to be small. Figure 2.39 shows the active tooth length (on the fixed plate) as l, air gap as x, tooth width as w; if number of teeth-pair is n and air permittivity is ε_a, the capacitance C is given as

$$C = \frac{\varepsilon_a l w n}{x} \tag{2.95}$$

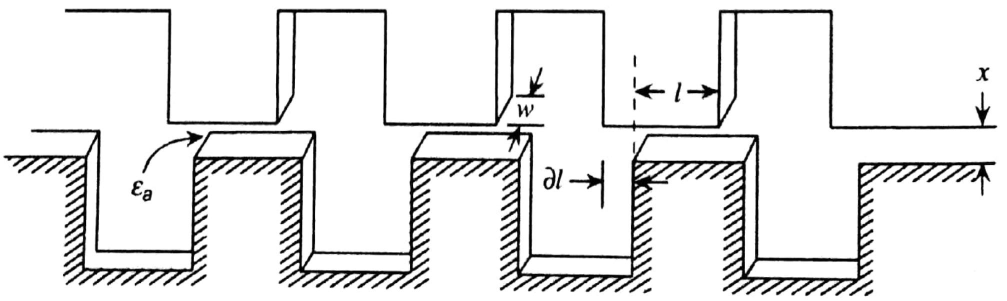


Fig. 2.39 Serrated electrode capacitance sensor with changing active tooth length.

so that for a small relative movement ∂l of the moving plate, we obtain

$$\frac{\partial C}{C} = \frac{\partial l}{l} \tag{2.96}$$

This simplified relation assumes no fringing effect. However, by drawing actual equipotential lines and parallel flux lines between the pair of teeth, the leakage can be allowed in the relation. Therefore,

$$\frac{\partial C}{C} = \frac{\partial l}{l}\left(\frac{1}{1+\frac{kx}{l}}\right) \tag{2.97}$$

where the expression within the brackets can be termed as the sensitivity factor, β_s, which decreases with increasing x/l as shown in Fig. 2.40. This factor β_s is actually the ratio of nonleakage to total flux.

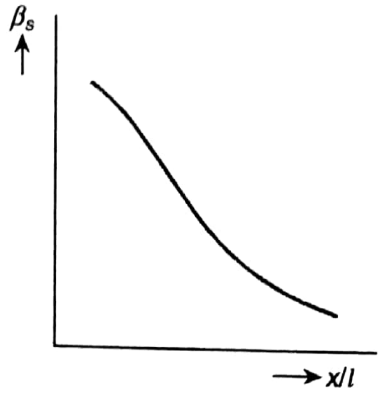


Fig. 2.40 Sensitivity versus normalized gap curve.

2.5.3 Variable Permittivity or Variable Thickness Dielectric Capacitive Sensor

This type of capacitive sensors can be represented as shown in Fig. 2.41. With plate effective area α and other dimensions as shown in the figure, the capacitance C is given by

$$C = \frac{\alpha}{l - x + \frac{x}{\varepsilon_d}} \tag{2.98}$$

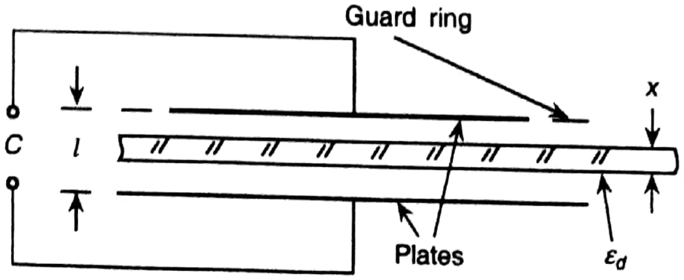


Fig. 2.41 Scheme of a variable permittivity (or thickness) dielectric type sensor.

where ε_d is the permittivity of the dielectric material. Following the development in Section 2.5.1, one obtains the normalized change in capacitance as

$$\left(\frac{\partial C}{C}\right)_{\varepsilon_d} = \pm\frac{\partial \varepsilon_d}{\varepsilon_d}\,\frac{1/[1+\varepsilon_d(l-x)/x]}{1 \pm \dfrac{1}{1+x/(\varepsilon_d(l-x))}\cdot\dfrac{\partial\varepsilon_d}{\varepsilon_d}} \tag{2.99}$$

Here, $1/(1 + \varepsilon_d(l - x)/x)$ is the sensitivity factor β_s and the nonlinearity factor is $\eta_n = 1/(1 + x/(\varepsilon_d(l - x)))$. If $\eta_n \partial\varepsilon_d/\varepsilon_d$ is small, we obtain, with first order approximation,

$$\left(\frac{\partial C}{C}\right)_{\varepsilon_d} = \frac{\partial \varepsilon_d}{\varepsilon_d}\cdot\frac{1}{1+\varepsilon_d(l-x)/x}\left[1 \mp \frac{\partial\varepsilon_d/\varepsilon_d}{1+x/(\varepsilon_d(l-x))}\right] \tag{2.100}$$

Obviously, with $x/(l - x)$ high, β_s is high and η_n is low which must be a good choice.

Instead of variation in ε_d, there may be variation in x, so that we have

$$\left(\frac{\partial C}{C}\right)_{x} = \frac{\partial x}{x}\,\frac{\dfrac{\varepsilon_d-1}{1+\varepsilon_d(l-x)/x}}{1 \mp \dfrac{\varepsilon_d-1}{1+\varepsilon_d(l-x)/x}\,\dfrac{\partial x}{x}} \tag{2.101}$$

and if $[(\varepsilon_d - 1)/(1 + \varepsilon_d(l - x)/x)]\partial x/x << 1$, taking the first order term only, the expression for $(\partial C/C)_x$ is obtained as

$$\left(\frac{\partial C}{C}\right)_{x} = \frac{\partial x}{x}\,\frac{\varepsilon_d-1}{1+\varepsilon_d(l-x)/x}\left[1 + \frac{\varepsilon_d-1}{1+\varepsilon_d(l-x)/x}\,\frac{\partial x}{x}\right] \tag{2.102}$$

In this case, the sensitivity factor and the nonlinearity factor are identical and given by $(\varepsilon_d - 1)/(1 + \varepsilon_d (l - x)/x)$. It means that the sensitivity is good with high $x/(l - x)$ as also ε_d, but the nonlinearity also increases.

2.5.4 Stretched Diaphragm Variable Capacitance Transducer

Such transducers with a very thin diaphragm are used in differential arrangement in transmitters these days where the stiffness in bending is ignored. Other kinds are used for direct pressure measurement which are thicker though thin with respect to diameter. Their stiffness in bending cannot be ignored like ones with thin diaphragms.

A typical scheme of the former type (non-differential mode) is shown in Fig. 2.42. With the dimensions shown after a maximum central deflection d of the diaphragm with a pressure p has occurred, the depression x at a radial distance r from the centre of the diaphragm under tension t_d is given by

$$x = \frac{2t_d}{p}\left[\sqrt{1-\left(\frac{rp}{2t_d}\right)^2} - \sqrt{1-\left(\frac{Rp}{2t_d}\right)^2}\right] \tag{2.103}$$

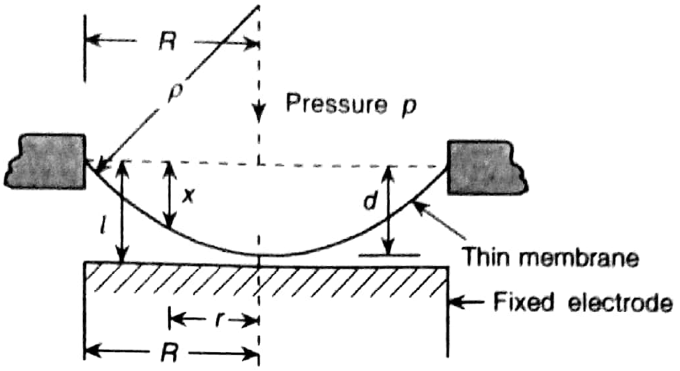


Fig. 2.42 Stretched diaphragm type capacitance sensor.

Expanding the right hand side in series form and accepting only the first order term for small deflection, that is, $(d/R)^2 << 1$,

$$x = \frac{p}{4t_d}(R^2 - r^2) \tag{2.104}$$

The small capacitance formed by the fixed electrode and a narrow annular area of the depressed membrane of width dr at a radius r, as shown in the figure, is given by

$$dC = \frac{2\pi r\, dr \varepsilon_a}{l - x} \approx \left\{\frac{2\pi r\, dr\, \varepsilon_a}{l}\right\}\left(1 + \frac{x}{l}\right) \tag{2.105}$$

for $x/l << 1$, so that the total capacitance, using Eq. (2.104), is

$$\int_0^R dC = \frac{2\pi\varepsilon_a}{l}\int_0^R \left(1 + \frac{x}{l}\right) r\, dr$$

$$= \frac{2\pi\varepsilon_a}{l}\int_0^R \left(1 + \frac{p}{4t_d l}(R^2 - r^2)\right) r\, dr \tag{2.106}$$

The first part $\pi\varepsilon_a R^2/l$ is the capacitance of the pair when the diaphragm is undeflected, while the incremental capacitance ∂C is computed as

$$\partial C = \left(\frac{\pi\varepsilon_a R^4}{8l^2 t_d}\right) p \tag{2.107}$$

so that

$$\frac{\partial C}{C} = \frac{R^2}{8t_d l} p \tag{2.108}$$

represents the sensitivity of the capacitance system.

Diaphragm system is frequently used in microphones where the vibrating diaphragm is backed by a thin layer of air which also tends to vibrate with it giving a cushioning effect, and by reducing the dynamic sensitivity, it increases dynamic stiffness. The effect is reduced to a greater extent by providing perforation in the fixed electrode. The vibrating layer of air also increases the diaphragm inertia affecting the frequency response.

A diaphragm formed by machining from the solid to avoid large hysteresis losses is said to be clamped type and although it may be made to have its thickness small enough with respect to its diameter, it does provide a stiffness to bending. If the diaphragm thickness is τ and material Poisson's ratio ν, Young's modulus Y, for other dimensions as shown in Fig. 2.42, the deflection x is given by

$$x = \frac{3p}{16} \cdot \frac{1-\nu^2}{Y\tau^3}(R^2 - r^2)^2 \tag{2.109}$$

Following the similar procedure as above, the sensitivity may be derived as

$$\frac{\partial C}{C} = \frac{(1-\nu^2)R^4}{16Ylt^3}\, p \tag{2.110}$$

2.5.5 Electrostatic Transducer

Similar to the electromagnetic transducer discussed in Section 2.4.5, capacitive type transducer can also be developed with bilateral characteristics, where it is used with dc polarization. Such a transducer is also referred to as an *electrostatic transducer*. A typical scheme of such a system is shown in Fig. 2.43. A capacitor is formed with a 'flexible' diaphragm which can move due to application of force and a rigid plate p_1. There is bias voltage V_s which is sufficiently large. When the system acts as a transducer, the gap x between the plates changes as by some pressure in case of an 'electrostatic microphone'. This pressure may be considered sinusoidal in nature for analysis purpose. A circuit consisting of a resistance R and capacitance C 'varying sinusoidally' allows V_s to send a sinusoidal current i to flow in it and hence, a sinusoidal output V_o across resistance R is obtained.

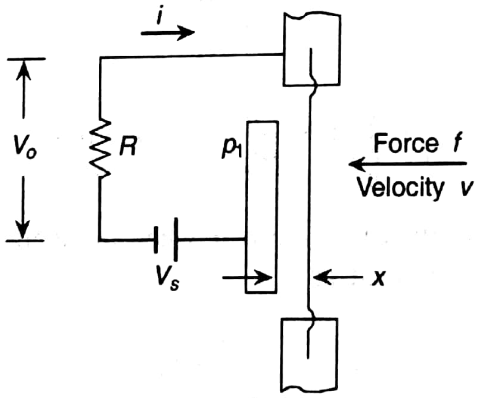


Fig. 2.43 Electrostatic transducer.

Analyzing as in the case of electromagnetic transducer, V_o corresponding to a force f can be obtained in terms of the parameters V_s, x, R, C, ω, mass m, stiffness k, and damping (ζ) of the system. In fact, the dynamic transfer function is given by

$$\frac{V_o(s)}{f(s)} = \frac{s x_o R C_o V_s}{s^3 x_o^2 m R C_o + s^2 (m x_o^2 + x_o^2 R C_o \zeta) + s(x_o^2 \zeta + x_o^2 R C_o k) + (x_o^2 k + V_s^2 C_o)} \tag{2.111}$$

where, C_o and x_o are the initial values of x and C, and s may be replaced by $j\omega$ where ω is the input circular frequency.

Frequency response analysis of this shows a flat response upto a frequency $\omega_o = (k/m)^{1/2}$, at which a resonance occurs and range is obviously specified by the same. Also below $\omega_b = (C_oR)^{-1}$, the response is not constant. Hence, the frequency range is $(\omega_o - \omega_b)$.

In case of generating action, alongwith bias V_s, a sinusoidal input voltage is also applied so that the diaphragm undergoes electrostatic vibration.

2.5.6 Piezoelectric Elements

Crystals of certain classes are said to show piezoelectric effect which essentially means electric polarization produced by mechanical strain in the crystals. Such a polarization is believed to occur because of asymmetric crystal structure. The effect is reversible in the sense that a strain may be produced in the crystal by electrically polarizing it using an external source. While the mechanical input to electrical output form is used in developing transducers extensively, the reverse effect is used in many modern gadgets such as sonar systems, ultrasonic non-destructive test equipment, ultrasonic flowmeters, pump for inkjet printers, and so on.

Also a piezoelectric crystal is represented by a set of three Cartesian coordinates so that the polarization P can be represented in the vector form as

$$\mathbf{P} = P_{xx} + P_{yy} + P_{zz} \tag{2.112}$$

However, P_{xx}, P_{yy}, and P_{zz} are again related to the stresses, axial and shear, σ, and χ, in terms of a set of axes-dependent coefficients called d-constants of the crystal. With the axial and shear axes as shown in Fig. 2.44 with reference to the crystal axes X-Y-Z, we obtain

$$\begin{bmatrix} P_{xx} \\ P_{yy} \\ P_{zz} \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \chi_{yz} \\ \chi_{zx} \\ \chi_{xy} \end{bmatrix} \tag{2.113}$$

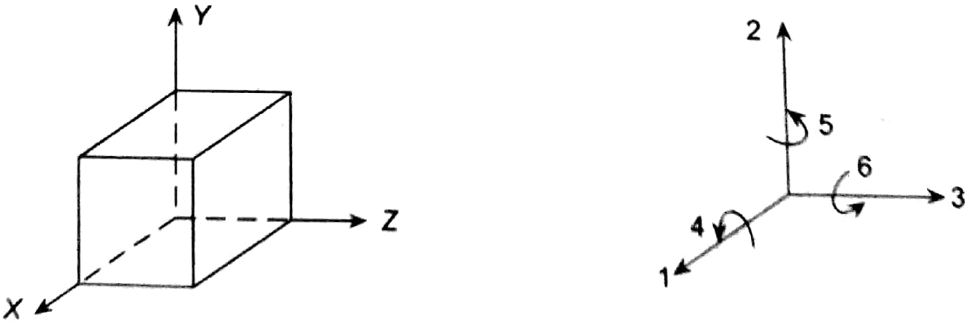


Fig. 2.44 The piezoelectric crystal defined in X-Y-Z axes.

The d-constants are defined as

$$d_{ij} = \frac{\text{charge generated in direction } i}{\text{force applied in direction } j} = \frac{Q_i}{f_j} \tag{2.114}$$

expressed as coulomb per Newton usually. The reverse effect *d*-coefficients are similarly defined as

$$d_{ij} = \frac{\text{strain in direction } i}{\text{field applied in direction } j} = \frac{\varepsilon_i}{E_j} \tag{2.115}$$

expressed usually in (m/m)/(V/m).

One other coefficient which is of importance in practical design is the *g*-coefficient and is related to the *d*-coefficient by the dielectric constant of the material. It is defined as the voltage gradient or field in the crystal per unit pressure imparted to it. Maintaining the direction as before, it can be shown that

$$g_{ij} = \frac{Q_i}{\varepsilon_d f_j} = \frac{d_{ij}}{\varepsilon_d} \tag{2.116}$$

A third coefficient, the *h*-coefficient, is defined as the voltage gradient per unit strain which also appears to be the reciprocal of d_{ij} given by Eq. (2.115). The *h*-coefficient is easily obtained from the *g*-coefficient by multiplying it with the Young's modulus in the appropriate direction.

Crystals, for various uses, are characterized by coupling coefficient which actually is a measure of the efficiency of the crystal as energy converter. Its application in transducer engineering is limited but it is a necessary parameter when used in generators. The numerical value of coupling coefficient is given by

$$K_{ij} = (d_{ij}\, h_{ij})^{1/2} \tag{2.117}$$

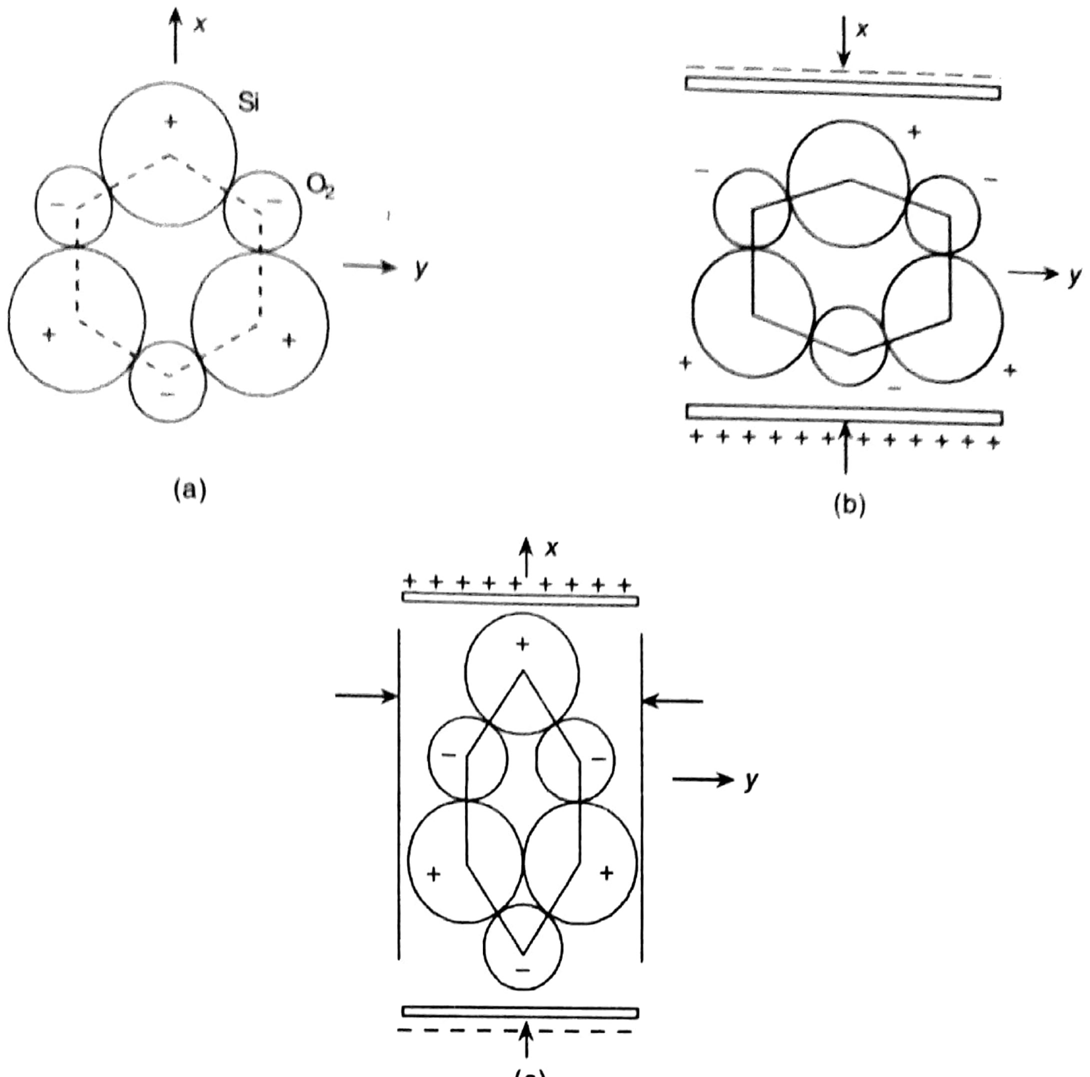
The value of d_{11} for quartz is 2.3×10^{-12} coulombs/N and its dielectric constant is 4.06×10^{-11} F/m. Hence, its g_{11} value is 56×10^{-3} (V/m)/(N/m^2).

Piezoelectric materials

Materials for piezoelectric sensors have been divided into two groups: (i) those occurring naturally such as quartz, rochelle salt $NaKC_4H_4O_6$, $4H_2O$, tourmaline and so on, (ii) those produced synthetically such as lithium sulphate (LS), $NH_4H_2PO_4$ or ammonium dihydrogen phosphate (ADP), and $BaTiO_3$ or barium titanate (BT). Barium titanate is actually a ferroelectric ceramic and requires to be polarized before use. Besides, there are certain polymer films which also exhibit the piezoelectric property.

Crystals like quartz have natural asymmetric structure which is responsible for this property. Quartz is representable as a helix along which one silicon and two oxygen atoms interlace. The planar view of the crystal cell, perpendicular to the *z*-axis also called the optic axis, shows a hexagonal shape with one Si and two oxygen occupying the vertices alternately as shown in Fig. 2.45(a). The chemical structure gives the formula SiO_2. In the normal unstressed condition, the positive charges of silicon and the negative charges of oxygen compensate each other without showing any electrical output.

However, with application of a force (compression) in the direction of *x*-axis, the crystal is deformed to the extent of being polarized so that positive and negative charges are generated as shown in Fig. 2.45(b). If this force is applied in the *Y*-direction, the deformation produced is such that opposite charges are now generated on the two faces as shown in Fig. 2.45(c). These two cases are known as longitudinal and transverse effects respectively. Changing the type of force, that is, from compression to tension, reversal in the polarity of charge generation occurs.



(a)

(b)

(c)

Fig. 2.45 (a) The quartz crystal model, (b) charge generation with force applied in the direction of the electrodes, and (c) charge generation with the force applied perpendicular to the position of electrodes.

As a result of the symmetry of the crystal structure in the z-direction, there does not occur any charge 'discrepancy' or polarization when force is applied in this direction and this axis is, therefore, termed as the *optic axis*.

It may be noticed that polarization deep inside the crystal is cancelled out and only the surface layers are affected to produce the free charges. The degree of distribution is thus, important for the amount of charges on the two faces which means that the force applied is the main criterion. This is true specially for the case of Fig. 2.45(b). However, in case of Fig. 2.45(c), the transverse charge 'size' in the x-direction has a multiplying factor α_x/α_y where α is the face area.

The material properties that are relevant to the piezoelectric sensors are (i) dielectric constant, (ii) d-coefficients (xx, say), (iii) resistivity (specifically, volume resistivity is considered), (iv) Young's modulus, (v) humidity range (since above or below this range large absorption of moisture occurs changing volume resistivity and performance characteristics), (vi) temperature range, and (vii) density. A comparative study of these properties is made in Table 2.5.

Table 2.5 Properties of piezoelectric materials

Material	d (*relative*)	$d_{xx}(\times 10^{-12})$ (cou/N)	ρ_v (Ω - m)	$Y(\times 10^9)$ (N/m^2)	H_R (%)	T_R (°C(max))	Density ($\times 10^3$) (kg/m^3)
Quartz	4.5	2.3	10^{12}	80	0–100	550	2.65
Rochelle Salt	350	550	10^{10}	10–20	40–70	45	1.77
Tourmaline	6.7	2–2.25	10^{11}	160	0–100	1000	3.10
LS	10.3	13–16	10^{10}	46	0–95	75	2.05
ADP	15.3	25–45	10^{8}	19.5	0–94	125	6.8
Titanates	500–1750	80–500	10^{9}–10^{13}	47–80	—	200–400	5.8–7.8

Inspite of some deficiencies such as low mechanical strength, limited humidity and temperature range, large hysteresis, and fatigue, Rochelle salt is often used in microphones and also in gramophone pickups because of high shear sensitivity and permittivity. Although available as naturally occurring, it is industrially grown now for bigger requirements.

Tourmaline has poor sensitivity ($d_{xx} \approx 2$–2.5) and is costly. It is, therefore, rarely used as a sensor of this type. But it has two specific advantages—(i) it has a long, perhaps the longest, temperature range, and (ii) it is the only naturally occurring variety that shows large volume-expander mode capability, that is, with high force in all three directions it gives a large *d*-value in *x-x* direction.

Lithium Sulphate is good in volume-expander mode but ammonium dihydrogen phosphate is used quite extensively for acceleration and pressure sensing purposes although it has low permittivity. It can also be used in twisting applications.

Among the titanates, barium titanate ($BaTiO_3$)—a polycrystalline ceramic has high ε_d and with induced polarization is very conveniently used in many transducers. Ferrroelectric materials can be analyzed analogous to the ferromagnetic ones and its polarization is effectively explained with the help of the 'domain' structure. The material is assumed to consist of 'zones' with spontaneous polarization (for example, Weiss zones in ferromagnetics) which can be partially oriented by the application of external electric field. A barium titanate crystal is modelled as shown in Fig. 2.46. The crystal cells are tetragonal with the axes ratio 1.01 and the central Ti atom has a preferred direction of movement between the oxygen atoms in which polarization can occur. Above Curie point (120°C), the structure reduces to a cubic form and the polarizability is lost.

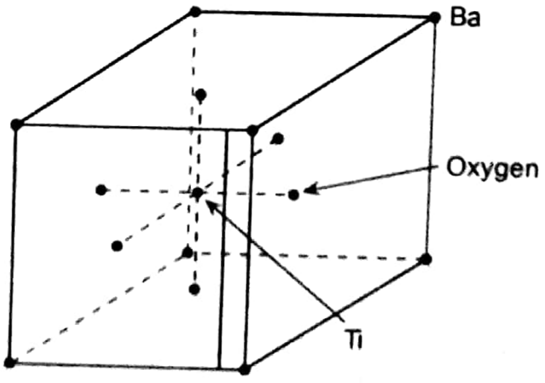


Fig. 2.46 The model of a $BaTiO_3$ crystal.

As in the case of soft magnetic material, ferroelectric material also loses polarization with time as the remanent polarization depends on the coercive force of the dipoles. This is understood from the hysteresis loop. This loss can be prevented and stability increased, by introducing polarization impurities such as lead, calcium, yittrium and so on. However, for transducers, lead zirconate titanate has been found to be more suitable than the simple ones suggested previously. Lead zirconate titanate is a solid solution of lead titanate and lead zirconate which is only 10–60 mole percent of the former. Depending on the amount of lead zirconate and also on processing techniques, values of *d*-coefficients differ greatly, the Curie point being pushed up in almost all the cases from 200° to 300°–350°C. Another composition consists of lead actaniobate which has the highest Curie point.

The dielectric constant, *d*-coefficients, and dissipation in a ferroelectric ceramic change with temperature. The nature of such changes are shown in relative response plots in Fig. 2.47. These can be compared with those of quartz, specially the variation of *d*-coefficients and ε_d. Figure 2.48 shows the plots.

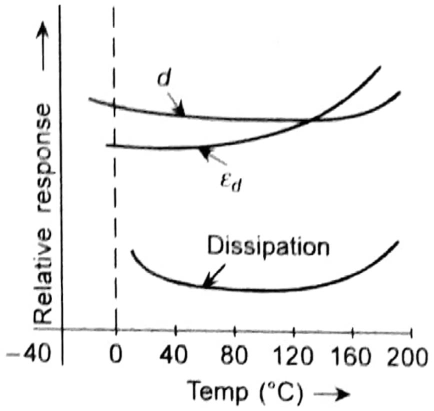


Fig. 2.47 Relative response-temperature curves for *d*-coefficients, dielectric constant and dissipation of $BaTiO_3$.

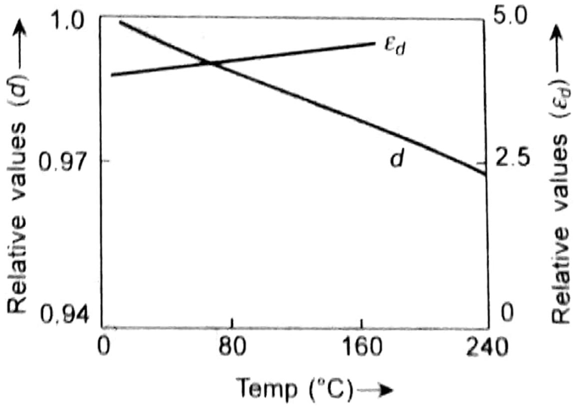


Fig. 2.48 Variation of *d*-coefficients, dielectric constant with temperature for quartz.

Titanates are synthetically produced by pressure, film-casting or extrusion, and finally sintering—the ohmic contacts are obtained by silver or palladium coating on which soldering of lead-wires can be done before polarization. Polarization is usually affected at a voltage of 2 KV/mm and is kept for a few minutes depending on the material.

Considering a quartz sensor of thickness t obtained by cutting perpendicular to its x-axis, two faces which have same areas (α each) and are perpendicular to this axis are metallized; if now, a force f_x is applied to it along the x-direction, the charge Q_x generated would be

$$Q_x = d_{11} f_x \tag{2.118}$$

The capacitance C_x of the sensor is then given by

$$C_x = \frac{\varepsilon_d \alpha}{t} \tag{2.119}$$

so that voltage V_x is

$$V_x = \frac{Q_x}{C_x} = \frac{d_{11} f_x t}{\varepsilon_d \alpha} \tag{2.120}$$

For a crystal of dimensions as shown in Fig. 2.49 with a force f_y in the y-direction, the charge on the plates perpendicular to x-direction is given by (as already mentioned)

$$Q_x = d_{12}\left(\frac{l_y}{l_x}\right) f_y \tag{2.121}$$

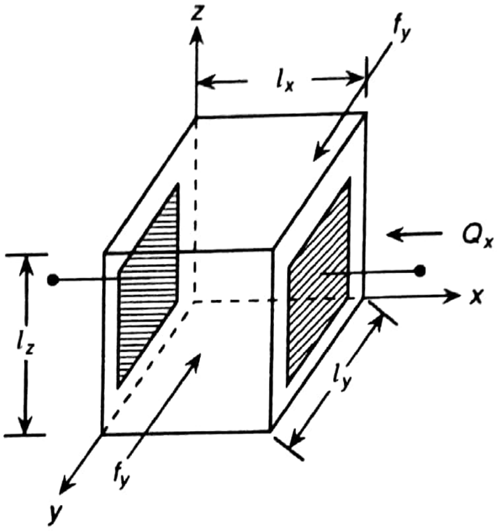


Fig. 2.49 A crystal with electrodes and marked dimensions.

However, for quartz, all the d-coefficients given in Eq. (2.113) are not finite nonzero values. In fact, the d-matrix for quartz is given as

$$[d] = \begin{bmatrix} d_{11} & -d_{11} & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & -d_{14} & -2d_{11} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{2.122}$$

so that Eq. (2.121) is modified as

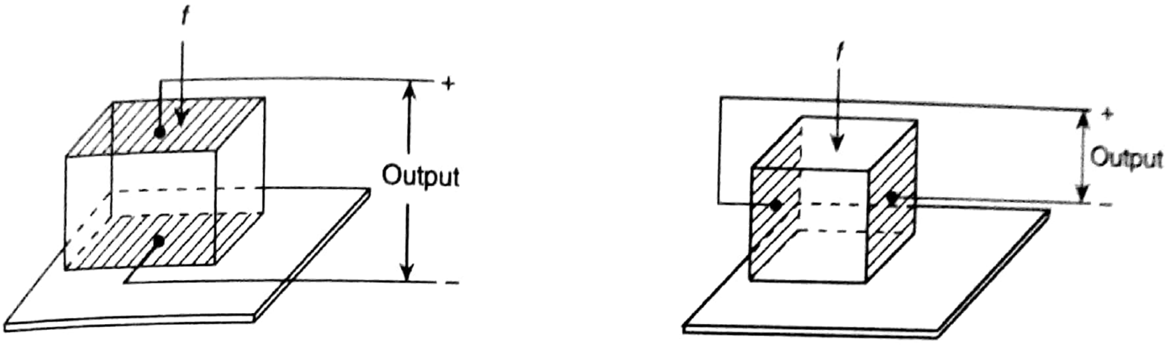
$$Q_x = -d_{11}\left(\frac{l_y}{l_x}\right) f_y \tag{2.123}$$

and a voltage V_x is given by

$$V_x = \frac{-d_{11} f_y}{\varepsilon_d l_z} \tag{2.124}$$

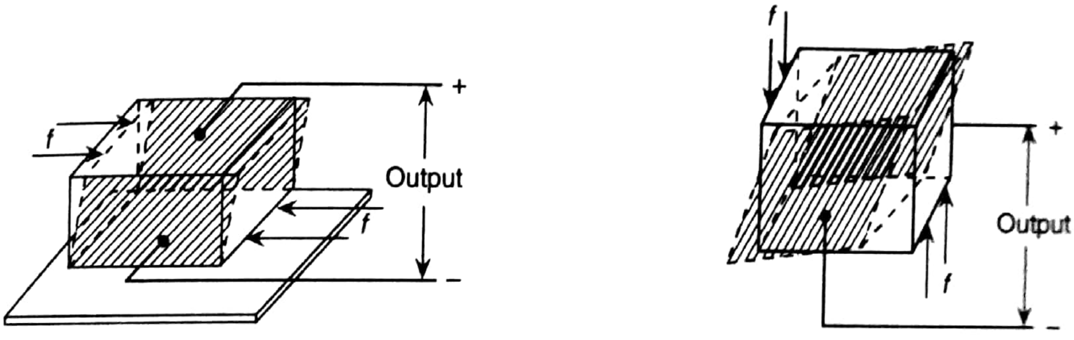
Deformation modes and multimorphs

Piezoelectric sensors can produce outputs in the form of charge or voltage with force, acceleration, velocity, as (displacement) inputs and then occurs 'deformation' (in the crystals). This deformation is of different types depending on the application of inputs in it. Accordingly, a number of modes are listed. In the preceding subsection, it was the thickness that changed, and accordingly the mode is named 'thickness expander mode' (TEM). The others of consequence are shown in Fig. 2.50. Other modes are length expander mode (LEM), thickness shear mode (TSM), face shear mode (FSM) and volume expander mode (VEM).



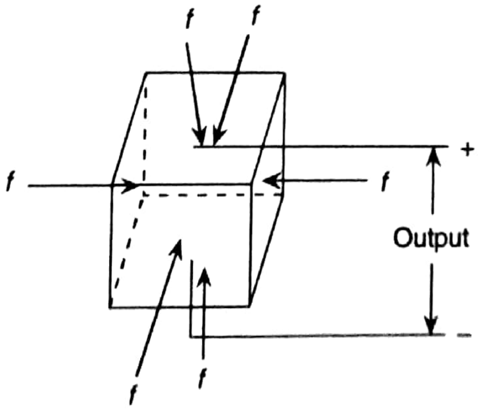
(a) TEM

(b) LEM



(c) TSM

(d) FSM



(e) VEM

Fig. 2.50 Representation of different deformation modes: (a) thickness expander mode, (b) length expander mode, (c) thickness shear mode, (d) force shear mode, and (e) volume expander mode.

Instead of a single element sensor, it is possible to cement together two such elements as in a sandwich to obtain larger (ideally double) output. Such elements are often termed as 'bimorphs'. Proceeding in a similar way, multimorphs may be obtained for more than two elements. Bimorphs may be obtained by series sandwiching or by parallel arrangement. Figure 2.51(a) and (b) show the two cases. In these cases, the polarization of the two plates with respect to each other, is different so that the series or parallel arrangement may be achieved. Typical bimorph cantilevers for bending (strain) and torque are shown in Figs. 2.52(a) and (b) respectively.

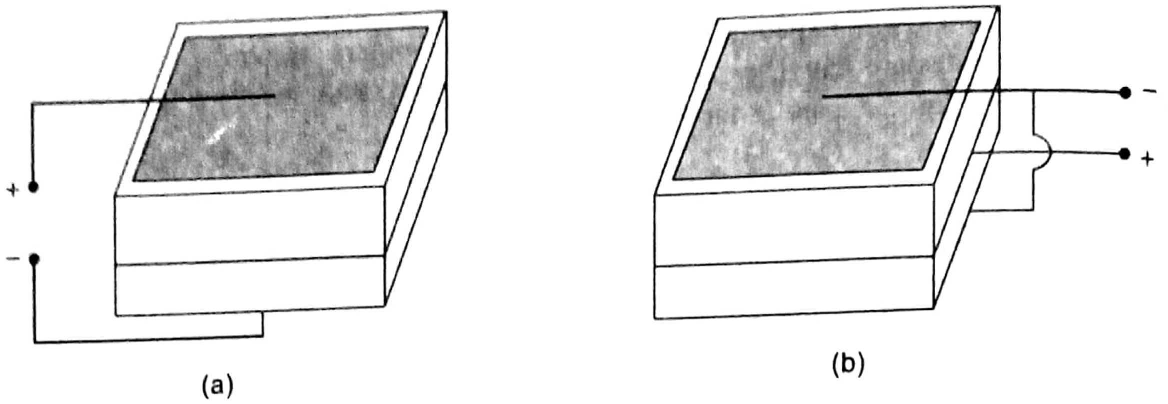


Fig. 2.51 Multimorphs: (a) series, (b) parallel.

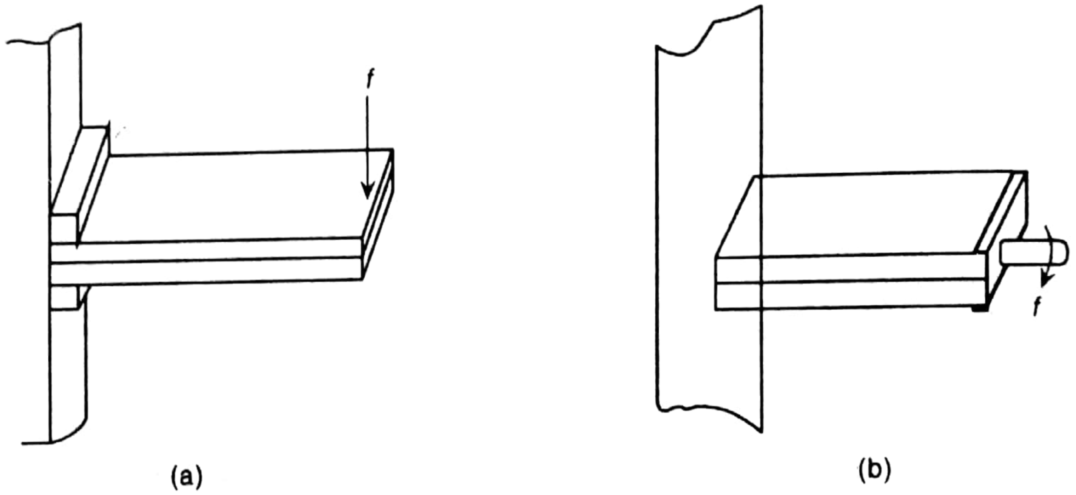


Fig. 2.52 Multimorphs applied in (a) bending, (b) torque.

2.5.7 The PZT Family

The compounds of the solid-solution system $PbZrO_3$–$PbTiO_3$, called PZT, show strong piezoelectric effect and they have same structures as pervoskites. The piezoelectric properties depend on the Ti/Zr ratio. In the phase diagram, it is seen that there are both rhombohedral and tetragonal ferroelectric phases and the best composition for piezoelectricity is one where it lies close to the morphotropic boundary between the rhombohedral and tetrahedral phase when Ti : Zr : : 1 : 1. Most piezoelectric ceramics are based on this PZT group. In fact, attempts have been made to develop 'better' materials by replacing Pb^{2+} with bivalents like Ba, Ca, Sr, Cd, and Ti^{4+} and Zr^{4+} with tetravalents such as Sn^{4+} (the results are available in literature and patents).

A very important material is obtained by incorporating lanthanum into PZT that shows both piezoelectric as well as electro-optic effects such as change in refractive index with application of external fields. This variety produces a new group of materials called PLZT, usually Pb replaced by La. A generalized structure may be written as $Pb_{1-x} La_x (Zr_y Ti_{1-y})_{1-x/4}O_3$. For piezoelectric applications, PLZT has less than 5% lanthanum whereas for electro-optic applications, PLZT contains about 6% lanthanum.

Piezoelectric ceramics are used as capacitors, pressure sensors, resonators, electroacoustic transformers, and so on. In fact, PZT as piezoelectrics are applied in developing ultrasonic motors and ultraprecision grinders whereas the electro-optic variety is used in optical shutters and modulators, displays, optical waveguides, holographic recording, image storage, and so forth.

2.6 FORCE/STRESS SENSORS USING QUARTZ RESONATORS

When stress is applied to a flexurally vibrating quartz beam through its mountings (the stress producing a tension along the axis), the beam has a fundamental mode of flexural resonance frequency f given by

$$f = f_o\sqrt{1 + k_1\left(\frac{S}{Y}\right)\left(\frac{l}{t}\right)^2} \tag{2.125}$$

with f_o as the frequency in absence of stress and is given by

$$f_o = k_2\left(\frac{t}{l^2}\right)\left(\frac{Y}{\rho}\right)^{1/2} \tag{2.126}$$

where S = stress,
Y = Young's modulus,
l = beam length,
t = beam thickness,
ρ = quartz density, and
k_1 and k_2 are constants.

The beam is generally machined out from a stock of quartz with semiflexible mounting for minimizing the mounting misalignments that can affect the vibrating frequency mode. One such scheme is shown in Fig. 2.53(a). The vibrational bending moments that might induce distortion are sought to be cancelled by a double beam design as shown in Fig. 2.53(b). The vibration in the two beams are opposite to each other. The Q-factor in such a structure can be made as high as 10^5. For sustenance of the fundamental mode and frequency measurement, the beams are excited by applying a voltage to the electrode pairs on the beam, when a shearing force is set up in the

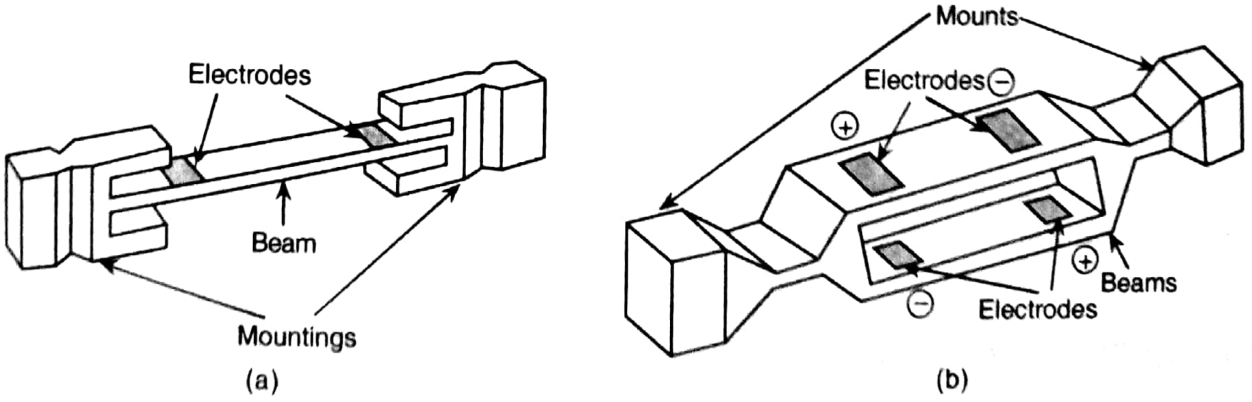


Fig. 2.53 (a) A quartz beam with semiflexible mounting, (b) Double-beam design of the cantilever.

quartz crystal in consequence of which a small component of flexural deformation is produced in it. The electrodes are produced on the faces of the beams by evaporation technique. As shown in Fig. 2.53(b), the electrodes are so supplied that opposite polarization is set up in the beams that can initiate the desired stress pattern for obtaining the fundamental flexural mode. Electronic oscillators are used for supplying the electrodes.

Tuning fork type design of the beams has also been developed using photolithographic techniques, two schemes of which are shown in Figs. 2.54(a) and (b). Beam depicted in Fig. 2.54(a) vibrates in the plane of the 'plate' while the other vibrates perpendicular to it.

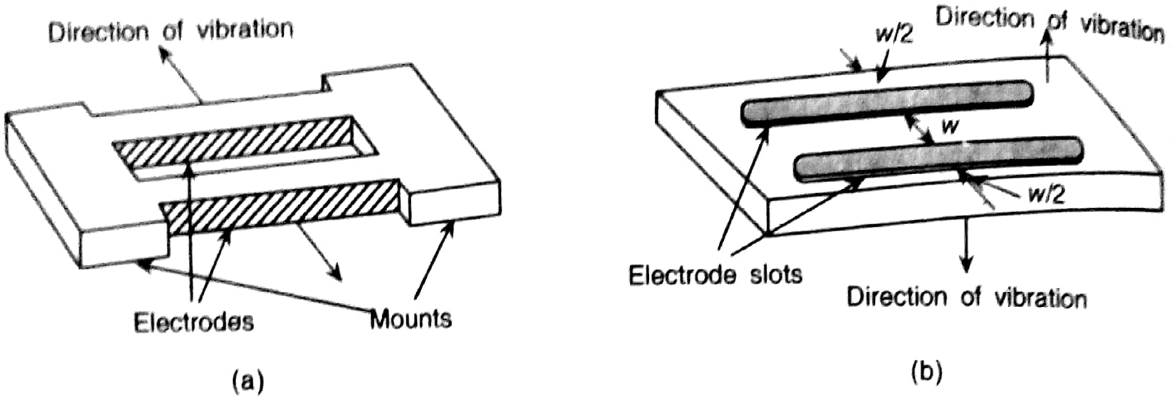


Fig. 2.54 Tuning fork type design of the beams vibrating in opposite phase (a) in the plane of the paper, (b) at right angles to the plane of the paper.

In the scheme of Fig. 2.54(a), the two beams are polarized by oscillator input in such a way that the beams vibrate in opposite phase. Polarization in the other case is so arranged that the central beam, which has a width double that of the side ones, vibrates in opposition to the side beams. More number of beams can be produced in a single assembly if desired.

During production by etching or machining, the crystal axes are properly oriented such that thickness-shear deformation is produced with the application of field. AT and NT cuts are generally recommended.

The stress sensitivity of frequency $\Sigma_S^f = (df/dS)/(f/S)$ is obtained from Eq. (2.125) as

$$\Sigma_S^f = \frac{k_1\left(\frac{S}{Y}\right)\left(\frac{l}{t}\right)^2}{1 + k_1\left(\frac{S}{Y}\right)\left(\frac{l}{t}\right)^2} \tag{2.127}$$

indicating nonlinearity in f–S relationship. Σ_S^f, however, increases with (l/t), but increase of (l/t) reduces mechanical strength.

2.7 ULTRASONIC SENSORS

Piezoelectric effect of certain crystalline materials has been successfully utilized in ultrasound production and sensing. This is described in detail in Section 2.5.6. Basically, it is the converse piezo-effect, that is, when an electrical field is applied to the crystal it changes its shape. This property is utilized in generating acoustic or ultrasound wave. It is to be noted that for transmitting the wave through a medium, it is necessary that an appropriate interfacing is provided. Special types of grease are available for the purpose. Good contact is established by this interfacing.

Of the synthetic piezoelectric crystals, barium titanate ($BaTiO_3$) stands out as the major material which, however, requires prior polarization. It consists of randomly oriented tiny piezoelectric crystallites which are properly oriented mostly by DC polling field of several thousand volts per cm, and the material is cooled through Curie temperature. A strong piezoelectric effect has been observed in compounds such as $PbZrO_3$–$PbTiO_3$ called PZT materials (Section 2.5.7). This also has perovskite structure like $BaTiO_3$ (shown in Fig. 2.46).

Piezoelectric transducers can generate continuous wave ultrasound or pulsed ultrasound—latter being used in SONAR or other similar systems. Ultrasonic piezocrystals operate in the range of 0.5–10 MHz. They are directly attached to the transmitting medium or are separated by a small distance which is filled with coupling materials of suitable acoustic properties. Typical couplants at low temperatures are water, grease, and petrojelly and for higher temperatures special polymer couplants may be used.

For continuous wave operation, the sensor is energized by a tuned oscillator while for pulsed application 'relaxation' oscillators are used to charge a capacitor which is discharged across the sensor.

Analytical models describing the interactions of electrical and mechanical phenomena in piezoelectric media have been proposed but found to be inadequate for the design of piezoelectric transducers with realistic geometries and parameters of the material. Numerical solutions in three dimensions of the fundamental equations of the system, coupling the electrical and mechanical phenomena in the piezo element, are found to be necessary for the purpose. A finite element scheme is often adopted because of its inherent flexibility in handling arbitrary device geometries and anisotropies in the materials. Besides, one has to take account of the interactions of the transducer with the ambient media solutions to the wave equations which govern the propagation if acoustic waves in the ambient media flourish.

REVIEW QUESTIONS

1. (a) How is the output of a potentiometric sensor affected due to shorting of windings by jockey?

For a 100 turn potentiometer, if once the 50th wire is only contacted while at the next instant, 50th and the 51st wires are shorted by the jockey, what would be the percent loss in resolution in the second case if the supply voltage is 10 V?

[*Hint:* Actual resolution in percentage is

$$100 \times \frac{\Delta V - \Delta V_k}{\Delta V} = \{1 - nk[1/(n-1) - 1/n]\}100$$

$$= \{1 - 100 \times 50[1/99 - 1/100]\}100$$

$$= 49.49\%]$$

(b) What are the different principles or schemes adopted to eliminate or at least reduce this effect? Explain with diagrams.

Chapter 3

Thermal Sensors

3.1 INTRODUCTION

Thermal sensors are primarily temperature sensors and their operating principles have long been established, specially those of the primary sensors, also called thermodynamic sensors, and which are the subjects of discussion in this chapter. Any physical quantity, say Q, is usually expressed as its magnitude in number N and in unit U so that

$$Q = NU \tag{3.1}$$

If it is possible to relate temperature T directly in the form of Eq. (3.1), from the first principles, in a sensing system, then it is called a *primary sensor*.

Even though the principles of thermal sensing are well established, newer innovations are added to the stock of sensors dependent on these principles with improved quality and better practical approaches. Many of the commonly used practical 'thermometers' are, however, not primary in that sense and may be called *secondary* as the relationship between Q and T used by them is largely empirical.

A brief classification of primary and secondary temperature sensors is presented in Table 3.1.

Table 3.1 Classification of sensors

Primary sensors	*Secondary sensors*
1. Gas thermometer	1. Thermal expansion types: solid, liquid and gas
2. Vapour pressure type	2. Resistance thermometer
3. Acoustic type	3. Thermoemf type
4. Refractive index thermometer	4. Diodes, transistors, or junction semiconductor types
5. Dielectric constant type	5. Adapted radiation type
6. He low temperature thermometer	6. Quartz crystal thermometer
7. Total radiation and spectral radiation type	7. NQR thermometer
8. Magnetic type	8. Ultrasonic type
9. Nuclear orientation type	
10. Spectroscopic techniques (not sensors in that sense)	
11. Noise type	

There are different kinds of heat flux sensors which measure heat flux in terms of temperature difference. Even in temperature measurement, there are special types of sensors such as pneumatic type, pyroelectric type and so on.

The following discussion describes the primary sensors, perhaps, in principles alone, mainly because of their limited applications in industry. Some of these are transformed to or adapted in commercial applications with minor changes. The overall measuring systems are not discussed but the basic sensing mechanisms are dealt with greater emphasis.

3.2 GAS THERMOMETRIC SENSORS

Gas thermometric sensors are based on the gas law

$$PV = nRT \tag{3.2}$$

where P = the pressure,
V = volume of the gas,
R = the gas constant,
T = the temperature in K-scale, and
n = the number of moles

The relation is, however, true for all ideal gases and is approximately true for real gases at low pressures. For a real gas, a series relation is usually considered which is given by

$$PV = nRT\left[1 + \beta_1(T)\left(\frac{n}{V}\right) + \beta_2(T)\left(\frac{n}{V}\right)^2 + \dots\right] \tag{3.3}$$

where β_i's are virial coefficients which are different for different gases and are functions of temperature. Contributions of the higher order terms become larger at lower temperatures and higher pressures since the gases depart from the ideal nature under such conditions. Even if the first order term is to be retained, knowledge of $\beta_1(T)$ is required.

Gas thermometers can be of two different types, both based on the same basic law. These are: (i) constant volume thermometers where P is proportional to T and (ii) constant pressure thermometers where volume V is proportional to T. However, constant volume thermometer is more easily realized in practice. Usually, the term higher than first order term in Eq. (3.3) is negligible so that, on approximation, we obtain

$$PV = nRT\left[1 + \beta_1(T)\left(\frac{P}{RT}\right)\right] \tag{3.4}$$

If the reference conditions are known *a priori* and also the corresponding pressure and temperature P_r and T_r, then, for constant volume

$$T = T_r\left(\frac{P}{P_r}\right)\left[\frac{1 + \beta_1(T_r)\dfrac{P_r}{RT_r}}{1 + \beta_1(T)\dfrac{P}{RT}}\right] \tag{3.5a}$$

Obviously, $\beta_1(T)$ and P/T in the denominator of the right hand side of Eq. (3.5a) pose problem even if $\beta_1(T_r)$ is known. Extrapolation techniques are known for determining the virial coefficients but obviously, these are not applicable in day-to-day activities. The secondary means is adopted where Eq. (3.2) is good enough for the purpose of simplifying Eq. (3.5a) to

$$T = T_r\left(\frac{P}{P_r}\right) \tag{3.5b}$$

For commercial use, direct application of Eq. (3.2) is also suitable when, by enlarging the volume of the gas, the output may be made large as the scale multiplier is $V/(nR)$ between T and P. The schematic of such a transducer is shown in Fig. 3.1.

In measurement, often a reference system is coupled and the pointer movement may be made differential. The gas used is an inert one though nitrogen is a good choice. The bulb volume is made at least 100 times larger than the combined volume of the capillary and Bourdon. Any change in the temperature of the bulb which is immersed in the process causes change in gas pressure which is transmitted to the Bourdon.

Care must be taken to compensate for the expansion of the bulb volume at the process temperature which is varying. If the expansion coefficient of the material is known, it can be easily corrected. Also, the gas in the capillary and Bourdon does not expand and correction for this must be made knowing the temperature distribution along the capillary line and the Bourdon tube. Besides, for such a system some other errors are there which need be taken into consideration.

A consequence of the gas pressure thermometer is the vapour pressure thermometer where the temperature scale is obtained from calibration with respect to reference points. A feasible practical form of it is similar to that of Fig. 3.1 except that a suitable liquid now fills the bulb partially, keeping enough space above the surface of the liquid for vapour pressure to form and even be saturated at all temperatures of interest for the particular liquid. With temperature, the above pressure increases according to Claussius–Clapeyron equation

$$T\frac{dP_s}{dT} = \frac{H_v}{V_g - V_l} \tag{3.6}$$

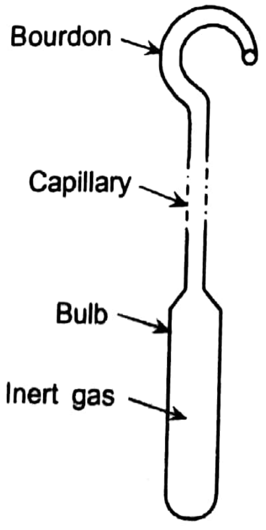


Fig. 3.1 The schematic of a gas pressure thermometer.

where P_s = saturated vapour pressure
H_v = molar heat of vaporization
V_g = molar volume in gaseous state
V_l = molar volume in liquid state.

The solution of Eq. (3.6) for deriving a relation between P_s and T for practical utility is quite involving. Instead, a series equation of the form

$$\ln\left(\frac{P_s}{P_{os}}\right) = \sum_{j=-k}^{k} \alpha_j T^j \tag{3.7}$$

where P_{os} is the saturation pressure at reference temperature (0°K) and k is an arbitrary order determined by the 'characteristic vaporization' of the gas.

The important aspect of the sensor is that it is the temperature of the liquid–gas interface that determines the pressure P_s and hence, the indication made by the Bourdon element would be independent of the volumes of the bulb, capillary, and Bourdon as well as ambient temperature. As is apparent in Eq. (3.7), the P_s versus T curves for different liquids are of the type shown in Fig. 3.2. Wide variety of ranges can be expected with different liquids and the scale range of each liquid is limited by its boiling point and a critical temperature at which the vapour disintegrates. Large factors of safety are, however, kept on both sides of the scale. Table 3.2 shows the ranges for some commonly used liquids.

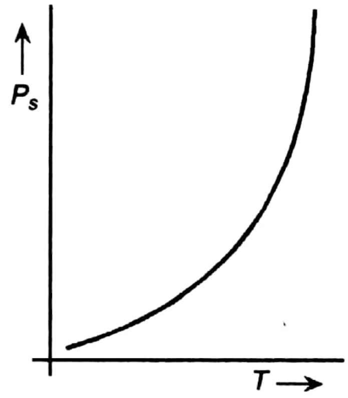


Fig. 3.2 Vapour pressure variation with temperature.

Table 3.2 Temperature ranges in vapour pressure thermometers

Liquid	*Range* (°C)
Methyl alcohol	0–50
n-Butane	20–80
Methyl Bromide	30–85
Ethyl chloride	30–100
Ethyl ether	60–160
Ethyl alcohol	30–180
Toluene	150–250

For very low temperature, Argon is used covering a range of –250°C to –100°C while water can be used between 120°C and 200°C. Rapid heating often produces bubbles which pass on to the capillary causing errors in indication in which cases it is recommended that a nonvolatile liquid immiscible with the operating liquid be used to fill the Bourdon and the capillary keeping the vaporizing surface as usual as shown in Fig. 3.3

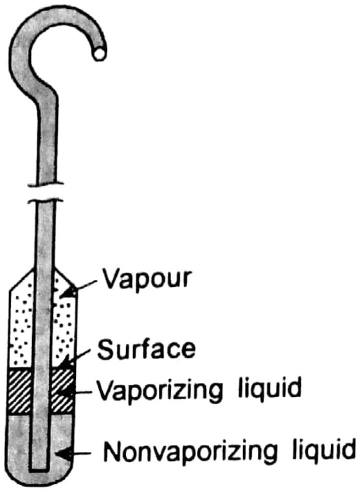


Fig. 3.3 Scheme of a vapour pressure thermometer.

3.3 THERMAL EXPANSION TYPE THERMOMETRIC SENSORS

The thermal expansion types thermometric sensors including the ones specified in Section 3.2 are, perhaps, the oldest varieties still used commercially to a certain extent.

Earliest of this kind is the solid expansion type bimetallic sensor which uses the difference in thermal expansion coefficients of different metals. Two metal strips *A* and *B* of thickness t_A and t_B and thermal expansion coefficients α_A and α_B are firmly bonded together at a temperature, usually the lowest or the reference temperature, to form a cantilever or a helix with one end fixed as shown in Figs. 3.4(a) and 3.4(b) respectively. When the temperature of the cantilever or the helix is raised by heating or lowered by cooling, one strip expands or contracts more and free end of either of the two moves as shown. The cantilever, in fact, bends into a circular arc with radius of curvature *R* given by the relation

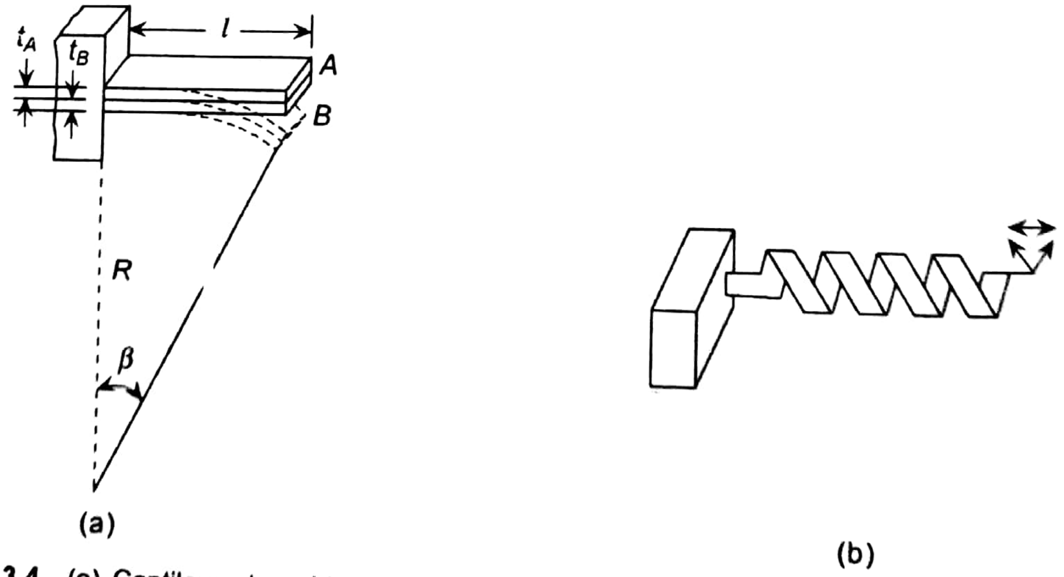


Fig. 3.4 (a) Cantilever type bimetal thermometer, (b) helix type bimetal thermometer.

$$R = \frac{(t_A + t_B)\left[3\left(1 + \frac{t_B}{t_A}\right)^2 + \left(1 + \left(\frac{t_B}{t_A}\right)\left(\frac{Y_B}{Y_A}\right)\right)\left\{\left(\frac{t_B}{t_A}\right)^2 + \frac{t_A Y_A}{t_B Y_B}\right\}\right]}{6(\alpha_A - \alpha_B)(T_h - T_b)\left(1 + \frac{t_B}{t_A}\right)^2} \tag{3.8}$$

where Y is the Young's modulus,
T_h is the raised temperature, and
T_b is the bonding temperature.

Equation (3.8) is simplified using $t_A = t_B = t$ and $Y_A \approx Y_B$. This gives

$$R = \frac{4t}{3(\alpha_A - \alpha_B)(T_h - T_b)} \tag{3.9}$$

The angular deflection, β, per unit temperature change, that is, sensitivity (for small β) is given by

$$S_T^\beta = \frac{\beta}{(T_h - T_b)} = 3l\,\frac{\alpha_A - \alpha_B}{4t} \tag{3.10}$$

where l is the length of the cantilever.

S_T^β increases linearly with length and inversely with strip thickness for a given pair of metal elements. Usually element B is made of invar (a Ni–Fe alloy) of $\alpha_B \approx 1.7 \times 10^{-6}$/°C which is quite low and element A is brass or steel of different alloying compositions. Such sensors can work precisely but not very accurately in a range –50–400°C. Besides cantilever and helix forms, they are also made in spiral and disc forms in different control applications.

Next in line is the liquid-in-glass thermometer—the liquid in majority of the cases being mercury. With mercury, this thermometer is almost the basic temperature measuring unit in home (as clinical thermometer), in laboratories and even in industries. It utilizes the expansion property of the liquid kept in a bulb to which a capillary, closed at the far end, is attached through which the expanded liquid rises and an indication in mm, calibrated directly in temperature scale, is obtained. The schematic is shown in Fig. 3.5. The range of mercury thermometer is normally

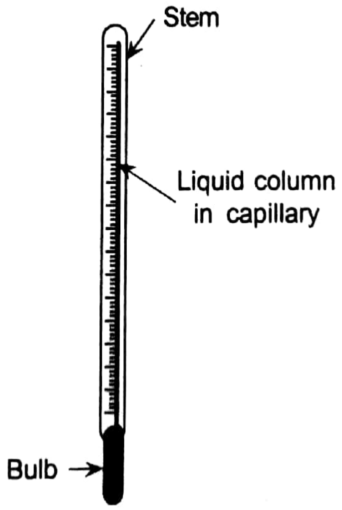


Fig. 3.5 Liquid-in-glass thermometer.

–35–300°C and the upper limit is 357°C, its boiling point. The range can be extended upto 600°C by filling the volume above mercury with pressurized dry nitrogen. The volume of the bulb is made 100 to 400 times larger than the capillary volume. Other liquids used as expansion media are given in Table 3.3 with their corresponding ranges.

Table 3.3 Thermometric liquids and their ranges

Liquid	*Range (°C)*
Pentane	–200–30
Alcohol	–80–70
Toluene	–80–100
Creosote	–5–200

When the measurement is made, the thermometer should be immersed upto the meniscus in the capillary which means that the thermometer is to be moved for varying temperatures. Alternatively, the entire thermometer is immersed, or, only the bulb is immersed. The last alternative is the most common one and for this purpose, a correction has to be applied for the mercury column above the immersion line because the column is at a different temperature t_c than the measured value t_m. The correction term is

$$\Delta t = \gamma_d n \, (t_m - t_c) \tag{3.11}$$

where γ_d is the differential thermal expansion coefficient of volume between mercury and glass and

n is the number of degrees indicated by the column, that is, exposed degrees.

γ_d has a value of about 1.6×10^{-5}/°C.

An extension of this is the industrial type liquid filled-in system which consists of a metallic bulb attached to a metallic capillary. The other end of capillary is fitted with a Bourdon. The expansion of the liquid in the bulb is transmitted to the Bourdon which uncurls in the usual manner. The basic scheme is similar to that presented in Fig. 3.1. A number of compensations are necessary to obtain correct indication by the measurement system using such a sensor. The correction methods are available in standard texts on industrial instrumentation.

3.4 ACOUSTIC TEMPERATURE SENSOR

When a longitudinal (acoustic) wave propagates through an ideal gas, it has a speed C_i given by

$$C_i = \left(\frac{\gamma RT}{M}\right)^{1/2} \tag{3.12}$$

where M is the molecular weight of the gas and $\gamma = C_p/C_v$ is the ratio of specific heats ($\gamma = 5/3$ for monoatomic gases).

Knowing the gas and measuring velocity C_i, temperature T can be given by

$$T = \frac{MC_i^2}{\gamma R} \tag{3.13}$$

The realization of this technique is made in acoustic helium interferometer whose working is explained through Fig. 3.6. A quartz crystal excited to its resonance frequency is used to transmit this wave through a gas (He) column, to be faced by a piston. The wave is reflected at the piston surface to form a pattern as shown. When the path length l has a multiple number of half-wavelengths and correspondingly the gas column is set to resonate at each such half-wavelength gap, with the piston moving away from the crystal at each resonant peak, the crystal gives out maximum energy and hence the voltage V_Q across the crystal defines peaks as shown in Fig. 3.6(c). If the piston moves by a distance d to give n such peaks, $d = n\lambda/2$ from which C_i is determined and thence temperature T. The piston movement must be accurately monitored to within, say, 1 μm.

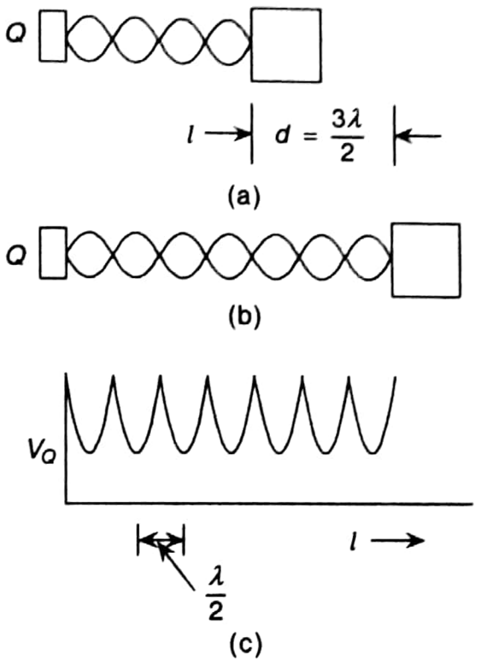


Fig. 3.6 Principles of acoustic temperature sensor: (a) the system, (b) the system with changed position of piston for maintaining resonance, and (c) the crystal output peak positions.

In non-ideal gas, correction as per Van der Waal's equation

$$V - b\left(P + \frac{a}{V}\right) = MRT \tag{3.14}$$

has to be applied, where M is the molecular weight of the gas, and a and b are functions of 'molecular' constants. The corrected velocity C_c is then given by

$$C_c = \sqrt{\frac{\gamma RT}{M}\left[1 + \frac{\alpha P}{RT}\right]} \tag{3.15}$$

where α is a function of a, b, T, and V.

There is a nonresonant acoustic sensor that utilizes the pulse-echo transit time difference which changes with temperature. Figure 3.7 is a schematic representation of the sensory parts of the measurement system. An ultrasonic pulse is transmitted through the sensor, a part of which is reflected at the entrance (a discontinuity) and a part at the end, as shown. The reflected pulses are received by the transreceiver coil at an interval of t_{tr} called the transit time. The pulse that travels the entire length of the sensor is delayed more/less depending on the change in the sensor temperature. This temperature dependence is a function of the path length l, sensor material, temperature range, and vibration mode even if the first echo is considered. The materials which show distinctive t_{tr} are listed in Table 3.4 with their temperature ranges.

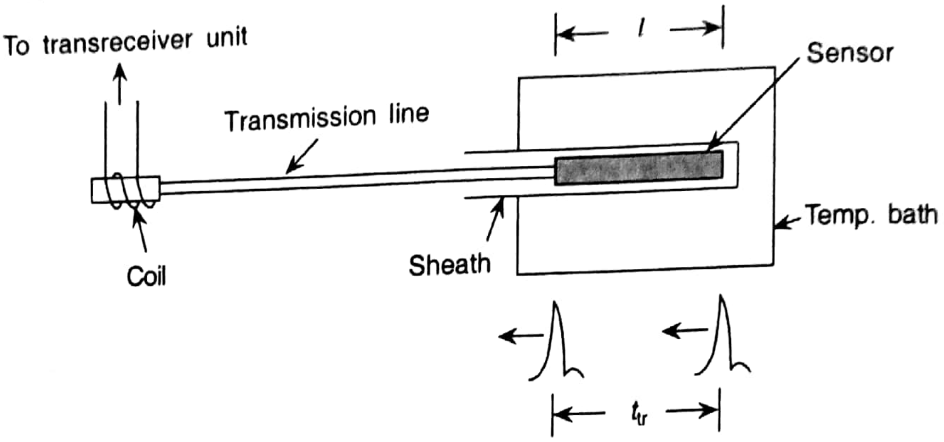


Fig. 3.7 Pulse-echo transit time difference technique of temperature measurement.

Table 3.4 Materials versus temperature range

Material	*Temperature range* (°C)
Aluminium	≤500
Stainless steel	≤1100
Sapphire	≤1600
Molybdenum, Ruthenium	≤2100
Wolfrum, Rhenium, ThO_2–W(2%)	≤2700

The nature of the plot between t_{tr} and temperature T is shown in Fig. 3.8.

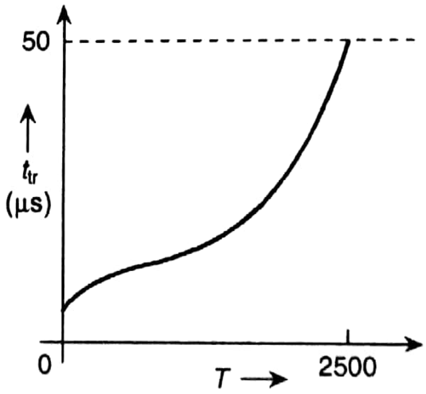


Fig. 3.8 Transit time versus temperature plot.

The sensor may be made in the form of a thin wire with restrictions or constrictions at intervals of space where the reflections would occur. The wire diameter varies from 0.03–3 mm and spacing between restrictions varies from 5–10 mm in a sensor length of 15–50 mm, and a number of echos can then be produced. There should not be any inhomogeneity in the material faced by the wave except for the restrictions.

3.5 DIELECTRIC CONSTANT AND REFRACTIVE INDEX THERMOSENSORS

The above thermosensors are developed basing on two well known relations: (i) Clausius–Mossotti relation and (ii) the relation between refractive index μ and dielectric constant χ of a gas. The sensors are useful for gas temperature measurement.

The Clausius-Mossotti relation is valid for an ideal gas and is given by

$$\frac{\chi - 1}{\chi + 2} = M_\chi \frac{n}{V} \tag{3.16}$$

where χ = dielectric constant and
M_χ = the molecular polarizability of the gas.

Using Eq. (3.2), Eq. (3.16) transforms to

$$T = \frac{(\chi + 2) M_\chi}{(\chi - 1) R} P \tag{3.17}$$

Thus, knowing χ, M_χ, and P, we can measure T. M_χ is available by calculation or in a table or by measurement and χ is measured by measuring capacitance which is given by the relation

$$\chi = \frac{C(P)}{C(0)} \cdot \frac{1}{1 + \phi_c P} \tag{3.18}$$

where $C(P)$ denotes capacitance at pressure P and ϕ_c is the capacitance compressibility factor that is considered to account for the change in the capacitor dimensions with pressure.

For real gases, however, virial expansion of the dielectric constant has to be taken into account and 'extrapolation' technique is adopted. For practical purposes, an empirical calibration is the best solution.

Refractive index thermometer uses the relation

$$\frac{\mu^2 - 1}{\mu^2 + 2} = \frac{M_\chi n}{V} = M_\chi \frac{P}{RT} \tag{3.19}$$

since $\mu^2 = \chi$, Eq. (3.19) is basically the transformation of the Clausius–Mossotti equation. A practical technique is used to measure $\mu - 1$ by passing a laser beam through a Michelson interferometer with one of its arms containing the gas sample. With pressure, the optical path length L increases and a relation

$$\begin{aligned} \frac{\Delta L}{L} &= \mu - 1 \\ &\propto \rho \\ &\propto P/T \end{aligned} \tag{3.20}$$

holds good. Here, ρ is the gas density. Equation (3.19) can be used for finding T with the knowledge of μ, M_χ, and P.

For non-ideal gases again, a virial expansion of $(\mu^2 - 1)/(\mu^2 + 2)$ is accommodated. The technique is yet to gain commercial importance.

4.2 SENSORS AND THE PRINCIPLES BEHIND

In effect, the ΔY effect is an outcome of magnetostriction. Change in dimension due to magnetostriction in a material is actually caused by rotation of the magnetization. A demagnetized ferromagnetic material, when undergoes a mechanical stress, develops two types of stresses in it, namely (i) the plain mechanical elastic strain ε_s and (ii) the magnetoelastic strain ε_m which is the result of reorientation of magnetic domains by the applied stress S_a; thus, giving the Young's modulus of the demagnetized material as

$$Y_{dm} = \frac{S_a}{\varepsilon_s + \varepsilon_m} \tag{4.1a}$$

However, for a saturated sample no magnetoelastic strain is produced because no further reorientation is possible, and hence, the Young's modulus becomes

$$Y_{sm} = \frac{S_a}{\varepsilon_s}$$

where Y_{sm} is the Young's modulus of the saturated material.
So that,

$$\frac{\Delta Y}{Y_{dm}} = \frac{Y_{sm} - Y_{dm}}{Y_{dm}} = \frac{\varepsilon_m}{\varepsilon_s} \tag{4.1b}$$

Magnetoelastic strain is obviously a function of applied stress and the amount of anisotropy in the material.

The ΔY effect occurs in Ni–Fe based crystalline alloys and in some amorphous alloys such as Fe(40) Ni(38) Mo(4) B(18). Such an alloy can be used for making magnetic field sensors. One typical construction is shown in Fig. 4.1.

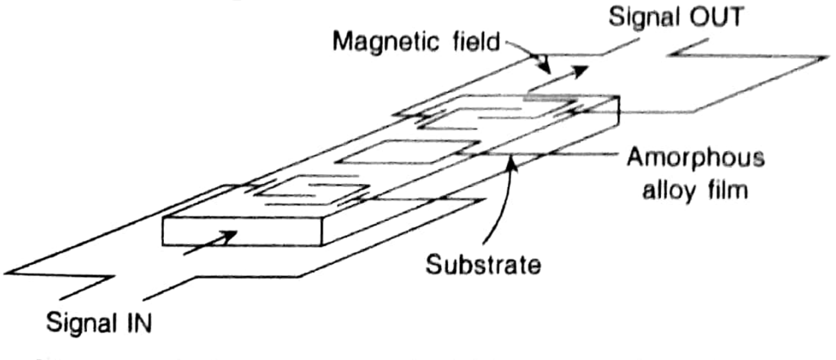


Fig. 4.1 Sketch of a magnetic field sensor using ΔY-effect.

A delay line using tunable surface acoustic wave components as transducers has been designed where the basic substrate is a piezoelectric material and an amorphous film spread as depicted in the figure. The sound velocity is given by the relation

$$v = \sqrt{\frac{Y}{\rho}}$$

where ρ is the density of the material.
The change in velocity Δv, in the film, is given by

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta Y}{Y}}$$

For the material mentioned, this figure varies depending on the annealing condition (temperature) of the material. A characteristic set of curves for the annealed alloy is presented in Fig. 4.2. The critical temperature is t_c which usually is close to the annealing temperature. Curve I in the figure corresponds to the magnetized state while curve II, the nonmagnetized state. In the alloy mentioned, a change in v of about 10% can be obtained at room temperature.

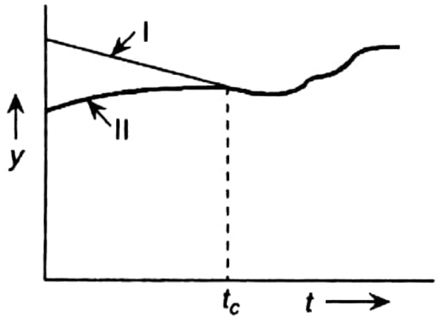


Fig. 4.2 Characteristic curves for annealed alloy: curve I corresponds to magnetized state, and, curve II to the nonmagnetized state.

Matteucci effect is closely related to a non-general form of Wiedemann effect. Villari effect is, to an extent, the reciprocal of the ΔY effect and is close to Wiedemann and Matteucci effects. Sensors developed on the basis of these effects are of similar kind in operation and construction. Wiedemann effect has subsequently been demonstrated to be a consequence of magnetostriction in a material and is tensorially related to this property. If longitudinal and transverse magnetostriction constants in a material are λ_l and λ_t, and the longitudinal and circular magnetic fields are H_l and H_r respectively, then the twist angle θ in a rod of length l and diameter d subjected to these fields, as shown in Fig. 4.3, is given by the relation

$$\theta = (\lambda_l - \lambda_t)\frac{4l}{d}\,\frac{H_l H_r}{H_l^2 + H_r^2} \tag{4.2}$$

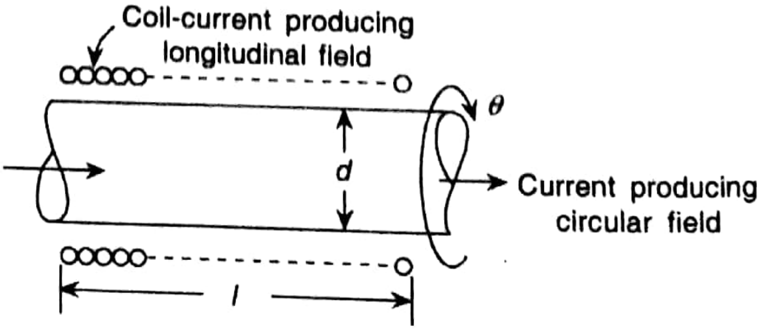
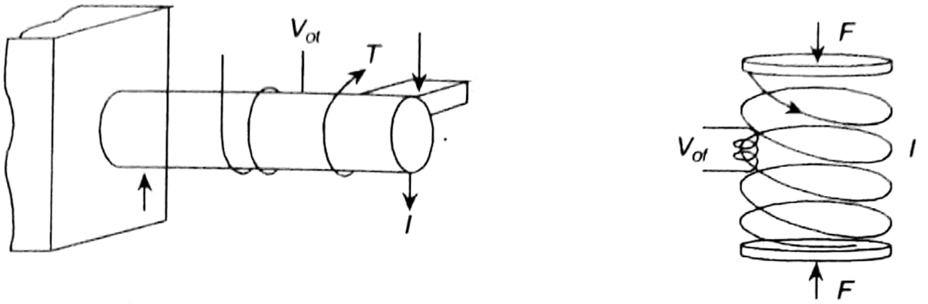


Fig. 4.3 Twist in a material, subjected to magnetic fields.

Wiedemann effect is used to make torque/force sensors, as has already been mentioned. The design principles are explained in Figs. 4.4(a) and (b). With a current I passing in direction as shown in figures and a torque produced in the rod of Fig. 4.4(a), an output voltage V_{ot} is obtained that gives a measure of the torque. Similarly in Fig. 4.4(b), V_{of} is the output voltage for the force in the balanced condition.



(a) Torque sensor

(b) Force sensor

Fig. 4.4 (a) A torque/force sensor using Wiedemann effect. (b) A typical force sensor using magnetostrictive effect.

The Wiedemann effect has two inverse effects:

(a) when a ferromagnetic rod which is circularly magnetized, is twisted, a longitudinal magnetic field is produced in it and

(b) when such a rod with longitudinal magnetization is twisted, a circular magnetic field is produced in it which essentially is the Matteucci effect.

Basically, for magnetoelastic sensors, there occur magnetoelastic interactions and conversion of elastic energy E_s into magnetic energy E_m takes place or vice versa. Various other types of energies are involved in a magnetic material apart from these two forms. In fact, E_m is proportional to the product of field strength and polarization and is often called the *magnetic field energy*; E_s is related to magnetostriction and is, therefore, called the *elastic stress energy*. In crystalline materials, depending on the material, there appears a *crystalline energy* E_{cr}. During magnetic annealing in materials, both crystalline and amorphous, an energy E_{ua} arises which is called the *uniaxial anisotropy energy* and depending on the demagnetization factor N, another type, the *shape anisotropy energy* E_N is developed.

The magneto-mechanical coupling factor K_{33} is defined as the ratio of the elastic stress energy to the total stored energy such that

$$K_{33} = \frac{E_s}{E_s + E_m + E_{cr} + E_{ua} + E_N} \tag{4.3}$$

For large values of K_{33}, E_m, E_{cr}, E_{ua}, and E_N must be small. In fact, soft magnetic materials such as Co–Fe and Ni–Fe alloys have very small E_{cr} and E_{ua} and a proper selection of the shape may render a small E_N so that effectively

$$K_{33} = \frac{E_s}{E_s + E_m} \tag{4.4}$$

If the saturation polarization is J_s, H is the field, that is, the coercive force, S is the stress applied to a strip, λ_s is the saturation magnetostriction, μ_0 is a magnetic constant, and α is the angle between the magnetization and specimen axis, then

$$E_m = -J_s H \cos \alpha \tag{4.5a}$$

and

$$E_s = \frac{3}{2} \lambda_s S \sin^2 \alpha \tag{4.5b}$$

If now the total energy ($E_s + E_m$) is minimized, Eq. (4.4) can be written as

$$S = \frac{1}{\mu_r} \frac{J_s^2}{3 \mu_0 \lambda_s} \tag{4.6}$$

where μ_r is the relative permeability.
From Eq. (4.6), we obtain

$$\mu_r = \frac{J_s^2}{3 \mu_0 \lambda_s Y \varepsilon} \tag{4.7}$$

with strain ε and Young's modulus Y.

Figure 4.5 shows the theoretical (solid lines) and practical curves for soft alloy strip material with tensile load. In the ideal situation, μ_r decreases, becoming inversely proportional to S. Materials are available for which K_{33} can be as large as 0.95, for example, in amorphous Fe(81) {B, Si, C}(19).

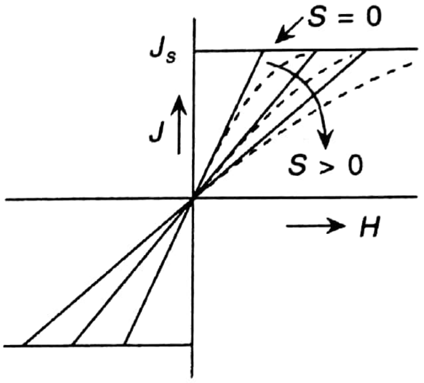


Fig. 4.5 J_s–H curves for soft alloy strip materials (soild lines denote theoretical values and dotted lines indicate practical curves).

Based on Villari effect, three basic types of magnetoelastic sensors may be designed, namely

(a) the type in which mechanical loading is unidirectional so as to produce compression or tension and this changes the inductance or permeability with the specimen having predefined magnetic flux path, as in choke or coil type design,

(b) one in which mechanical loading changes the flux in two directions or in a plane as in circular rings or laminated cores, and

(c) the third in which loading changes the flux spatially, that is 3-dimensionally in torque transducers for shafts.

In the first type, strips or pot core sensors are used as shown in Figs. 4.6(a) and (b) when inductance variation is actually measured.

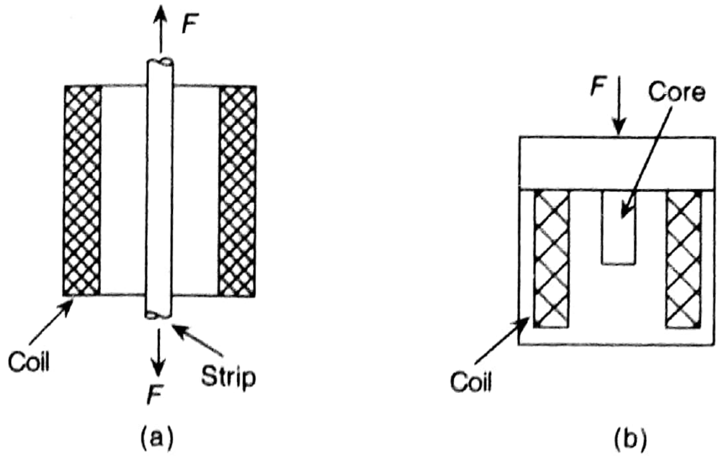


Fig. 4.6 Inductance variation sensors (a) strip and (b) pot core sensors.

The circular ring in the second type is deformed into an elliptical form as shown in Fig. 4.7 and a change in inductance of the ring or a change in voltage in the secondary winding ΔV gives the value of the load.

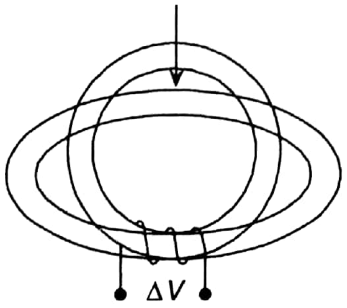


Fig. 4.7 Ring type sensor.

In case of laminated core load cells, isotropic magnetic materials are used which become anisotropic under stress due to varying deformation in longitudinal and transverse directions relative to the load axis and a change in voltage can be derived in the ring type design.

By far, the most important are the torque sensors. If the shaft material does not have the requisite magnetic properties such as magnetostriction, an additional magnetic coating on the shaft surface produces the desired mechanical stress on this surface that is to be measured.

In the solid or hollow cylindrical shafts, stress develops in two principal orthogonal directions, one compressive and the other tensile, each at an angle of ±45° with the shaft axis in a screw-like fashion around the shaft as shown in Fig. 4.8. For a hollow shaft of inner and outer diameters D_i and D_o, the angle of torsion ϕ, the length of the shaft l, torque produced is given by

$$T = \frac{C\pi\phi}{32l}(D_o^4 - D_i^4) \tag{4.8}$$

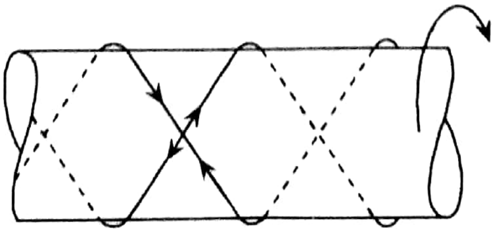


Fig. 4.8 Stress directions in hollow cylindrical shaft.

The maximum stress on the surface of the shaft is

$$S_m = \frac{16D_oT}{\pi(D_o^4 - D_i^4)} \tag{4.9}$$

and maximum strain ε_m is

$$\varepsilon_m = \frac{S_m}{Y}(1 + \nu) = \frac{16D_o(1 + \nu)}{\pi(D_o^4 - D_i^4)Y}T \tag{4.10}$$

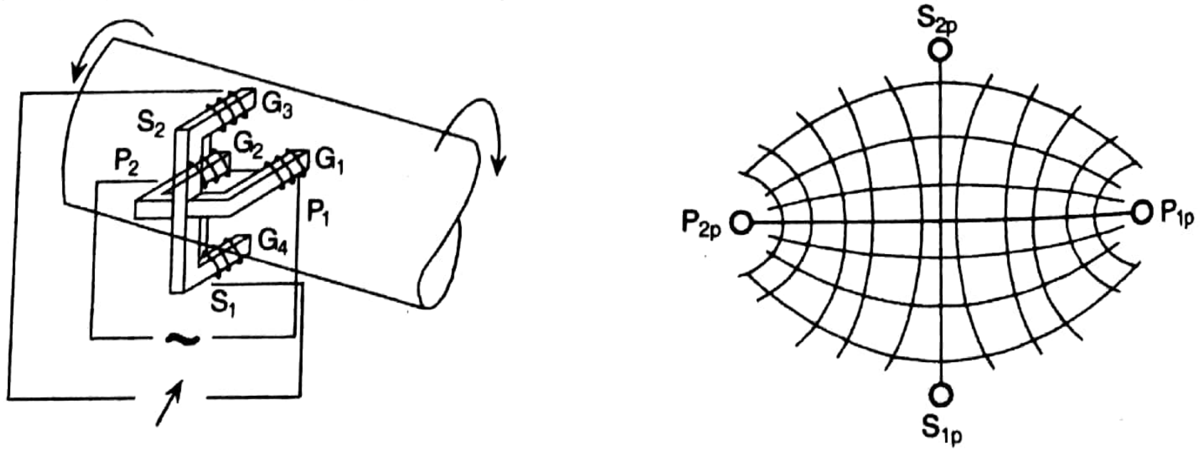
where ν = Poisson ratio.

The magnetoelastic interactions because of the complex stress–strain paths can be picked up by complex arrangement of the pick-up coils as it is not possible to arrange detectors so that change in permeability μ, along the principal stress axis is directly picked up. But it must be remembered that there is symmetry in stress–strain paths and coils can be arranged so that field and signal detection at ±45° to the principal stress axis can be made. Two types of designs are known for the purpose—(a) Yoke coil type and (b) the cylindrical coil type—which are mounted coaxially with respect to the shaft.

4.2.1 The Yoke Coil Sensors

The yoke coil type sensors can further be subdivided into (i) The cross transductor shown in Figs. 4.9(a) and (b) the four branch type torque sensor shown later in Fig. 4.10(a). In the former, the U-shaped magnetic pole pieces are mounted in a crossed fashion facing the shaft surface to provide narrow air gaps. One U-branch is used as primary with two coils, P_1 and P_2 excited by an ac supply, the poles are arranged to be along the shaft axis and the other branch is mounted at right angles to it with two secondary sensing coils S_1 and S_2 and poles at right angles to shaft axis. Without torsion, the surface magnetic flux pattern so obtained is symmetrical as shown in Fig. 4.9(b) and with torsion, if magnetostriction is positive (λ_s positive), flux density increases in the direction of tensile stress and decreases in the direction of compressive stress and the flux pattern gets distorted as shown in Fig. 4.9(c). The secondary pole pieces (S_{1p} and S_{2p}) then face unbalanced magnetic potential and a flux difference, resulting in an induced voltage in the coils S_1 and S_2, occurs which obviously is a function of the torque.

The equivalent magnetic circuit of the system is shown in Fig. 4.9(d). Inductive impedances are represented as X, subscripts t and c refer to tensile and compressive stress conditions and l is used for leakage fluxes in the primary pole pieces. In the balanced condition, X_t's and X_c's are equal hence, balancing the bridge. Under torque when X_t's ≠ X_c's the balance of the bridge is disturbed. Ohmic resistances allow for eddy losses.



(a) (b)

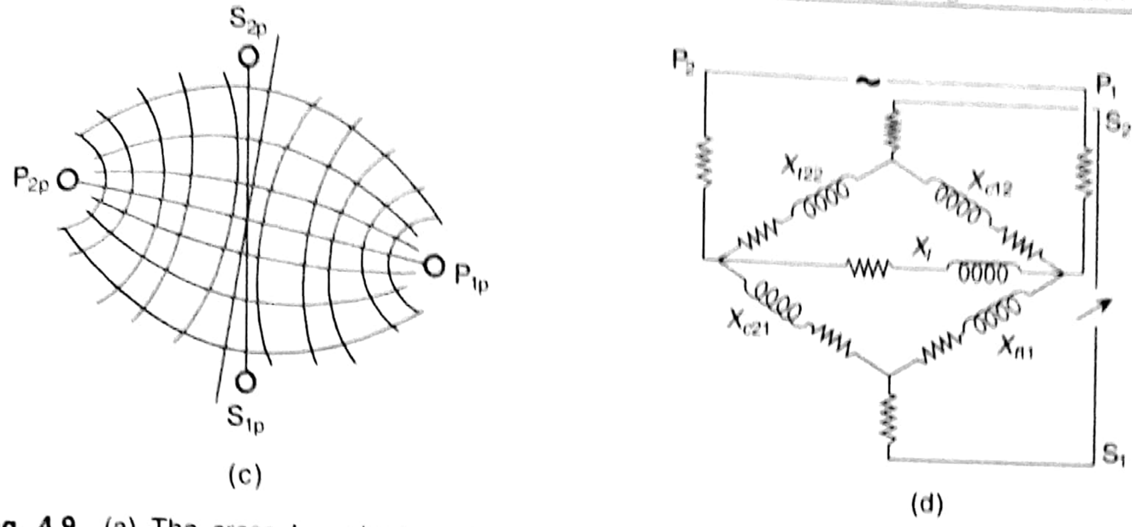


Fig. 4.9 (a) The cross transductor yoke coil type sensor, (b) The surface magnetic flux pattern without torsion, (c) The pattern with torsion, (d) Equivalent 'magnetic' circuit.

The four branch design is shown schematically in Fig. 4.10(a). At centre is the excitation pole provided by the exciter coil E_x. Four corner poles, two on the tensile stress lines and two on the compressive stress lines, are arranged with the sensing coils 1, 3 and 2, 4. Air gap between the coil cores is less than 1 mm. The permeability dependent reluctances shown by X_t's and X_c's and eddy losses by resistances are represented in the magnetic circuit diagram of Fig. 4.10(b). The four sensing arms are now arranged so that outputs from coils 2 and 4 are deducted from outputs of coils 1 and 3.

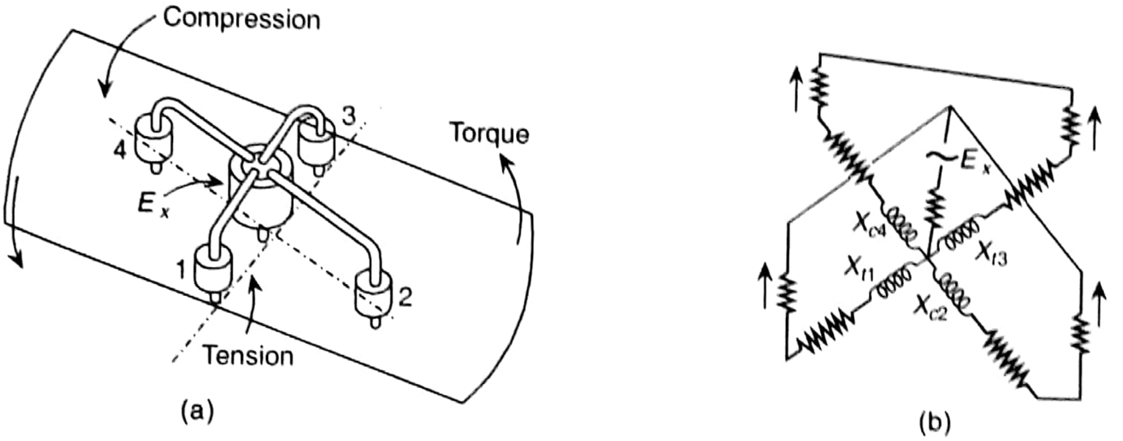


Fig. 4.10 (a) The four branch type sensor, (b) The equivalent magnetic circuit.

Depending on the material, the sensitivity of the transducer system changes. For example, for the four branch type design, sensitivity varies from 1 mV/Nm to 2.5 mV/Nm when material is C15 steel or Cr–MoV steel. In general, torque sensitivity decreases with increasing hardness for a ferromagnetic material. This varying sensitivity problem can be solved by coating the shafts or providing a sleeve on the shafts with a ferromagnetic material of satisfactory and uniform magnetoelastic property.

Other parameters governing the sensitivity are the excitation frequency—which is chosen on the basis of (a) transient requirements, (b) shaft speed, (c) shaft material, (d) oscillator power and, of course, (e) the output signal, besides, the air gap between the pole faces and shaft surfaces.

Frequency can be chosen on the basis of the counts specified in the three different ranges:

- Power range: 50–60 Hz,
- Audio range: 400–20,000 Hz, and
- Radio range: 100–200 kHz.

The gap changes due to radial shaft displacement. Also, magnetic inhomogeneities at the shaft surface tend to change the torque signal. This is overcome to a large extent by ring type torque transducers which can again be designed either on the principle of (i) cross type, or, (ii) four branch type sensors.

The cross type design consists of three pole rings with coils arranged on it for excitation and pick-ups. The middle ring holds the excitation coils and the outer ones hold the sensing coils. Figure 4.11(a) shows the arrangement of the rings on the shaft with 8 poles per ring as shown in Fig. 4.11(b) whereas Fig. 4.11(c) depicts the pole faces on the evolved ring and also the winding schemes. P poles are displaced by a 1/2 polepitch relative to S poles and are equidistant so that the functioning as in the cross type of Fig. 4.9(a) can be maintained.

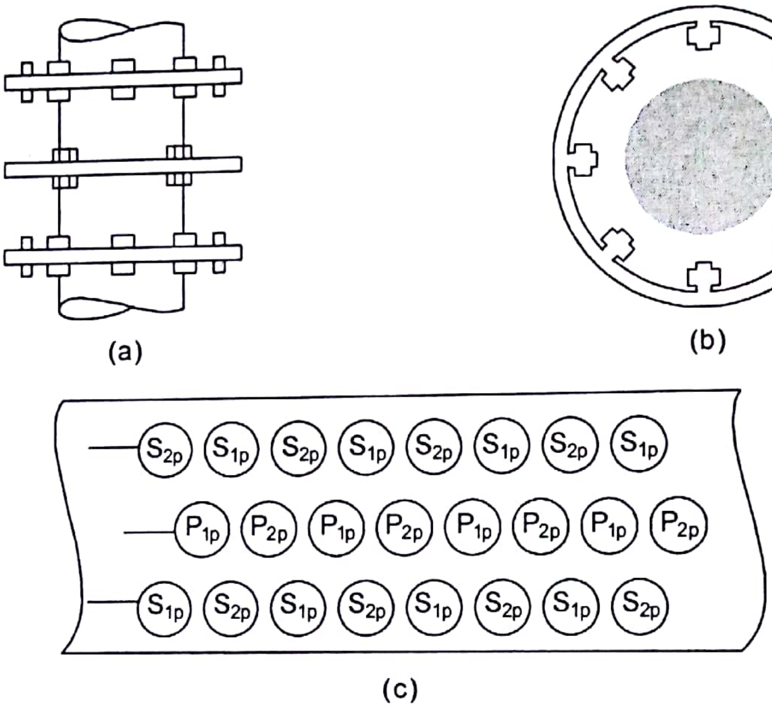


Fig. 4.11 Ring type torque transducer: (a) arrangement of the rings on the shaft, (b) the cross sectional view showing 8 poles per ring, and (c) pole faces on the evolved ring.

The four branch type design may, similarly, consist of a number of coils enclosed in common ring held to surround the shaft. A scheme with four branch type design is shown in Fig. 4.12(a) with the excitation poles in the centre portion and the sensing poles on the outside portions of the ring (as shown in Fig. 4.12(b)).

All magneto-elastic sensors are required to be calibrated with requisite standards.

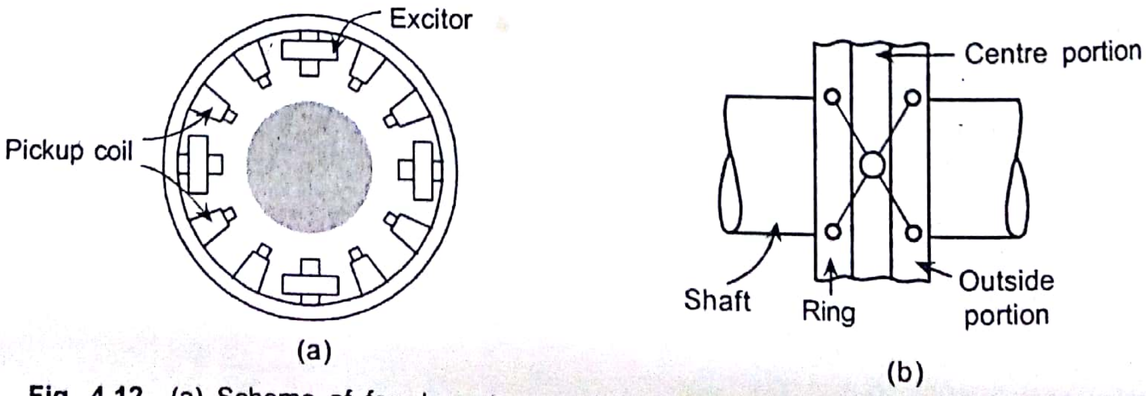


Fig. 4.12 (a) Scheme of four-branch type ring design, (b) sensing poles shown on the outside portion of the rings.

4.2.2 The Coaxial Type Sensors

The coaxial type design largely overcomes the effects of material inhomogeneity and gap length variation with less complexity than the ring type design. Over the last two decades, since its inception in the late seventies, this type has undergone many modifications and improvements.

The torque sensor, in its current improved form, is based on surface magnetic anisotropy of the shaft, intentionally introduced in such a way that the direction of such anisotropy is in the direction of the main torsional stresses to be produced in the shaft under loading, that is, effectively at ±45° to the principal stress axis of the shaft. This imposed anisotropy on the shaft surface is being excited by a coil around the shaft and magnetic flux is produced in this 'preferred' direction. Two identical secondary coils connected differentially would now be induced by the linkage from the primary through this ±45° anisotropy-induced magnetization. Under no torsion, equal induced voltages produce zero output from the secondary. In the presence of torsion, however, tensile and compressive stresses occur and flux conduction is either aided for compression or opposed for tension or vice versa depending on the negative or positive magnetostriction and the arrangement of the anisotropy direction in the two parts as illustrated in Fig. 4.13. Consequently, there is increase in flux in one of the secondary coils compared to the other giving a non-zero output voltage V_o for a given V_i. The magnitude of this voltage is dependent on the torque while its sign depends on the direction of the torque for a given set up.

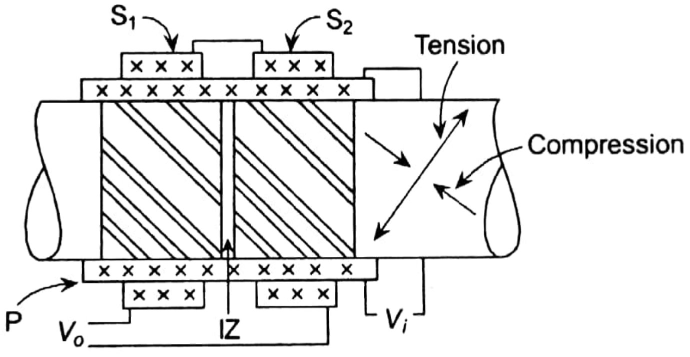


Fig. 4.13 Coaxial torque sensor.

The surface anisotropy, as mentioned, is produced by

(i) mounting magnetic strips on the shaft at ±45°,

(ii) mounting magnetic foil on the shaft in a pre-stressed condition of the shaft, or

(iii) pre-stressing a magnetic foil and then mounting it on the shaft by a special ring arrangement, and so on.

This method has been applied for shafts with diameters varying from 1 cm to 10 cm and a torque range of 10–5000 Nm producing a strain in the range 0.005–0.057 with symmetry and linearity within ±2%.

The magnetic strip material may have a composition of amorphous soft materials such as Co(75) Si(15) B(10), Co(68) Ni(10) B(14) Si(8), and so forth.

As already mentioned, torque measurement is influenced by many factors—two major ones being variation of air gap and shaft surface inhomogeneity (as has already been discussed). The other factors that affect torque measurement are:

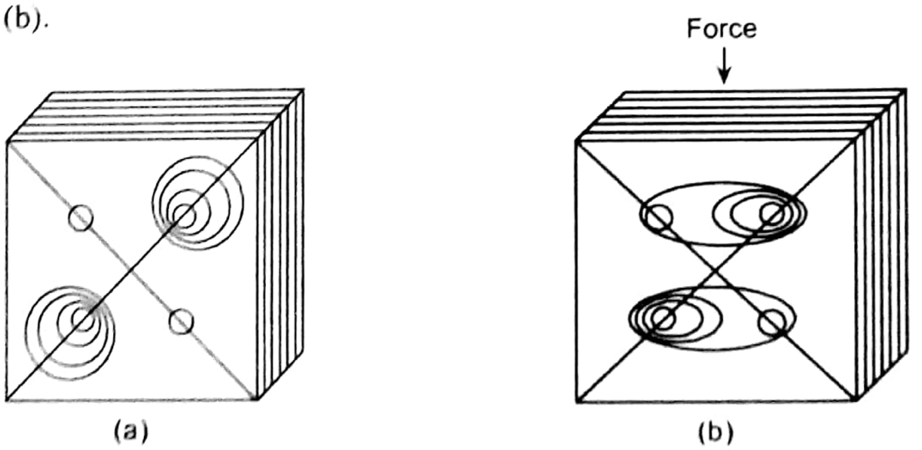
(i) shaft speed, which tends to decrease output signal because of enhanced skin effect but this, in turn, depends on shaft surface material, excitation frequency, and amplitude. Measuring circuit can be designed to compensate for the variation, the effect is insignificant for high frequency excitation and ferromagnetic amorphous surface coating,
(ii) axial displacement for coaxial design, which is often reduced by separating the active surface zones by an inactive zone (IZ), in Fig. 4.13, splitting the primary coil into two, and placing them closer to the secondary coils,
(iii) temperature: mainly comes as a temperature coefficient of magnetization and expansion and reduced largely by choice of material. Circuit compensation is easier in this case.

4.2.3 Force and Displacement Sensors

Magneto-elastic sensors are easily adapted to force-sensing in the load cell form. Or in the complex structure, a component can be considered as the sensing element.

Magnetic load cell may be a stress sensitive solid cylinder made of a Mo–Permalloy, Ni–Fe alloy, or Al–Fe alloy. A winding on the cylinder is done on concentric grooves made in it. With lengthwise compression in the cylinder, the cross-sectionwise stress distribution is considered to be uniform which is ensured with large l/d ratio. The decrease in inductance under compression is measured by an ac bridge.

Of more recent designs is the transformer type magneto-elastic force transducer named as the *pressductor*. It essentially consists of a stack of transformer core sheets provided with four holes symmetrically made on the diagonals of the stack. Each diagonal pair of holes is provided with windings so that the two windings cross each other at right angles. One winding acts as the primary with a supply given to it. With the stack unloaded, there is no magnetic linkage between the two windings while on loading the stack, a compressive stress is developed in the core sheets. As a result, the sheet permeability becomes anisotropic and the flux paths are distorted. As a consequence, the secondary winding is magnetically linked with the primary and a voltage is induced in it which, obviously is proportional to the load or force. The situation is explained in Figs. 4.14(a) and (b).

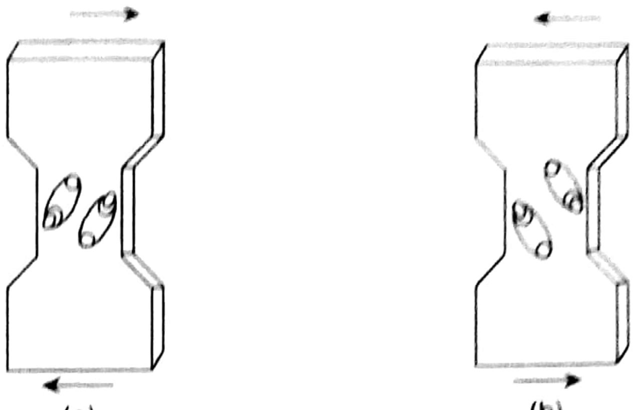


(a) (b)

Fig. 4.14 Schemes of pressductor (a) without force, and (b) with force applied.

The shape of the core sheets is important for proper distribution of the force/stress so that magneto-elastic sensing is appropriate. Various shapes are proposed for different applications. Round and rectangular designs are most common. For shearing force measurement, a design shown in Figs. 4.15(a) and (b) has also been used. Hole locations are also changed here. The frequency usually is 50 Hz, but with special material, it can lie in the range 1–10 kHz.

Pressductors are available in single unit upto 25 kN to 5 MN. Multiple unit designs exist for higher loads upto about 15 MN. Good quality elasto-sensing load cells are available with accuracy of ±0.1%, linearity ±0.1%, and, precision 0.1%. Operating temperature range is 20–70°C and the cells can take 3 times the nominal load without damping the performance characteristics.



(a) (b)

Fig. 4.15 Pressductors used for shearing force sensing (a) and (b) force in two directions opposite to each other.

It must be mentioned at this stage that the cross yoke type or the four branch type sensors can be used for force measurement or stress analysis with the sensing element making no contact with test specimen. A typical scheme is shown in Fig. 4.16. Displacement and position sensors are quite common in process industries these days which use differential transformer principles as in LVDT, proximity sensors, and other inductive sensors, discussed briefly in Chapter 2.

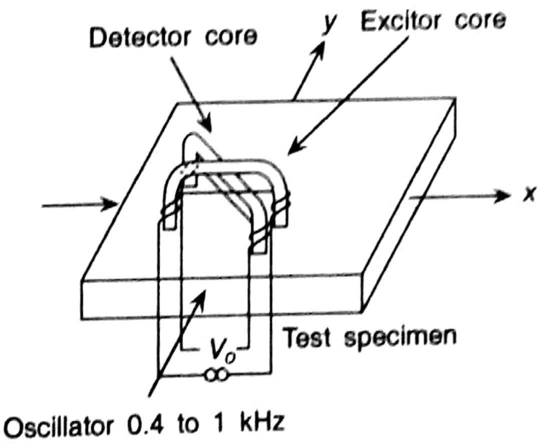


Fig. 4.16 Four branch type displacement sensors.

A ring type design, somewhat similar to that of Fig. 4.7, utilizes, however, the magnetostrictive effect for measurement of displacement or position in relation to force working the ring within elastic limit. The ring is made of amorphous metal. Figure 4.17 schematically represents this design. A circular ring made of single/multilayer ribbons of diameter 5–10 mm with, usually, positive magnetostriction is used for the purpose. The ring is used as a transformer and as a spring. When it is deformed into an ellipse, its hysteresis loop is also flattened and hence, for an input V_i the output V_o reduces considerably. When the material works within the elastic limit and the load is released, the shape is regained by the spring and the secondary voltage returns to the original value. Extensometers can be developed on this principle. The material Fe(78) Mo(2) B(20) is often used for the purpose, a four-layer core ring of diameter

10 mm is common with a displacement upto 5 mm. Linearity for this sensor is about 2% and temperature stability as good as 0.02%/°C, that can be used upto 90°C.

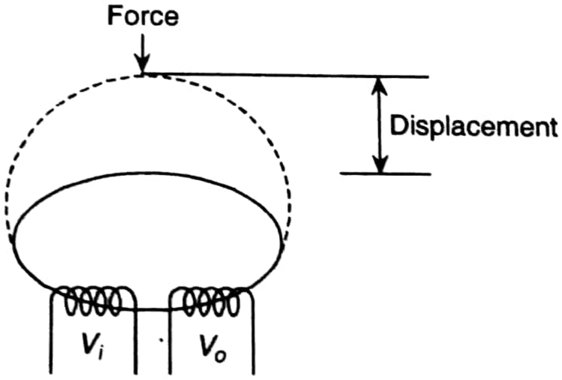


Fig. 4.17 Ring type displacement sensor.

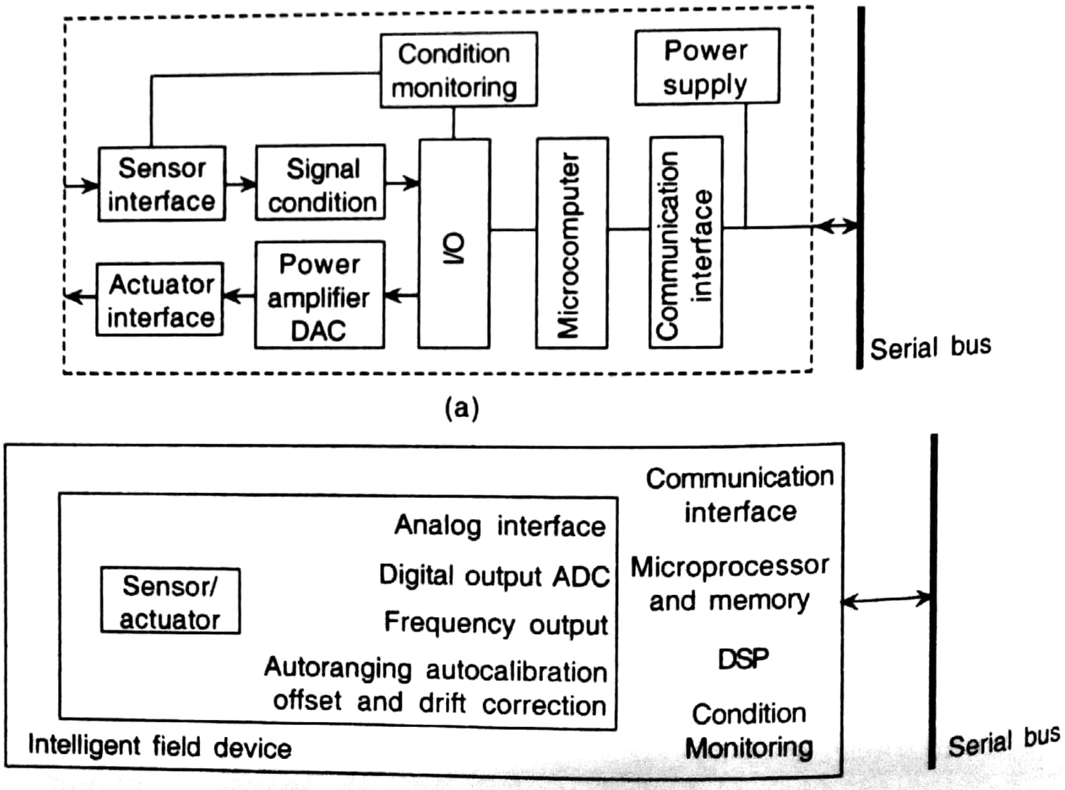
Chapter 7

Smart Sensors

7.1 INTRODUCTION

A sensor producing an electrical output when combined with interface electronic circuits is said to be an intelligent sensor if the interfacing circuits can perform (a) ranging, (b) calibration, and (c) decision making for communication and utilization of data.

Both sensors and actuators are used as intelligent components of instrumentation systems. In fact they are used as field devices. The block diagram of one such intelligent equipment is shown in Fig. 7.1(a). Figure 7.1(b) shows the simplified version with facilities of processing that can be incorporated.



(a)

(b)

Fig. 7.1 (a) Typical intelligent sensor and actuator and (b) simplified version of (a).

An intelligent field device possesses the following properties:

1. automatic ranging and calibration through a built-in digital system,
2. auto-acquisition and storage of calibration constants in local memory of the field device,
3. autoconfiguration and verification of hardware for correct operation following internal checks,
4. autocorrection of offsets, time, and temperature drifts,
5. autolinearization of nonlinear transfer characteristics,
6. self-tuning control algorithms, fuzzy logic control is being increasingly used now,
7. control programme may be locally stored or downloaded from a host system and dynamic reconfiguration performed,
8. control is implementable through signal bus and a host system,
9. condition monitoring is also used for fault diagnosis which, in turn, may involve additional sensors, digital signal processing, and data analysis software, and
10. communication through a serial bus.

Intelligent sensors are also called smart sensors which is a more acceptable term now. The initial motivation behind the development of smart sensors include (i) compensation for the non-ideal behaviour of the sensors and (ii) provision for communication of the process data with the host system. Traditional sensors that are being used, have varying requirements of compensation and signal processing objectives and the number of measurands in industrial establishments is growing each day. The variety of variables, both physical and chemical, is also increasing and newer sensing mechanisms are being exploited increasing the load on signal processing.

Thus, for each type of variable a different kind of processing is required and with increasing number of types of variables in industries, centralized computers have been overloaded with processing load. The smart sensor is intended to sense as well as do the sensing-related processing within itself. Further, it communicates the response to the host system so that the efficiency and accuracy of information distribution are enhanced with cost reduction.

Advanced processing technologies have now replaced earlier ones used for developments of smart sensors. Sensor elements are open to process although they are now being built in the smart system itself. Certain sensors require supply, constant voltage or constant current along with comparison capabilities; the feature is included in sensor subsystem. Amplification is necessary which usually analog, may also be controlled digitally. Earlier analog filters were employed which have now been replaced by digital counterparts. These three systems, namely the supply, amplification, and filters, comprise the analog signal processing unit (ASPU). Smart sensor also requires a data conversion module either from analog to digital (A/D) or from frequency to digital (F/D) which interfaces with the microprocessors for information processing and bus interfacing for communication. Figure 7.2 shows a stack-block simplified version of the scheme.

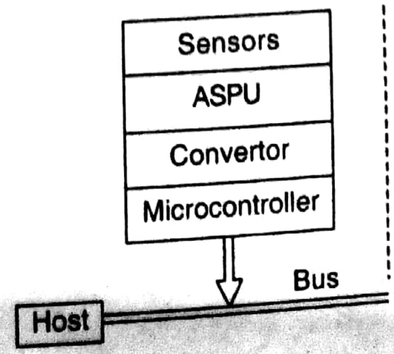


Fig. 7.2 A sensor interfaced with a host system.

The smart sensor devices integrate complementary trends such as

(a) new sensing methods,
(b) improved computing capability, and
(c) digital communication.

New sensing methods are realized through synthesis of those from individual sensors with combined technologies and integration techniques. Digital correction in such new techniques improves performance by

(i) compensating for sensor non-linearity,
(ii) permitting a larger proportion of sensors to meet specifications,
(iii) incorporating programmable gain,
(iv) changing sampling rate,
(v) changing interaliasing filter frequency, and so on.

Digital communication, on the other hand, plays an important role in reducing or overcoming noise and quantification errors to send error-free data.

7.2 PRIMARY SENSORS

Existing sensors of all kinds with a cascaded block for providing electrical output in the form of voltage or current can be adapted to an integrated processing system but the system can then be hardly called a smart sensor.

External stimuli such as strain/stress, thermal/optical agitation, and electric/magnetic field change the behaviour of materials at atomic/molecular level or in crystalline state. This concept is utilized in designing a primary sensing element for particular stimulus or a specific physical variable so that, in response to this, the considered material yields a maximized output and its response to other stimuli is minimized. This is not an easy task as a particular material block has to be developed as a controlled system responding maximally only to a single set of variables yielding electrical output which is amenable to be processed by integrated information schemes.

One way to understand response maximization in electrical forms to one or a set of target variables while ignoring others on the part of a sensor element is to state that it should show negligible reaction to interferences and parasitic effects. For reliable operation of a sensor, environmental conditions have to be maintained where parasitic effects do exist though limited. In some cases, these effects are eliminated by correcting in the processing units. In fact, a sensor has its own characteristics which can be broadly be classified as (a) static, (b) dynamic, (c) reliability, and (d) response/sensitivity (to environmental effects).

For integrating processing and sensing units, attention has long been on the type of materials that could be so used. Since electrical/electronic circuits are now largely silicon-based, silicon has been an element of interest for primary sensing elements. Also, it has been well established that electrical behaviour of silicon changes with change in temperature, electrical and magnetic fields, stress/strain, radiation, and even doping. Silicon-based designs of some such sensors have already been discussed in earlier chapters. New technologies and techniques have evolved for realization of such integrated sensing elements. Micromachining of silicon, for example, has been used to produce vibrating systems of the kind of cantilevers, diaphragms and so on, which are small yet robust and serve as high frequency devices.

Silicon thermosensors and chemical sensors have also been produced. A single chip realization of primary sensors and processing elements has, therefore, been advanced to the extent of developing smart sensors and further extension of the same to smart transmitters where communication between these and the control gears receives equal emphasis.

Silicon-based microsensor technology has been of great use in the in vivo adaptation of various types of sensors. Pressure sensor is an example at hand. It consists of a thin, deformable silicon diaphragm with piezoresistors arranged along the edges of the diaphragm. These piezoresistors are then connected in the form of a bridge circuit. A single chip pressure sensor with signal conditioning unit may look like the one shown in Fig. 7.3.

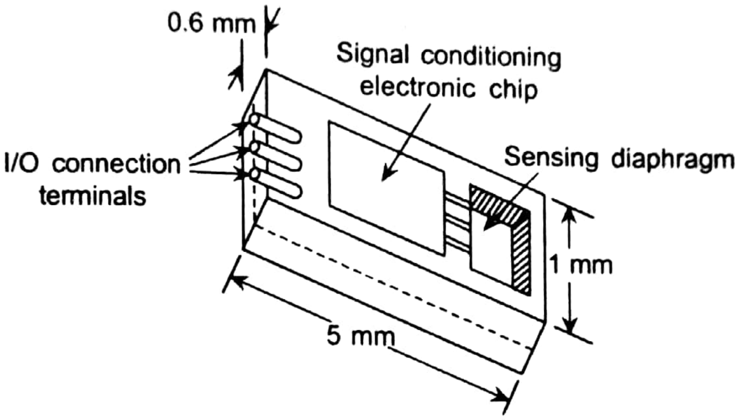


Fig. 7.3 Single chip pressure sensor with signal conditioning units.

A single transistor temperature sensor is well-known now, although for desired proper output in specific relation to the variable, a single smart sensor is also commercially available but it is only a dedicated type device. This has been described in the chapter on thermal sensors.

Thermal sensors based on thermoemf or Seeback effect in the form of thermopiles have also been made in ICs. They are now being batch-fabricated with addition of on-chip signal conditioning electronics.

Two semiconductors are coupled together with a difference of temperature ΔT between the junctions, the open ciruit emf ΔV is given by the relation (Fig. 7.4)

$$\Delta V = \alpha_s \Delta T \tag{7.1}$$

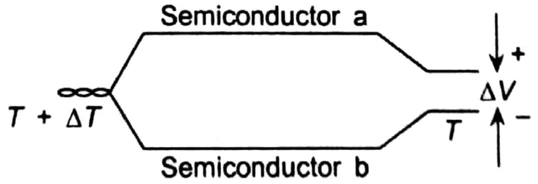


Fig. 7.4 Semiconductor thermoemf elements.

where α_s is the Seebeck coefficient.

If E_f is the Fermi energy so that with charge q, the electrochemical potential ϕ_f is given by

$$\phi_f = \frac{E_f}{q} \tag{7.2}$$

and, hence, for known E_f, α_s for silicon is obtained as

$$\alpha_s = \frac{1}{q}\left(\frac{dE_f}{dT}\right) \tag{7.3}$$

As temperature increases, silicon becomes more intrinsic; charge carriers attain a higher average velocity; and the temperature difference causes phonon flow from hot to cold 'space'.

For conduction band edge energy E_c, conduction band density of charge N_e, electron density (by doping level change) n, and Boltzmann constant k_B, increase in intrinsic behaviour of silicon with temperature rise causes

$$\frac{1}{q}\left(\frac{dE_f}{dT}\right)\Bigg|_{E_c-E_f} = -\frac{k_B}{q}\left\{\ln\left(\frac{N_e}{n}\right)+\frac{3}{2}\right\} \tag{7.4}$$

When the average velocity of charge carriers increases with increase in temperature, a charge builds up on the cold side of the silicon; also, scattering occurs. A parameter called the mean free time interval between two successive collisions of charge carriers, τ is important. If λ is an exponent to denote relation between τ and the charge carrier energy, then,

$$\frac{1}{q}\left(\frac{dE_f}{dT}\right) = -\frac{k_B}{q}(1+\lambda) \tag{7.5}$$

With the net movement of phonons from hot to cold part, it is possible that a transfer of momentum from these to charge carries occurs if silicon is nondegenerate. This momentum drags the charge carriers towards the cold portion of the silicon and for this

$$\frac{1}{q}\left(\frac{dE_f}{dT}\right)\Bigg|_{\phi_n} = -\left(\frac{k_B}{q}\right)\phi_n \tag{7.6}$$

where ϕ_n denotes the relevant drag effect.

Thus, the coefficient α_s is given by

$$\alpha_{sn} = -\left(\frac{k_B}{q}\right)\left\{\ln\left(\frac{N_e}{n}\right)+\frac{5}{2}+\lambda_n+\phi_n\right\} \quad \text{for n type} \tag{7.7a}$$

and

$$\alpha_{sp} = \left(\frac{k_B}{q}\right)\left\{\ln\left(\frac{N_p}{p}\right)+\frac{5}{2}+\lambda_p+\phi_p\right\} \quad \text{for p type} \tag{7.7b}$$

In these relations, λ varies from -1 to 2 and ϕ ranges from 0 (for high doping) to 5 (for low doping) at around room temperature. For lower temperatures, the value of ϕ for low doping increases to 100 or even more. In any case, the approximation of α_s is done by a simplified relation

$$\alpha_s = \left(\frac{mk_B}{q}\right)\ln\left(\frac{\rho}{\rho_0}\right) \tag{7.8}$$

where

$m = 2.5\text{–}2.6$

resistivity $\rho_0 = 5 \times 10^{-6}\ \Omega\text{m}$.

Both m and ρ_0 have been obtained experimentally.

However, integrated thermopiles have been produced with strips of deposited aluminium forming junction with silicon. Figure 7.5 shows a schematic representation, where n-silicon has been used as epilayer.

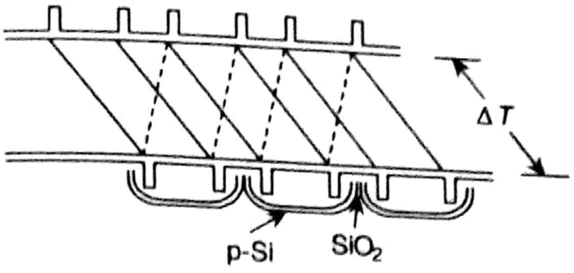


Fig. 7.5 An integrated thermopile system.

7.3 EXCITATION

Although *excitation* is a generalized term used for supply to the primary sensors, when necessary this also means the supply for the entire chip including the processing units. This supply may be required to provide different output to different stages of the system. In the thermocouple form of sensors, no excitation to the sensors is needed while for resistive bridge, an extremely stable supply is required. In stages of electronic processing units, ac supply or else pulsed form supply may be required for phase sensitive detection in the processor unit. In any case, as per requirement the facilities are to be made available for the entire chip to be self-sufficient.

7.4 AMPLIFICATION

Considering the output of the sensor to be generally small, amplification is essential in all smart sensors. If the gain requirement is very high, noise becomes a problem. However, stage-wise approach with adequate compensation realizes the requirement, the design and layout being critical as well.

7.5 FILTERS

Analog filters are often resorted to although filters are necessary at conversion stages, mainly because the digital type, consume large real time processing power.

7.6 CONVERTERS

Conversion is the stage of internal interfacing between the continuous and the discrete processing units. The conversion, in most of the situations, does not have one-to-one correspondence. Often, controlled conversion through software is provided with range selection and so on.

Data conversion from analog amplitude to frequency is often done for convenience of signal transmission, internally or externally, and/or for subsequent digital conversion. Voltage-controlled oscillators are used for these purposes. One such converter is a multivibrator shown in Fig. 7.6. Analysis shows that the time period of the generated square wave is given by

$$T = 2RC \ln\left(1 + 2\frac{R_2}{R_1}\right) \tag{7.9}$$

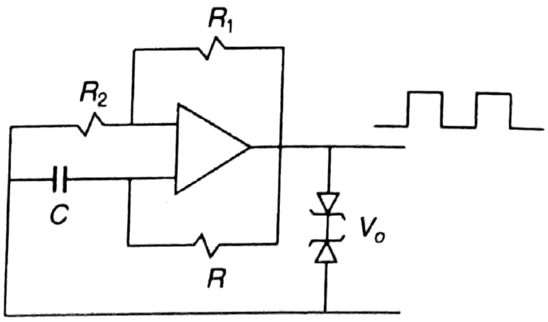


Fig. 7.6 A multivibrator.

The parameters R and C can be related to the input voltage. Fixing R_2/R_1 at 0.859, T is obtained as

$$T = 2RC \tag{7.10}$$

or, frequency f is given by

$$f = \frac{1}{2RC} \tag{7.11}$$

In fact, the capacitance or resistance may be the sensed instead of the input voltage or measurand/sensor output voltage. Ring oscillator realized with MOS technology is one popular V–f converter (or signal-to-frequency converter). A scheme of the V–f converter is shown in Fig. 7.7 which consists of an odd number of cascaded NOT, NOR, or NAND gates with its last gate-output fed back to the first stage to form the ring. With the gain of each stage being greater than one, the circuit is self-oscillatory with the frequency determined by the number of gates and their delays. Supply frequency and chip temperature need be controlled on which also depends the frequency.

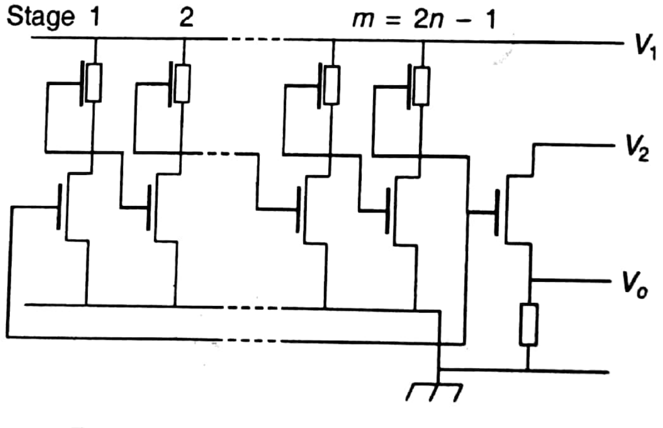


Fig. 7.7 An integrated ring oscillator.

If the MOS channel resistance is a piezoresistance whose value may be made dependent on the pressure exerted on it; this would change the gate delay and there is a frequency change. Supply frequency and temperature changes are usually compensated by using two ring oscillators and the ratio of two frequencies is taken as the output.

Next is the frequency to digital conversion. It must be remembered that when a voltage output is straightaway obtained from a sensor, other direct digital converters such as ADC's can be used. But, there are instances where the sensor is so designed that it inherently provides analog frequency output as in the case discussed in precedence, with the ring oscillators integrated on Si-diaphragm and pressure sensors utilizing the piezoresistive effect. Some other examples are (i) capacitive/inductive sensors controlling oscillator frequencies, (ii) photoresistances for illuminance sensing used in harmonic/relaxation oscillators, and (iii) quartz tuning fork as frequency standard.

In digital conversion, frequency from the 'sensor oscillator' is 'counted' by actually counting clock pulses in a pulse-width of the oscillator. There are various ways of doing it. One arrangement is shown in Fig. 7.8. Over the time period $T_x = 1/f_x$, f_{ref} would be counted; dividing f_x by a suitable factor n, this time interval is suitably increased to obtain a better resolution. In fact, the resolution R_n is given by

$$R_n = \frac{1}{n}\left(\frac{f_x}{f_{ref}}\right) \tag{7.12}$$

where $1/R_n$ is the actual count.

It must be remembered that there are variations of this circuit incorporating facilities required for different applications.

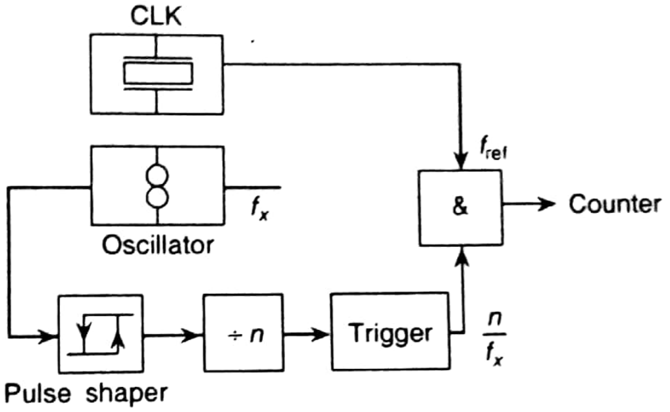


Fig. 7.8 A typical digital conversion method.

7.7 COMPENSATION

Compensation is an attempt to counter all sorts of nonideality in the primary sensor characteristics as well as environment of measurement. The commonly encountered sensor defects are:

(a) nonlinearity,
(b) noise,
(c) response time,
(d) drift,
(e) cross sensitivity, and
(f) interference.

Manufacturing tolerance may be combined under drift whereas temperature and/or other environmental effects are accommodated in noise.

7.7.1 Nonlinearity

Analog processing shows serious nonlinearity which at one time, was solved by piecewise linear segment approach modelled by linear electronic circuits. With digital processing methods in use now, more readily available general techniques are there to be used for the purpose. One very common technique is to refer to look-up tables while others are polygon interpolation, polynomial interpolation, and cubic splines interpolation techniques of curve fitting.

(a) *Look-up table method:* In this method, the sensor characteristic is described by a number of reference points very close to each other which are stored in ROM with linearized values. Response of the sensor for a measured value is referred to the ROM to look up for the corresponding linearized value which is then passed on for display or further processing. For good accuracy, this requires a large storage capacity or memory.

(b) *Polygon interpolation:* It is intended for soft nonlinearity where sectionalized linearization can be adopted. This method assumes that the nonlinear range is divided into a few linear sections and hence, a fewer reference points serve the purpose of linearization since between these stored reference points, the sensor is considered to behave linearly. For hard nonlinearity, the technique fails because the reference points are numerous. Figure 7.9 shows the technique of polygon interpolation.

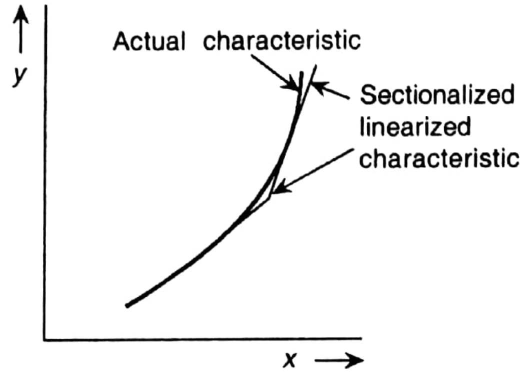


Fig. 7.9 Polygon interpolation.

(c) *Polynomial interpolation:* This technique is again a standard technique which is based on the functional relationship between n selected measured points on the sensor characteristics and a polynomial of order $\leq (n - 1)$ over the range covering the characteristics. Lagrange's interpolation technique is a very common such technique. The curve is represented by the formula

$$y = \sum_{i=0}^{m} a_i x^i \tag{7.13}$$

The modification of this method for full-scale linearization is to generate a complementary curve for this characteristic as

$$y_c = \sum_{j=0}^{m} b_j x^j \tag{7.14}$$

and then, obtain the arithmetic, geometric, or root mean square mean as,

$$y_{\text{linear}} = \frac{1}{2}(y + y_c) \tag{7.15a}$$

$$y_{\text{linear}} = (y y_c)^{1/2} \tag{7.15b}$$

or,

$$y_{\text{linear}} = \left(\frac{y^2 + y_c^2}{2}\right)^{1/2} \tag{7.15c}$$

Figure 7.10 shows the linearization principle graphically. The polynomial interpolation method is usable under limitations of order. Increase in order often leads to oscillations.

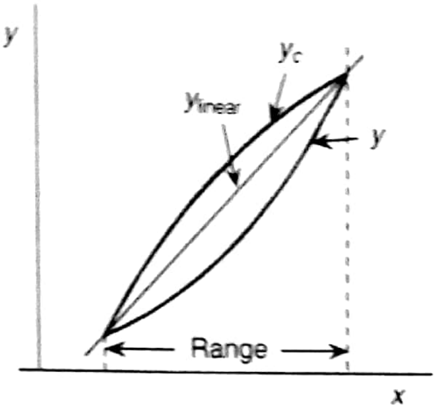


Fig. 7.10 Linearization using complementary function.

(d) *Cubic spline interpolation:* This method is so named as the sections of the characteristic curve of the sensor between a selected pair of reference (measured) points are represented by cubic spline functions as

$$S_i(x) = a_i + b_i(x - x_i) + c_i\,(x - x_i)^2 + d_i(x - x_i)^3 \tag{7.16}$$

with $x \in [x_i, x_{i+1}]$ and $i = 0, 1, 2, \ldots, (n - 1)$.

Each section on two sides, except the first and the last sections (Fig. 7.11) which have one end free, have junction points that are also represented by the adjacent spline functions. Both these functions must coincide with each other in function values, gradient, and curvature at these points, from which, conditions for the polynomials are derived. The end-points or the range binding points possess separate features—often it is considered that at these points, curvature is zero. With all these specifications, we obtain

$$\begin{aligned}
S_i(x_i) &= y_i, & i &= 0, 1, \ldots, n\\
S_i(x_i) &= S_{i-1}(x_i), & i &= 0, 1, \ldots, n, \text{ for function values;}\\
S_i'(x_i) &= S_{i-1}'(x_i), & i &= 0, 1, \ldots, (n-1), \text{ for gradients;}\\
S_i''(x_i) &= S_{i-1}''(x_i), & i &= 0, 1, \ldots, n-1, \text{ for curvatures;}
\end{aligned} \tag{7.17}$$

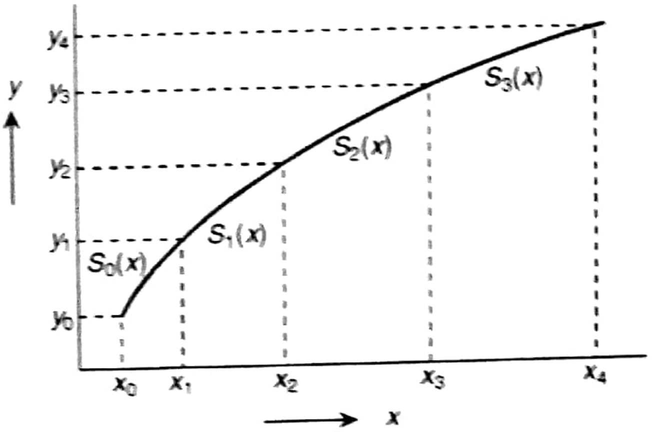


Fig. 7.11 Cubic spline interpolation.

for the points other than the end-points. It is advantageous to choose y-direction increments equal for the reference points and from the given conditions, the coefficients are evaluated. For success of the technique, at least five reference points, including the end-points, are to be taken.

Basically, interpolation is to fit a polynomial through the points around the point y where the function value is to be found. This polynomial is an approximation of the function and is used to find $f(r)$.

Assuming a second order polynomial of the form

$$f(x) = a_1(x - x_2)(x - x_3) + a_2(x - x_1)(x - x_3) + a_3(x - x_1)(x - x_2) \tag{7.18}$$

even by inspection, one easily gets,

$$\left.\begin{aligned} a_1 &= \frac{f(x_1)}{(x_1 - x_2)(x_1 - x_3)} \\ a_2 &= \frac{f(x_2)}{(x_2 - x_1)(x_2 - x_3)} \\ a_3 &= \frac{f(x_3)}{(x_3 - x_1)(x_3 - x_2)} \end{aligned}\right\} \tag{7.19}$$

so that the nth order polynomial can be expressed as

$$f(x) = \sum_{i=1}^{n+1} f(x_i) \prod_{\substack{j \neq i \\ j=1}}^{n+1} \frac{(x - x_j)}{(x_i - x_j)} \tag{7.20}$$

which is known as the Lagrange's polynomial.

Approximation and regression

Appropriate choice of the reference points for obtaining an efficient interpolation is very important. The coefficients obtained for the interpolated characteristic should be such that they have minimum deviation at 'each' point of the characteristic from the actual characteristic. The obtained function as it is an approximation of the actual function, is likely to deviate from the actual one and the errors between the 'approximate' values $\bar{y}$'s for the approximate function are given as

$$\bar{y} = f(a_1, a_2, \ldots, a_m, x) \tag{7.21}$$

and the reference points y_i, as measured, can be written as

$$d_i = y_i - \bar{y}_i = y_i - f(a_1, a_2, \ldots, a_m, x_i) \tag{7.22}$$

For deviation to be minimum, it is proposed that certain principles be adopted and the minimization should not be individual point to point process. Some of the proposed principles are

1. $\text{Min}\{d(a_1, a_2, \ldots, a_m)\} = \sum_{i=1}^{n} w_i \left| y_i - f(a_1, a_2, \ldots, a_m, x_i) \right|$

$$= \left[\min \sum_{i=1}^{n} \left| (y_i - \bar{y}_i) \right| \right] \tag{7.23a}$$

2. $$\text{Min}\{d(a_1, a_2, \ldots, a_m)\} = \sum_{i=1}^{n} w_i \{y_i - f(a_1, a_2, \ldots, a_m, x_i)\}^2$$

$$= \left[\min \sum_{i=1}^{n} (y_i - \bar{y}_i)^2\right] \qquad (7.23b)$$

3. $$\text{Max}|\{d(a_1, a_2, \ldots, a_m)\}| \leq \sum_{i=1}^{n} w_i |y_i - f(a_1, a_2, \ldots, a_m, x_i)|$$

or $$\leq D \qquad (7.23c)$$

The left hand side of Eq. (7.23a) is called R function and the approximation is known as L_1 where one or two wayout points in the 'fit' are ignored. Similarly, in Eq. (7.23b), it is called S function in L_2 approximation when minimization is in the least square sense, and in Eq. (7.23c), it is T function when maximum deviation is allowed but within specified limits. This is known as *Chebyshev approximation*. The term w_i is the weight factor for points (y_i, x_i).

Minimization in the least square sense is an approximation method and often called *regression*. This is very often used in the calibration of sensors and instrumentation systems. One specific kind of regression is linear regression.

Polynomial regression begins with

$$\min S = \min \sum_{i=1}^{n} (y_i - \bar{y}_i)^2 \qquad (7.24)$$

where

$$\bar{y}_i = a_n x_i^n + a_{n-1} x_i^{n-1} + \ldots + a_1 x_i + a_0$$

$$= \sum_{j=0}^{n} a_j x_i^j \qquad (7.25)$$

Here, S becomes a function of $(n + 1)$ unknown variables $a_0, a_1, \ldots, a_n$. Taking partial derivatives of S with respect to $a_0, a_1, \ldots$ and setting these to zero, a set of $(n + 1)$ equations is obtained as

$$\frac{\partial s}{\partial a_j} = \sum_{i=1}^{n} 2\left(y_i - \sum_{j=0}^{n} a_j x_i^j\right)(-x_i^j) \qquad (7.26)$$

These $(n + 1)$ equations, called *normal equations* for polynomial regression, are solved for $(n + 1)$ coefficients by Gaussian elimination procedure. Higher the number of coefficients, more severe becomes the numerical difficulties and hence, simpler techniques such as transforming the nonlinear function into a linear function and then using the linear regression, are adopted. The following example makes the process clear. Let the function be exponential

$$y = \alpha \exp(-\beta x) \qquad (7.27)$$

$$\Rightarrow \qquad \log y = -\beta x + \log \alpha$$

But, log α is a constant, (say a_0) and $-\beta$ is another constant, say a_1, so that using the regression analysis

$$a_0 = \frac{\Sigma(\log y_i)\Sigma x_i^2 - \Sigma x_i\, \Sigma(x_i \log y_i)}{n\Sigma x_i^2 - (\Sigma x_i)^2} \tag{7.28a}$$

and

$$a_1 = \frac{n\Sigma(x_i \log y_i) - \Sigma x_i\, \Sigma(\log y_i)}{n\Sigma x_i^2 - (\Sigma x_i)^2} \tag{7.28b}$$

Coefficients α and β are now given as

$$\alpha = \exp(a_0)$$

and

$$\beta = -a_1 \tag{7.29}$$

7.7.2 Noise and Interference

Thermal noise is important in almost all sensors. Besides, there are other unwanted signals that may be picked up due to external magnetic fields (sort of an interference) when the structure is not adequately screened. Noise is also introduced at different stages of signal processing such as data conversion, analog to digital interfacing by stray effects, and so forth.

The methods of minimization of noise are appropriate signal conditioning techniques that include filtering, signal averaging, and correlation among others. If the signal is periodic as in the case of the output of the frequency converter, the correlation technique improves the signal-to-noise ratio by a large value. This is due to the superposition property of autocorrelation.

Again, if the input is corrupted at any stage by noise, specifically white noise, a cross correlation technique can be used to obtain the system response/function without this corruption. This is obtained in Fig. 7.12.

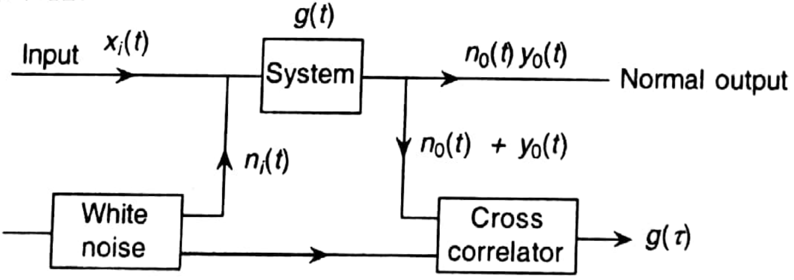


Fig. 7.12 The cross-correlation technique for noise reduction.

For a signal $f_1(t)$, the autocorrelation function is

$$\phi_{11}(\tau) = \lim_{T\to\infty}\left(\frac{1}{2T}\right)\int_{-T}^{T} f_1(t)\, f_1(t+\tau)\,dt \tag{7.30a}$$

If the output for a signal $f_1(t)$ is $f_o(t)$, the cross correlation function is

$$\phi_{12}(\tau) = \lim_{T\to\infty}\left(\frac{1}{2T}\right)\int_{-T}^{T} f_1(t-\tau)\, f_o(t)\,dt \tag{7.30b}$$

7.7.3 Response Time

Because of the presence of storage and dissipative elements, a sensor is likely to have quite inferior time response characteristics and the 'dynamic correction' of sensor becomes necessary. This is possible with the use of microprocessors/microcomputers with suitable algorithm if the dynamic parameters are known through solving the convolution integral. In fact, it is the facility of the inverse operation of deconvolution that is available in such processes and makes such a correction possible. If the sensor function is given by $f(s)$, the signal processing unit should have a function $1/f(s)$ as shown in Fig. 7.13, so that we obtain

$$x_i(t) = \int_0^t x_o(t-\tau)\, g(\tau)\, d\tau = x_o(t) * g(\tau) \tag{7.31}$$

where $g(\tau) = \mathcal{L}^{-1}\left\{\dfrac{1}{f(s)}\right\}$

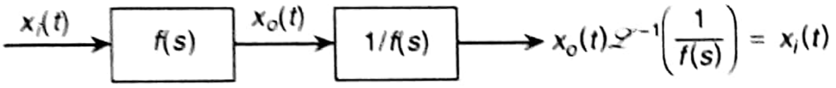


Fig. 7.13 Cascading complementary processing function.

Since $x_i(t)$ can be written in terms of the output $x_o(t)$, the correction can be easily made. In fact, for a second order system, the input $x_i(t)$ in terms of $x_o(t)$ is

$$x_i(t) = \frac{1}{K}\left\{x_o(t) + \left(\frac{2\zeta}{\omega_0}\right)\dot{x}_o(t) + \left(\frac{1}{\omega_0^2}\right)\ddot{x}_o(t)\right\} \tag{7.32}$$

where ζ is the damping factor and ω_0 is the natural frequency of oscillation. Thus, $x_i(t)$ is expressed in terms of the output and its derivatives. The same polynomial interpolation can be used with $x_o(t)$, $\dot{x}_o(t)$, and $\ddot{x}_o(t)$ as the reference points. The cubic spline polynomials are advantageous for second order systems.

Another method using the difference equation is also useful in digital systems for obtaining $\dot{x}_o(t)$, and $\ddot{x}_o(t)$ as

$$\dot{x}_o(t_j) = \frac{1}{T_s}[x_o(t_j) - x_o(t_{j-1})] \tag{7.33a}$$

and

$$\ddot{x}_o(t_j) = \frac{1}{T_s}[\dot{x}_o(t_j) - \dot{x}_o(t_{j-1})] \tag{7.33b}$$

T_s being the sampling interval.

7.7.4 Drift

Drift appears in a sensor because of slow changes in its physical parameters either due to ageing or deterioration in ways of oxidation, sulphation, and so on. Drift is a kind of noise and should be counteracted. As drift tends to change the sensor characteristics, the reference points for polynomial interpolation also tend to drift. These are required to be updated and hence, the coefficients are re-evaluated through an algorithm.

7.7.5 Cross-Sensitivity

A sensor, while responding to a specific variable, responds to others as well, may be, with much less sensitivity. It is therefore necessary to maximize the sensitivity for the desired measurand and minimize that for the others. A common undesired interfering variable is temperature for non-thermal sensors.

If the interfering variable is denoted as z, output as y and measurand as x, then the nominal or rated (constant) z, z_0 is taken as the base value of the interfering quantity while with varying z_0 from z, the characteristics are changed as shown in Fig. 7.14. The function $y(x, z)$ can be expressed as a series of the base characteristics $y_0(x, z_0)$ given by

$$y(x, z) = \alpha_0(z) + [1 + \alpha_1(z)]\, y_0(x, z_0) + \alpha_2(z)\, y_0^2(x, z_0) + \dots \tag{7.34}$$

For $z = z_0$, the function $\alpha_i(z)$, $i = 0, 1, \dots, n$ becomes zero, otherwise it describes the effect of interference by z. This function $\alpha_i(z)$ can be written as a polynomial function that can be written as

$$\alpha_i(z) = \sum_{j=1}^{m} \beta_{ij} (x - z_0)^j \tag{7.35}$$

By approximation methods and regression algorithm, β_{ij}'s are evaluated by sensor characteristics at different values of interference quantity z. The correction can be affected by measuring the sensor output and calculating its effective value with the base characteristics. Thus, one obtains a measured characteristic and also one evaluated at a value $z \neq z_0$. There is not only zero shift but may also be changes in gradient and curvature. The relative deviations for various x's are then obtained by calculating $100(\Delta y/y_{max})$ from the two curves shown in Fig. 7.14.

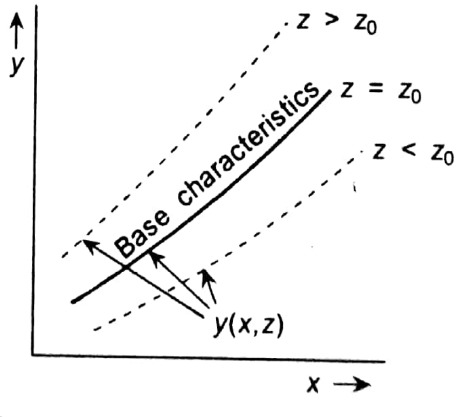


Fig. 7.14 Curves pertaining to analysis of cross-sensitivity.

Compensation takes account of many undesired interfering influences and is, therefore, critically examined. As has been discussed, the compensation made through devising algorithm by monitoring the change in response characteristics because of any interfering quantity, is quite common as it is possible to develop the algorithm from 'measured' data. Such a compensation is often termed as *monitored compensation* and is very common in structuring modern day sensors where a number of sensors are possible to be produced on a common substrate. Also, in Si-technology, an in-built monitoring sensor can be used within the main sensor.

Besides, such compensation methods, it is attempted to design the sensor to be least responsive towards interfering quantities. In fact, the idea is to provide 'structural compensation' by giving symmetry to the sensor so that the desired output is derived through differential mode while the interfering signals are derived through common mode and are rejected.

Even taking proper care in the design with symmetry of the sensor, manufacturing or production tolerance may lead to error which needs be compensated. This means that individual sensor needs to be compensated depending on its performance and response to inputs. Such individual compensation is called *'tailored compensation'* and a dedicated algorithm has to be developed for the purpose or a specialized analog module has to be incorporated.

When none of the discussed compensation methodologies can be adopted because of 'physical inaccessability' in some cases, model reference data sets are considered and compensation values are deducted and incorporated. It is, to a certain extent, inferential and subject to errors for error in the model itself. However, such compensation is known as *deductive compensation*.

7.8 INFORMATION CODING/PROCESSING

It has so long been assumed that signal from a sensor is processed providing correction, compensation, linearization, freedom from cross-sensitivity and drift, and so on. It is also true that such a processed signal is finally to be made available in digital form and, perhaps, in a serial form. It is good to remember that smart sensors are generally multi-sensor systems and a number of signals are available for either display or further processing subsequently to be connected to the 'communication bus'.

Information, the state of the process in the form of a processed signal through sensor and signal processing systems, is first received by the information coding system. Some of these signals are released, some stored, some destroyed, and some restructured.

For indication purposes only, the signals are coded and displayed over appropriate display modules as is done in digital meters, indicators, recorders, and so forth. A typical IC temperature sensor-based smart sensor is depicted in Fig. 7.15.

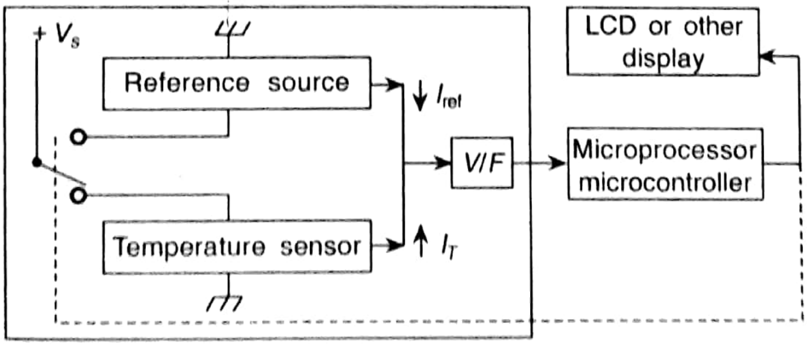


Fig. 7.15 A typical IC-temperature based smart sensor.

When these signals are required to be used for system control and surveillance as is usually the case, in addition to display, control system should be able to read the signals for their functioning. Information processing assembly in a smart sensor is basically an encoder, the encoded data from this are fed to the communication unit. As is usual, the conventional signal processing provides an output of 4–20 mA. One way is to get a corresponding voltage range which is then parallelly encoded into digital signal through a converter. When necessary, the 4–20 mA output is also drawn. Voltage-to-frequency converter is another kind which is quite extensively used (see Fig. 7.15), then using a reference frequency generator, frequency difference encoding is employed.

Mark-to-space ratio control of a square wave is another coding technique but not often resorted to. There are many other techniques and choice is largely based on the specific requirement and associated conditions.

7.9 DATA COMMUNICATION

Data communication is essential in smart transmitters where the sensor outputs are communicated with the host through bus-system. Coded data are processed for communication by a software processor and a suitable interface system communicates between the processor and the bus. The bus was, till lately, being standardized. Commercial versions available for quite sometime used their own protocol. Each smart sensor/transmitter has always been provided with a local operating system in a ROM, that consists of an application programme and library modules, for ADC and DAC hardwares, bus driving hardware, local interface hardware, and LCD/keyboard hardware.

Earlier manufacturers preferred to develop their own protocol. One such protocol is HART (Highway Addressable Remote Transducer) offered by Rosemount which superposes a digital transmission protocol on the standard 4–20 mA loop. A typical transmitter with HART protocol appears as the one shown in Fig. 7.16. Some other protocols that find use are High Level Data Link Control (HDLC), Synchronous Data Link Control (SDLC), Factory Instrumentation Protocol (FIP), and so on which are sufficiently advanced.

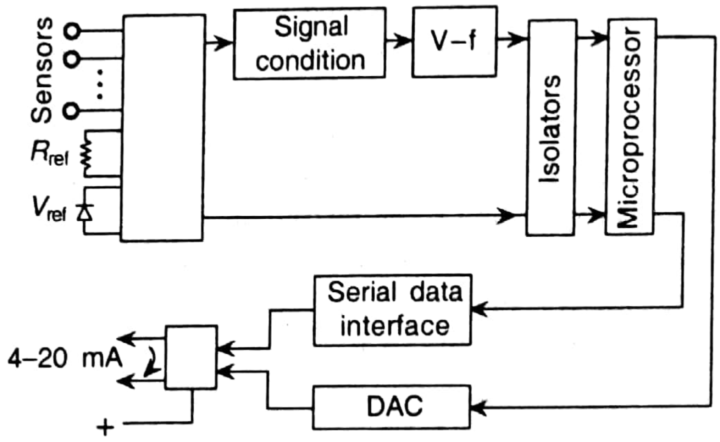


Fig. 7.16 A smart transmitter.

Recently, an international standard in protocols has been reached which permits any host to be in communication with the smart sensor/transmitter system. This ensures common field bus standard. This, however, is for the standardization of the communication unit. The actual smart sensor remains open to development for better operation with existing and emerging sensors and underlying technologies.

The HART protocol has been designed for direct use of 4–20 mA output device having facilities of digital communication with superimposed modulation between the field device and a host system. Such devices can be connected in parallel. The addressing procedure allows each unit to set its output for power supply at 4 mA and the device is forced to communicate only digitally. The parallel connection coverts the twisted pair into a multiloop bus but the number is limited to 15 as specified by this protocol. The power source, therefore, supplies a maximum of 60 mA. The basic multiloop connection method is presented in Fig. 7.17 while Fig. 7.18 shows the hardware requirements for microprocessor-based field devices.

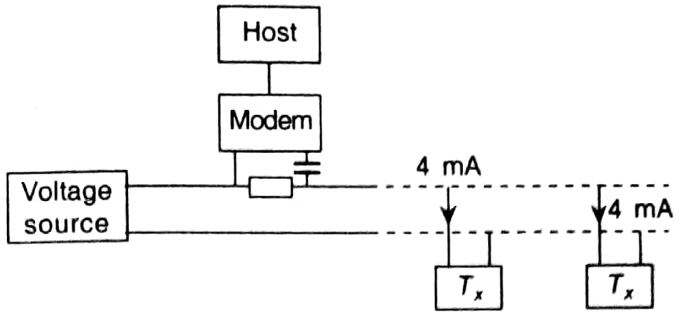


Fig. 7.17 The basic multiloop connection.

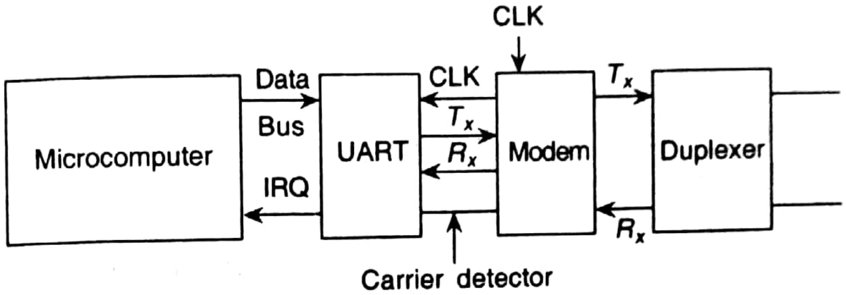


Fig. 7.18 Demonstration of hardware requirement of an intelligent field device.

Frequency shift keying (FSK) is used for coding digital information. Logic 1 is represented by 1200 Hz and 0 by 2200 Hz both with sine wave of amplitude 0.5 mA. Data rate is 1.2 Kb/s. The implementation of this digitally signalling technique can be done by using a modem of telephony standard.

In HART protocol, it is the master–slave proposition that works—the field device responds only when it receives instruction from the bus and in every reply message, the status of the field device is included to check its state.

Application specific integrated circuits (ASIC) are receiving attention more and more for the internal operation of the sensor and signal processing system of the smart sensor. ASIC and its supporting technology make available a host of ready items from which those required can be selected, incorporating variety in the smart sensor design and enhancing its capability.

7.9.1 Standards for Smart Sensor Interface

The ultimate goal of the standards is to provide the means for achieving transducer-to-network interchangeability and interoperability. The objectives are to define a set of common communication interfaces for connecting transducers to microprocessor-based systems, instruments, and field networks in a network-independent environment.

Figure 7.19 shows a scheme of communication using IEEE 1451. Here, NCAP (Network Capable Application Processor) information model is intended for defining a common object model for the components of the smart transducer working in networked mode and also to develop the software interface specifications for them. Such an object model provides two interfaces (i) to the transducer block with details of transducer hardware implementation and simple programming model—this resembles an I/O driver and (ii) to the NCAP block and ports with details of different network protocol implementation schemes, this is IEEE P 1451.1

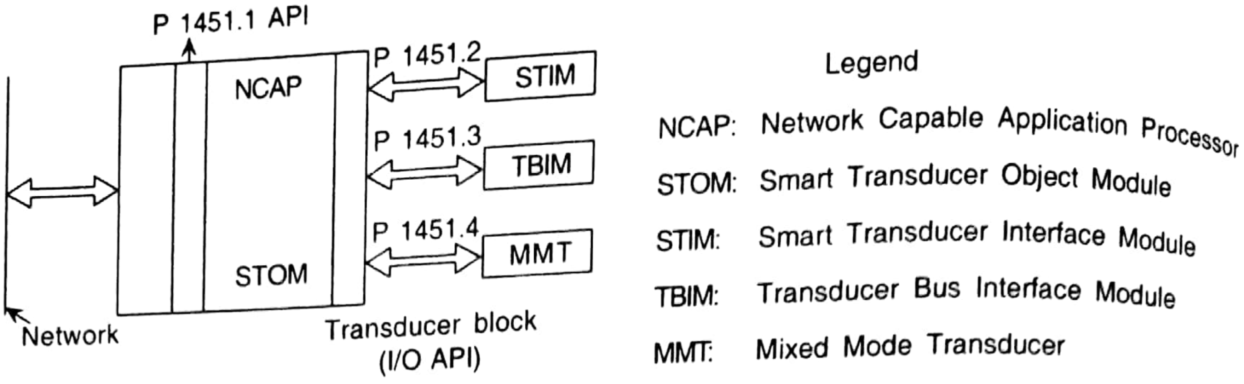


Fig. 7.19 A communication scheme through IEEE 1451.

The IEEE P 1451.2 provides the transducer-to-microprocessor communication protocols and transducer electronic data sheet (TEDS) formats. It also provides the digital interface and communication protocols between the transducers and microprocessors.

IEEE P 1451.3 provides digital communication and TEDS formats for distributed multiloop systems. This is basically intended to develop a standard digital interface for multiple physically isolated/separated transducers in multidrop configuration.

IEEE P 1451.4 provides mixed mode communication protocols and also the TEDS formats. This is intended to develop bidirectional communication of digital TEDS in addition to an interface for mixed mode transducers.

7.10 THE AUTOMATION

In modern control systems, signal communication standards have been of tremendous significance. The first signalling standard (IEC Technology Committee TC–65, 1971, namely IEC 381–1) established was 4–20 mA. In 1981, work on International standards for PLC; in 1985, for field bus; and in 1987, functional safety for programmable electronic systems started but proprietory standards still continue to exist.

Hierarchical structure of control of large complex processes has specific advantages. However, distributed control structure reduces the cost significantly by eliminating the need for long transmission lines between the controller, and the sensors and actuators. A typical scheme of such a structure is shown in Fig. 7.20. By connecting field-located devices with a serial bus and the field bus, cabling costs can be reduced further. An example is presented in Fig. 7.21.

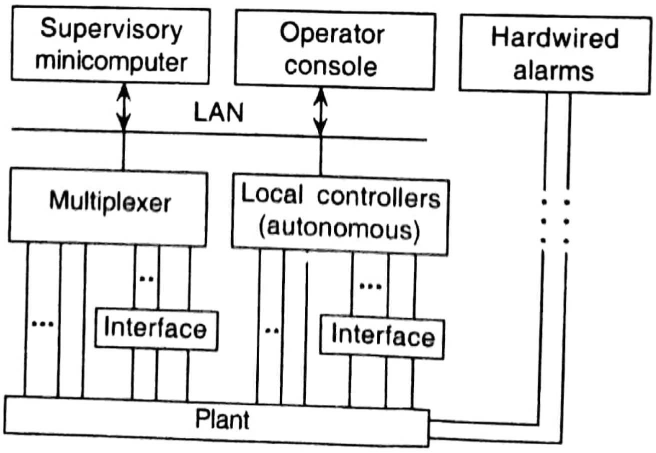
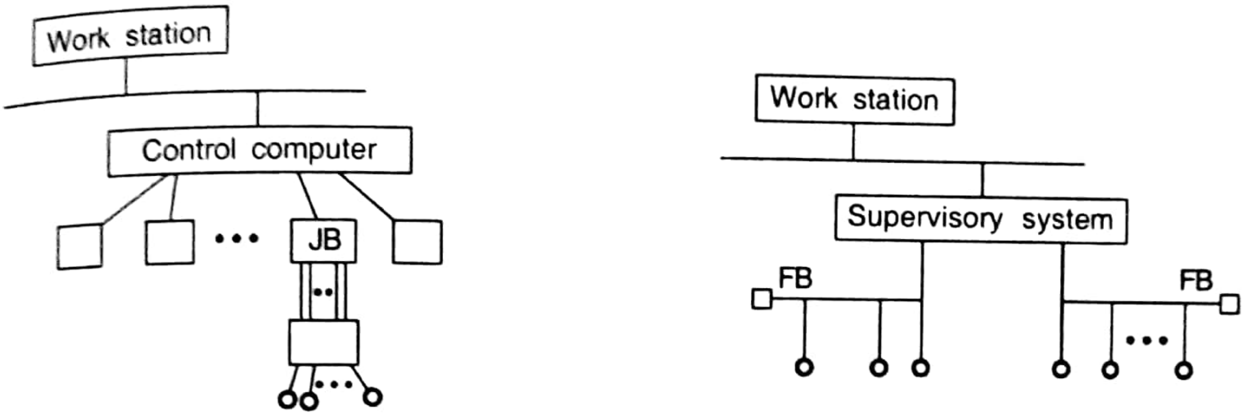


Fig. 7.20 Distributed control structure.



(a) Instruments and actuators star-connected to junction box (JB)

(b) Intelligent instrumentation and actuators linked by a field bus system

Fig. 7.21 Cost reduction in a field bus system.

Automation entered the area of flexible manufacturing satisfying quality specifications. This kind of manufacturing covers the aspects of disciplined (Just-in-time) production with enforced environmental legislation. Other than negative feedback, the strategy has now incorporated programmability and communication technology. The advancement of semiconductor technology has paved the way for all these to be integrated and applied at relatively low cost in the industrial processes. Thus, one can represent the system as

$$\begin{array}{l} \text{Instrumentation} + \text{Programmability} + \text{Communication} \Rightarrow \text{Automation} \\ \text{(negative feedback)}\ \ \text{Integrated low cost} \Leftarrow \text{Semiconductor technology} \ \lrcorner \end{array}$$

In recent years, process automation and factory (manufacturing) automation are using similar automation systems for closed loop control, man-machine interfaces, and for networking. Such convergence has been made possible by the use of IEC field bus standard designed for automation applications.

Chapter 9

Sensors—Their Applications

9.1 INTRODUCTION

An apt name of this chapter could be 'Sensors for miscellaneous applications'. Sensors elucidated here are only highlighted in terms of their applications as many of these are discussed in details in the earlier chapters. Their adaptation to specific applications has been given due consideration. In doing so, a little analysis of the sensor system has been made in some cases. Obviously not all fronts of application can be covered in the present text though the ones presented offer a wider exposure.

9.2 ON-BOARD AUTOMOBILE SENSORS (AUTOMOTIVE SENSORS)

Sensors for automobiles, that is, automotive on-board sensors come with some special constraints and features that include environment, reliability, cost, and resources and innovations.

Engine is the heart of the automobile which is exposed to vibration, dust, electrical noise, extreme temperature variations, and hence, the sensors used too get exposed to all these conditions even though the performance level has to be kept unabated. One such sensor is the flow-rate sensor as discussed in the following subsection. The engine compartment of an automobile has a temperature varying from –40 to 150°C and vibrational acceleration ranging from $3g$–$30g$. Exposure to water, oil, mud, electromagnetic interference, and the like are also to be taken into consideration for better performance.

Reliability in itself is important criterion for production to be trouble-free and for maintaining accuracy at least over ten years. Besides, safety can be ensured in this way—at least partially.

Reduced cost reduces price but it should not be done at the cost of safety and accuracy. Innovative designs are therefore often required for application in automotive conditions.

In present day automobile systems, sensing is required to be done majorly for (i) engine control, (ii) manouvering control, (iii) room and operational comfort control, (iv) safety and reliability, and (v) fuel consumption control.

9.2.1 Flow-rate Sensors

For the conventional engines with carburettor, such sensors are not necessary as the air-to-fuel ratio is self-adjustable here. For the upcoming electronic fuel injection engines, these sensors are made use of as the air volume input to the engine is estimated by flow-rate or pressure sensing. The estimation is done on the basis of engine revolution and the negative pressure measured at its intake. As an advancement, for engines using carburettor also the use of sensors is being considered now and the proposed sensors for this application are (a) ultrasonic flowmeters where the flow-rate is measured by measuring the difference between the speeds of sound both upstream and downstream. But the success of such sensors is yet limited because of large flow-rate changes and temperature variation. As in other areas, microsensors are making inroads into the automobile systems as well. Solid state sensors developed through semiconducting technology are used for sensing air and fuel flows. The underlying principle is to use a heating element in the form of a transistor or a 'semiconductor' resistance bridge. With the advancement of micromachining technology (described in the previous chapter), these can now be realized on silicon substrates. The schemes are shown in Figs. 9.1(a) and (b).

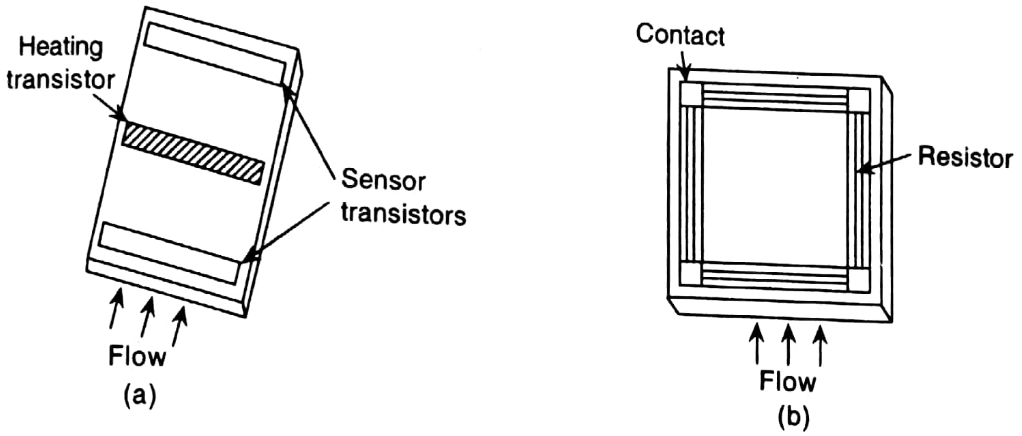


Fig. 9.1 Examples of semiconductor flow sensors.

9.2.2 Pressure Sensors

Pressure is a very important parameter in on-board automobiles and pressures of intake manifold, engine oil, brake oil, tyres, room atmosphere, and so on need be measured. The conventional diaphragms and bellows elements in association with strain gauge, LVDT, and capacitive elements are already in use for pressure measurement. The semiconductor capacitive devices and SAW devices are being increasingly used from which high frequency output can be derived for easier signal processing. With applied pressure, a crystal oscillator changes its frequency and is being tried now as also the PZT types devices. Such a pressure sensor processed by the semiconductor technology and MEMS is shown schematically in Fig. 9.2. For negative pressure sensing for the intake manifold, a semi-smart sensor is used.

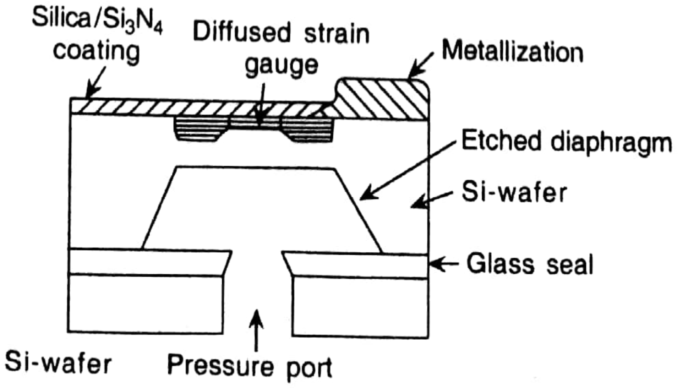


Fig. 9.2 Schematic of a pressure sensor.

Amplification, calibration, and temperature compensation are internally made for in the sensor using IC technology. A basic sensor unit uses a silicon diaphragm and a vacuum chamber is created. The sensor unit is depicted in Fig. 9.3. The sensing silicon chip is resistive in nature and is obtained by adding appropriate impurity to the diffused design.

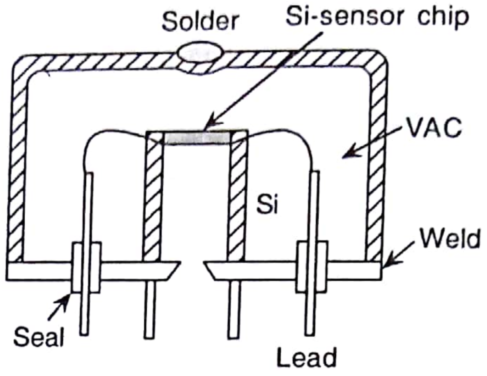


Fig. 9.3 Negative pressure sensing silicon chip.

9.2.3 Temperature Sensors

Temperature sensors for motor vehicles are of various kinds depending on the place where they are used. Temperature switches are pretty common that must be fast. High temperature sensitive sensors are also very much in demand and there are traditional types which are used for oil and water. Temperature ranges from −40–180°C in engine coolant, oil basin, and gear box while for the exhaust gas at the exhaust pipe it may rise upto about 1200°C; the temperature inside the car is less than 80°C, and so on. Therefore, sensors need to be carefully chosen to offer maximum output and reliability under these conditions.

In engine coolant and oil, bimetal elements are commonly used as thermorelays having hysteresis < 5°C for a temperature range of −40°–140°C, and switching current 6 A at a rated supply of 12 V.

For conversion of coolant, air, oil, and gas temperatures in automobiles into analog signal output for indication or for use by the computer/processor for regulation purposes, negative temperature coefficient thermistors are mostly used. The thermistor range lies between 50–150°C with 1 kΩ resistance at 25°C. However, for cylinder head, RTD (platinum resistance) appears to be a better choice. It is the design in either case that has got to be special to fit into the feature of the vehicle. Figure 9.4 shows a typical RTD used in the vehicle, it is an RTD 600 variety with a range of −40–300°C that possesses an accuracy of ±2°C.

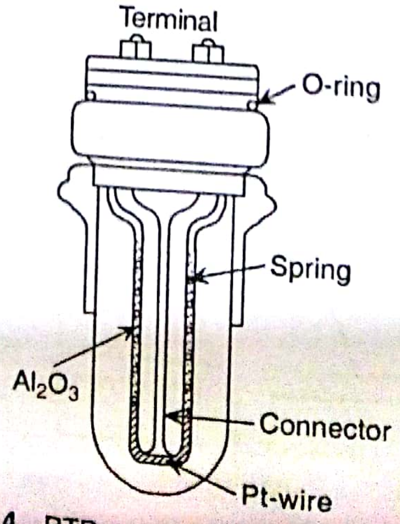


Fig. 9.4 RTD as used in automobiles.

For coolant, engine oil, and air experiencing temperature range of −40–140°C, quartz temperature sensors are now quite frequently used. These have an accuracy of ±1°C. The thermometer houses the electronic processing unit which is a surface-monitored device mounted on a ceramic hybrid system. It can also be adjusted by laser trimming system. The frequency of quartz changes with temperature and this property is exploited for detection. Figure 9.5 shows the basic schematic of such a system.

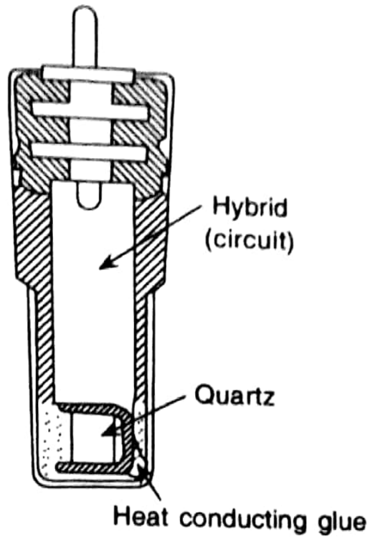
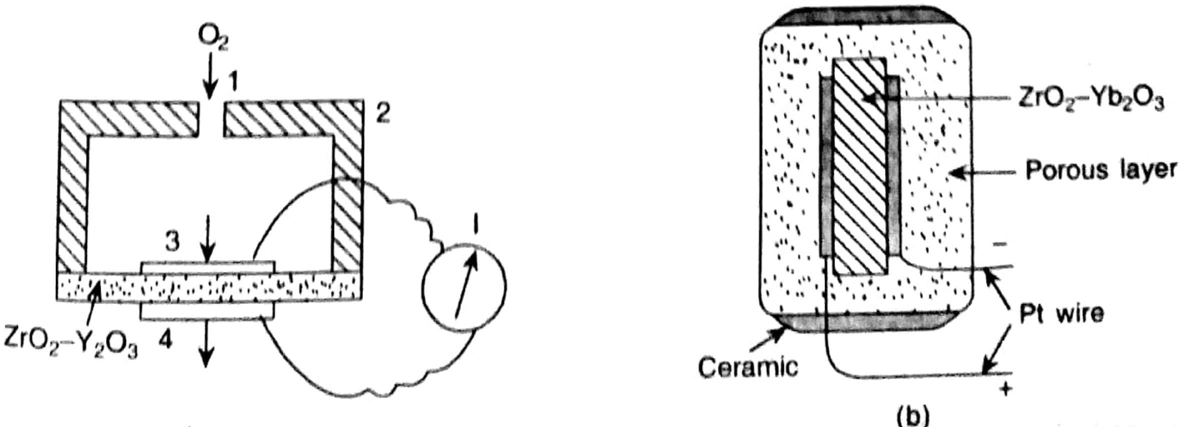


Fig. 9.5 Hybrid IC temperature sensor.

For exhaust gas temperature sensing, Ni–Cr/Ni thermocouples are used upto 1200°C which has a sensitivity of about 40 μV/°C. Thermocouples are gradually getting strong foothold in auto-monitoring because of their active nature.

9.2.4 Oxygen Sensors

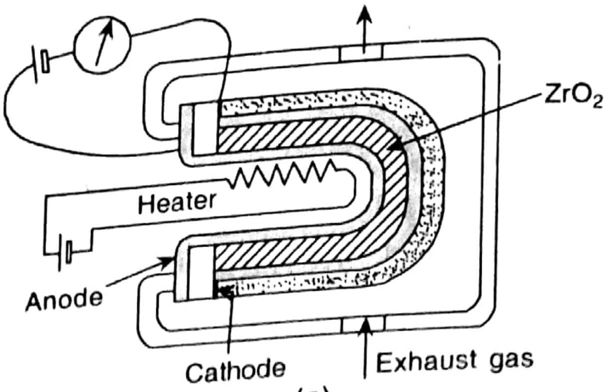
Oxygen is a very important parameter for autoexhausts and gas concentration inside the automobile. Appropriate oxygen sensors are installed in the emmision controlled systems to reduce the toxic exhaust and improve fuel consumption. Zirconia and titania sensors are being used for detecting air-to-fuel ratio for quite some time now. Niobium oxide sensors have also recently been introduced and are observed to show better performance. Sensors for checking smoke, humidity, and odour are fixed inside the automobiles and limiting current oxygen sensors are still extensively used in automobile exhaust. The saturation current, called the limiting current in these sensors is proportional to the ambient oxygen. Figures 9.6(a), (b), and (c) present three typical designs of such a sensor.



(a)

(b)

Fig. 9.6 Cont.

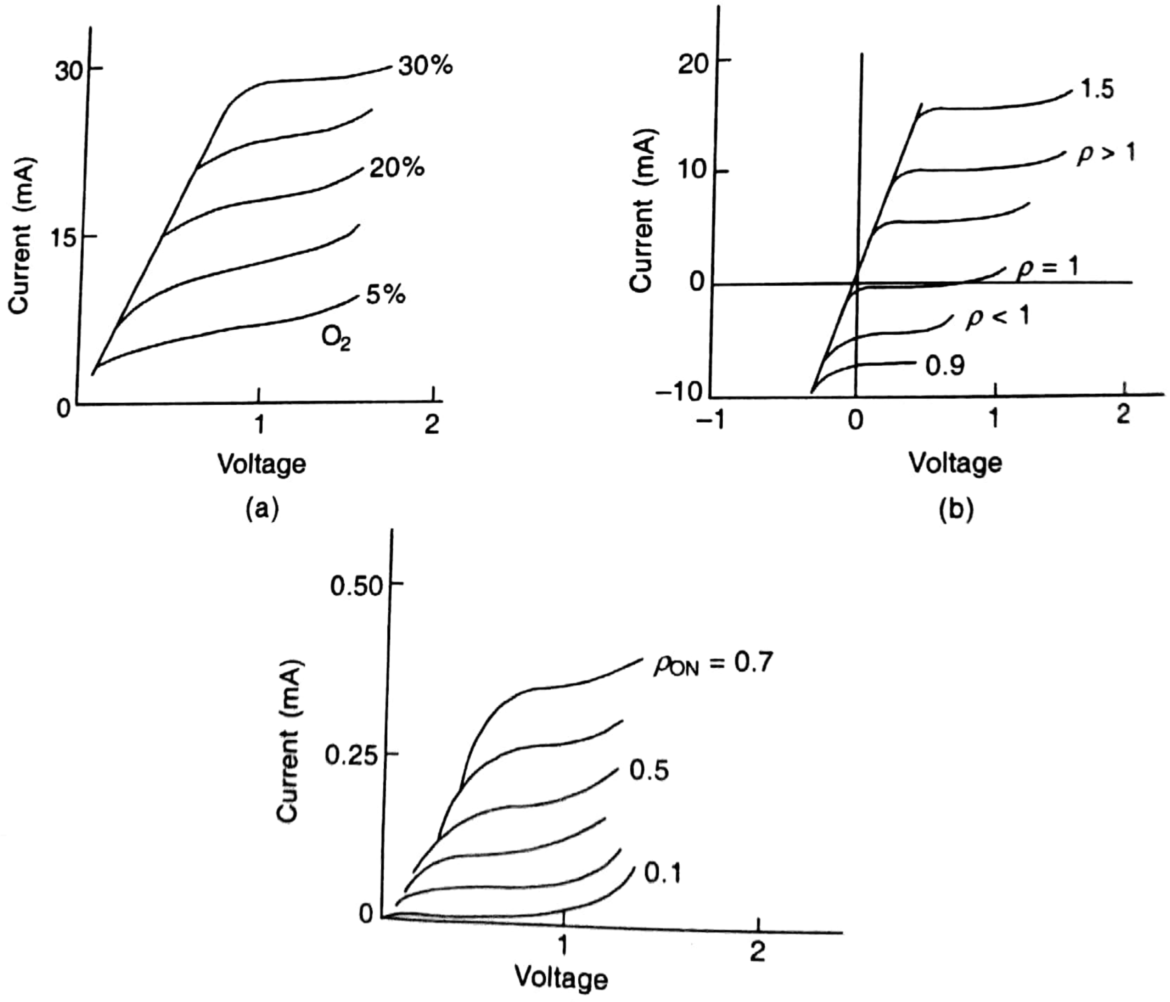


(c)

Fig. 9.6 Three typical designs of oxygen sensor.

In Fig. 9.6(a), the cathode is exposed through a pin hole made inside a cover that limits the diffusion of gas. The size of the pin hole is so chosen as to limit the rate in the transfer of oxygen at the cathode. The voltage–current relationship with oxygen concentration as a parameter for this device is shown in Fig. 9.7(a). For oxygen sensors to operate, temperature should be around 700°C which is easily available in the exhaust. The relation between the limiting current I_l and the molar concentration of oxygen, C, is given by

$$I_l = \left(\frac{4FD\alpha C_g}{l}\right) \ln\left(\frac{1}{1 - C/C_g}\right) \tag{9.1}$$



(a)

(b)

(c)

Fig. 9.7 (a) Current–voltage characteristics with oxygen as a parameter, (b) with ρ as a parameter, (c) with ρ_{ON} as a parameter.

where D = diffusion constant,
α = the cathode area,
C_g = total molar concentration of gases,
l = length of the pin hole, and
F = Faraday constant.

Obviously $C/C_g << 1$, so that

$$\ln\left(\frac{1}{1 - C/C_g}\right) = \ln 1 - \ln\left(1 - \frac{C}{C_g}\right) = \frac{C}{C_g} + \left(\frac{C}{C_g}\right)^2 + \left(\frac{C}{C_g}\right)^3 \cdots$$

$$= \frac{C}{C_g}$$

giving

$$I_l = \frac{4FD\alpha C}{l} = KC \tag{9.2}$$

The design to limit the diffusion rate by a pin hole has been redesigned with a porous layer used for diffusion, as shown in Fig. 9.6(b) and (c). In Fig. 9.6(b), it is shown that a zirconia disc about 0.3 cm diameter is used as an electrolyte which is made as a film; platinum electrodes are bonded to this electrolyte. Both the cathode and the anode are coated with a porous layer of minerals, for example spinel, for limiting diffusion of oxygen. The anode is protected against toxicity and thermal shock. The design shows that the sensor has small size, simple structure, and low time constant. Further improvement of this design is shown in Fig. 9.6(c) where a cylindrical heater has been incorporated for raising the temperature range to 610–700°C; the outside of the sensor is exposed to the exhaust gas. The inside, on the other hand, is exposed to air and the design resembles the conventional zirconia cell. Figure 9.7(b) shows the characteristics of such a sensor with air-to-fuel ratio (ρ) as a parameter.

There is another variety of temperature sensors where a thin film platinum cathode, a zirconia electrolyte slice, and a platinum anode are all deposited on a porous Al_2O_3 substrate by sputtering and on the other side, a platinum is deposited as a heater. Controlling the substrate porosity during the design stage itself limits oxygen transport by the diffusion process. The *V–I* characteristics are similar to those of Fig. 9.7(b) but calibration is in oxygen to nitrogen ratio, $\rho_{O/N}$ in volume percentage. These are shown in Fig. 9.7(c).

9.2.5 Torque and Position Sensors

The power trains by which an automobile is run consists of the engine itself, the transmission link, differential gear, axle, and wheels. The torque generated in the engine is distributed to the wheels through power trains. A torque sensor for each component at appropriate position of the power train provides quick and precise response to power controls. Non-contact sensor is found to be suitable for practical adaptability, particularly in its miniature form. Such a sensor is now available and works on the magnetoresistive effect and which can be installed in main bearing and hence, mean output torque can be detected for multicylinder engine with a single sensor. The design is packaged approximately within 12 × 8 × 16 mm small package in which both exciting and pick-up cores of laminated silicon steel and permalloy respectively are housed wound with 200–400 turns of wire. The sensor area exposed to the shaft at a gap of 0.2 mm is about 12 × 3 mm.

Position sensing is another important aspect in automobiles for detecting shaft position, engine speed, throttle position, potentiometer position, and so on. Here also non-contact sensors receive preference. The semiconducting sensors such as Hall and magnetoresistive ones and the other varieties such as ferromagnetic, electromagnetic pick up, optical modular device, Wiegand wire, and capacitive modular device are also considered suitable. Of the electromagnetic pick-up variety, proximity sensors are most common because of high resolution and low cost offered by them although its output varies with changes in rotational speed. Integrated magnetic sensor using ferromagnetic resistive element is also being increasingly used. It has high sensitivity at low magnetic field and is comparatively less sensitive to temperature variations. Figure 9.8 diagrammatically represents such a sensor. The sensing unit is the NiCo thin film deposited by electron-beam evaporation method. The IC contains a signal processing unit with a differential amplifier and other processing units leading to digital output. Figure 9.9 shows its mounting arrangement.

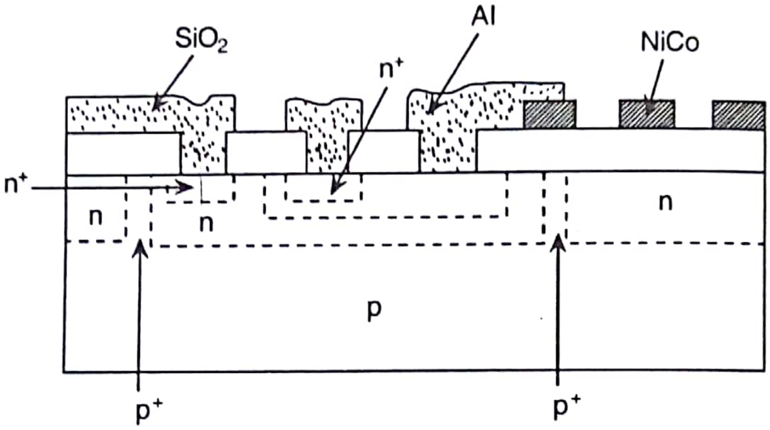


Fig. 9.8 Integrated magnetic sensor.

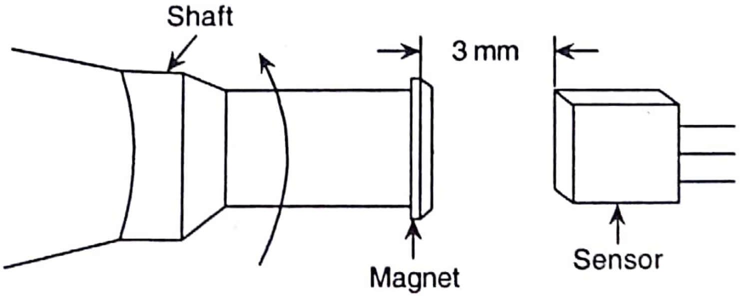


Fig. 9.9 Mounting of proximity sensor.

9.3 HOME APPLIANCE SENSORS

Home comfort depends to a great extent on the availability of automatic home appliances such as cleaner, refrigerator, washing machine, microwave ovens, and so forth. Semiconductor technology has grown fast over a last few decades leading to development of microminiaturized processors, circuits, and of course sensors therefore enhancing the capabilities of the home appliances in terms of automation, safety, and efficiency. Smart operation of the home appliances depends largely on appropriate sensors which have made the equipment more convenient, energy-economic, and safe.

Basically, the sensors are used in electronic control of the appliances and when coupled with microcomputers, all these requirements are almost fully met. Therefore, the basic requirements for the sensors for home appliances can now be revisited as they must have low cost, small size, light weight, better reliability, and easy handling.

The sensors used in home appliances are nothing new though the tendency is to miniaturize them retaining the reliability and efficiency. Sensors so used belong to all categories, that is, mechanical, chemical, magnetic, temperature, and radiation types—the last two types having major applications.

In the mechanical category, Silicon pressure sensors, metal diaphragms, and potentiometers are used in carpet cleaners, while bellows element types are being used in refrigerators. Potentiometers are also used in washing machines.

In the chemical type, humidity sensors have considerable applications in microwave ovens, clothes dryers, air conditioners, dehumidifiers, and also in VCR cameras, while gas sensors are used in ovens, and exhaust fans.

Magnetic sensors are widely used in electronic gadgets in entertainment. There are Hall sensors in VCR cameras, stereo sets and tape recorders. Magnetoresistive sensors are used in VCR cameras, and tape recorders.

In the temperature sensing category, thermistors are extensively used in ovens, cooking ranges, refrigerators, dishwashers, dryers, dehumidifiers, air-conditioners, exhaust fans, CD players, and stereoplayers. They are also used in electric carpet and blanket cleaners for temperature control. In contrast, PTC devices are used in cookers and electric cooking ranges; thermocouples are used in gas ovens; bimetallic elements find use in gas ovens and rice cookers while infrared sensors are employed in microwave ovens.

Radiation sensors, that is, photodiodes, and phototransistors are used as the major elements in refrigerators, washing machines, air-conditioners, TV sets, CD players, stereo players, and video disc players. Photoresistors such as CdS are used in TV sets while VCR camera uses charge control device (CCD) image sensors and MOS image sensors.

The pyroelectric IR sensor used in microwave ovens comes, in general, in TO package. It consists of a $LiTaO_3$ pyroelectric element on a silicon base plate and is irradiated through a silicon window. The sensor appears as shown in Fig. 9.10. Its responsivity is 200–300 V/W, NEP is less than 2 nW/Hz, response time is around 0.2 s, temperature range is –20°C to 100°C, and with silicon window the spectral response is 2–15 μm.

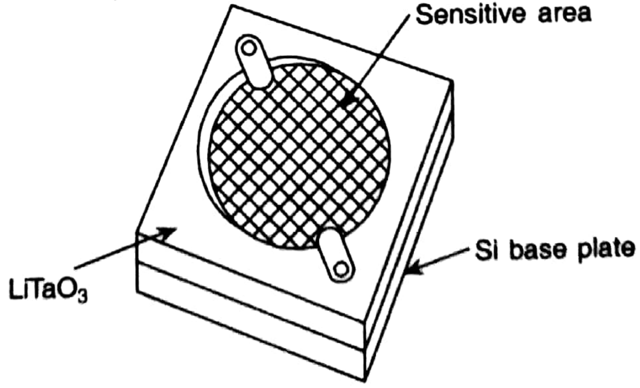


Fig. 9.10 Basic pyroelectric IR sensor.

In a microprocessor-controlled washing machine, water level is sensed using optics principles that comprise units like a light emitting diode (LED), a photodiode/phototransistor, and a light slit. The light slit is moved by the water level. This type of sensor is also used in rinsing chambers for the detection of degree of rinsing which provides information about the concentration of residual detergents. Here, two such systems are coupled—one for reference and the other for measuring. The outputs from the phototransistors of the two sets are compared for achieving a standard condition. The sensor is schematically shown in Fig. 9.11.

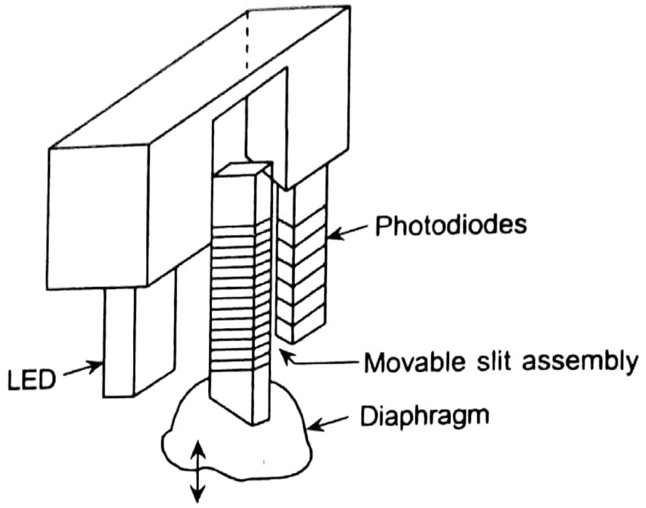


Fig. 9.11 Optical sensor for water level detection.

The sensor used for spin-dry system in washing machines is a PZT ceramic sensor. It is based on the principle that when water drips on to the surface of the sensor, voltage developed in the sensor becomes less with more impinging force of water on it. As the clothes are dried, voltage also increases. PZT, as discussed in an earlier chapter, is a solid solution of lead zirconate ($PbZrO_3$) and lead titanate ($PbTiO_3$)—it also belongs to pervoskite structures. Its piezoelectric property depends on Ti/Zr (T/Z) ratio. Most ceramic piezoelectric transducers belong to this group. Variations in properties have been obtained by partial replacement of Pb^{2+} by other divalent cations (such as Ba, Ca, and Sr) and Ti^{4+} and Zr^{4+} by tetravalent cations. Figure 9.12 gives the structure of a cubical pervoskite. The PZT ceramics are manufactured (see Chapter 8) in the same way as thermistors, from mixed oxide powders while sintering is done at 1200–1300°C at normal atmospheric pressure. Excess lead oxide (PbO) should be used, as a precaution, in a refractory enclosure during sintering as PbO has a high partial pressure. The grain-size and porosity of the ceramic are controlled by hot pressing which in turn controls the electrical property.

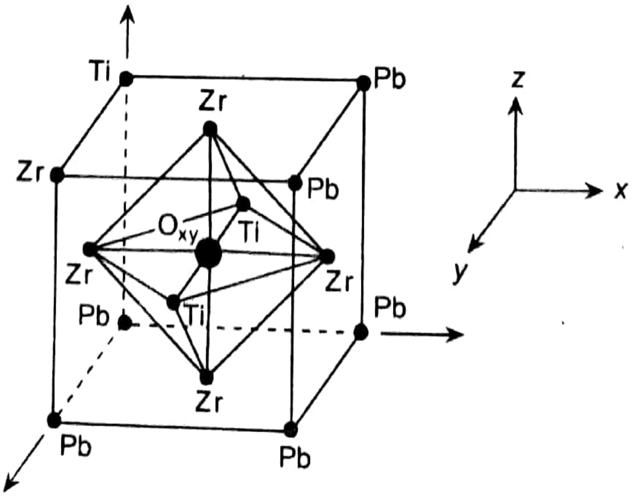


Fig. 9.12 The pervoskite cube.

Photodiode–LED assembly has also been used for frost detection in refrigerators. With frost, the light intensity received by the photodetector is reduced as in the case of a rinsing system. An alternative system for this use is piezocrystal oscillator and a PTC thermistor system. The crystal in an oscillator circuit vibrates at its natural frequency and with frost formation, its resonance frequency changes. PTC thermistor heats the crystal for making it frost free.

The video cassette recorders, for precise control of the servomotor that drives the playback and recording heads, use Hall and magnetoresistive sensors. For control of the cylinder head and its start and stop operations, photosensors are made use of. The video tape has to be protected from dew drops formed on the cylinder head of a VCR for which special humidity sensors have been developed as dew detectors. The detecting film is a hydrophilic acrylic polymer on which carbon particles are sprinkled.

Homes are moving towards being automated and for that alongwith the variety of sensors available, new sensors need be developed. Fortunately, the development is already underway. Three important categories in home automation are (i) house control, (ii) energy control/optimization, and (iii) home security. A block schematic of a home automation system with various sensors is shown in Fig. 9.13.

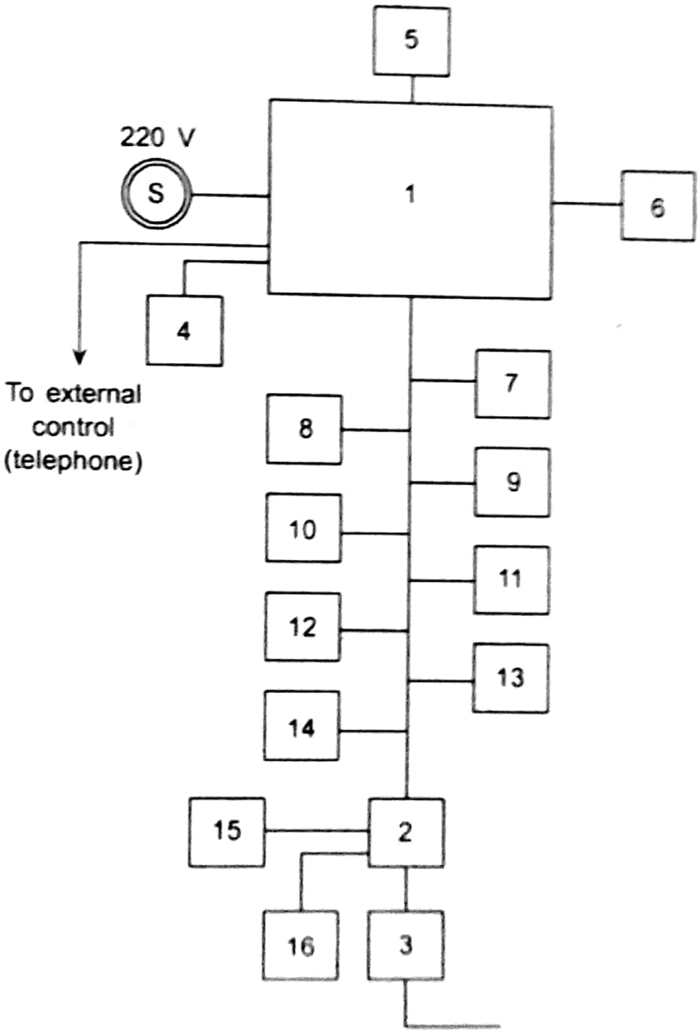


Fig. 9.13 Block schematic of a house automation system: (1) main controller, (2) and (3) secondary controllers, (4) air conditioners, (5) current sensor, (6) light control, (7) smoke control, (8) ventilation, (9) security, (10) gas, (11) thermal/electrical keys, (12) bath etc., (13) earthquake protection, (14) electrical keys (15) air adaptor, (16) light (secondary).

9.5 SENSORS FOR MANUFACTURING

Manufacturing, basically is a controlled process or system—the key to the control being the sensors used in automated manufacturing. Diagrammatic representation between sensors used in such manufacturing and various automation levels in a plant is shown in Fig. 9.19. Increased interconnection has been employed because of the invasion of the computer in manufacturing and special software based on process data available from signals delivered by the sensors at various stages and levels. The concept is known as computer-integrated manufacturing (CIM). Obviously, the prime task of the sensor in this is to run the automated production processes smoothly by compensating for disturbances, tolerances of workpieces, and environmental conditions as and when required. Quality control is also an important area where sensorial assistance is now largely sought. Intelligent sensors are gradually becoming essential as they can interface with each other through organized software processing of electronic signals.

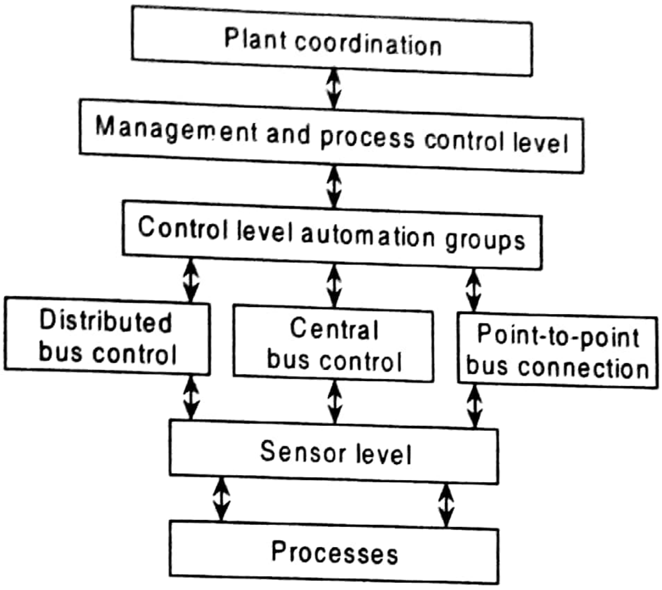


Fig. 9.19 Interaction diagram between sensors and levels of operations.

9.5.1 Sensors

Sensors used in production processes have to perform functions which are not conventional process control functions. The chart in Fig. 9.20 depicts the sensor functions briefly. They are not always as distinct as indicated in the diagram but may be performing in combination on demand. Most of the sensors used have been considered earlier but for robotic actions, specific sensors are applied in production engineering. Sensors used in such actions are discussed in this subsection with the actions for which they are meant for.

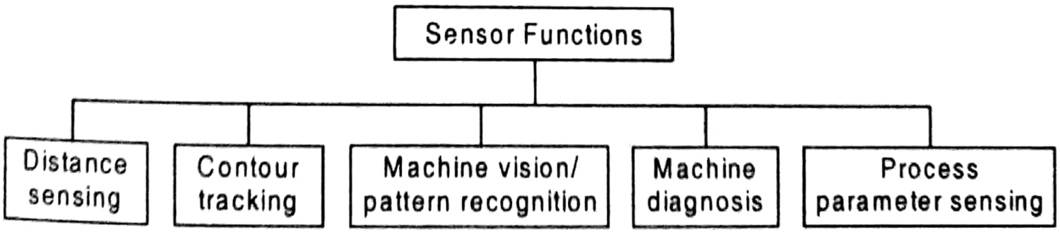


Fig. 9.20 Functional block diagram of the sensor.

Distance sensing: This can be done by (i) tactile sensors, (ii) electrical sensors such as inductive and capacitive, (iii) optical sensors using IR, UV, visible, and laser radiations, and (iv) acoustic sensors using ultrasonic principle.

Contour-tracking: This is a kind of scanning process and is performed by using (i) electrical sensors such as inductive and capacitive ones and (ii) optical sensors—mostly laser-based scanners.

Machine vision/Pattern recognition: Here also, tactile arrays and ultrasonic scanning serve some useful purpose. Besides optical systems with binary vision, grey level vision and stereovision are widely used.

Machine diagnosis: Well-known sensors are used to measure pressure, force, torque, speed (both linear and rotational), temperature, frequency, and a lot of other electrical parameters for obtaining indirect diagnostic data.

Process parameters: Parameters as mentioned in the preceding paragraphs are measured under different environmental conditions.

Distance sensing

During processing, the workpiece and the tool face the possibility of collision. Therefore, the distances between the two for various operations need be monitored. In some processing operations, the distance between the two should be maintained constant as in laser cutting.

Sensors for distance measurement are of two types, namely (i) contact type and (ii) non-contact type. The latter type is gaining ground because the sensors in this type are free from wear and tear.

Contact type distance sensors are common metrological instrument components such as pins, gauge blocks, dial gauges, and many others. Switches and buttons with potentiometric or inductive pick-up are also used. In the non-contact type distance sensors, inductive, capacitive, acoustic, and optical techniques are adopted. The inductive pick-ups are designed and named proximity sensors. Single coil and multi-coil designs are also common. Multi-coil designs allow to measure the distance in two coordinates. Example of an inductive proximity sensor used in distance measurement is schematically shown in Fig. 9.21. The middle coil, coil 2, is fed with ac of appropriate frequency allowing it to produce an ac magnetic field in its own proximity. Coil 1 and coil 3 symmetrically positioned with respect to coil 2 are also electrically energized with phase opposition with respect to supply of coil 2 in absence of any metallic body approaching the set up (coils 1 and 3). With any metallic body approaching, as shown, the magnetic field distributions to coils 1 and 3 change and a signal is generated which can be seen to be proportional to the distance and angle between the body and the coil (s).

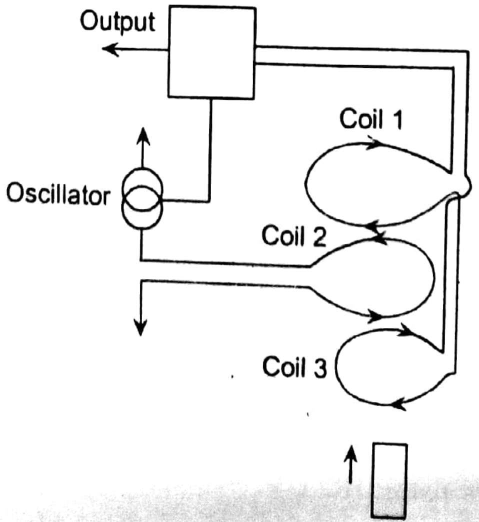


Fig. 9.21 Example of an inductive proximity sensor.

Ultrasonic sensors housed in robot gripper utilize the period between the reflected pulse (echo) and the original pulse sent by transmitter for distance measurement. Figure 9.22 shows this scheme. In this, h_r refers to the distance of reference plane and h_j is the height of the job attached to it. Two pulses, one from the plane and the other from the top of the job, are shown in Fig. 9.23. Focussed ultrasonic beam pulse after reflection undergoes change in the pulse height depending on the distance from where the reflection occurs. Figure 9.23 shows this change. For measurement of time, digital counting technique can be used.

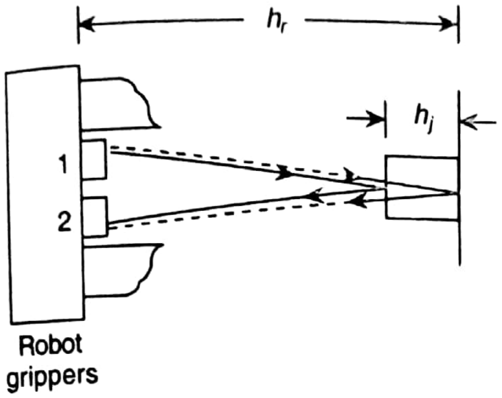


Fig. 9.22 Reflected pulse type distance sensor: (1) transmitter, (2) receiver.

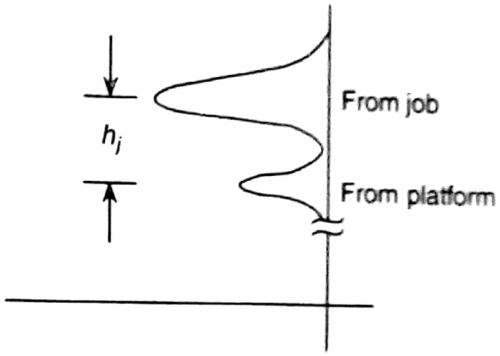


Fig. 9.23 Evaluation of the distance.

In optoelectronic technique of distance sensing, a laser beam is focussed on the approaching body and its reflection is then detected by a properly aligned photodiode after being converged by a lens. This can detect either (i) the intensity of light, or (ii) the angle of approach. The latter technique is known as *optical triangulation.* The detector system consists of about 1000 diodes arranged in an array which can help to enhance resolution. The scheme is shown in Fig. 9.24.

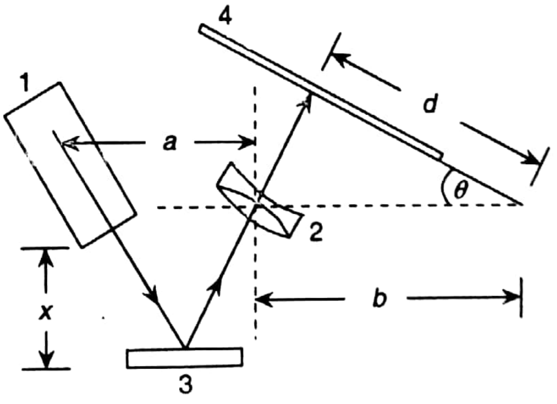


Fig. 9.24 Diode array sensor: 1. laser source, 2. focussing lens, 3. job, 4. diode array.

Obviously, distance d of the detecting diode is important here. From the figure,

$$x = \frac{ad\sin\theta}{b - d\cos\theta} \tag{9.9}$$

The angle θ, b, and a are fixed while x is a function of d. For the method to be successful, the approaching surface should have good polish for reflection. The technique can have a resolution of the order of tens of μm.

Triangulation principle is also used in contour tracking using preview laser scanner. The job profile is obtained by scanning it with a narrow laser beam and sensing the reflection from the job-piece with an array of diode detectors.

Machine vision is an intelligent sensing system. It involves scanning the object with a video camera whose output is converted to digital by an ADC for image processing, and feature computing and identification. Then comparison with model, called pattern recognition, is performed for the desired output. The system obviously requires a very sensitive viewing of the object with adequate resolution and discrimination. Images are obtained by (i) ultrasonic transducer scanner, (ii) X-ray scanner. However, for robotics, the tactile arrays which generate electrical signals from pressure sensing have been of special significance. The transducers so used may be conducting rubber type, the capacitance type, or piezoresistive type. The rubbing pressures produce change in resistance in the conducting rubber type transducers while capacitance changes in the second even by touching. In the piezoresistive transducer, the normal piezoresistive action takes place. The scanned output obtained from a multiplexer may be stored. Response time of each of such sensors is less than 1 ms per 100 units in an array. Figure 9.25 shows such a sensor system.

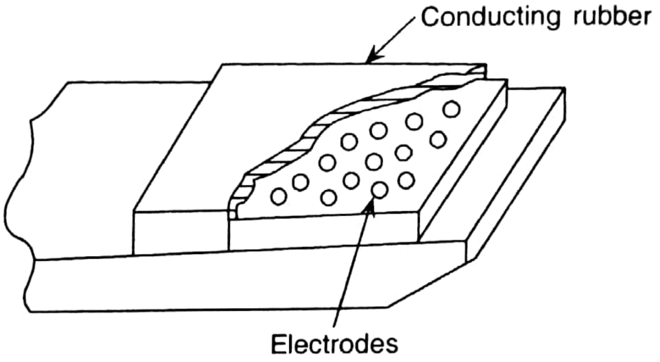


Fig. 9.25 Piezoresistive array sensor.

For machine diagnosis, the techniques applied are (i) process parameter monitoring, (ii) power consumption by the machine and edges of work-pieces (their condition), (iii) force and torque sensing, and (iv) change in the noise of the machine in operation. The first technique is not very straightforward. In force and torque sensing, strain gauges are extensively used. Noise sensing, however, has become an important technique with the advancement of device technology. Noise sensors are, in general, capacitive type. Often, ceramic pieces of PZT material consisting of lead zirconate and lead titanate are used for the purpose. One such scheme is shown in Fig. 9.26. Acoustic pressure is transmitted to ceramic beam with the conical diaphragm. Holes in the diaphragm are provided for equalizing average pressure. Back up plate prevents sag. Very small capacitive microphones have also been developed for sound intensity measurement. Their appropriate placement is a very important aspect. Figure 9.27 gives a schematic arrangement of the system where dynamic sound pressure p_d can be measured with static pressure p_s acting as 'buffer'.

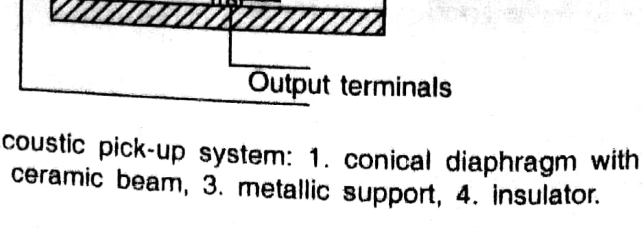


Fig. 9.26 PZT sensor acoustic pick-up system: 1. conical diaphragm with back-up plate, 2. PZT ceramic beam, 3. metallic support, 4. insulator.

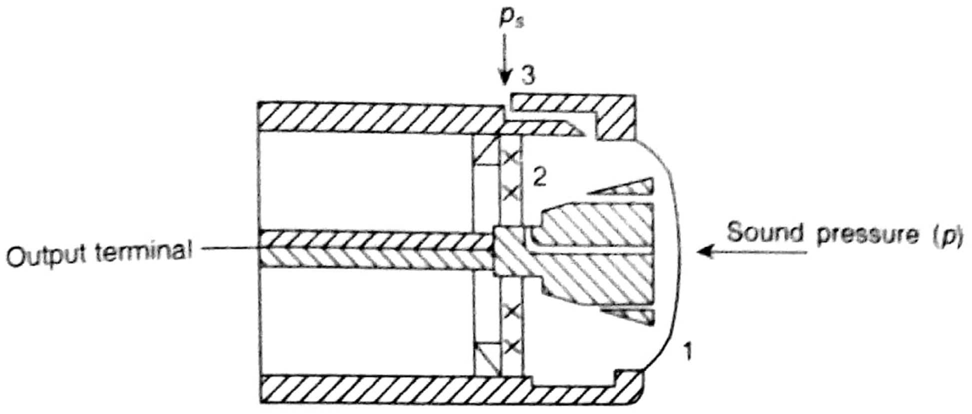


Fig. 9.27 Acoustic pressure sensor for static and dynamic pressure sensing: 1. diaphragm, 2. insulator, 3. air-leak.

9.6 MEDICAL DIAGNOSTIC SENSORS

With the advent of sensor technology involving different materials, processing, and size and shape, clinical studies are gradually being replaced by instrumental studies in medical science with the sensors serving as the interface systems between the instrument hardware and the biological systems. This requires that the sensors used have very stringent specifications.

The most important consideration is whether the sensor is invasive or noninvasive. Gradations have been made here, for example, in invasive type minimally invasive category has been defined where surgical implantation is not needed. Special sensors may be placed remote from the body.

When sensors are to be implanted and/or made indwelling type, they should have minimal effect on the biological system. This requires choice of materials for the sensors which is to be nontoxic and system compatible. It is to be remembered that often the sensor is in a package, so compatibility means that the packaging should also match the tissues in contact such that irritation and inflammation do not develop and measurement is not affected by any means. Noninvasive biosensing electrodes are often used on the skin surface leading to manifestation of allergy from the adhesive tapes for some patients. This is found to change with stretch conditions and is considered to be a mechanical mismatch.

A very important consideration for indwelling and implanted sensors packaged generally from ploymers is that the internal aqueous body environment containing chlorides and enzymes must not affect the sensor packages and the sterility of the sensors must persist.

9.6.1 Sensors

Conventional sensors and microsensors are being adopted more and more now in biomedical activities. Many of these are based on (i) radiation—electromagnetic and acoustic, (ii) force and pressure, (iii) temperature, (iv) electromagnetic variables, (v) chemical and electrochemical principles, (vi) variables related to blood flow, and (vii) kinematic and geometric etc.

Radiation

In the electromagnetic range of radiation, infrared radiation detection of human body by scanning is now quite common diagnostic technique for low-deep circulation abnormalities. These abnormalities produce a thermal image different from the normal case. This technique, known as *thermography*, now uses sensors such as photodetectors, LDR's and bolometers.

Photodiode detectors are also used in phototherapy which uses visible light to convert bilirubin in a new-born baby into naturally excreting materials.

In the shorter wave techniques, X-ray methods are very common and useful. In recent years, conventional ionization detectors or Geiger–Muller counters are replaced by radiation-to-electrical signal sensors, specifically Si-based semiconductor sensors, as these can easily be adopted in tomography, digital subtraction radiography, low intensity fluoroscopy, and so on. Scintillation detectors of special designs are also used for this purpose.

Ultrasonic sensors, that is, piezoelectric sensors are now quite effectively used in measurement of blood pressure, heartbeat of foetus, and grown up people. The conventional carbon microphone in stethoscope is now being replaced with new sensors that convert sound into electrical output. These are used for sensing breathing sound, gastrointestinal sound, and so forth.

Biomechanics

It is an area where sensors for measurement of force and pressure are required. Force sensors are basically load cells which are properly adopted to derive data from models that may provide informations regarding material properties of bone, skin, muscle, tendon, and the like. In direct measurement of human specimens, these sensors provide data for various activities like movements in sports, walking, and others.

Tactile sensors consisting of arrays of force sensors are mostly used in robotics. Thin film multi-element force sensors are also being used for measuring force in patients having difficulty in gripping.

Temperature

Temperature in medical diagnosis is now measured by electronic thermometers using infrared sensors or non-invasive skin-bound sensors which utilize resistive elements such as bolometers or pyroelectric devices.

Electromagnetic variables

In the recent past, electromagnetic mapping of the human body has been done quite extensively from which a lot of information can be extracted. In such mapping, resistance metal strips are used as electrodes. Basically, chemical gradients and membrane potentials are converted into electrical voltage signals by these electrodes. The strip is coupled to the body by an electrolyte layer. Silver–silver chloride form a good combination although toxic effect is not precluded under certain body conditions.

Studies of heart, muscle, brain, stomach, and position of eye are made possible by measuring bioelectric potentials using electrode systems which can be implanted in the tissue or tied to it surgically. These results are obtained as electrocardiograms, electromyograms, electroencephalograms, nerve action potential diagrams, electrogashograms, electrooptograms and so on. Measurement of resistance of tissues by measuring the current with a constant voltage applied between a pair of electrodes has also been used as a diagnostic tool particularly for diagnosis of blood volume in tissue (plethysmographic) or other fluid volume for monitoring breathing and more.

Chemical and electrochemical sensors

In medical/biomedical applications, these sensors are easily adopted. For example, enzyme electrodes are used for biochemical substrates, immunosensors for immunological reactions, polarography for body electrolytes and blood gases, and so on. Electrochemical sensors are more common. One such sensor is the Clark cell which consists of two electrodes for amperometric measurement where an oxygen permeable membrane is used. It is used for the measurement of partial pressure of oxygen in body fluids as well as tissues. Oxygen diffusing through the membrane is reduced following the reaction

$$O_2 + 2H_2O + 4e^- \Leftrightarrow 4OH^- \tag{9.10}$$

Enzyme electrodes have received more attention in recent years. The principle is to immobilize the enzyme in the sensor. Enzyme is a complex of proteins, it must be immobilized retaining its biochemical activity and kept in that condition for quite some time. Basically, a particular substrate (glucose, for example) enters a biochemical reaction either to consume or generate some substance which is detected by a chemical sensor (for example, membrane sensor).

Variables related to blood flow

Blood pressure and blood flow are two very important biological parameters which need be accurately determined for different parts of the body (for flow specifically). Blood pressure is determined by the conventional technique but in recent years, non-invasive electronic techniques are being used. Microsensor technology has been used to develop miniature pressure sensors which in probe form are packaged and introduced into the circulatory system.

Comparatively, blood flow measurement is more of an invasive method and microsensors have been developed which can be used for the purpose. Electromagnetic flow meters and ultrasonic Doppler methods are also being used for the purpose. In the ultrasonic Doppler method, the ultrasound is reflected off the cellular component of the blood; by measuring the Doppler shift in frequency of this reflected sound, both velocity and direction can be ascertained.

Kinematic and geometric

Sensors of linear and angular displacement, area, and volume related to biological systems have also been developed. Sensors are based on special type of strain gauges and are used for various detecting parameters such as position of joints, extra growth, bladder area, tumour size, and so forth.

Kinematic sensors are used to study movements of limbs and gait. Basically, accelerometers of very small sizes are attached to the limbs and the signals obtained therefrom are integrated for velocity and displacement and the computer is used for recreating gait for the patient.

9.7 SENSORS FOR ENVIRONMENTAL MONITORING

Entire living world is now at risk on counts of health and normal survivality due to hazards arising out of biological, chemical, and radiation effects on the environment which not only work locally but are also likely to affect around the globe through transportation. These hazards are thus, critical/serious environmental problems and to assess the extent to which they can affect human and other living entities, measurement of certain selective parameters are needed. Environmental monitoring is not possible to be done in a simple way by measuring temperature of a hot body—in fact, a few steps are involved in the process of monitoring. As environment is affected by pollution, the pollutants are to be identified. The quantity/concentration of pollutants in specific collected 'sample' need be determined.

As said, hazard occurring at a place is not endemic to that place alone and it is spread. The three main ways that cause this spread are (i) atmosphere, (ii) surface water, and (iii) ground water. The manner in which these hazards affect human/living being can be given by simple chart as shown in Fig. 9.28.

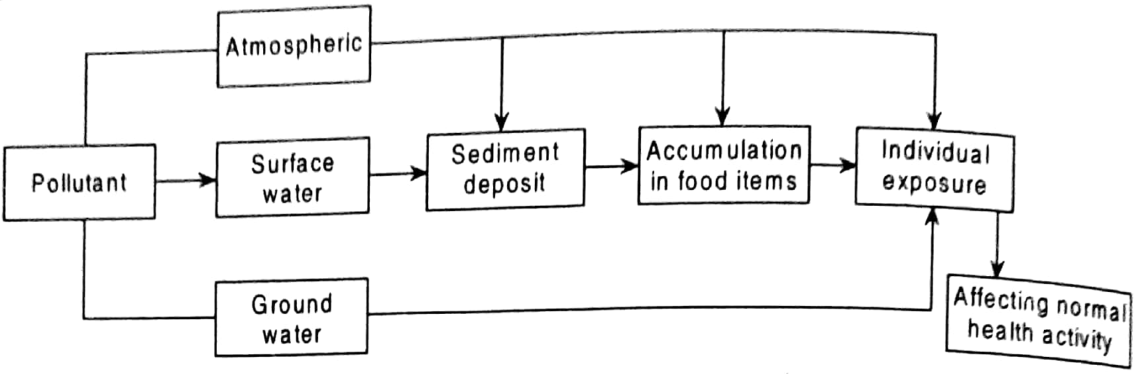


Fig. 9.28 The eco-hazard.

Monitoring the environment pollution again involves three steps, namely the (i) collection of sample representative enough of the environmental pollution content, (ii) pre-treatment of the sample using extraction, separation and so on, and (iii) analysis for identification and quantification of analytic pollutant in sample and expressing it in proper level of concentration.

Sampling (collection and preparation of a sample) is the major player in the three-stage process. Depending on the time and situation, the sampling techniques vary. Similarly, analysis techniques differ depending on the type of sample. The sensors/instrumentation in the analyzers are nothing new in general but their matching with the pollutant and source characteristics are important.

9.7.1 Pollution Hazards

Biological effects of the hazards of pollution on humans are manifested in the excreted wastes in general that may be considered for analysis. Of these, common ones are urine, stool, exhaled breath, sputum and so on. However, blood is an important medium and often nails, hair and fat too get affected. If people are exposed to chemical hazards, by analyzing the above samples, toxic levels can be found and compared to standard maximum that can be allowed. For example, maximum level for lead in blood is 0.5 mg/l and maximum concentration of creatinine in urine is 0.15 mg/g. The analysis is still done by standard chemical techniques or in some cases, where samples are properly available, by spectroscopic techniques. Selective sensors are not yet available widely but microsensors and chemical sensors using silicon and polymers are recently being experimented with.

As has been mentioned already, hazards evolve from various sources like (i) radiation—both ionizing and nonionizing, (ii) biological, (iii) chemical. Their monitoring is the first requirement and then control becomes mandatory. Ionizing radiation includes α-particles, β-particles, X-rays, neutrons, gamma-rays which are capable of biological mutation. Nonionizing radiation includes IR, UV, radiowave and microwave, and extremely low frequency (ELF) (within 300 Hz) radiation. Exposure of these radiations over long periods is also hazardous while IR radiation is known to cause injury to ophthalmic organs such as cornea, retina ($\lambda < 320$ nm), and to a certain extent skin ($760 \text{ nm} \le \lambda \le 1400$ nm). UV radiation is known to damage skin (cancerous), sunburn (erythema) and occular organs. Radio and microwave exposure may lead to cardiovascular nervous, and haematopoitic functions. ELF causes disharmony in reproductive system including cancer.

Biological hazards cause physiological and psychological diseases which are well-known by now. Chemical agents affect water, air, and soil leading to long-term biological afflictions.

9.7.2 Sensing Environmental Pollution

For ionizing radiation, different sensors are used depending on the characteristics of ionization. For low penetration, α-particles (He^{++}) ionization and proportional counters are recommended, scintillation detectors using ZnS as scintillators are also used. Semiconductor detectors have also begun to be used lately.

For β-particles (e^+, e^-), which are slightly more penetrating than α-particles, Geiger counters such as proportional counters. Scintillation counters with solid and liquid scintillators are used besides semiconductor detectors.

γ-rays and X-rays are even more penetrating radiations. These are sensed by NaI and/or $Bi_4Ge_3O_{12}$ scintillators. On the higher wavelength sides, sometimes Geiger–Muller and proportional counters are used. Thermoluminescent and semiconductor detectors are also being used in increased numbers. Li-loaded thermoluminescent detectors and p-n junction diodes are used for neutron radiation detectors. Gas-filled detectors using ^3He and BF_3 are also used for detecting X- and γ-rays.

For sensing non-ionizing radiations thermopiles, bolometers, and diodes are used. Thermopiles are used for microwave, the bolometers are used for radio-frequency, and the diodes are used for ELF, whereas for detecting IR radiation bolometers, photoconductors, Schottky barrier diodes and pyroelectric ($BaTiO_3$) detectors are extensively used. For visible and ultraviolet radiations, photovoltaic cells, photodiodes, thermocouples/thermopiles and Schottky diodes are used.

In semiconductor detectors, it is the charge transport property of the materials such as Ge, Ge(Li), Si, and Si(Li) that is being utilized. These sensors can be packaged and made handy for site measurement as portable units. Over the recent years, new scintillation materials have also been used for the purpose. As such, fluorescent emissions from solid organic and inorganic phosphors are also used. Photodiode scintillators and planar silicon detectors have also appeared in the arena. Cryogenic bolometers working in pulse mode are known to provide high resolution.

While biological polluting agents are very difficult to be sensed and quantify because of the 'omnipresence' of microorganisms in the environment, special 'culture' and microscopic studies have now become common. Counting 'colonies' after culture in a prescribed medium is a traditional practice though time consuming. In recent times, immunoassays have been used with success for microbiological and clinical analysis. Immunoassays can be performed by microsensor implementation.

9.7.3 Ecological Studies of Air

Air pollutants form a major group of identifiable and quantifiable 'parameters'. These include CO, CO_2, Ci, SO_2, NO, NO_2, NO_x (in general), H_2S, hydrides, NH_3, mercury vapour, O_3 and many more. Besides, suspended particles of duct origin or air-effluents such as carbon particles also harm ecology.

Sensing techniques vary with pollutants, their amount and state of occurrence. In many cases, reaction with reagents suggests analysis processes which are purely chemical techniques. Some of these techniques have been adopted in instrumental form. For example, many electroactive pollutants such as NO_x, H_2S, HCOH, SO_2, CO and so on are detected by amperometric or potentiometric methods when appropriate sensing cells are developed with electrode catalysts and membrane permeability. This technique can measure the presence of reactants upto concentration of a hundred ppb.

Flame ionization and photoionization are commonly used for detection of organic samples. Burning the sample in flame or photoionization with UV rays produces ions which are stripped in the form of current. In gas, chromatographic system flame ionization is quite extensively used for better selectivity. Photoionization produces high sensitivity.

Metal oxide semiconductors like SnO_x or metals in filament form such as platinum produce current when CO, H_2S, or hydrocarbons are oxidized on them. Selectivity, however, is not good with this method, although sensitivity is quite high (upto 100 ppm).

Spectrophotometry is extensively used in measurement and detection of pollutants in air and water. Absorption spectrometry is more of use than emission type. Absorption is proportional to gas concentration and the wavelength ranges of the spectral medium change with materials. Thus, for NO_2, visible range is quite common. For SO_2, O_3, and Hg vapour, UV radiation is recommended while IR radiation is used for organic and dipolar inorganic samples.

Aerosol photometry is another sensing mechanism used for particulate pollutants. Forward scattering that causes attenuation of incident radiation is used for the purpose. Particle size is important for detection, as also is the presence of particles in $\mu g/m^3$ which should not exceed 100–150 $\mu g/m^3$.

Elemental analysis including emission spectroscopy for metals appears to be a better choice. Of the various types of such techniques, inductively coupled plasma atomic emission type spectroscopy is more in use though graphite furnace atomic absorption spectroscopy is also sometimes used for monitoring ecological pollutants.

Table 1.1 Physical and chemical transduction principles

Output *Input*	*Mechanical*	*Thermal*	*Electrical*	*Magnetic*	*Radiant*	*Chemical*
Mechanical	Mechanical including acoustic effects. eg: diaphragm.	Friction effects, cooling effects. eg: thermal flowmeter.	Piezoelectricity, piezoresistivity, resistive, inductive, and capacitive changes.	Piezomagnetic effects.	Photoelasticity, interferometry, Doppler effect.	—
Thermal	Thermal expansion. eg: expansion thermometry.	—	Seebeck effect, pyroelectricity, thermoresistance. eg: Johnson noise.	—	Thermo-optical effects. eg: liquid crystals, thermo-radiant emission.	Thermal dissociation, thermally induced reaction.
Electrical	Electrokinetic effects. eg: inverse piezoelectricity.	Peltier effect, Joule heating.	Charge controlled devices, Langmuir probe.	Biot-Savart's electromagnetic law.	Electroluminescence, Kerr effect.	Electrolysis, electrically induced reaction. eg: electromigration.
Magnetic	Magnetostriction, magnetometers.	Magnetothermal effects (Righi-Leduc effect).	Ettinghaussen-Nernst effect, Galvanomagnetic effect. eg: Hall effect, magnetoresistance.	—	Magneto-optical effects. eg: Faraday effect, Cotton-Mouton effect.	—
Radiant	Radiation pressure.	Bolometer, thermopile.	Photoelectric effects. eg: photovoltaic cell, LDR's.	—	Photorefractivity, photon induced light emission.	Photodissociation, photosynthesis.
Chemical	Photoacoustic effect, hygrometry.	Thermal conductivity cell, calorimetry.	Conductimetry, potentiometry, voltametry, flame-ionization, chem FET.	Nuclear magnetic resonance.	Spectroscopy. eg: emission and absorption types, Chemiluminescence.	—

Table 1.2 Energy types and corresponding measurands

Energy	*Measurands*
Mechanical	Length, area, volume, force, pressure, acceleration, torque, mass flow, acoustic intensity, and so on.
Thermal	Temperature, heat flow, entropy, state of matter.
Electrical	Charge, current, voltage, resistance, inductance, capacitance, dielectric constant, polarization, frequency, electric field, dipole moment, and so on.
Magnetic	Field intensity, flux density, permeability, magnetic moment, and so forth.
Radiant	Intensity, phase, refractive index, reflectance, transmittance, absorbance, wavelength, polarization, and so on.
Chemical	Concentration, composition, oxidation/reduction potential, reaction rate, pH, and the like.

Table 1.3 Property based classification

	Property				
	Flow	*Level*	*Temperature*	*Pressure*	*Proximity and displacement*
Technology	Differential pressure, positional displacement, vortex, thermal mass, electromagnetic, Coriolis, ultrasonic, anemometer, open channel.	Mechanical, magnetic, differential pressure, thermal displacement, vibrating rod, magnetostrictive, ultrasonic, radio frequency, capacitance type, microwave/radar, nuclear.	Filled-in systems, RTDs, thermistors, IC, thermocouples, inductively coupled, radiation (IR).	Elastic, liquid-based manometers, inductive/LVDT, piezoelectric, electronic, fibre optic, MEMS, vacuum.	Potentiometric, inductive/LVDT, capacitive, magnetic, photoelectric, magnetostrictive, ultrasonic.

Table 1.3 *(cont.)*

	Property				
	Acceleration	*Image*	*Gas and chemical*	*Biosensors*	*Others*
Technology	Accelerometers, gyroscopes.	CMOS, CCDs (charge coupled devices).	Chemical bead, electrochemical, thermal conductance, paramagnetic, ionization, infrared, semiconductor.	Electrochemical, light-addressable potentiometric (LAP), surface plasmon resonance (SPR), resonant mirror	Mass, force, load, humidity, moisture, viscosity.

Table 1.4 Emerging sensor technologies

	Sensors			
	Image sensors	*Motion detectors*	*Biosensors*	*Accelerometers*
	Technology: CMOS-based	*Technology: IR, ultrasonic, microwave/radar*	*Technology: electrochemical*	*Technology: MEMS-based*
Applications	Traffic and security surveillance, blind-spot detection as autosensors (robots etc.), video conferencing, consumer electronics, biometrics, PC imaging	Obstruction detection (robots, auto), security detection (intrusion), toilet activation, kiosks videograms and simulations, light activation	Water testing, food testing (contamination detection), medical care device, biological warfare agent detection	Vehicle dynamic system (auto), patient monitoring (including pace makers etc.)

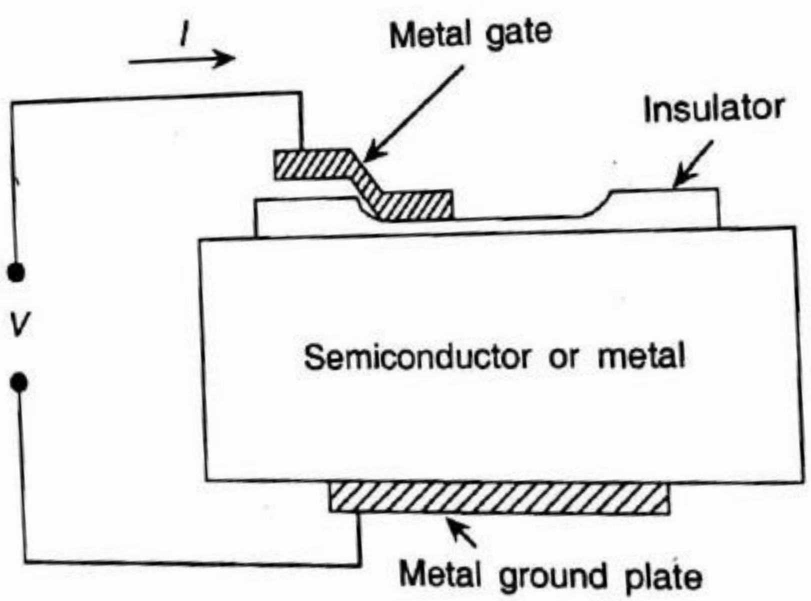
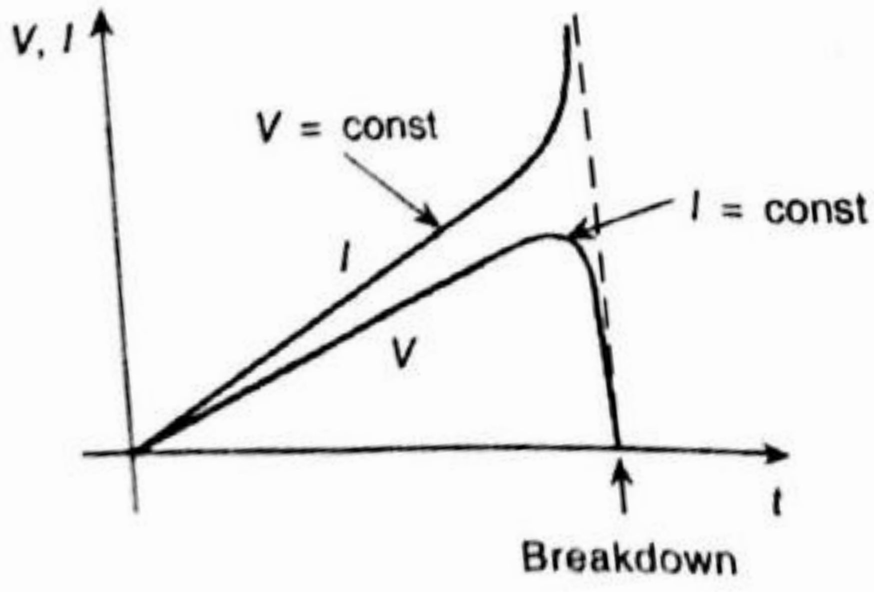
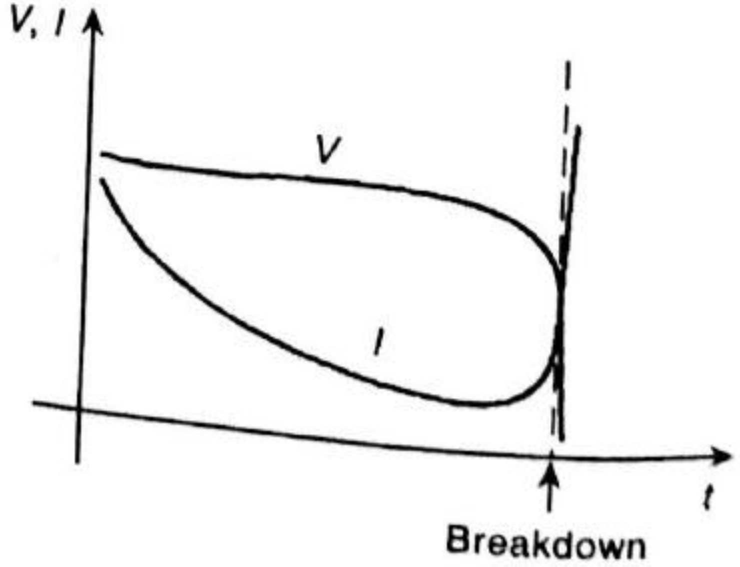
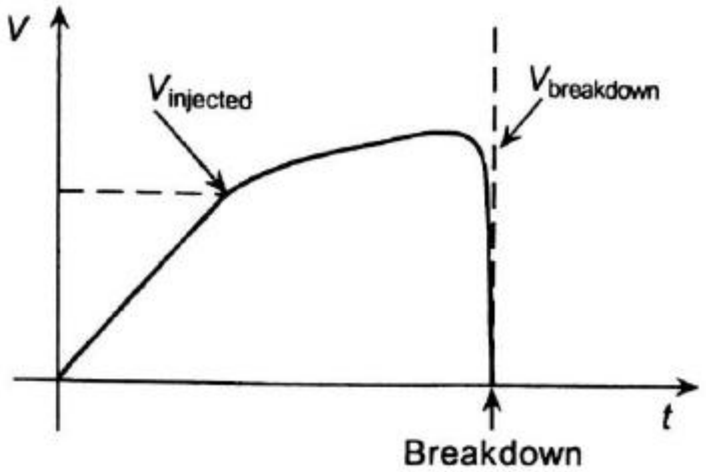


Fig. 1.4 Structure of a metal oxide semiconductor.



(a)





$$R(x) = 1 - F(x) = \int_{x} f(t)\,dt$$

$$= \frac{\text{No. of 'sound' components at instant } x}{\text{Total no. of components at } x = 0}$$

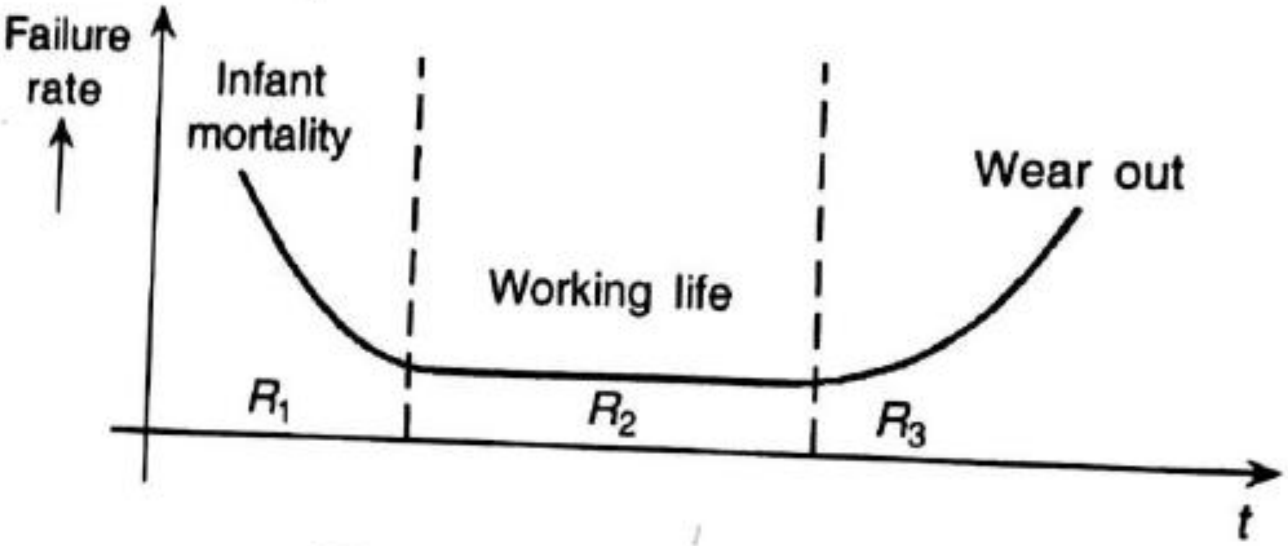


Fig. 1.6 The bath-tub curve.

$$\Delta V = \frac{V}{n}$$

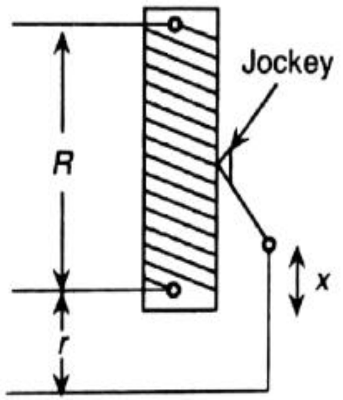


Fig. 2.1 Wire-wound potentiometer.

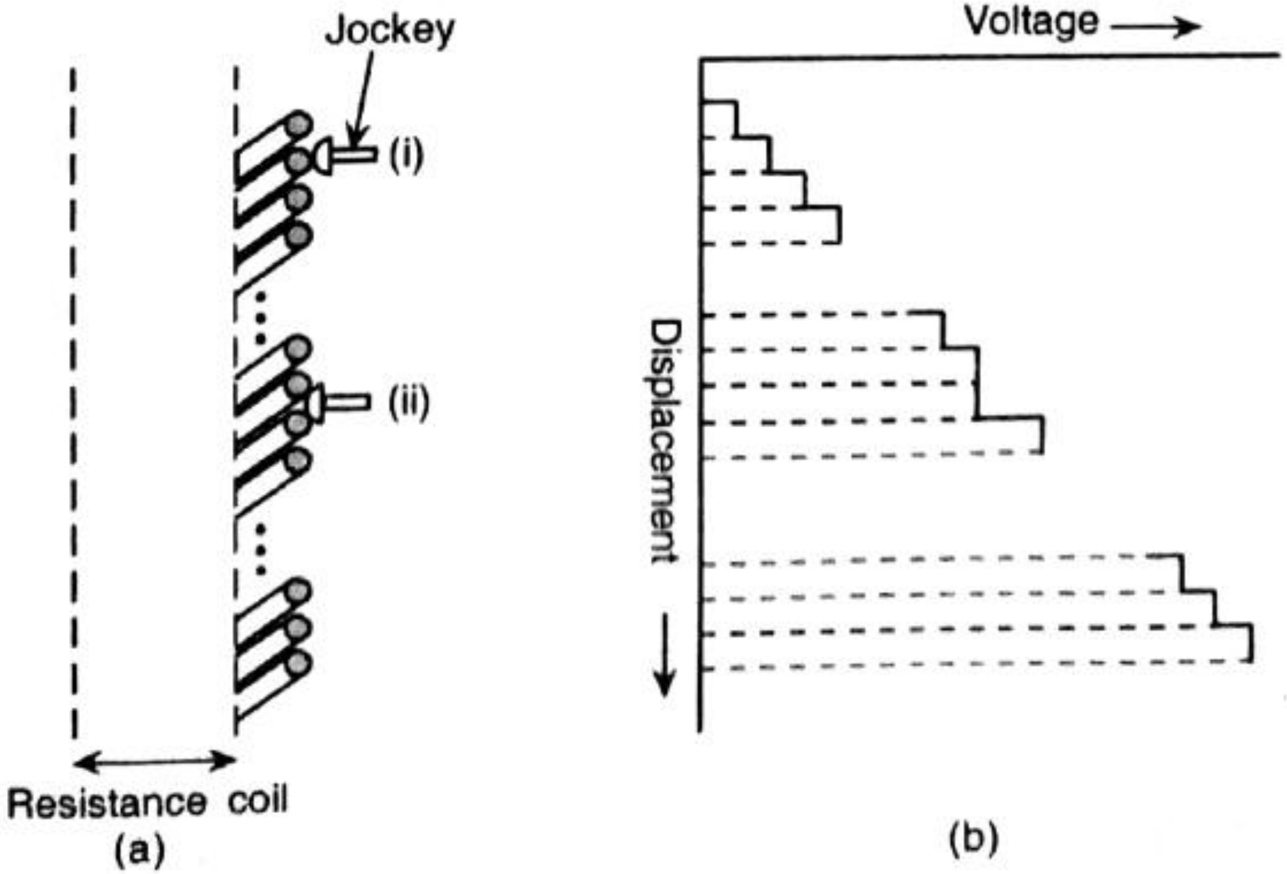


Fig. 2.2 (a) Jockey contact schemes: (i) single wire contact, (ii) two-wire shorting, (b) corresponding voltage levels.

Table 2.1 Materials for wire and jockey

	Wire	*Jockey*
1.	Copper–nickel alloys like constantan (Cu 55–Ni 45), advance, ferry alloy, eureka and so on.	(a) Gold, gold–silver, (b) Ni 40–Ag 60, 10% graphite in Cu or 2–5% graphite in Ag.
2.	Nickel–chromium alloys such as nichrome (Ni 80, Cr 20), Karma and so forth.	Group (b) above, and/or Rh or Rh-plated metals, gold–silver, osmium–iridium, Cu 40–Pd, ruthenium 10–Pt, Gold.
3.	Silver–palladium alloys	Pt–iridium, Au 10–Cu 13–Ag 30–Pd 47.
4.	Platinum–iridium	Pt–iridium

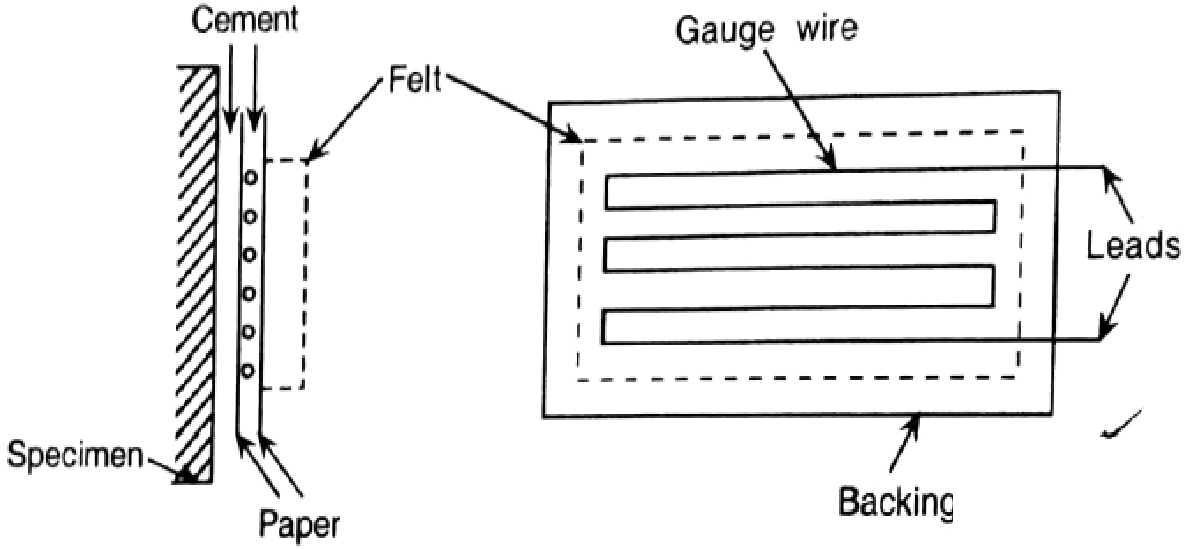


Fig. 2.9 Grid type gauge.

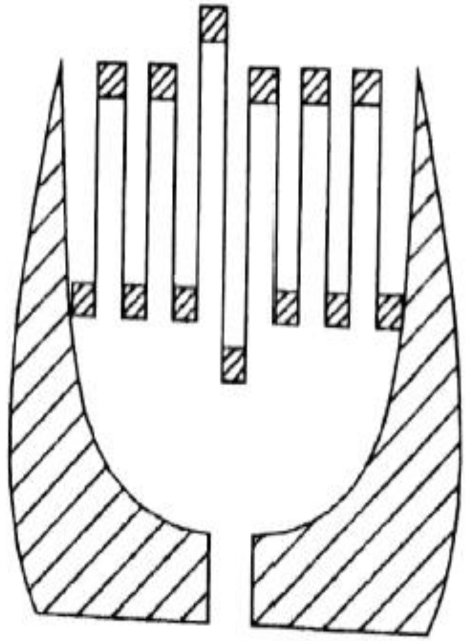


Fig. 2.10 Grid structure gauge with reduced transverse strain sensitivity.

Table 2.2 Strain gauge materials and their properties

Material	*Approx. nominal composition (%)*	*Gauge factor*	*Thermal coefficient of resistance (%/°C)*	*Nominal resistivity ($\mu\Omega$ cm)*
Constantan, Advance, Ferry	Ni 45, Cu 55	2.1–2.2	2×10^{-3}	0.45–0.48
Karma	Ni 74, Cr 20, Fe 3 Cu 3	2.1	2×10^{-3}	1.25
Nichrome V	Ni 80, Cr 20	2.2–2.6	10^{-2}	1.00
Isoelastic	Ni 36, Cr 8, Fe 52, Mn–Si–Mo 4	3.5–3.6	1.75×10^{-2}	1.05
Pt–W alloy	Pt 92, W 8	3.6–4.5	2.4×10^{-2}	0.62
Nickel	Ni 100	12	0.68	0.65
Manganin	Cu 84, Mn 12, Ni 4	0.3–0.48	2×10^{-3}	—
Platinum	Pt 100	4.8	0.4	0.1

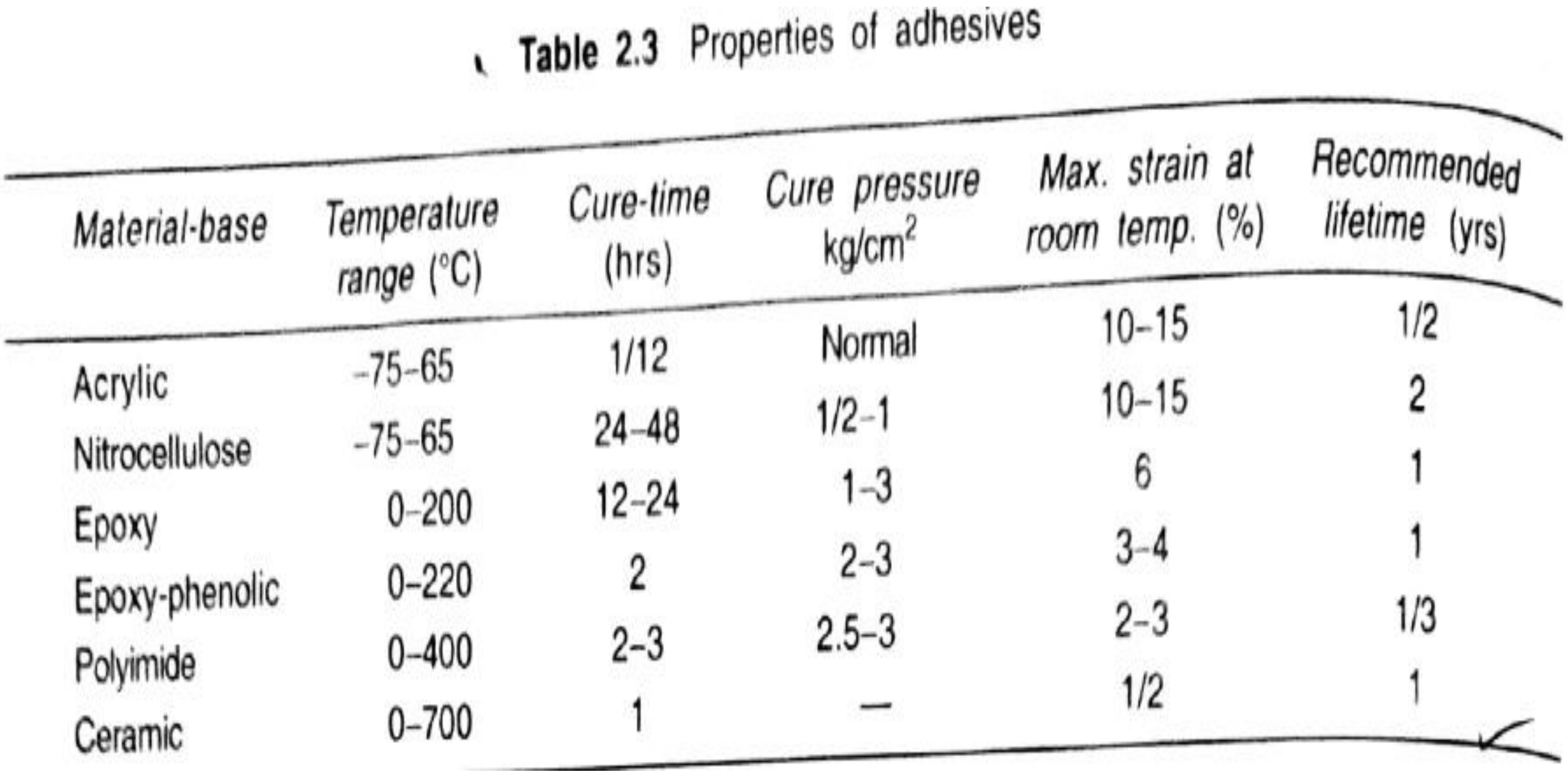


Table 2.3 Properties of adhesives

Material-base	*Temperature range (°C)*	*Cure-time (hrs)*	*Cure pressure kg/cm^2*	*Max. strain at room temp. (%)*	*Recommended lifetime (yrs)*
Acrylic	–75–65	1/12	Normal	10–15	1/2
Nitrocellulose	–75–65	24–48	1/2–1	10–15	2
Epoxy	0–200	12–24	1–3	6	1
Epoxy-phenolic	0–220	2	2–3	3–4	1
Polyimide	0–400	2–3	2.5–3	2–3	1/3
Ceramic	0–700	1	—	1/2	1

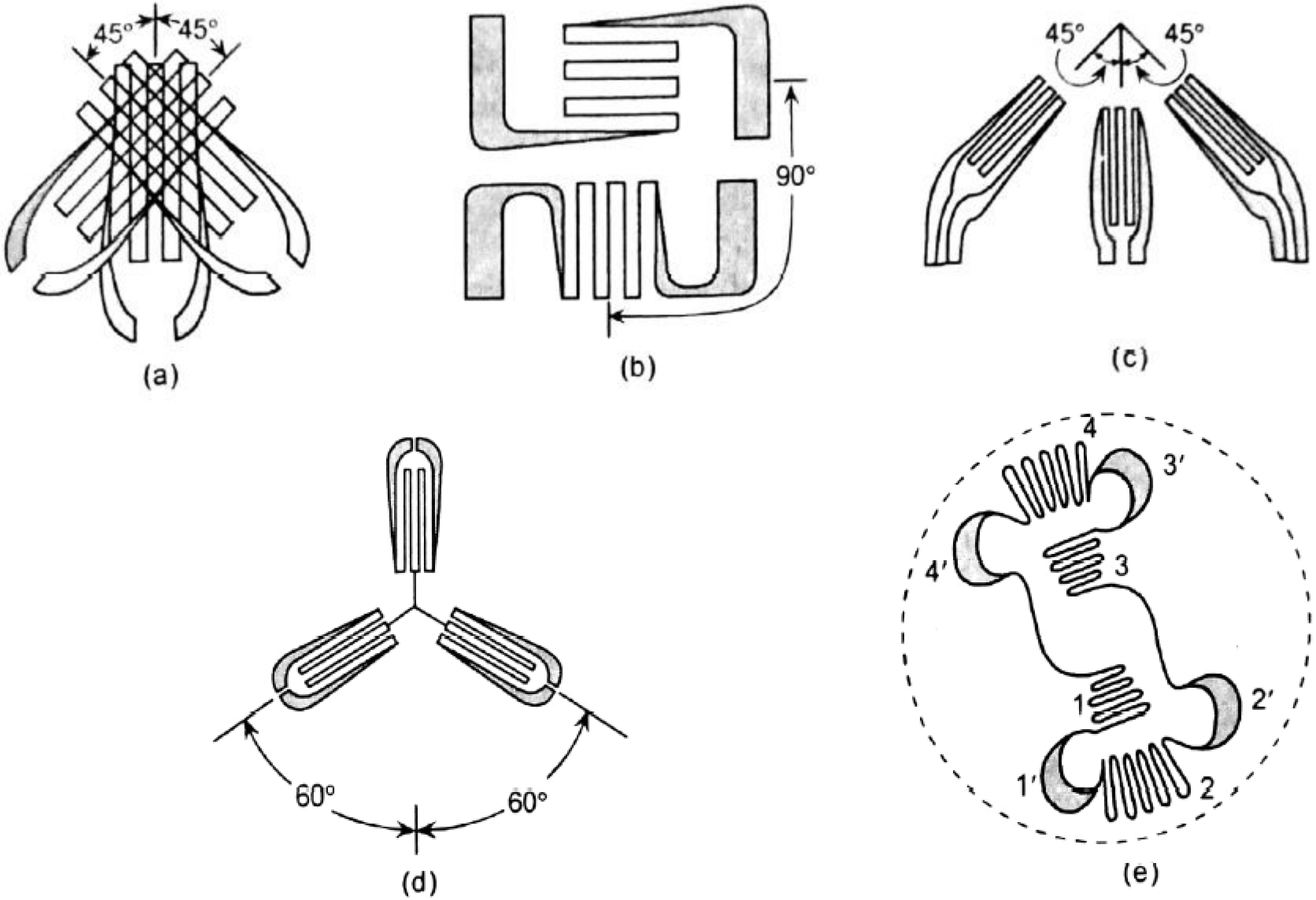


Fig. 2.11 Rosetted strain gauges: (a) three-element stacked type, (b) two-element right-angled, (c) three elements at 45° to each other, (d) three elements at 120° to each other, (e) gauge pattern on a diaphragm.

- https://www.youtube.com/watch?v=XO3PAx5ZpI0
- https://www.youtube.com/watch?v=o0LLV5GP6Ow

BASIC OF THERMAL & MAGNETIC SENSORS

UNIT-3

PRIMARY AND SECONDARY SENSORS(THERMAL)

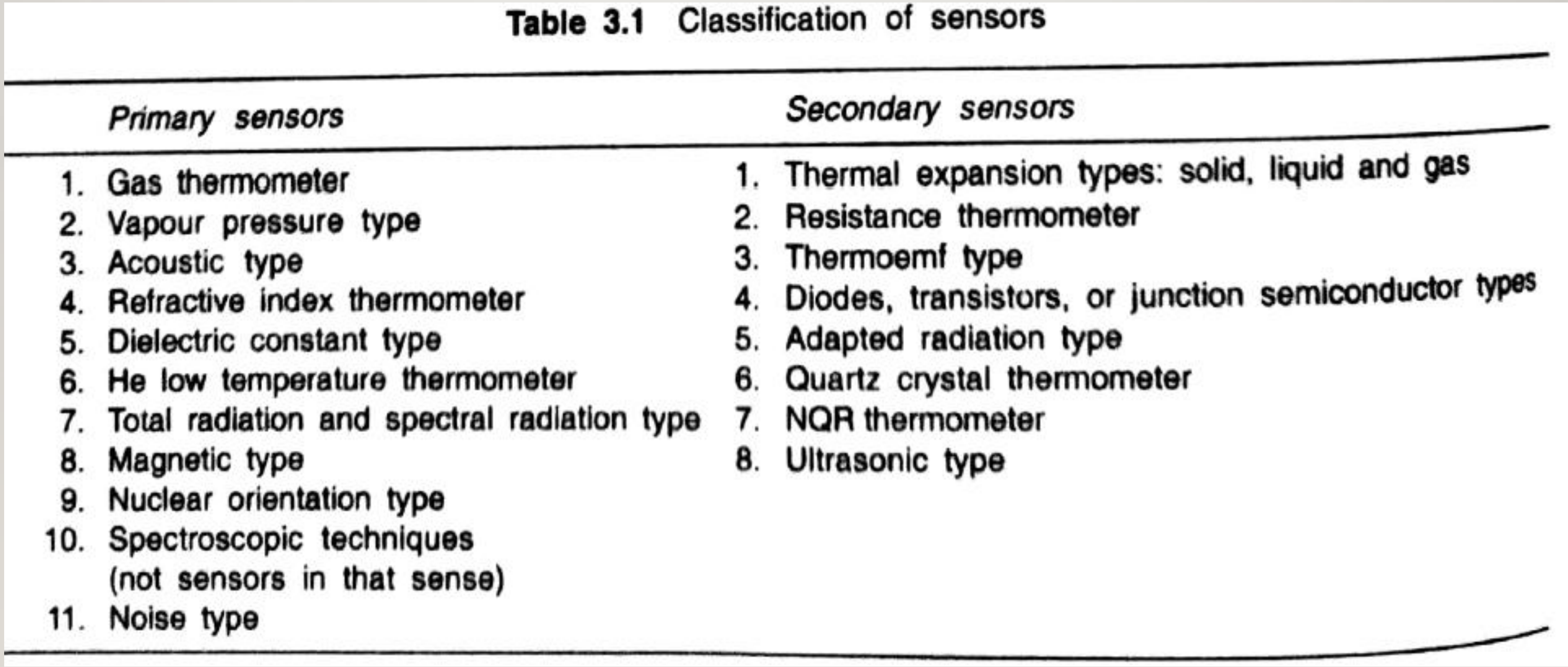


Table 3.1 Classification of sensors

Primary sensors	*Secondary sensors*
1. Gas thermometer	1. Thermal expansion types: solid, liquid and gas
2. Vapour pressure type	2. Resistance thermometer
3. Acoustic type	3. Thermoemf type
4. Refractive index thermometer	4. Diodes, transistors, or junction semiconductor types
5. Dielectric constant type	5. Adapted radiation type
6. He low temperature thermometer	6. Quartz crystal thermometer
7. Total radiation and spectral radiation type	7. NQR thermometer
8. Magnetic type	8. Ultrasonic type
9. Nuclear orientation type	
10. Spectroscopic techniques (not sensors in that sense)	
11. Noise type	

GAS PRESSURE THERMOMETER

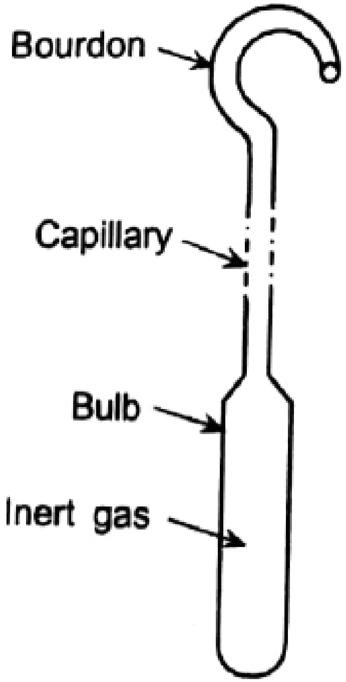


Fig. 3.1 The schematic of a gas pressure thermometer.

GAS PRESSURE THEROMETER

Bourdon Tube
C Tube

VAPOUR PRESSURE VARIATION WITH TEMPERATURE

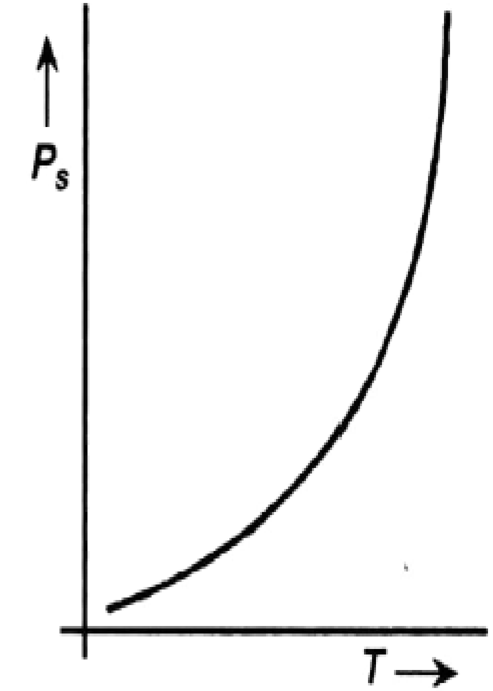


Fig. 3.2 Vapour pressure variation with temperature.

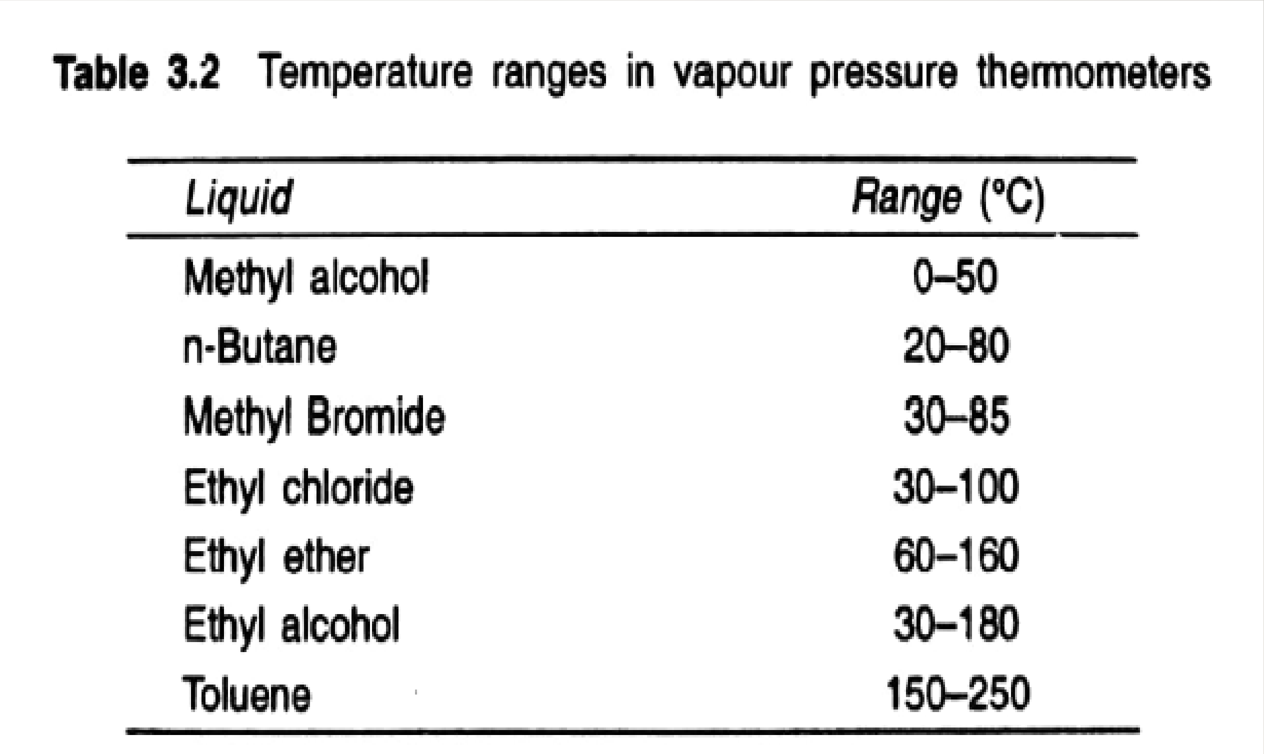


Table 3.2 Temperature ranges in vapour pressure thermometers

Liquid	*Range* (°C)
Methyl alcohol	0–50
n-Butane	20–80
Methyl Bromide	30–85
Ethyl chloride	30–100
Ethyl ether	60–160
Ethyl alcohol	30–180
Toluene	150–250

THERMAL EXPANSION TYPE THERMOMETRIC SENSORS

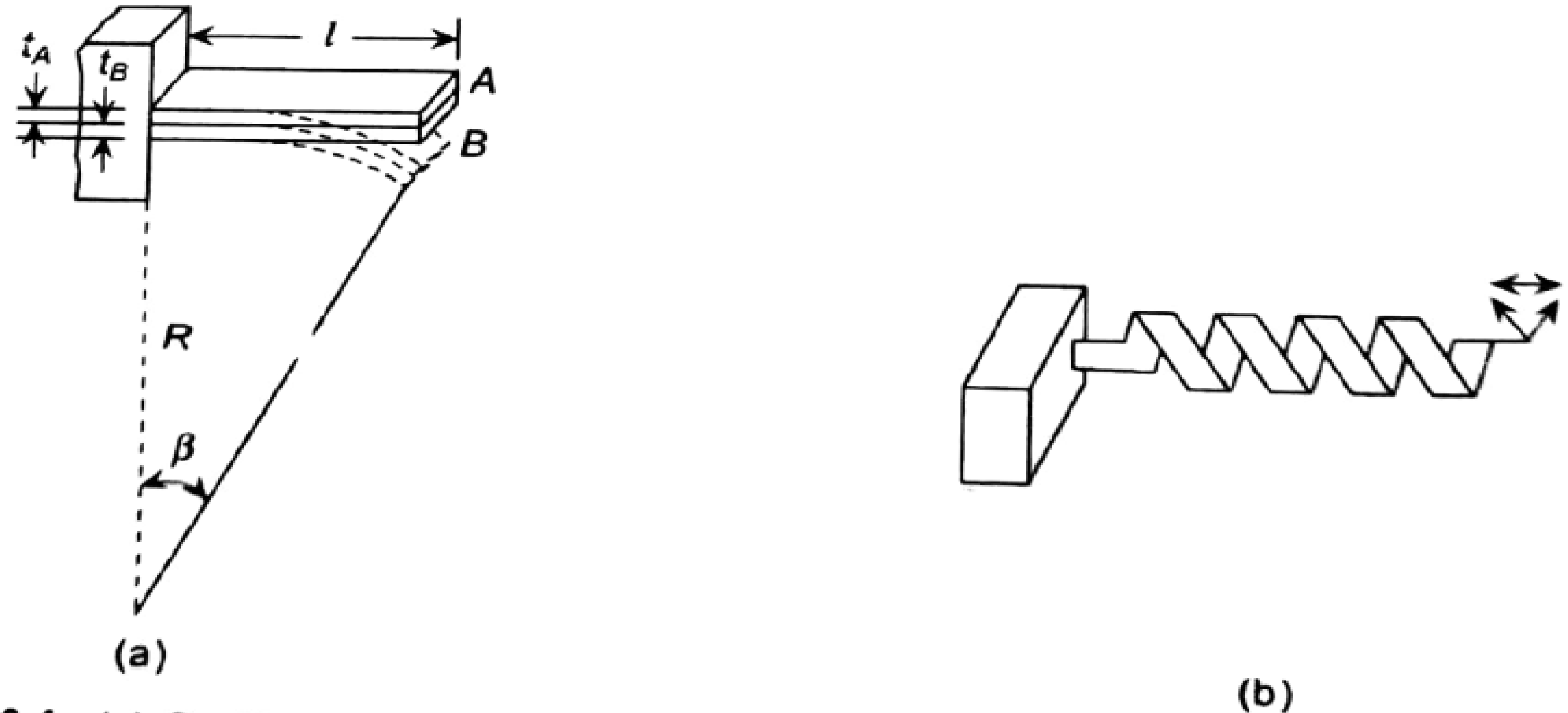


Fig. 3.4 (a) Cantilever type bimetal thermometer, (b) helix type bimetal thermometer.

LIQUID-IN-GLASS THERMOMETER

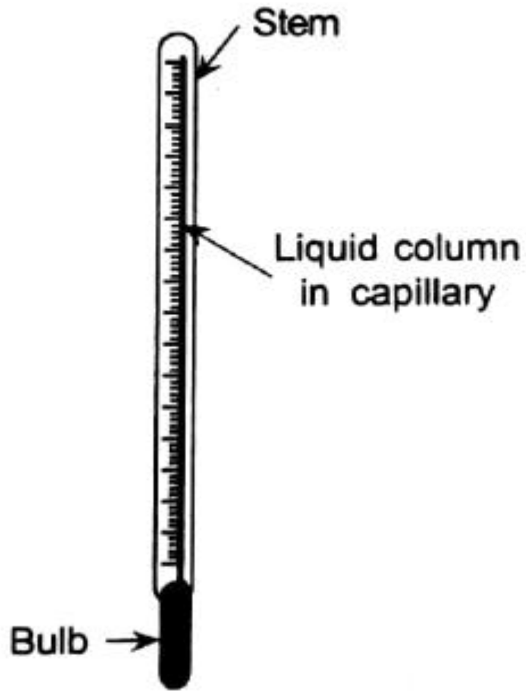
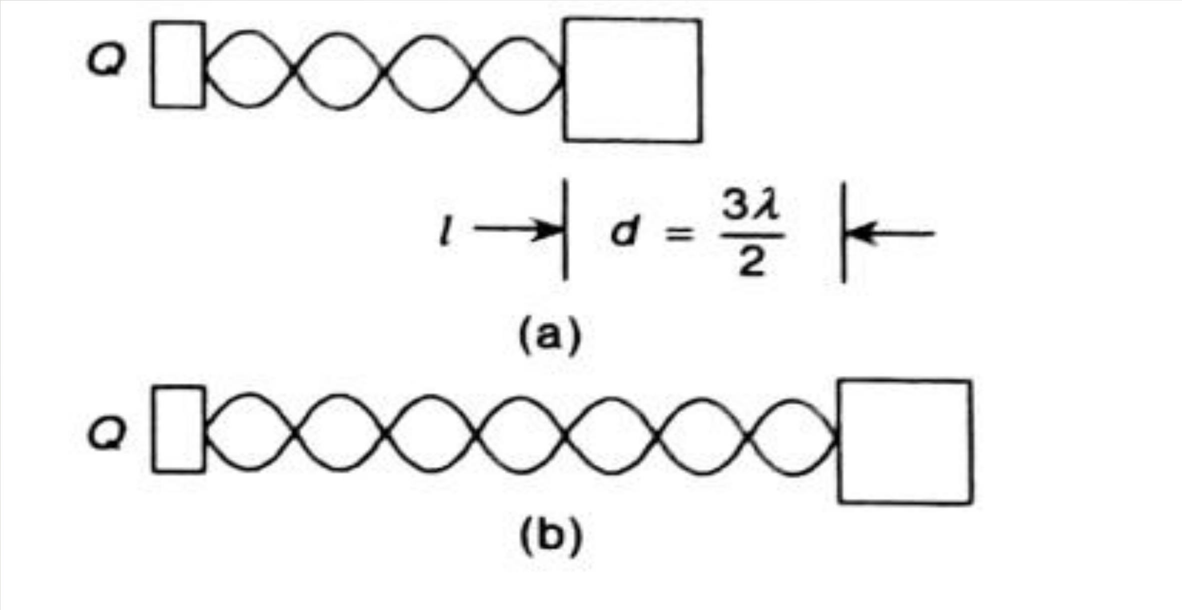


Fig. 3.5 Liquid-in-glass thermometer.

ACOUSTIC TEMPERATURE SENSOR

- Acoustic wave sensors are so named because their detection mechanism is a mechanical, or acoustic, wave. As the acoustic wave propagates through or on the surface of the material, any changes to the characteristics of the propagation path affect the velocity and/or amplitude of the wave. Changes in velocity can be monitored by measuring the frequency or phase characteristics of the sensor and can then be correlated to the corresponding physical quantity being measured.
- Virtually all acoustic wave devices and sensors use a piezoelectric material to generate the acoustic wave

ACOUSTIC TEMPERATURE SENSOR



NON RESONANT ACOUSTIC TEMPERATURE SENSOR

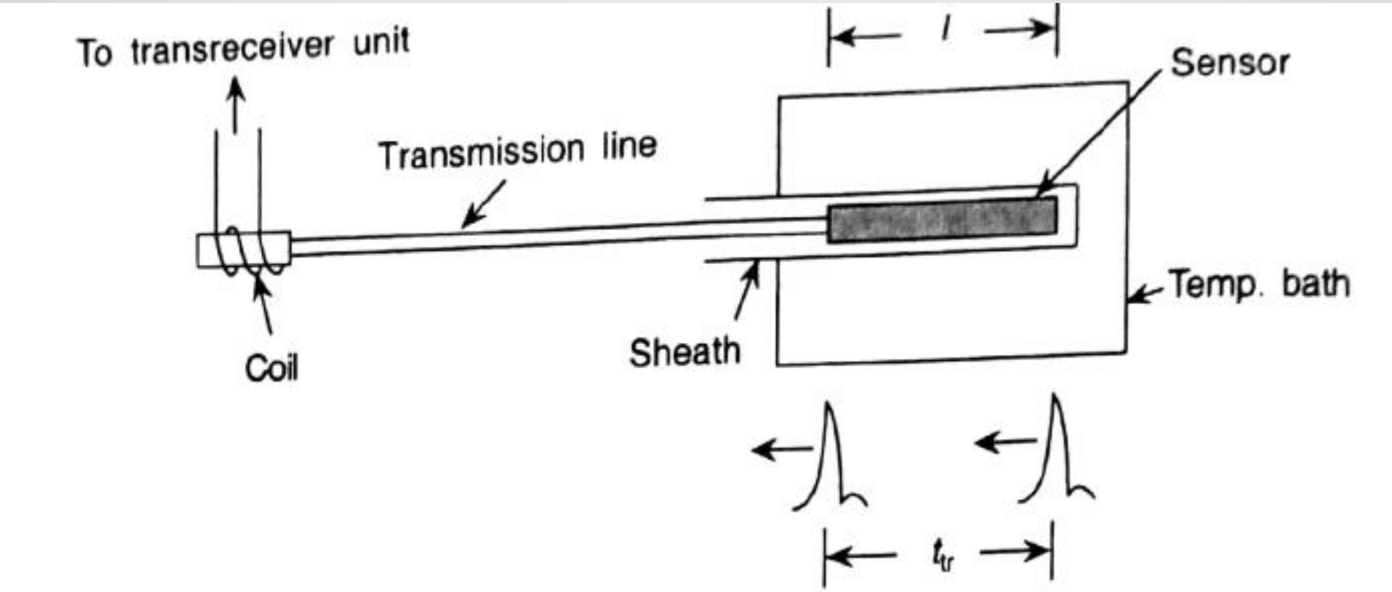


Fig. 3.7 Pulse-echo transit time difference technique of temperature measurement.

DIELECTRIC CONSTANT & REFRACTIVE INDEX THERMOSENSORS

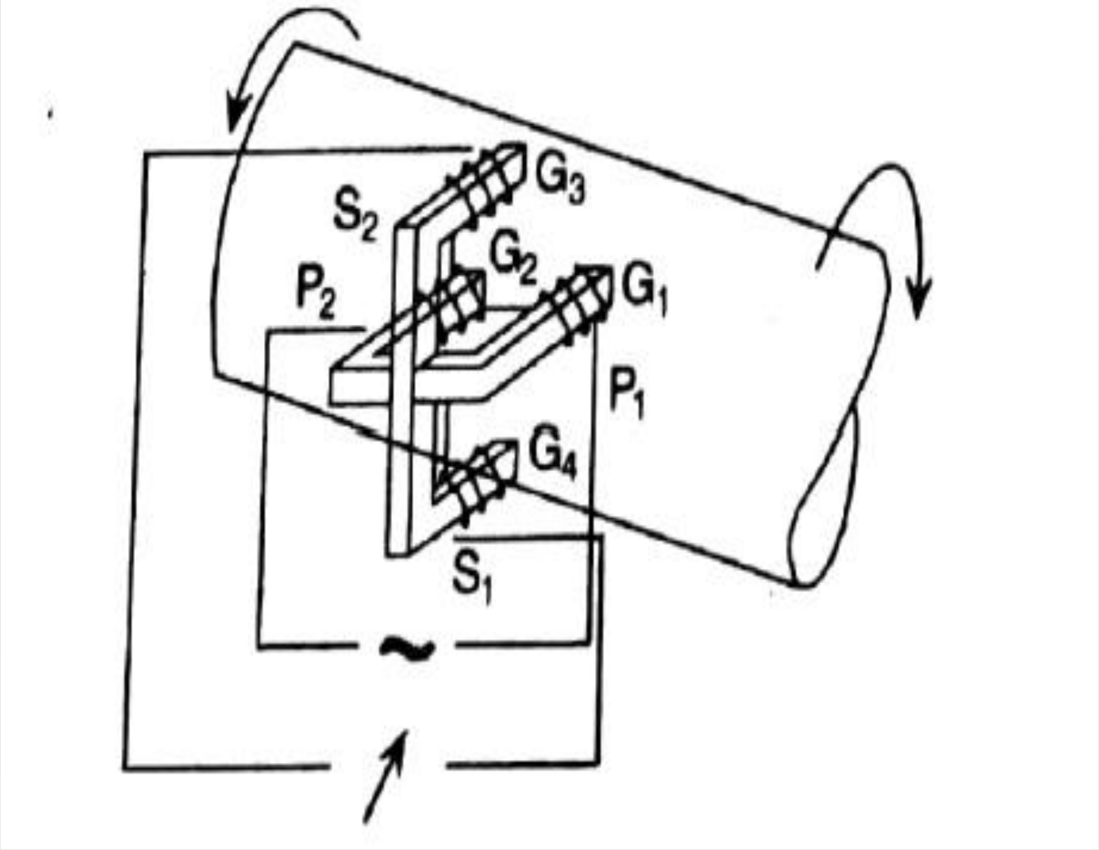
- Clausius-Mossotti Relation
- The relation between refractive index and dielectric constant

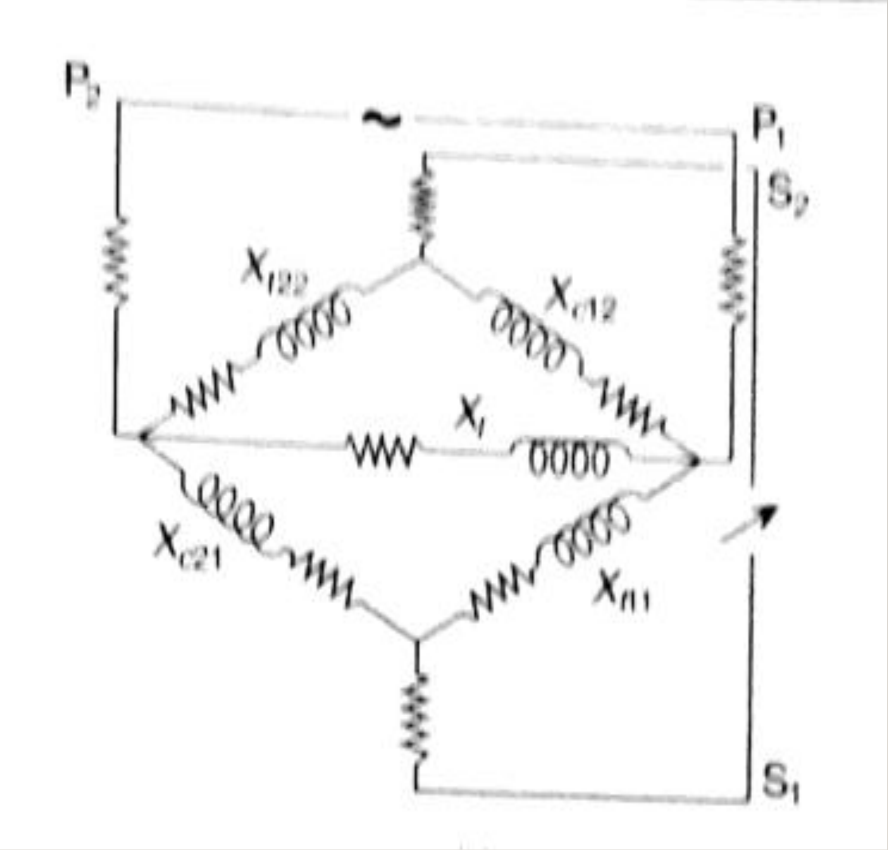
SENSORS AND THE PRINCIPLES USED ---MAGNETIC SENSORS

- Magnetostriction
- Villarian or Magnetoelastic or Inverse Magnetostrictive Effect
- Widemann Effect
- Matteucci Effect

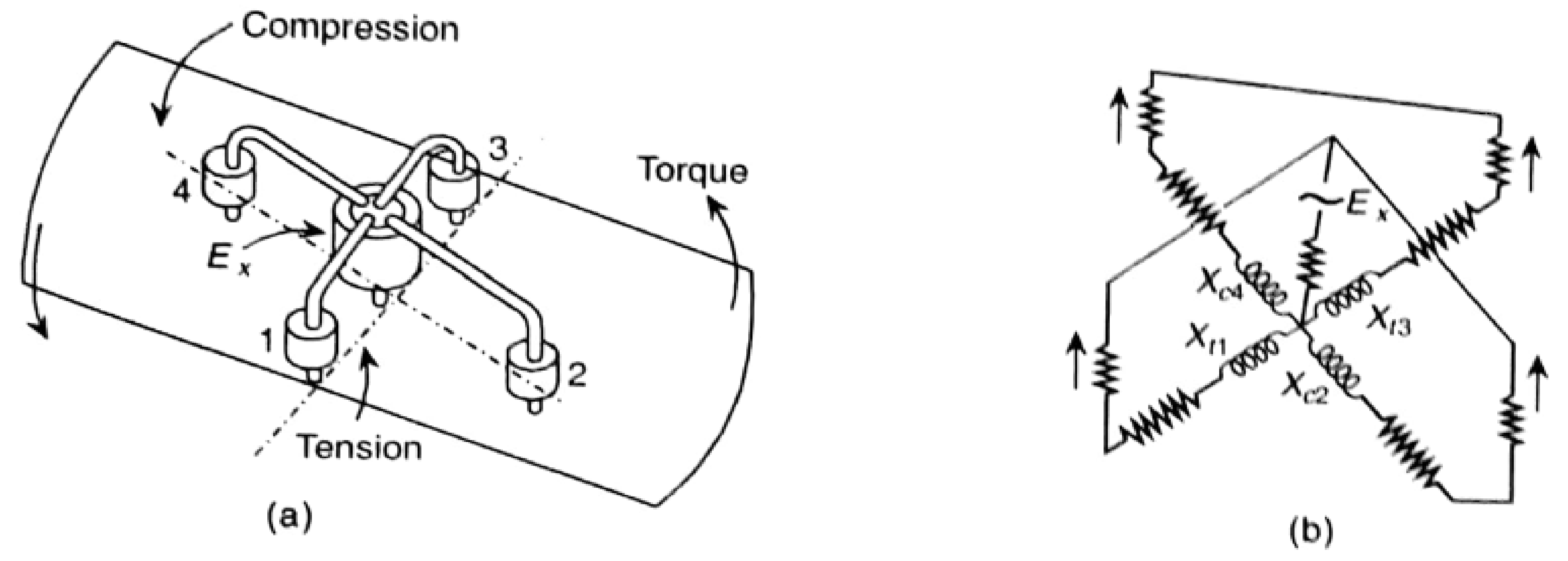
MAGNETOSTRICTION

YOKE COIL SENSORS

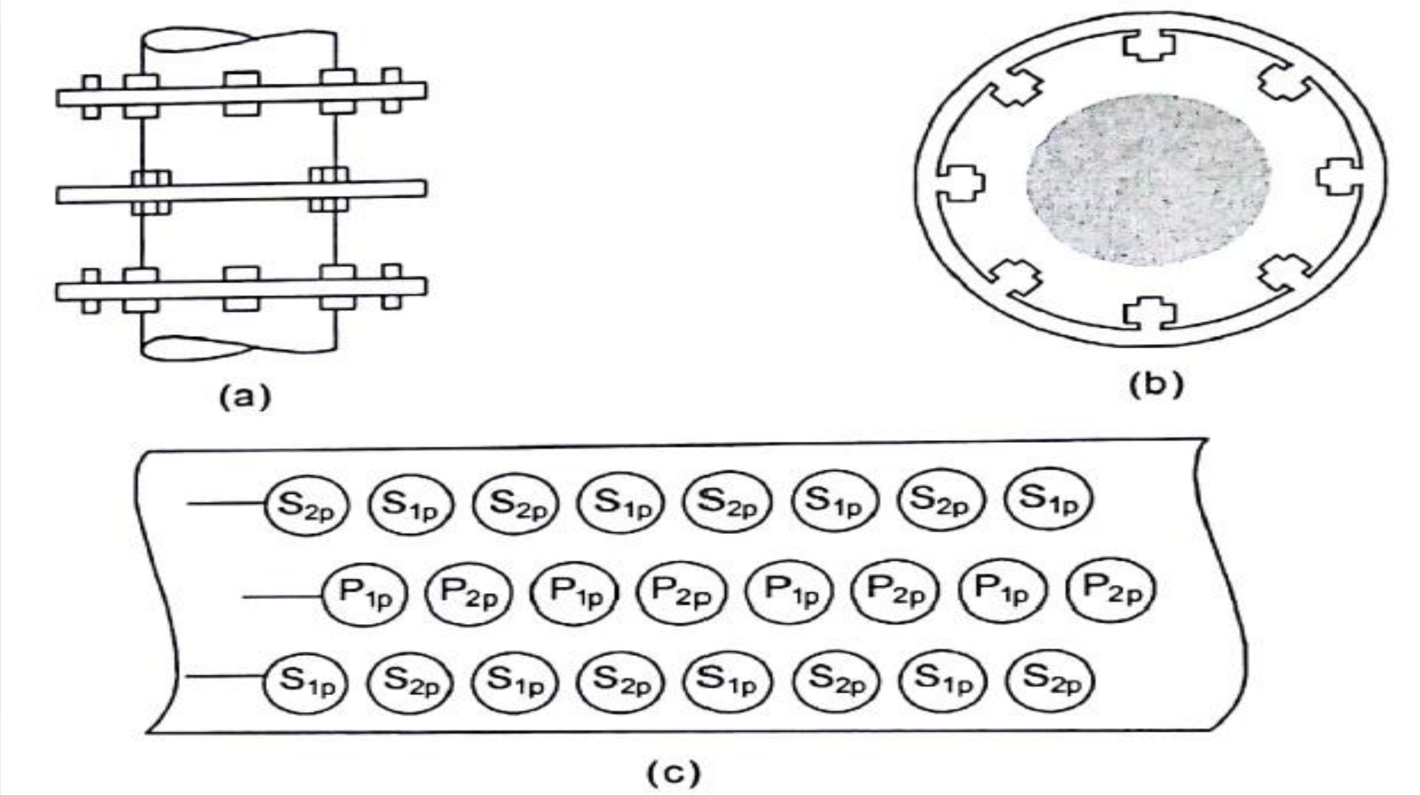




THE FOUR BRANCH TYPE SENSOR



RING TYPE TORQUE TRANDUCER



FOUR-BRANCH TYPE RING DESIGN

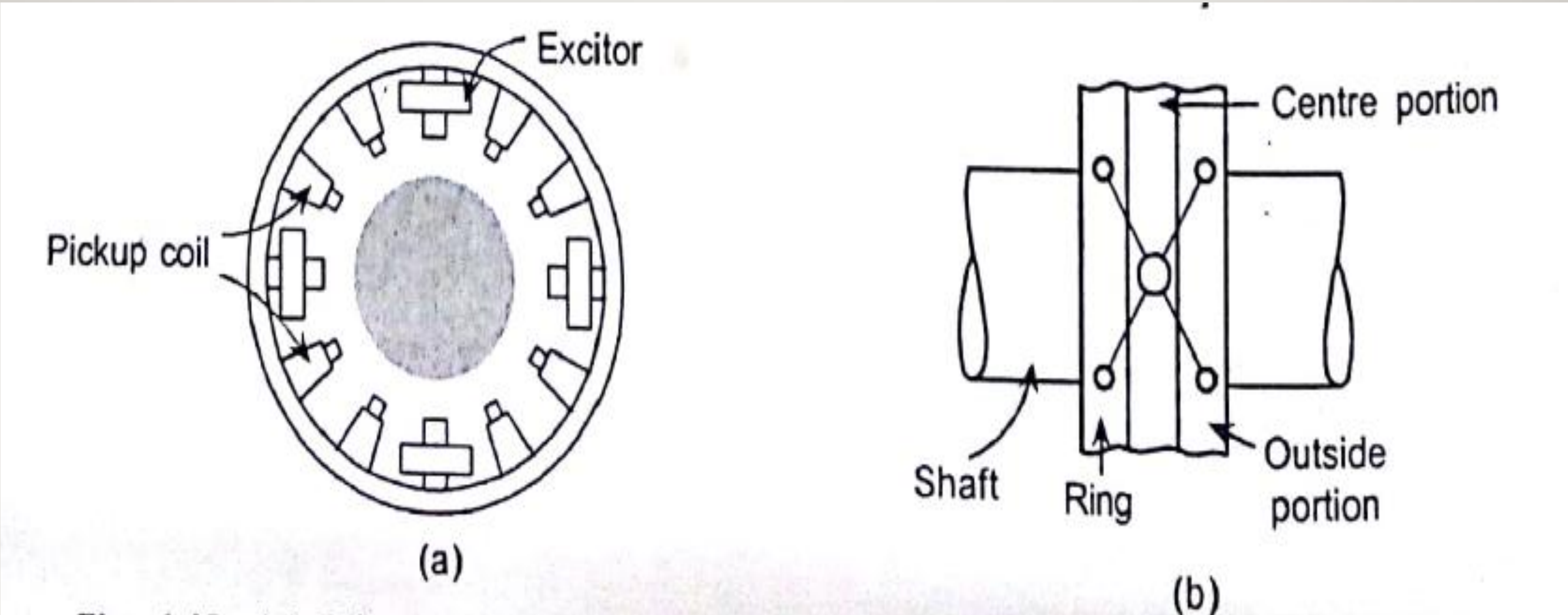


Fig. 4.12 (a) Scheme of

COAXIAL TYPE SENSOR

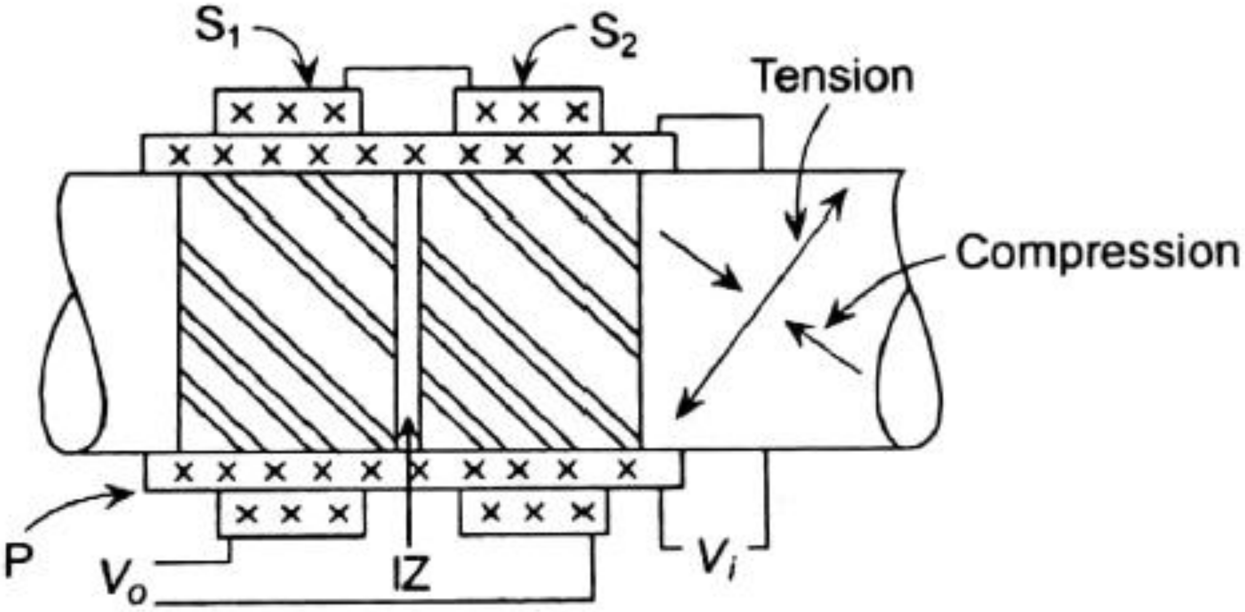
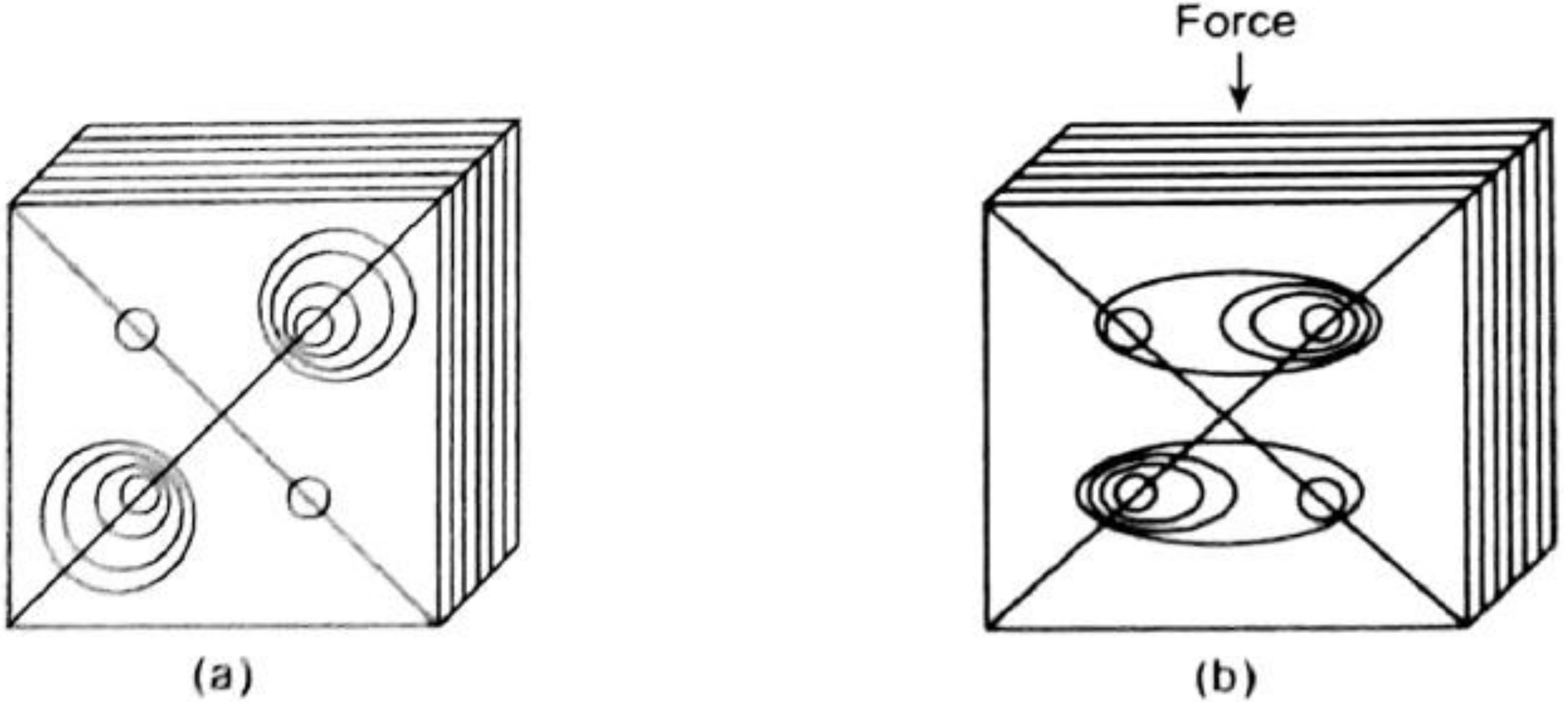


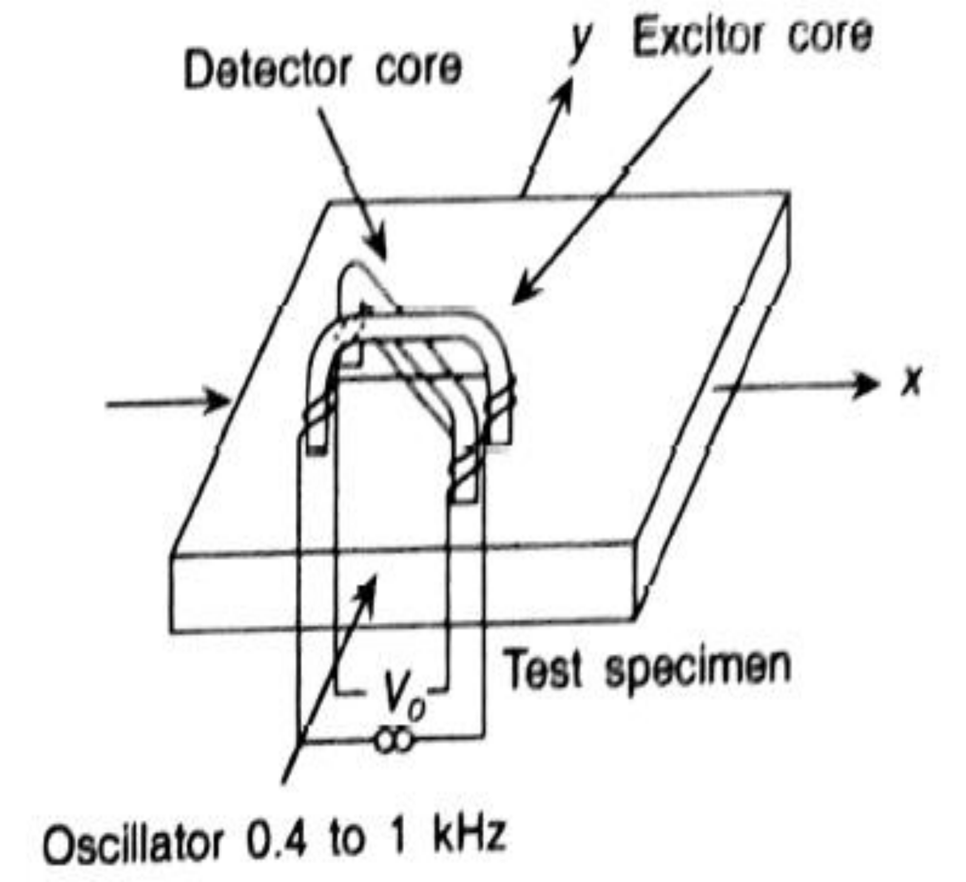
Fig. 4.13 Coaxial torque sensor.

FORCE AND DISPLACEMENT SENSORS

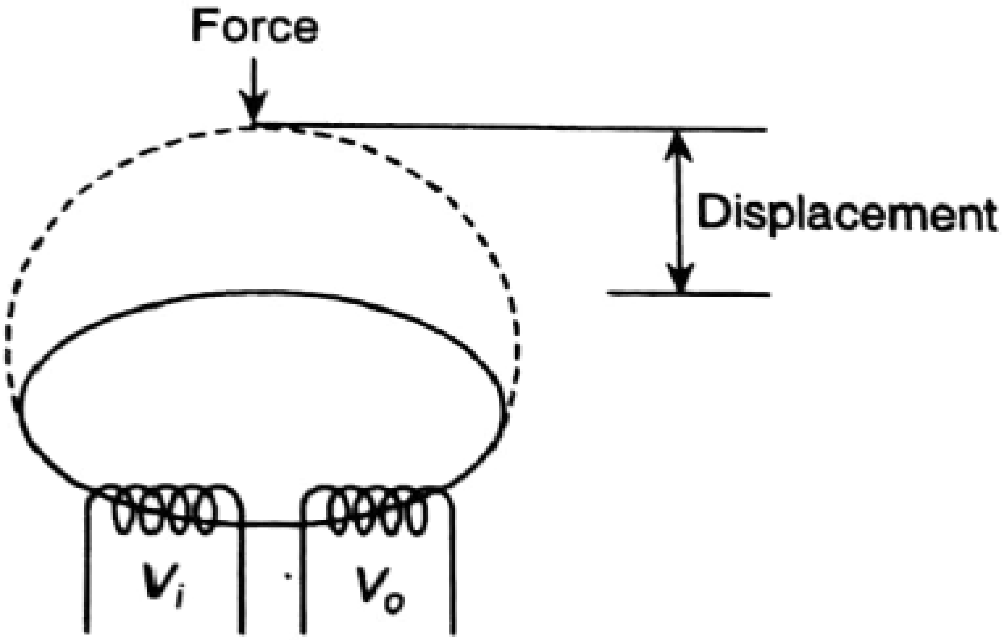


Schemes of pressductor (a) without force, and (b) with force applied.

FOUR BRANCH TYPE DISPLACEMENT SENSORS



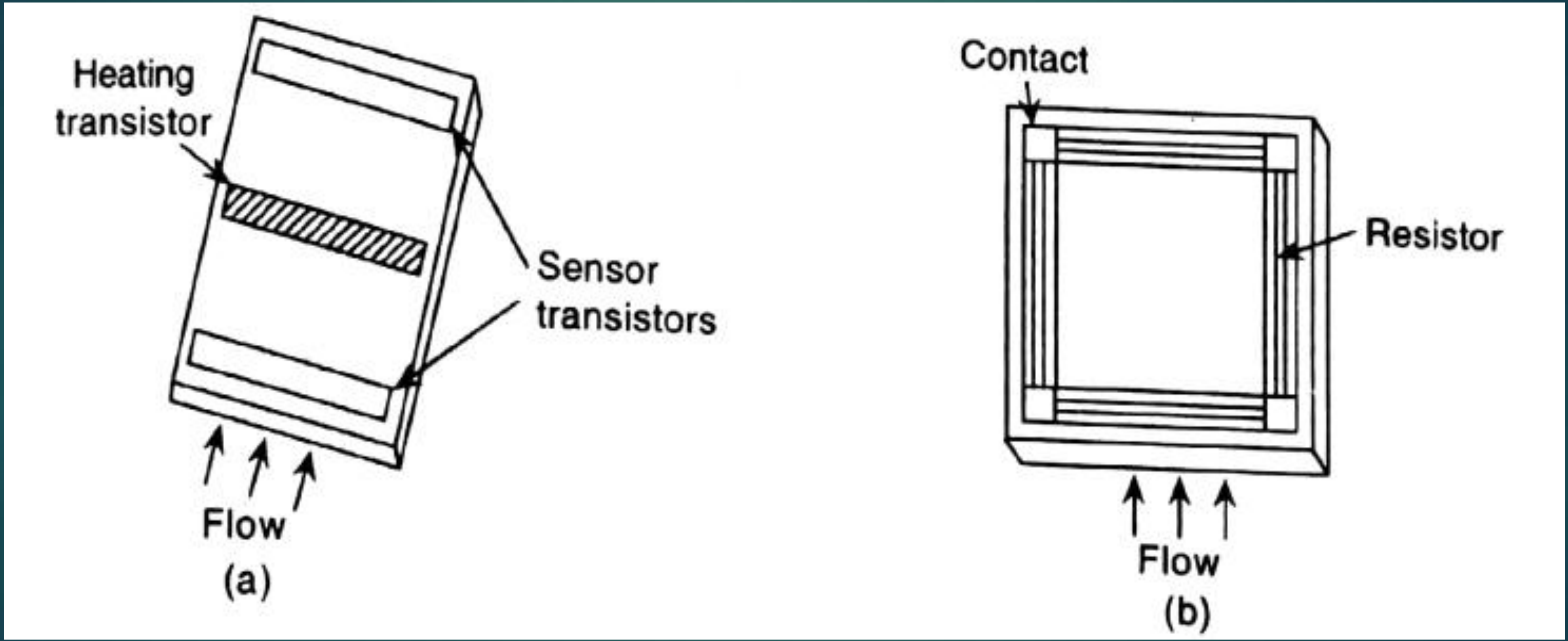
RING TYPE DISPLACEMENT SENSOR



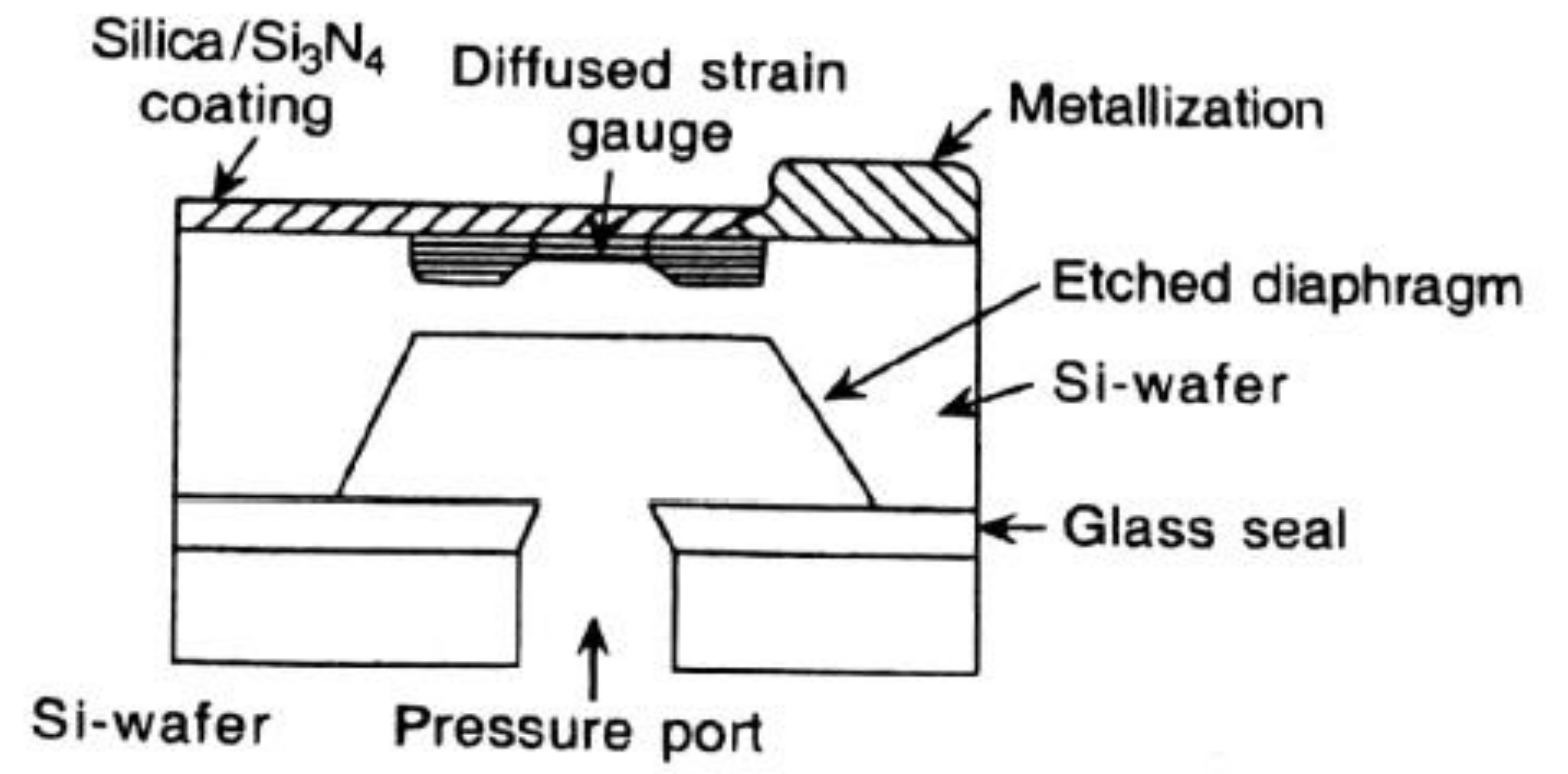
Ring type displacement sensor.

SENSORS THEIR APPLICATIONS

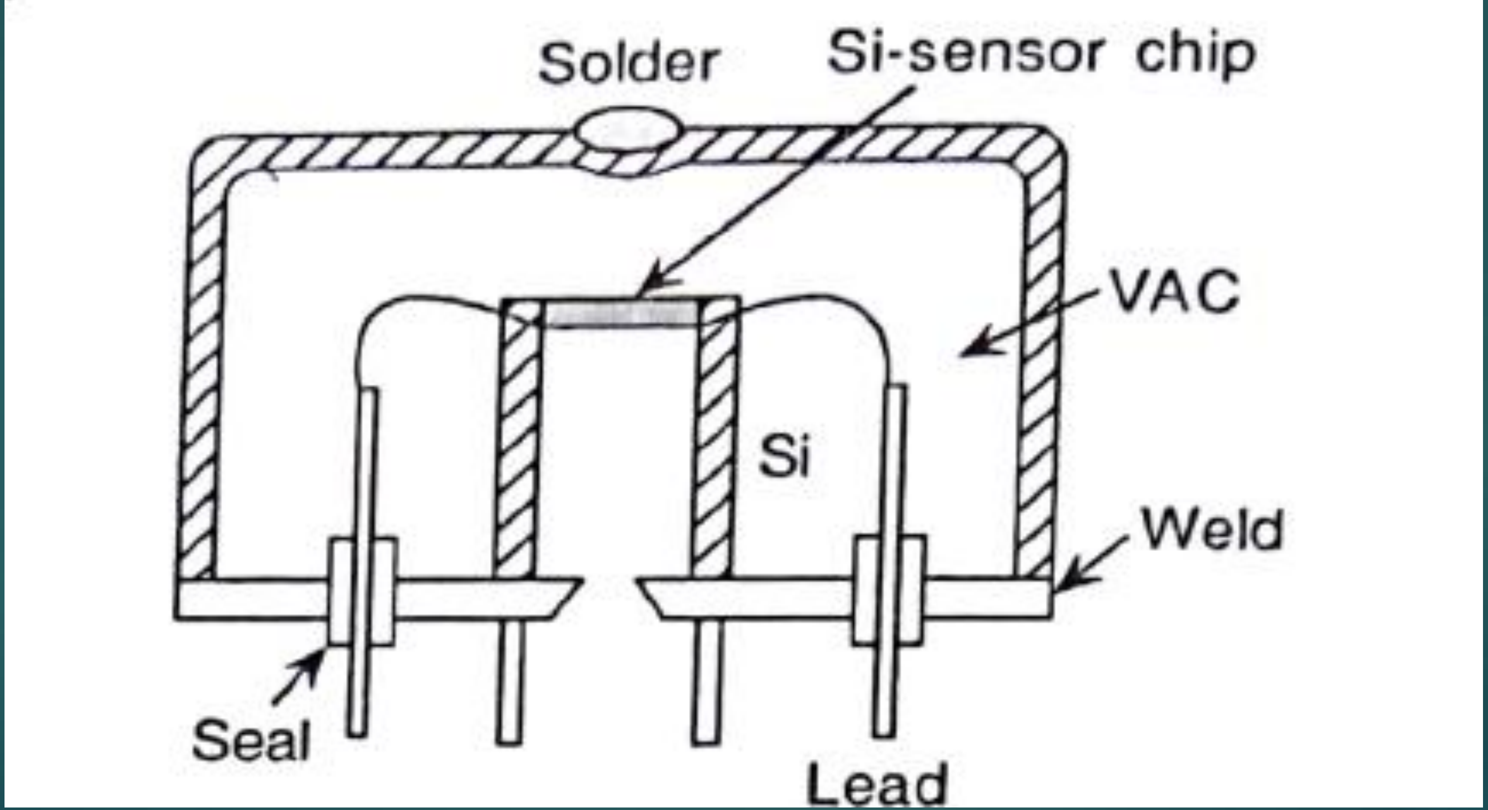
FLOW-RATE SENSORS



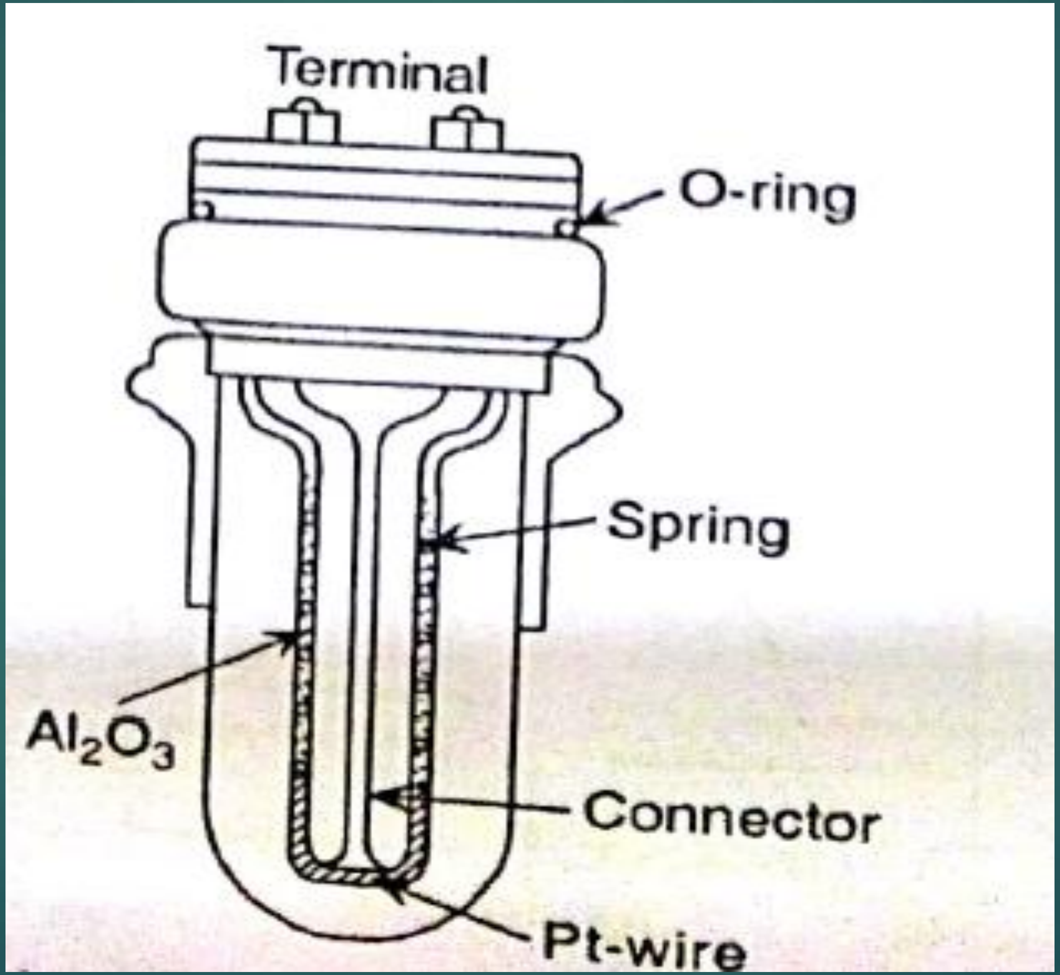
PRESSURE SENSOR



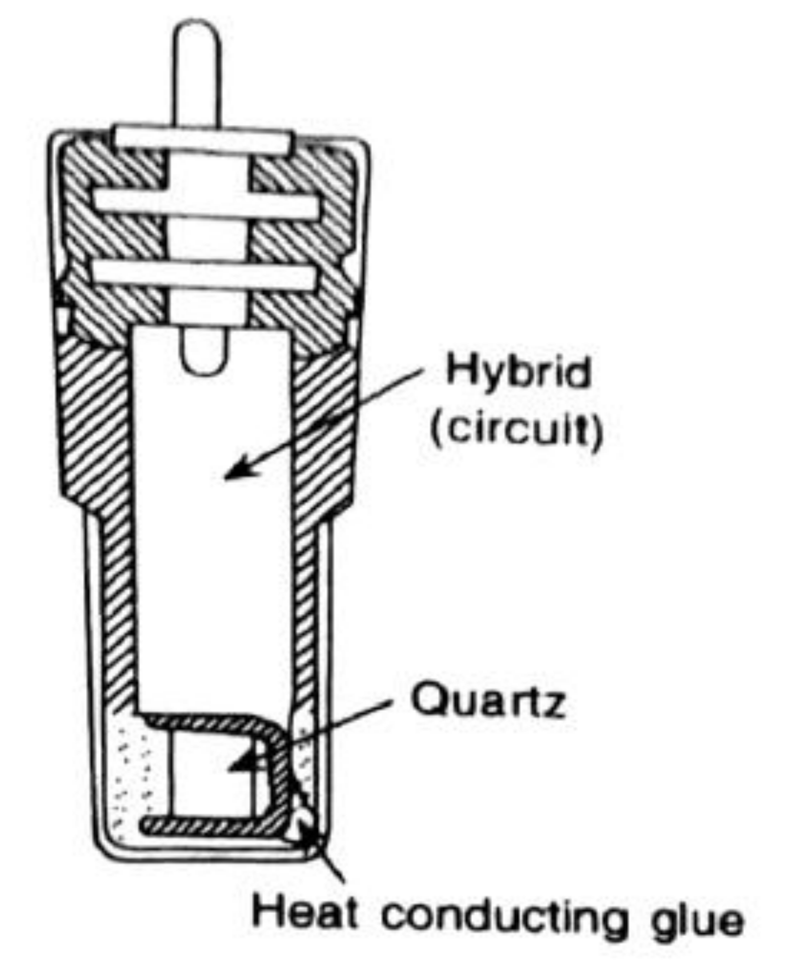
NEGATIVE PRESSURE SENSING SILICON CHIP



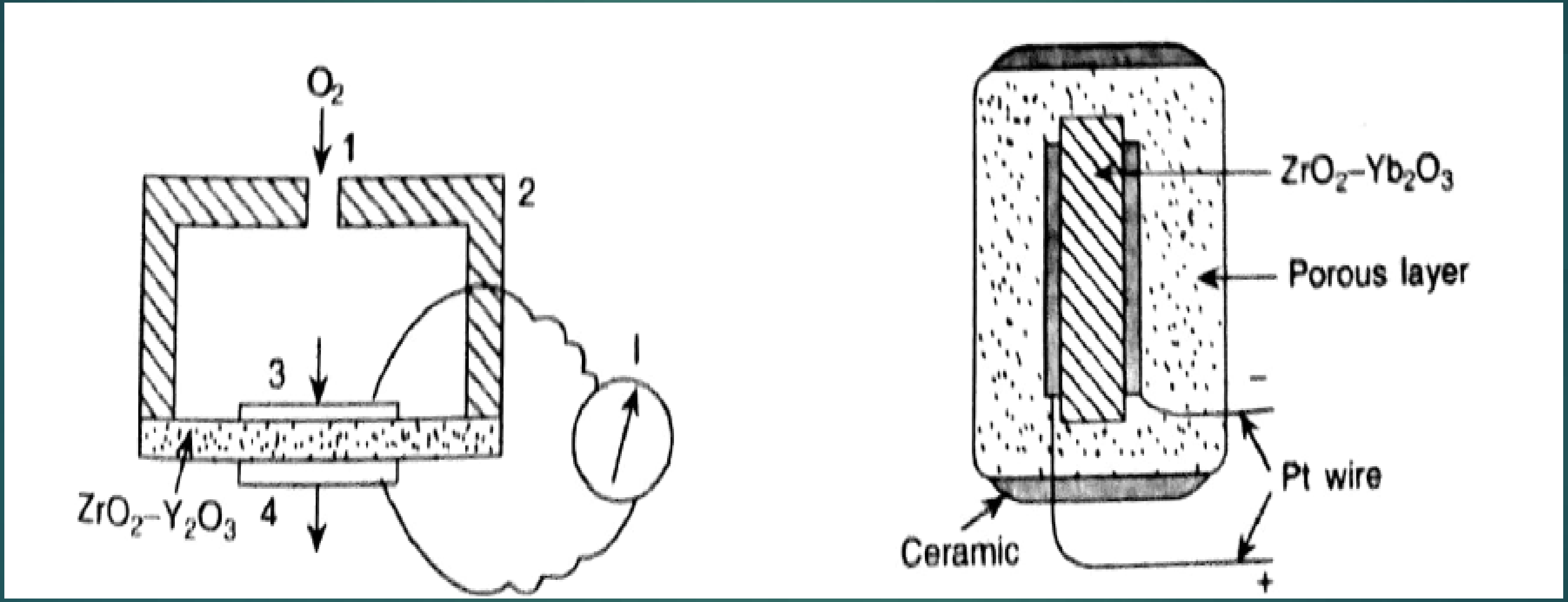
TEMPERATURE SENSORS-RTD as used in AUTOMOBILES



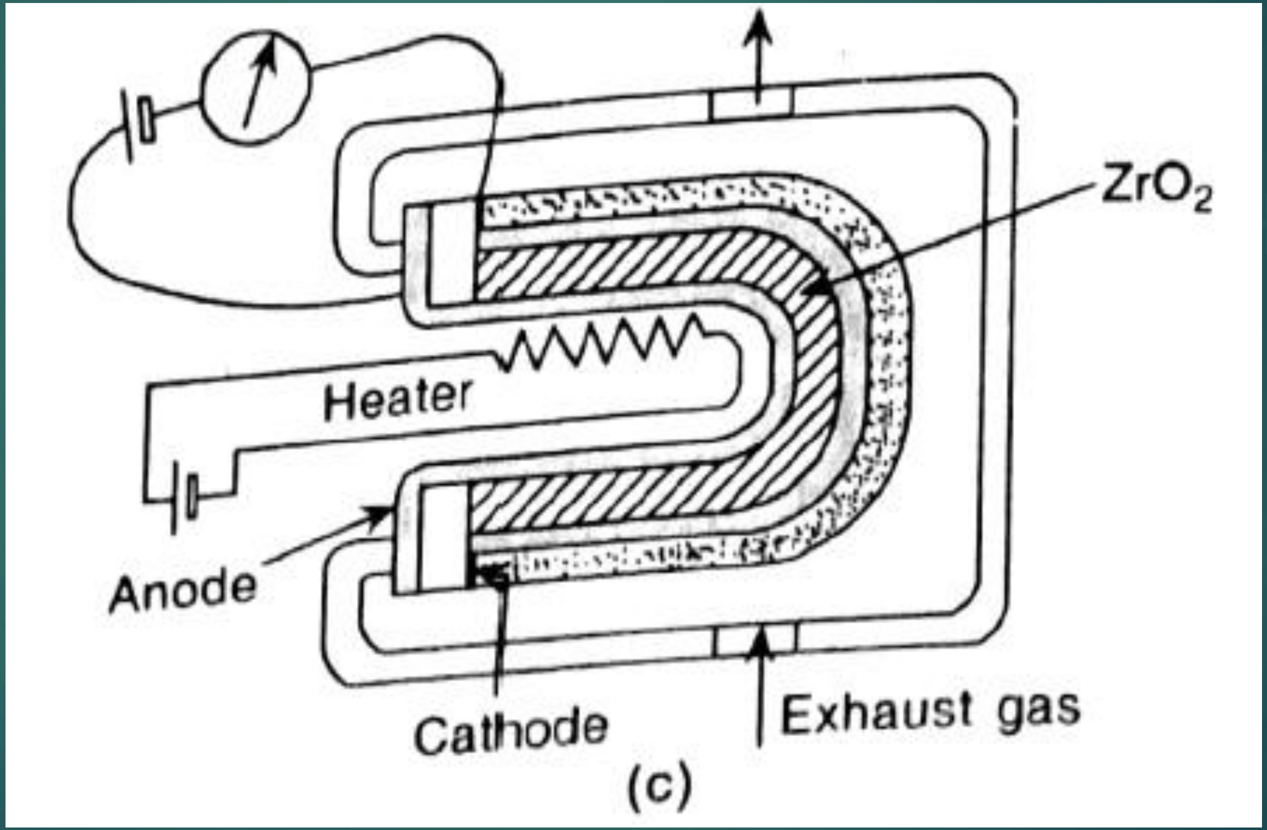
HYBRID IC TEMPERATURE SENSOR



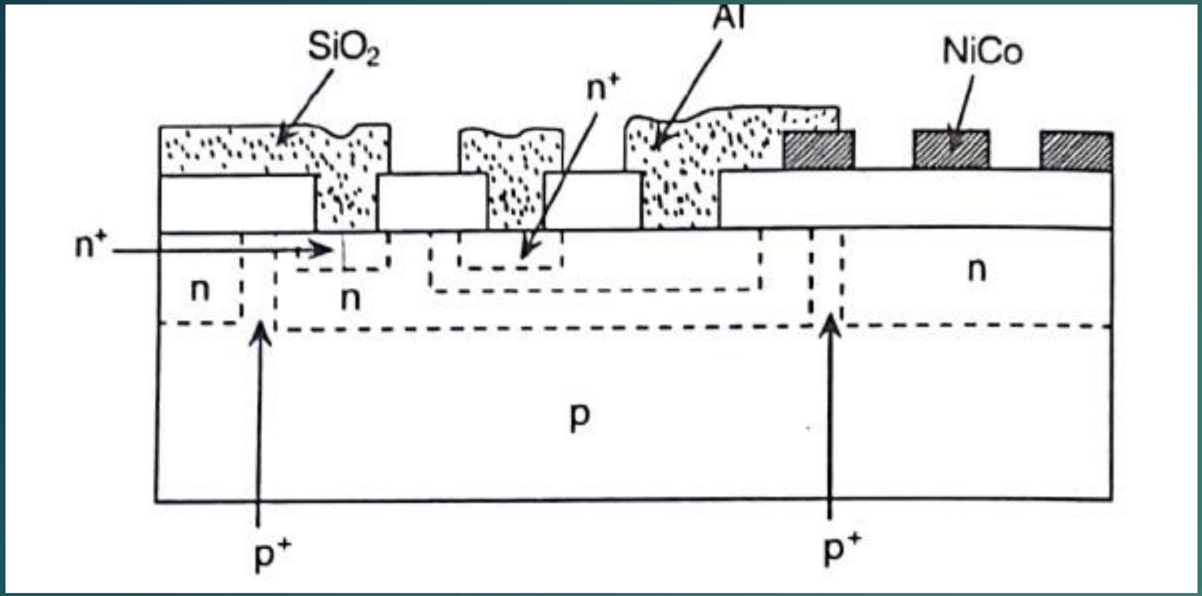
Oxygen sensors

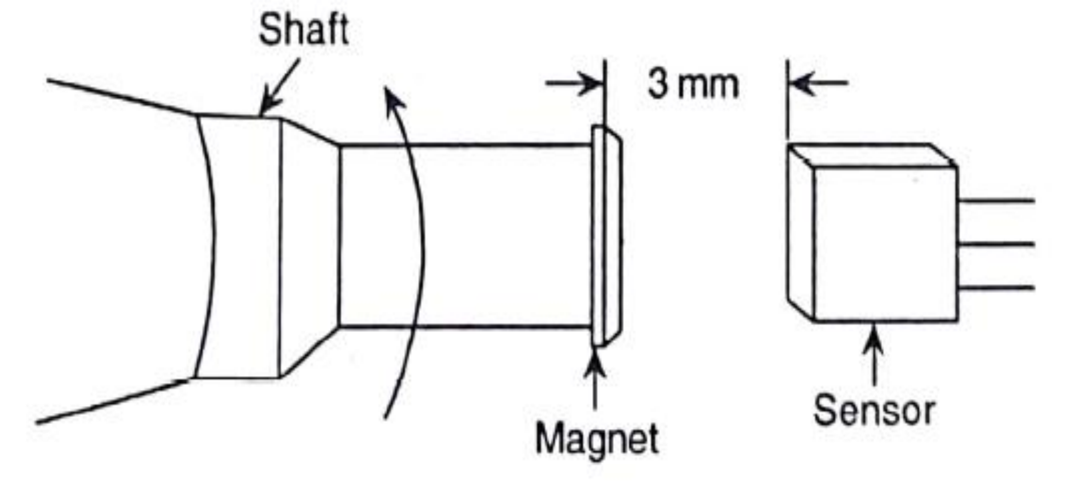


Oxygen Sensors



Position Sensors





1.Mechanical Category : silicon pressure sensors- regrigerators

potentiometers – carpet cleaners, washing machines.

2. Chemical type: Humidity sensors – microwave ovens, clothes dryers, air conditioners, dehumidifiers, VCR camers.

Gas sensors – ovens and exhaust fans.

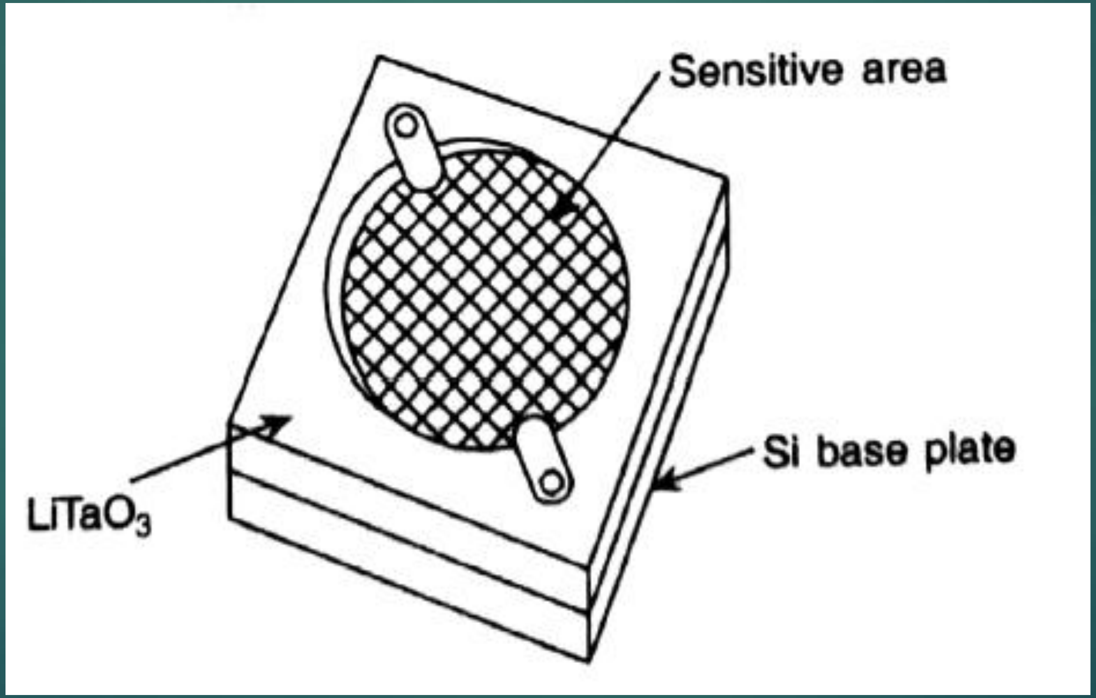
3.Magnetic sensors: electornic gadgets

Hall sensors – VCR cameras, stereo sets, tape recorders

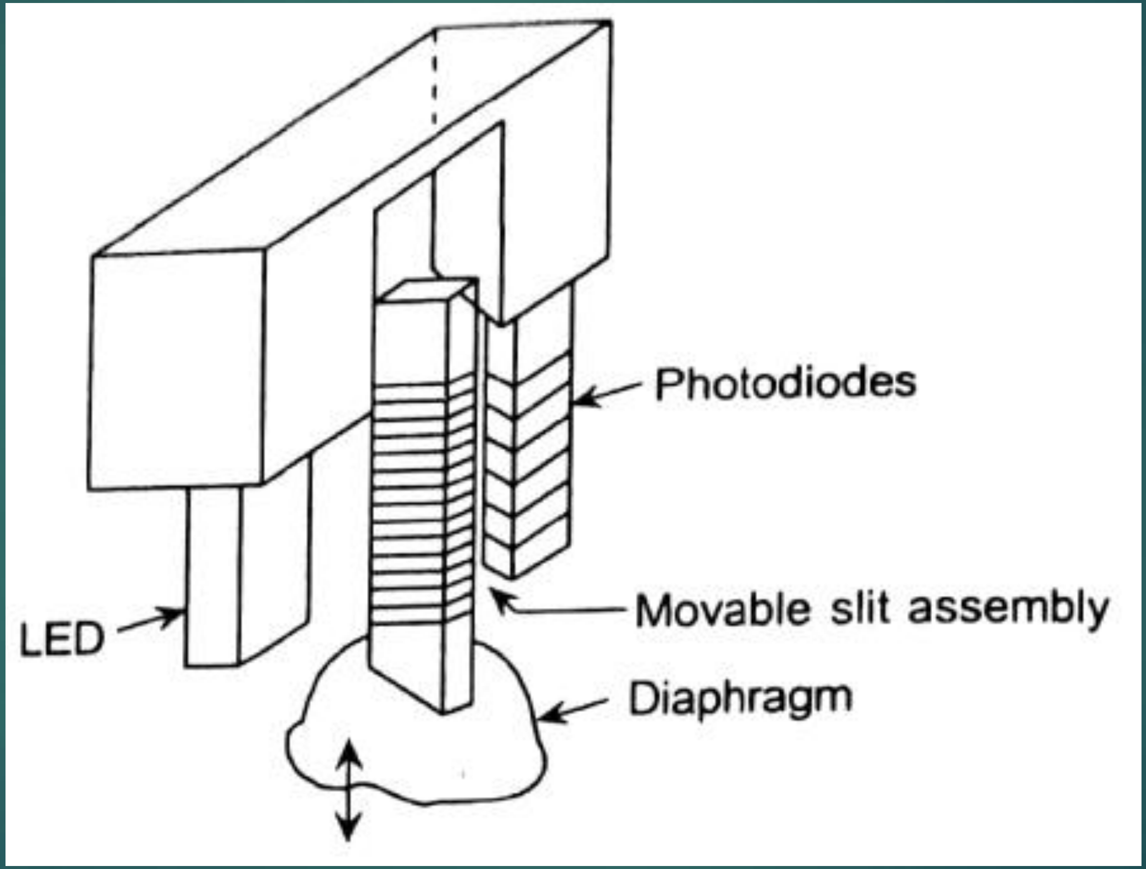
4. Temperature type: ovens, refrigetors, dishwashers, dryers, dehumidifiers, air-conditioners, exhaust fans, CD players.

5.Radition sensors : Photodiodes, Phototransistors –refrigetors, washing machines, air-conditons, tvsets, cd players, etc.

Basic pyroelectric IR sensor

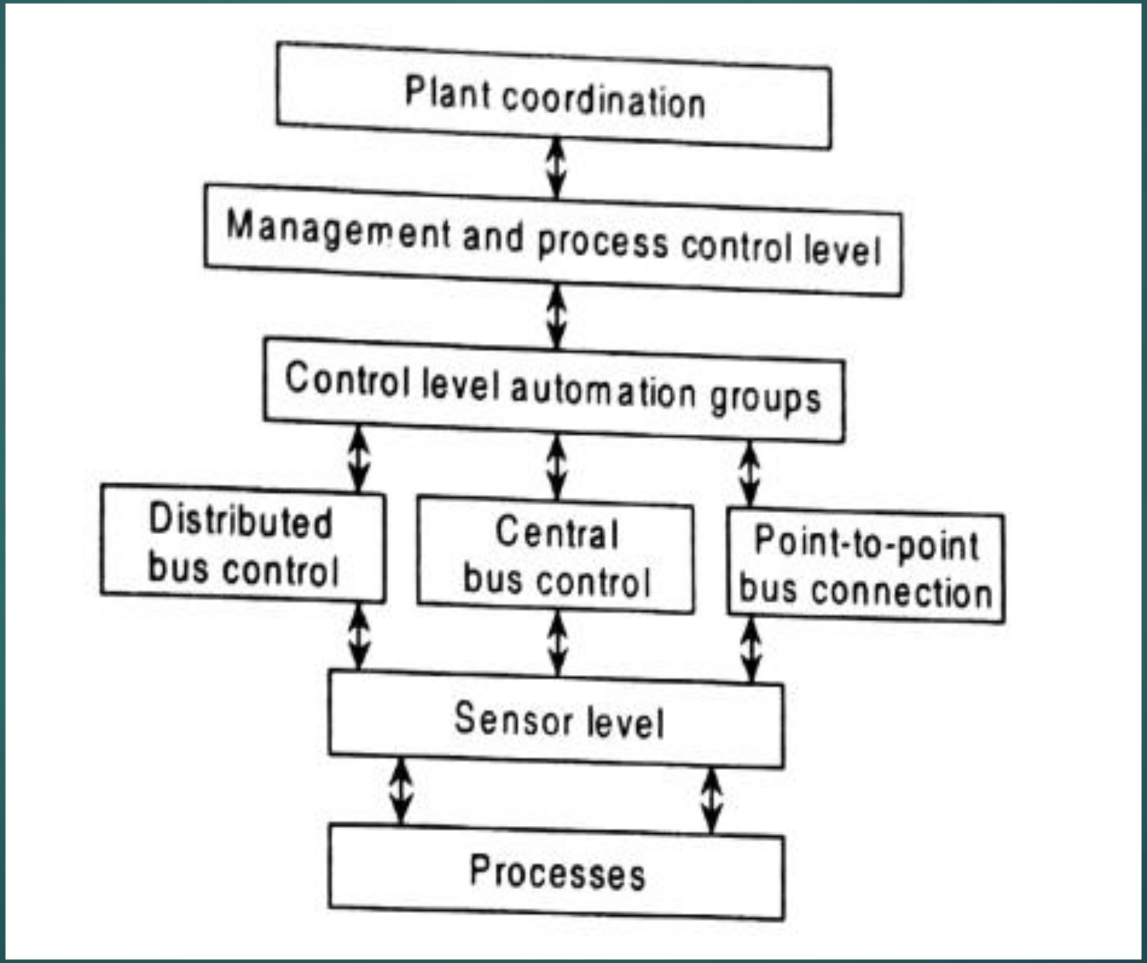


Optical Sensor for Water Level Detection



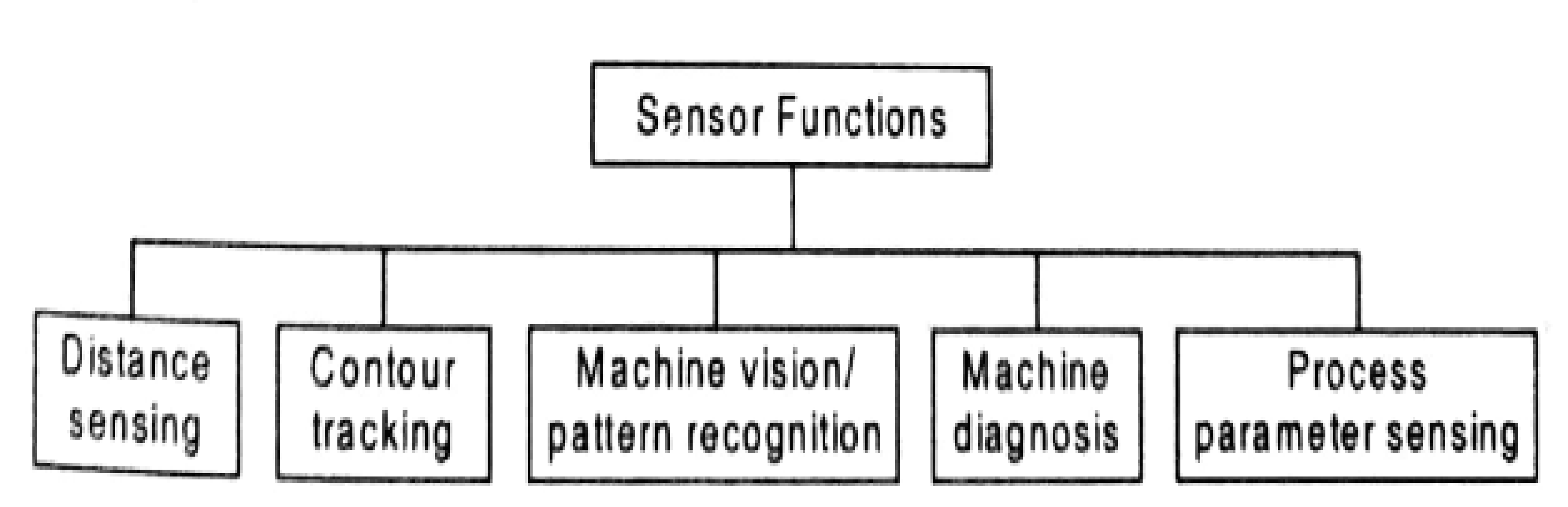
SENSORS FOR MANUFACTURING

Interaction between Sensors & Level of Operation OR Computer –Integrated Manufacturing(CIM)



Functional diagram of Sensors

Sensors used in production processes

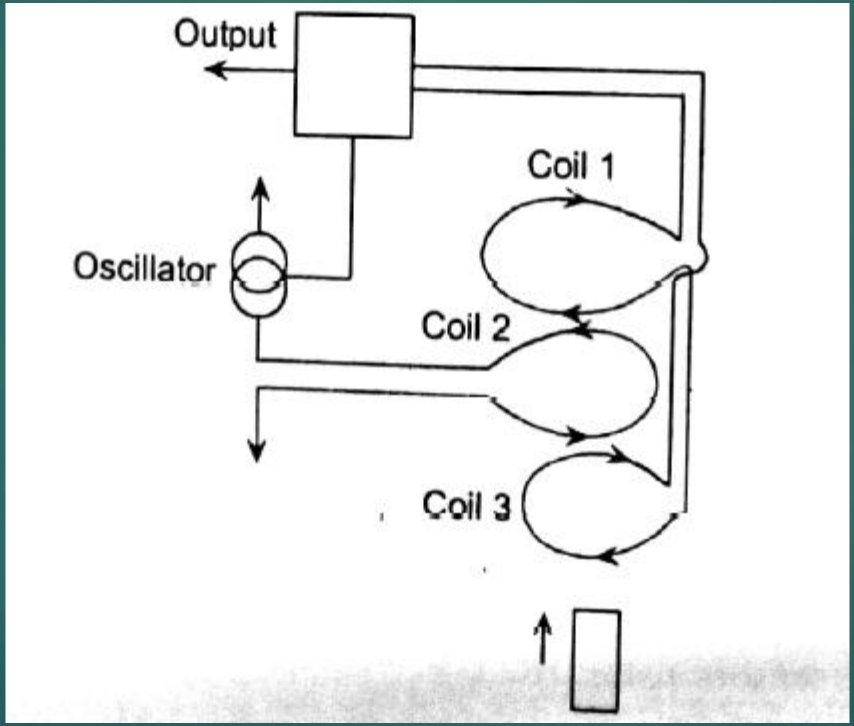


Sensors in production process

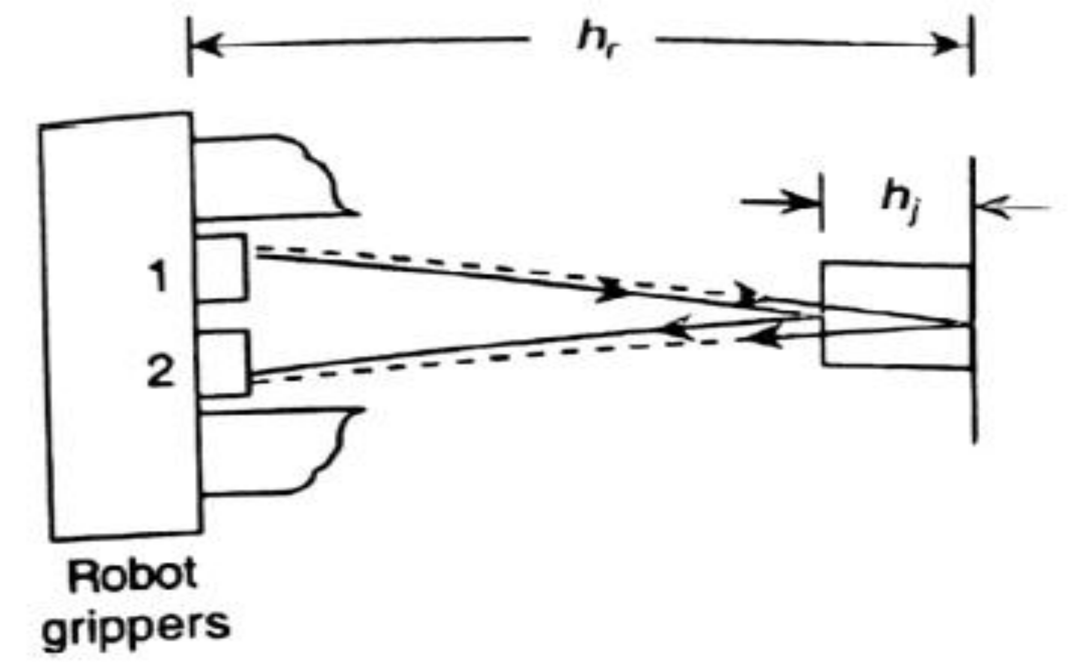
- Distance sensing : Tactile sensors, electrical sensors, optical sensors acoustic sensors
- Contour-tracking : kind of scanning process electrical sensors, optical sensors
- Machine vision/pattern recognition: ultrasonic scanning. Besides optical systems with binary vision, grey level vision and stereovision are used.
- Machine diagnosis: pressure, force, torque, speed temperature, frequency etc
- Process parameters: different environmental conditions

Distance Sensing

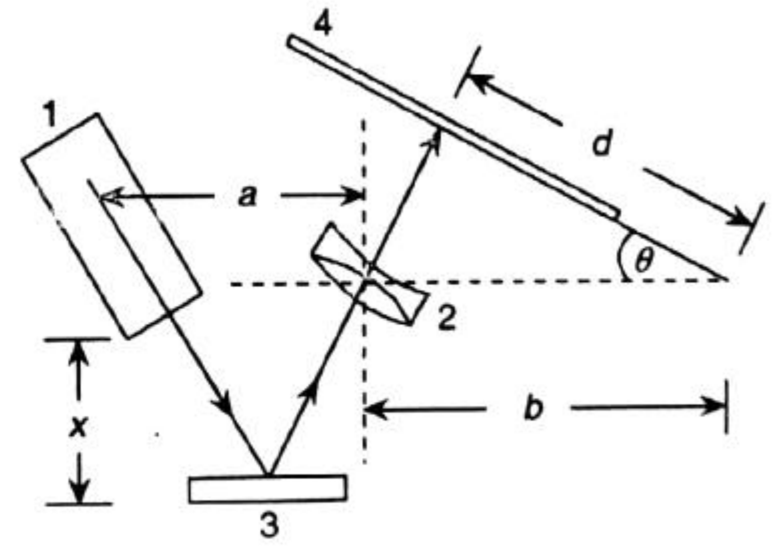
a)Inductive Proximity sensor



b)Ultrasonic type distance sensor

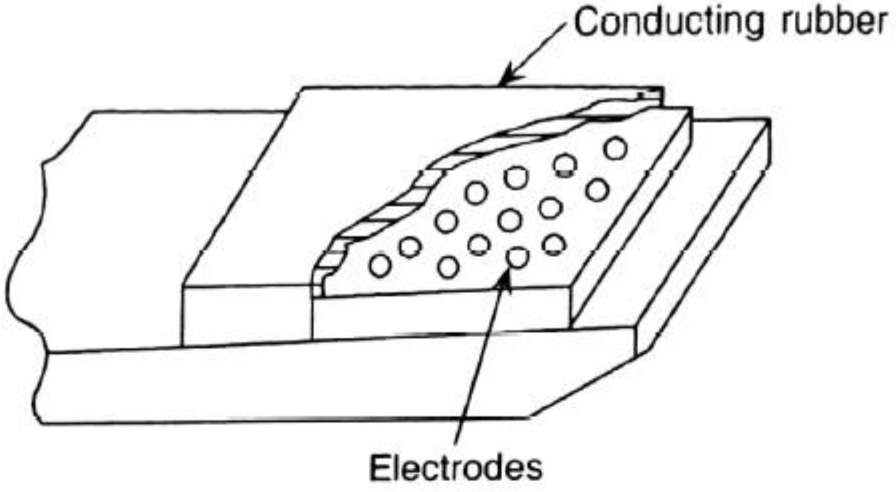


Optoelectronic technique

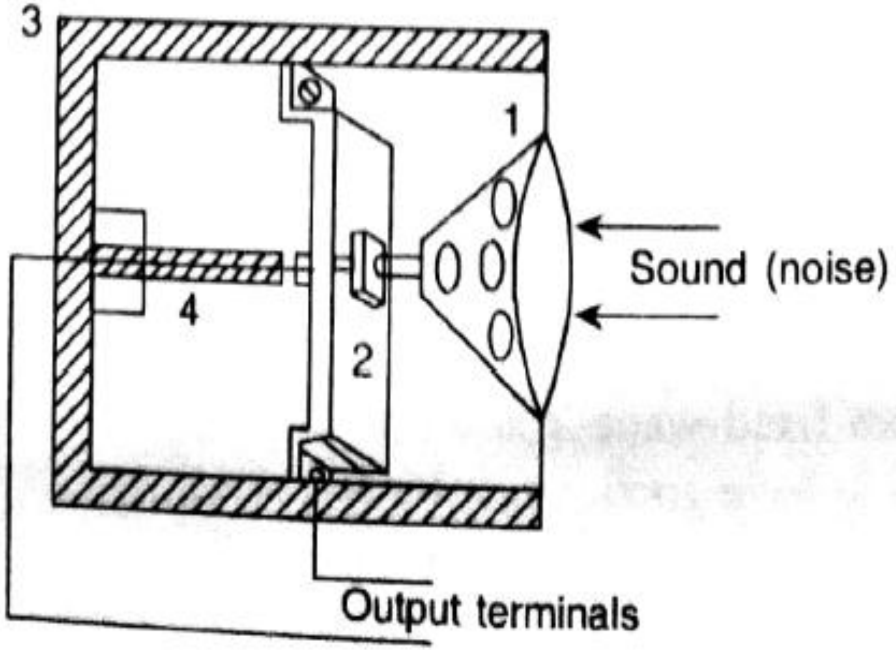


Diode array sensor: 1. laser source, 2. focussing lens, 3. job, 4. diode array.

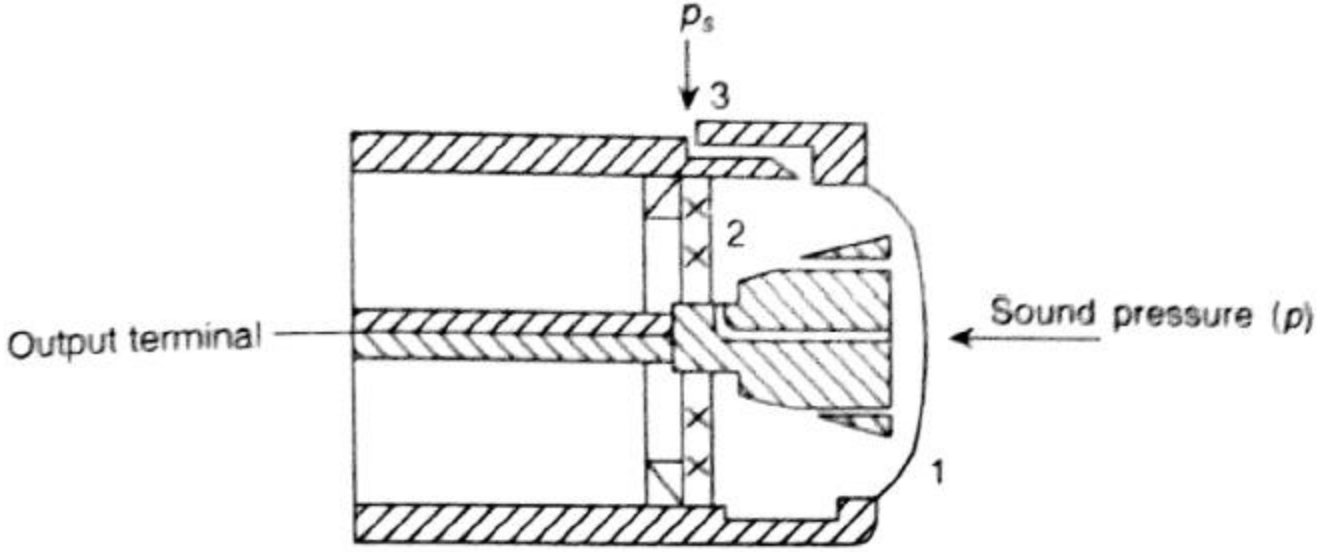
Machine vision/Pattern recognition



Piezoresistive array sensor.



PZT sensor acoustic pick-up system: 1. conical diaphragm with back-up plate, 2. PZT ceramic beam, 3. metallic support, 4. insulator.



Acoustic pressure sensor for static and dynamic pressure sensing:
1. diaphragm, 2. insulator, 3. air-leak.

Tutorial

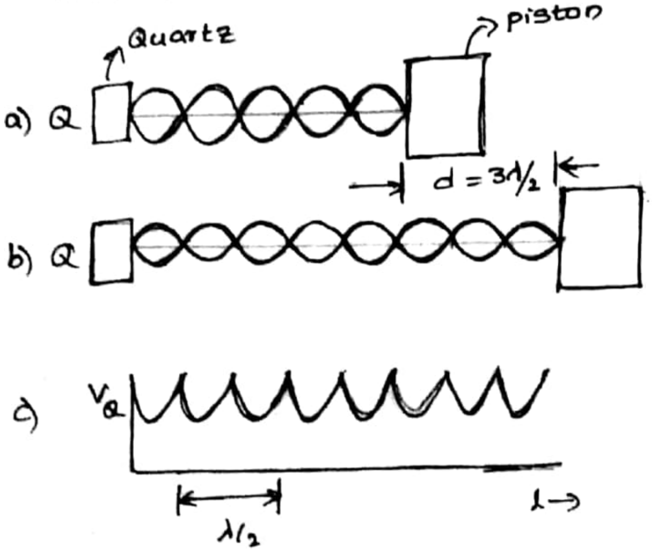
Acoustic Temperature Sensor :-

- When a longitudinal sound wave propagates through an ideal gas or any non ideal gas, by knowing its speed, temperature can be calculated.
- When a longitudinal wave propagates through an ideal gas, its speed is $C_i = \left(\frac{\gamma RT}{M}\right)^{1/2}$ where

C_i = speed
$\gamma = \frac{C_p}{C_v} = \frac{5}{3}$ for mono atomic gases
M = Molecular weight of gas
R = Gas constant.
T = Temperature

$$\Rightarrow \boxed{T = \frac{MC_i^2}{\gamma R}}$$

- **Resonant Acoustic temperature sensor :-**
- The realization of this technique is made in acoustic helium interferometer.



Principles of acoustic temperature sensor
a) the system
b) the system with changed position of piston for maintaining resonance
c) the crystal o/p peak positions

- Q is quartz crystal.
- A quartz crystal excited to its resonant frequency, is used to transmit the wave through 'He' gas, to be faced by a piston.
- The wave reflects at piston.
- When the path length 'l' has multiple no. of half wavelengths and

correspondingly the gas column is set to resonate by moving piston, the crystal gives max. energy and hence V_a across crystal defines peak as shown in fig (c).

* If pistons moves by distance 'd' to give 'n' such peaks, then $\boxed{d = n\lambda/2}$ from this C_i can be calculated and hence T.

* The piston movement must be monitored accurately eg. 1 μm.

For non ideal gas :-

Vander waal's equation is used for correction.

$$V-b\left(P-\frac{a}{V}\right) = MRT$$

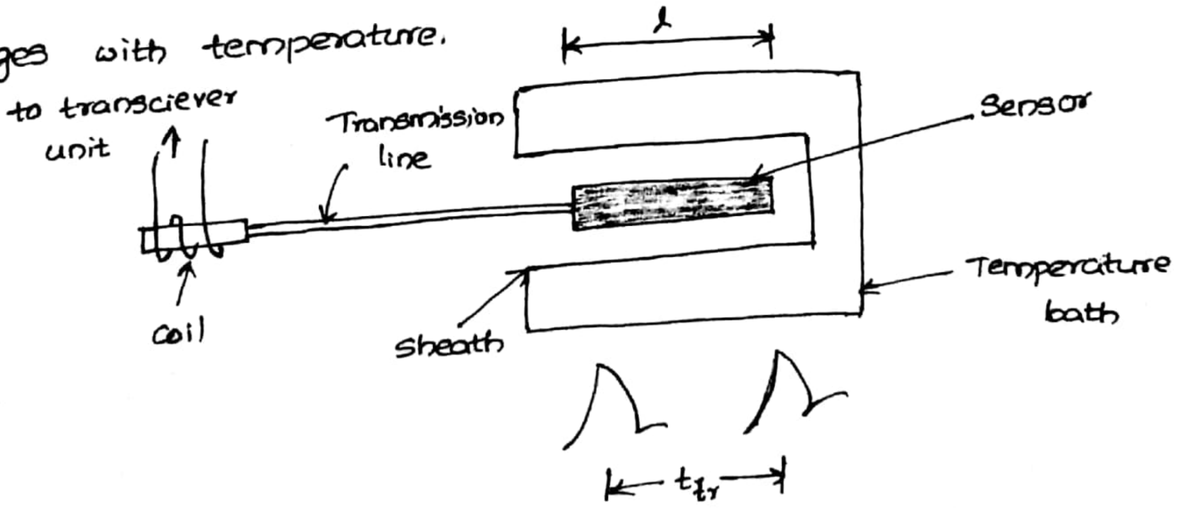
a, b are functions of molecular constants.

Corrected Speed $C_c = \sqrt{\frac{\gamma RT}{M}\left[1+\frac{\alpha P}{RT}\right]}$

where α is a function of a, b, T & V.

* There is a non resonant acoustic sensor :-

* ~~There is~~ It utilizes the pulse-echo transit time difference which changes with temperature.



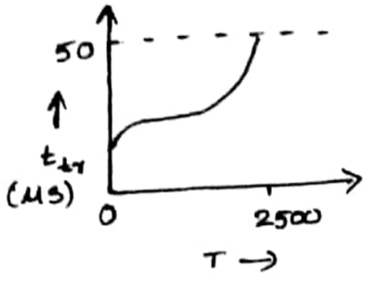
* The ultrasonic pulse is transmitted through the sensor, a part of which is reflected at the entrance and a part at the end.

* The reflected pulses are received by the transceiver coil at an interval of transit time t_{tr}.

* The pulse that travels the entire length of the sensor is delayed depending on the change in sensor temperature.

* The temperature depends on path length 'l'
sensor material
temperature range
vibration mode

Material	Temperature range (°c)
Aluminium	≤ 500
Stainless Steel	≤ 1100
Sapphire	≤ 1600
Molybdenum, Ruthenium	≤ 2100
Wolfrum, Rhenium, ThO_2- W (2%)	≤ 2700



Transit time Vs Temperature

* Sensor can be made in the form of thin wire with restrictions or constrictions.

* Diameter varies from : 0.03 – 3 mm
Spacing b/w restrictions : 5 – 10 mm
Sensor length : 15 – 50 mm

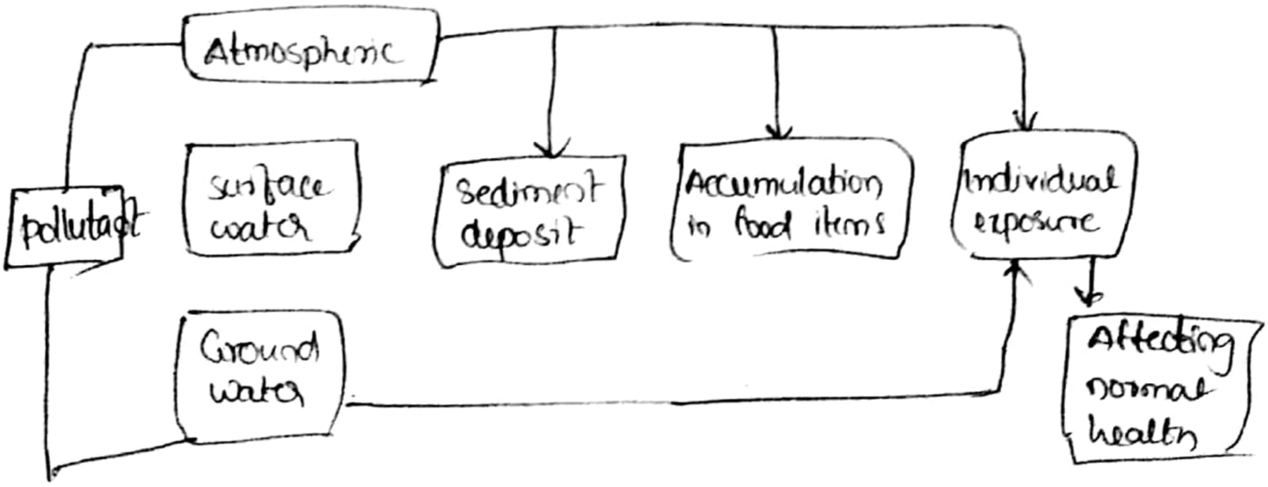
* There should not be inhomogeneity in the material.

10/5/18

SENSORS & TRANSDUCERS

- Sensor for environmental monitoring
  - Entire living world is now at risk on counts of health and normal survivality due to hazards arising out of biological chemical and radiation
- This cannot be done in a simple way by measuring temperature of hot body - infact, a few steps are involved in monitoring
- As environment is affected by pollution, pollutants are to be identified.
- The three main ways of spread of pollution is

  (i) Atmosphere (ii) Surface water (iii) Ground water.



- Again monitoring the environment pollution (again) involves three steps
  1. collection of sample representive enough of environmental pollution content.
  2. pre-treatment of sample using extraction, separation
  3. Analysis for identification and qualification and expressing it in proper level of concentration

Primary sensor

→ Existing Sensors of all kind with a Cascaded block for providing electrical output in the from Voltage or Current adapted to an integrated processingsystem.

→ These System Can hardly Called a Smart Sensors

→ External stimuli such as strain/stress, thermal/optical agitation, and electric/magnetic field change the behaviours of materials at atomic/molecular level or in Crystalline state

→ This Concept is utilized in designing a primary sensing element. to yeld maximized output

→ It is not an easy task as a particular material block has to be developed as a Controlled system responding maximally.

→ For reliable operation of a sensor environmental Conditions have to be maintained where parasitic effects do exist though limited.

→ These effects are eliminated by correcting in the processing unit.

→ A Sensor has its own characteristics which Can be broadly classified as
a) Static b) dynamic c) reliability and d) response/Sensitivit

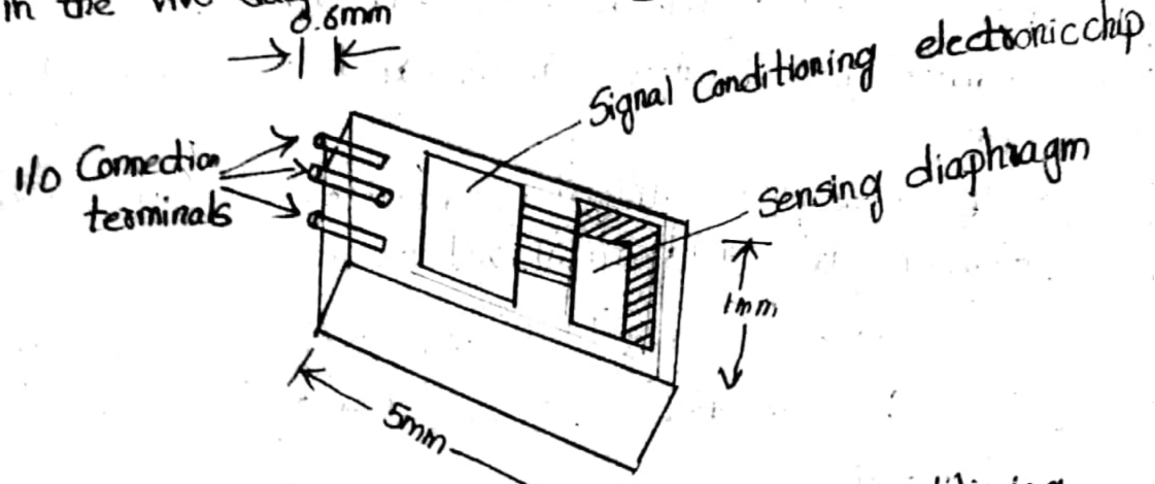
→ Since electrical/electronic Circuts are now largely Si-based, Silicon has been an element of interest for primary sensing element

→ Electrical behaviours of Si changes with change in temperature, electrical and magnetic field, stress/strain radiation and doping

→ Silicon thermo sensors and chemical sensors have also produced A Single chip realization of primary advanced to the extent of developing Smart Sensor.

→ Further extension of the Same to smart transmitter where Communication b/w these and the Control gears receives equal emphasis.

→ Si based microsensor technology has been of great use in the vivo adaption of various types of sensors.



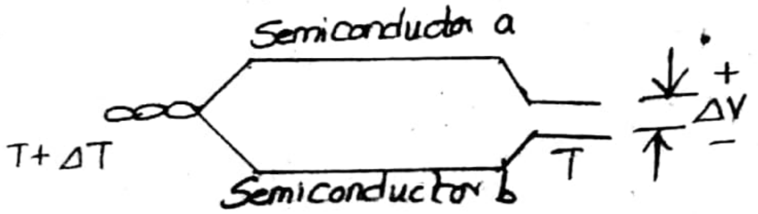
Single chip pressure sensor with signal Conditioning units.

→ A single transistor temperature is well-known.

→ Thermal sensors based on thermoemf or Seeback effect in the form of thermopiles have also been made in ICs.

→ Two Semiconductors are Coupled together with a difference of temperature ΔT b/w the Junction, the open Circuit emf ΔV is given by the relation

$$\Delta V = \alpha_s \Delta T$$



α_s is the Seebeck Coefficient.

If E_f is the fermi energy so that with charge q, the electrochemical potential ϕ_f is given by

$$\phi_f = \frac{E_f}{q}$$

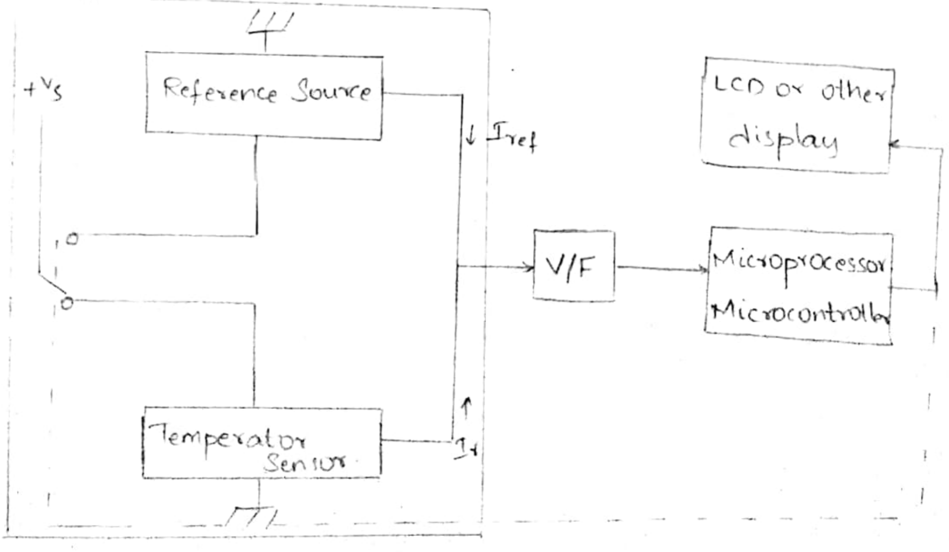
8/6

Information Coding / Processing.

Sensor signal is processed providing correction, compensation, linearization, freedom from cross-sensitivity and drift, and so on. Such a processed signal is finally made available in digital form and, perhaps, in serial form. Smart sensors are generally multi-sensor systems and a number of signals are available for either display or further processing subsequently to be connected to the 'communication bus'.

Information, the state of the process in the form of a processed signal through sensor and signal processing systems, is first received by information coding system. Some of these signals are released, some stored, some destroyed, and some ~~reconstructed~~ restructured.

For indication purposes only, the signals are coded and displayed over appropriate display modules as in digital meters, indicators.



A typical IC-temperature based smart sensor

(8) adapted to force-sensing in the load cell form.

When these signals are required to be used for system control and survelliance as is usually the case, in addition to display, control system should be able to read the signals for their functioning. Information processing assembly in a smart sensor is basically an encoder. the encoded data from this are fed to the communication unit. The conventional signal processing provides an output of 4-20mA. One way is to get a corresponding voltage range ~~pa~~ which is then encoded parallely into digital signal through converter. Voltage-to-frequency converter is another kind which is ~~quiel~~ quite extensively used, then using a reference frequency generator, frequency difference encoding is employed.

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

COGNITIVE LEVEL MAPPING

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…GR17A3152

Name of the Faculty: U.Vijaya laxmi Dept: ..EEE…

Subject :S&T

CO	Cognitive Learning Level					
	1	2	3	4	5	6
1					X	
2	X					
3		X				
4					X	
5			X			
6			X			
7			X			

Cognitive Learning Levels:

CLL1: Remembering

CLL2: Understanding

CLL3: Applying

CLL4: Analyzing

CLL5: Evaluating

CLL6: Creating

ASSESSMENT METHODS:

1. Regular attendance to classes.
2. Written tests clearly linked to learning objectives
3. Classroom assessment techniques like tutorial sheets and assignments.
4. Seminars.

1. **Program Educational Objectives (PEOs) –Vision/Mission Matrix** (Indicate the relationships by mark "X")

PEOs	**Mission of department**			
	Higher Learning	Contemporary Education	Technical knowledge	Research
Graduates will have a successful technical or professional careers, including supportive and leadership roles on multidisciplinary teams	H	H	H	H
Graduates will be able to acquire, use and develop skills as required for effective professional practices		H	H	M
Graduates will be able to attain holistic education that is an essential prerequisite for being a responsible member of society	H	M	H	M
Graduates will be engaged in life-long learning, to remain abreast in their profession and be leaders in our technologically vibrant society.	H		H	H

2.Program Educational Objectives(PEOs)-Program Outcomes(POs) Relationship Matrix (Indicate the relationships by m

P-Outcomes PEOs	a	b	c	d	e	f	g	h	i	j	K	l
1	M	M			H			H		H		H
2	M	M			H			H			H	
3			M	M	H	H	H					H
4				M	M	H	M	H	H		M	H

3. Course Objectives-Course Outcomes Relationship Matrix (Indicate the relationships by mark "X")

Course-Outcomes Course-Objectives	1	2	3	4	5	6	7
1	X	X		X			X
2	X		X	X	X	X	X
3		X	X	X	X		
4	X		X	X	X	X	X

4.Course Objectives-Program Outcomes (POs) Relationship Matrix
(Indicate the relationships by mark "X")

P-Outcomes C-Objectives	a	b	c	D	e	f	g	h	I	j	K	L
1	X	X	X		X		X	X			X	X
2	X				X		X		X	X		X
3	X	X	X	X	X		X	X		X	X	X
4	X				X				X		X	

5. Course Outcomes-Program Outcomes(POs) Relationship Matrix (Indicate the relationships by mark "X")

P-Outcomes C-Outcomes	a	b	c	D	e	f	g	h	I	j	k	l
1	H	H	H	M		H		M	H		H	H
2		H	H	M		H		M	H	H	H	H
3	H	M		H		H	H		M			M
4	H		H	M		M	H	M	M		H	M
5	H	H	M	M		H	H	H			H	M
6		H	H	M		H	H	M	H	M	H	H
7	H	H	H	M		H		M	H		H	H

6.Courses (with title & code)-Program Outcomes (POs) Relationship Matrix (Indicate the relationships by mark "X"

P-Outcomes Courses	a	b	C	d	e	f	g	h	I	j	k	l
S&T- GR15A3162	X	X	X	X	X	X	X		X	X	X	X

7. **Program Educational Objectives (PEOs)-Course Outcomes Relationship Matrix** (Indicate the relationships by mark "X")

P-Objectives(PEO) Course-Outcomes	1	2	3	4
1	X		X	X
2	X	X		X
3		X		X
4	X	X	X	
5		X	X	
6		X		X
7	X	X		X

8.Assignments & Assessments-Program Outcomes (POs) Relationship Matrix (Indicate the relationships by mark "X")

P-Outcomes Assessments	a	b	c	d	e	f	g	h	i	j	k	l
1	X			X	X	X	X	X	X	X		
2	X				X	X			X			
3	X			X	X	X		X	X	X		X
4	X	X		X			X		X		X	

9.Assignments & Assessments-Program Educational Objectives (PEOs) Relationship Matrix (Indicate the relationships by mark "X")

P-Objectives (PEOs) Assessments	1	2	3	4
1		X	X	X
2	X	X		X
3		X		X
4	X	X	X	X

Department of Electrical & Electronics Engineering

ASSIGNMENT / TUTORIAL SHEET – (for units 1 to 5)

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**.… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…GR17A3152

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Q1. What are the different types of magnetic sensors? On what principles do they work? Outline briefly.

Q2. What is basically the concept of 'smart sensors'? What are the essential elements in such an unit? Show with the help of a diagram, the arrangement of these elements

Q3. Draw the sketch of a laser beam operated system of distance sensing and explain its operation. What types of detectors are used here?**(**

Please write the Questions / Problems / Exercises which you would like to give to the students and also mention the Objectives/Outcomes to which these Questions / Problems / Exercises are related.

Objective Nos.:
……………1,3&4…… ………………………………………………………………….

Outcome Nos.:
………………4,5&6… ………………………………………………………………….

Signature of HOD Signature of faculty

Date: Date:

*** copies of student written assignments sheets will be filed for proof ***

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

EVALUATION STRATEGY

Academic **Y**ear : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech**……**… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…GR17A3152

Name of the Faculty: U.Vijaya laxmi Dept: ..EEE…

Designation: Assistant Professor

1. TARGET:

A) Percentage for pass:40%

b) Percentage of class:85%

2. COURSE PLAN& CONTENT DELIVERY
(Please write how you intend to cover the contents: i.e., coverage of Units/Lessons by lectures, design, exercises, solving numerical problems, demonstration of models, modelpreparation, experiments in the Lab., orbyassignments,etc.)

3. METHOD OF EVALUATION

3.1 ☐ Continuous Assessment Examinations (CAE-I, CAE-II)

3.2 ☐ Assignments/Seminars

3.3 ☐ Quiz

3.4 Semester/ End — Examination ☐

4. List out any new topic(s) or any innovation you would like to introduce in teaching the subjects in this Semester.

…………………………………………………………………………………………………..

Signature of HOD	Signature of faculty
Date:	Date:

RUBRIC

OBJECTIVE: **Work effectively with others**

STUDENT OUTCOME: **Ability to function in a multi-disciplinary team**

S.No.	Student Name	Performance Criteria	Unsatisfactory	Developing	SatisfactorY	Exemplary	Score
			1	2	3	4	
1.	Vikas	**Research & Gather Information**	Does not collect any information that relates to the topic.	Collects very little information some relates to the topic	Collects some basic Information most relates to the topic.	Collects a great deal of Information all relates to the topic.	2
		Fulfill team role's	Does not perform any duties of assigned team role.	Performs very little duties.	Performs nearly all duties.	Performs all duties ofassigned team role.	3
		Share Equally	Always relies on others to do the work.	Rarely does the assigned work--often needs reminding.	Usually does the assigned work--rarely needs reminding.	Always does the assigned work without having to be reminded	2
		Listen to other team mates	Is always talking--never allows anyone else to speak.	Usually doing most of the talking--rarely allows	Listens, but sometimes talks too much.	Listens and speaks a fair amount.	3

				others to speak.			
						Average score	2.5
2.	Akhila	**Research & Gather Information**	Does not collect any information that relates to the topic.	Collects very little information --some relates to the topic	Collects some basic information--most relates to the topic.	Collects a great deal of information--all relates to the topic.	3
		Fulfill team role's	Does not perform any duties of assigned team role.	Performs very little duties.	Performs nearly all duties.	Performs all duties of assigned team role.	3
		Share Equally	Always relies on others to do the work.	Rarely does the assigned work--often needs reminding.	Usually does the assigned work--rarely needs reminding.	Always does the assigned work without having to be reminded.	3
		Listen to other team mates	Is always talking--never allows anyone else to speak.	Usually doing most of the talking--rarely allows others to	Listens, but sometimes talks too much.	Listens and speaks a fair amount.	3

				speak.			
						Average score	3
3	Prasanth	**Research & Gather Information**	Does not collect any information that relates to the topic.	Collects very little information --some relates to the topic	Collects some basic information--most relates to the topic.	Collects a great deal of information--all relates to the topic.	4
		Fulfill team role's	Does not perform any duties of assigned team role.	Performs very little duties.	Performs nearly all duties.	Performs all duties of assigned team role.	4
		Share Equally	Always relies on others to do the work.	Rarely does the assigned work--often needs reminding.	Usually does the assigned work--rarely needs reminding.	Always does the assigned work without having to be reminded.	4
		Listen to other team mates	Is always talking--never allows anyone else to speak.	Usually doing most of the talking--rarely allows others to speak.	Listens, but sometimes talks too much.	Listens and speaks a fair amount.	4
						Average	4

						score	

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

COURSE COMPLETION STATUS

Academic Year : 2018-2019

Semester : II

Name of the Program: EEE……… B.Tech……… Section: A/B

Course/Subject: …Sensors and Transducers…Code:…GR17A3152

Name of the Faculty: U.Vijaya Laxmi Dept: ..EEE…

Designation: Assistant Professor

Actual Date of Completion & Remarks, if any

Units	Remarks	No. of Objectives Achieved	No. of Outcomes Achieved
Unit 1	Completed on 10/01/18	1	2
Unit 2	Completed on 30/01/18	2	3
Unit 3	Completed on 21/02/18	3	5
Unit 4	Completed on 08/03/18	4	6
Unit 5	Completed on 02/04/18	4	7

Signature of HOD

Date:

Signature of faculty

Date:

Note: After the completion of each unit mention the number of Objectives & Outcomes Achieved.

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

CO Attainment I Mid Sec-A &B

S.NO	ROLL NO.	1[CO2]	2[CO1]	3[CO4]	4[CO4]
1	15241A0243		2	2	
2	16241A0201	1			
3	16241A0202	3	4		2
4	16241A0203	5	5	5	
5	16241A0205	2	2	2	
6	16241A0206	4	5	4	
7	16241A0207	2	1	3	
8	16241A0208	4		1	
9	16241A0209	5	5	4	
10	16241A0210	1	2	2	
11	16241A0211	1	3	4	
12	16241A0212			5	
13	16241A0213	5	4		5
14	16241A0214	2	2	1	
15	16241A0216	1		1	
16	16241A0217	5	5	5	
17	16241A0218		1	4	2
18	16241A0219	2	2		2
19	16241A0220	1	2		
20	16241A0221	5	4		
21	16241A0222	2	2		
22	16241A0223		5	5	5
23	16241A0224			2	
24	16241A0225	3	4		4
25	16241A0226		4	4	4
26	16241A0227	4	4		3
27	16241A0228				
28	16241A0229			5	
29	16241A0230		2	5	
30	16241A0231	2	1	2	
31	16241A0232				
32	16241A0233	3	3		1
33	16241A0234	2	3		3
34	16241A0235	2	2		2
35	16241A0236		4	1	2
36	16241A0237			1	
37	16241A0238		1	1	
38	16241A0239			4	2
39	16241A0240	5	5	3	
40	16241A0241		2	1	2
41	16241A0242	5	5	4	
42	16241A0243	3	3	2	
43	16241A0244	3	4		1
44	16241A0245	5			2
45	16241A0246	5	5	4	

46	16241A0247	5	4	4	
47	16241A0248	5	4	4	
48	16241A0249	3	4	4	
49	16241A0250	4	5	5	
50	16241A0251	3	2		
51	16241A0252	4	5		2
52	16241A0253		1	1	1
53	16241A0254	3	5	5	
54	16241A0255	4	2		2
55	16241A0256	5	5	5	
56	16241A0257	4	3	4	
57	16241A0258	1	2	1	
58	16241A0259	5	5	5	
59	16241A0260	2	2	1	
60	17245A0201	5	5	3	
61	17245A0202	2	3		
62	17245A0203	2	2	1	
63	17245A0204	3	3	3	
64	17245A0205	5	5	5	
65	17245A0206	1	1		2
66	17245A0207	2	3	3	
67	17245A0208		1	1	
68	17245A0209	5	5	5	
69	17245A0210	4	3	4	
70	17245A0211				
71	17245A0212	5	5	5	
		1[CO2]	2[CO1]	3[CO4]	4[CO4]
	Grand Total	175	191	154	49
	NSA	53	58	48	20
	Attempt %=(NSA/Total no of students)*100	74.6479	81.69	67.606	28.169
	Average (attainment)= Total/NSA	3.30189	3.293	3.2083	2.45
	Attainment % = (Total/no.of max marks*no.of students attempted)*100	49.2958	53.8	43.38	13.803

S.NO	ROLL NO.	1[CO2]	2[CO1]	3[CO4]	4[CO4]
1	16241A0261	4	5	5	
2	16241A0262	5	5	5	
3	16241A0263	3	3		1
4	16241A0264		1		
5	16241A0265	1	1		1
6	16241A0266		3	5	5
7	16241A0267		5	3	5
8	16241A0268	5	5		1
9	16241A0269	5	5	5	
10	16241A0270		5	4	
11	16241A0271		2	5	2
12	16241A0272	5	5	5	
13	16241A0273	2	5		
14	16241A0274	5	5	5	
15	16241A0275		4	3	2
16	16241A0276	5	5		4
17	16241A0277	1		1	
18	16241A0278	5	3	5	
19	16241A0279		5	3	2
20	16241A0280	2	3		2
21	16241A0281	4	3	2	
22	16241A0282	2		2	3
23	16241A0283		1	1	
24	16241A0284		1	1	
25	16241A0285	5	5		3
26	16241A0286	2			4
27	16241A0287		1	1	1
28	16241A0288		3		
29	16241A0289	2	3		3
30	16241A0290	5	5	4	
31	16241A0291	1	3		2
32	16241A0292		5	4	5
33	16241A0293	2		3	3
34	16241A0294		2		
35	16241A0295	2	3		2
36	16241A0296		5		2
37	16241A0297		5	2	2

38	16241A0298				2
39	16241A0299		4	1	1
40	16241A02A0		5	2	2
41	16241A02A2		3	1	3
42	16241A02A3	3	2		1
43	16241A02A4	2	4		3
44	16241A02A5	5	5	5	
45	16241A02A6				2
46	16241A02A7		5	5	5
47	16241A02A8	5	5	5	
48	16241A02A9		1	5	2
49	16241A02B0		2		2
50	16241A02B1		4	2	2
51	16241A02B2		2		2
52	16241A02B3	3	4		1
53	16241A02B4		4	5	2
54	16241A02B5		5	5	3
55	16241A02B6	4	3		2
56	16241A02B7		5	5	5
57	16241A02B8	3	5	4	
58	16241A02B9		4	1	1
59	17245A0213	1	3	1	
60	17245A0214	5	5	5	
61	17245A0215	**5**	**4**		
62	17245A0216	4	3		
63	17245A0217			1	2
64	17245A0218		5	4	5
65	17245A0219	5	5		1
66	17245A0220	5	4	4	
67	17245A0221	5	5	4	
68	17245A0222	3	3		2
69	17245A0223		4	4	2
70	17245A0224	3			
71	18241A0201		5	5	4
		1[CO2]	2[CO1]	3[CO4]	4[CO4]
	Grand Total	134	233	143	108
	NSA	38	62	42	44
	Attempt %=(NSA/Total no of students)*100	53.5211	87.32	59.155	61.972
	Average (attainment)= Total/NSA	3.52632	3.758	3.4048	2.4545
	Attainment % = (Total/no.of max	37.7465	65.63	40.282	30.423

	marks*no.of students attempted)*100				

[CO2]	43.7
[CO1]	60.15
[CO4]	32.07

GOKARAJU RANGARAJU
INSTITUTE OF ENGINEERING AND TECHNOLOGY

Department of Electrical & Electronics Engineering

CO Attainment II Mid Sec-A &B

S.NO	ROLL NO.	Name of the Student	1[CO7]	2[CO5]	3[CO6]	4[CO3]
1	15241A0243	R.Raashik Kumar			5	5
2	16241A0201	AARE UPENDRA		5	5	
3	16241A0202	AENUGULA RAJENDHAR	2		5	5
4	16241A0203	ALLA NAGA SAI KEERTHI	5	5		5
5	16241A0205	APPALA BHAVANI SRIJA		3	4	5
6	16241A0206	ARUKALA PRANATHI	5	5	5	
7	16241A0207	BADDAM ARUN			5	5
8	16241A0208	BANDHARI GALLA ROHIT RAO			5	5
9	16241A0209	BHAIRISHETTI HEMANTHKUMAR	5	5	5	
10	16241A0210	BHUKYA KOUSHIK ARYAN			5	5
11	16241A0211	CHALLA SAI SURESH REDDY	3	2		5
12	16241A0212	CHUPPALA ROHITH RAVI RAJA		5	5	
13	16241A0213	DESABATHINA TEJASWI	5	5	3	
14	16241A0214	GEORGE MICHAEL	5	5		
15	16241A0216	GADDEY MOHAN KRISHNA SAI			5	5
16	16241A0217	GADEELA VISHAL	5		5	5
17	16241A0218	GARLAPATI VARUN GUPTA			5	5
18	16241A0219	GUGULOTH SUMAN	5	5	5	
19	16241A0220	GUNDA SAITEJA			5	5
20	16241A0221	JAGARAPU SIDDI SAI SATVIK		2	5	5
21	16241A0222	K TONISHA	5	5	5	
22	16241A0223	K. VIKAS	5		5	5
23	16241A0224	KONDEPUDI LAKSHMI GANESH	5		5	5
24	16241A0225	KALYANAMPUDI VINOD KUMAR	5	5	5	
25	16241A0226	KAMMARI HARISH	5	5	5	
26	16241A0227	KARIVEDA ANJALI		5	5	
27	16241A0228	KOTHA RMAYA SREE			5	5
28	16241A0229	KUMMARI LAKSHMI NARAYANA			5	5
29	16241A0230	LYADELLA SAINATH			5	5
30	16241A0231	M. VENUGOPAL	5	2	5	
31	16241A0232	M.NITIN KUMAR				
32	16241A0233	MANDARI RUPESH		5	5	
33	16241A0234	M MANIKANTA			5	5
34	16241A0235	MARELLA V RAJ KUMAR	5	3	5	
35	16241A0236	MATTA SESHU KUMAR		5	5	
36	16241A0237	MD AKEEM PARVEZ			5	5
37	16241A0238	MEENUGU REVANTH			5	5
38	16241A0239	MOHAMMED KHALEEF			5	5
39	16241A0240	MOKA DURGA PRASHANTH		5	3	5
40	16241A0241	MOOD SUMAN		3	2	5
41	16241A0242	MUNAGALA KARUNYA		5	2	5
42	16241A0243	NALAGAMA MALATHI	5	5	5	
43	16241A0244	P SHRAVAN KUMAR	5	5		

44	16241A0245	PENAGANTI SURYA SRIRAM	5			5
45	16241A0246	RAMPALLY SURYA TEJA		1	5	5
46	16241A0247	REKULGI MANISHA	5		5	
47	16241A0248	RIMAH	5	5	5	
48	16241A0249	SAI HAVANIKA		5	5	5
49	16241A0250	SANKATALA PRANAY KUMAR		5	5	
50	16241A0251	SHIVEN GOYEL		5	5	
51	16241A0252	SIMRAN AGARWAL		5	5	5
52	16241A0253	TETALA SURYA VENKATA NAGASAI PRANEETH REDDY		5	5	
53	16241A0254	T SRIVASTAVI				
54	16241A0255	THUMU MANIDEEP		5	5	5
55	16241A0256	TUMULA SRIVIDYA	5	5	5	
56	16241A0257	UNDETY MOUNIKA	5	5	5	
57	16241A0258	VEGESNA NAGA MEGHANA	5	5	3	
58	16241A0259	VIPPARTHI SOWMYA	5	5	5	
59	16241A0260	YELLOJU BHARATH RAJKUMAR		5	5	
60	17245A0201	AKULA CHANDANA	5	5		5
61	17245A0202	A IRMIA		2	5	5
62	17245A0203	BODDU SHASHANK	5	5	1	
63	17245A0204	CHATLA SUDHIR KUMAR			5	5
64	17245A0205	CHILUKA PRANAVI	5	5		5.0
65	17245A0206	DEVATH SRIKANTH	5	5	1	
66	17245A0207	DULLA AKSHAY KUMAR YADAV		5	5	
67	17245A0208	DUNNA SRIKANTH	5	5	1	
68	17245A0209	GARIKAPATI ANNAPURNA KARTHIKA	5	5		5
69	17245A0210	GOPANAPELLY SHRAVANI	5	5		5
70	17245A0211	G SANDEEP KUMAR	5	5	5	
71	17245A0212	G VASAVI	5	5		5
			1[CO7]	2[CO5]	3[CO6]	4[CO3]

Grand Total	165	218	265	180
NSA	34	48	58	36
Attempt %=(NSA/Total no of students)*100	47.89	67.61	81.69	50.704
Average (attainment)= Total/NSA	4.853	4.542	4.569	5
Attainment % = (Total/no.of max marks*no.of students attempted)*100	46.48	61.41	74.648	50.704

S.NO	ROLL NO.	Name of the Student	1[CO7]	2[CO5]	3[CO6]	4[CO3]
1	16241A0261	A PRASHANTH	3		5	5
2	16241A0262	ADEPU SOWMYA	5	5	5	
3	16241A0263	AMGOTH RISHITHA PAMAAR		5	5	3

4	16241A0264	ARVIND NAIDU				
5	16241A0265	BOLISHETTI SAIJEEVAN			3	5
6	16241A0266	BOLLUR YASHWANT	5	5		2
7	16241A0267	BOMRASPET PHANIDER	5	5	5	
8	16241A0268	CHALLAGUNDLA SOWMYA	5			5
9	16241A0269	CHINTAPOOLA SWATHI	5	5	5	
10	16241A0270	DESHPANDE PRAVALIKA	5		5	5
11	16241A0271	GONE SOWMYA	5		5	
12	16241A0272	GOPIDI VENKAT REDDY	5	5		5
13	16241A0273	GORENKALA MEGHA SAIKRISHNA	3		5	5
14	16241A0274	INDURI PAVANI	5	5	5	
15	16241A0275	JALAMANCHILI RAMA SURYAM		2	5	5
16	16241A0276	JONNAVALASA DEVI PRASAD		5	5	5
17	16241A0277	K V S SANDEEP	5	5		
18	16241A0278	KALYANAPU VENUGOPAL	5	5	5	
19	16241A0279	KANNE SACHIN		5	5	
20	16241A0280	KARAM SANDHYARANI	5	5	5	
21	16241A0281	KATTA MOUNIKA	5	5	5	
22	16241A0282	KIDAMBI SREE GOVIND	5		5	5
23	16241A0283	KOLLIPARA CHAITANYA SAI	5	5		
24	16241A0284	KONDA ANIL KUMAR	5		5	5
25	16241A0285	KUNCHALA MOHANBABU		5	5	2
26	16241A0286	LANKA ROHITHA SRI	5	5		5
27	16241A0287	MADAPATHI SACHIN	5	3	2	
28	16241A0288	MALAKA UDAYASAGAR	5	5		
29	16241A0289	MALAVATH JAIPAL	5	5		5
30	16241A0290	MANGANAPALLY ROOPA	5	5	5	
31	16241A0291	MOHAMMED KHALEEL			5	5
32	16241A0292	MUKKAMULA RAMYA SREE	5		5	5
33	16241A0293	MUNDRA SUBHASHINI	5	5		3
34	16241A0294	MYSA VINOD KUMAR	5		5	
35	16241A0295	NAGARAM VAMSHI	5	5		
36	16241A0296	NAGARAPU PRADEEP	5	5	5	
37	16241A0297	PATHAPATI DIVYA	5	5	5	
38	16241A0298	POTTA SURYATEJA	5		5	
39	16241A0299	PRODDUTUR MOHAN SAI		5	5	
40	16241A02A0	PUDOTA ADITYA CECIL RAJ			5	5
41	16241A02A2	SADANAVENA RAHUL	5	5	5	
42	16241A02A3	SAI TEJASWI NOOKA	5	5	5	
43	16241A02A4	SAKETH M	5		5	

44	16241A02A5	SANGEM SOUJANYA	5	5	5	
45	16241A02A6	SANGISETTY RAKESH SAGAR		1		
46	16241A02A7	SHASTRALA SRAVYA	5	5		5
47	16241A02A8	SURAM SHIRISHA	5	5	5	
48	16241A02A9	SURYA SANJAY BANDARI	5	5	5	
49	16241A02B0	T LAKSHMI ASRITH	5	5		
50	16241A02B1	TERATPALLY YESHWANTH	5	3	5	
51	16241A02B2	THELLA SAI KRISHNA		5	5	
52	16241A02B3	THOTAKURI VISHAL		3	1	1
53	16241A02B4	TUMMALACHARLA PRAVEEN	5	3	5	
54	16241A02B5	VANGA RITHVIKA	5	5	5	
55	16241A02B6	VIDYA KANURI	5	5	5	
56	16241A02B7	VINEESHA SRAVYA LAKSHMI . B	5		5	5
57	16241A02B8	VUJJINI HARSHITHA	5	5		5
58	16241A02B9	BHANU KAUSTUBA WALTATI		5		5
59	17245A0213	K RAGHAVENDER	5		5	
60	17245A0214	K VAISHNAVI	5	5		5.00
61	17245A0215	MANNELI KRANTHI KUMAR		**5**	**5**	
62	17245A0216	MARTHA REVAN KUMAR			5	5
63	17245A0217	MASANNAGARI RAKESH REDDY			5	5
64	17245A0218	NARSING SHRAVANI	5		5	5
65	17245A0219	PONNAM ADITHYA		2	5	5
66	17245A0220	POOSALA NAVYARANI	5		5	5
67	17245A0221	P SWATHI	5	5		5
68	17245A0222	SABAVATH PARAMESH		5	5	5
69	17245A0223	SHAIK ASIF AHMED		5	5	
70	17245A0224	SHAIK SOHEL		5	5	
71	18241A0201	K.AKHILA				
			1[CO7]	2[CO5]	3[CO6]	4[CO3]
	Grand Total		241	227	251	146
	NSA		49	49	52	32
	Attempt %=(NSA/Total no of students)*100		69.01	69.01	73.239	45.07
	Average (attainment)= Total/NSA		4.918	4.633	4.8269	4.5625
	Attainment % = (Total/no.of max marks*no.of students attempted)*100		67.89	63.94	70.704	41.127

1[CO7]	57.17
2[CO5]	62.65
3[CO6]	72.65
4[CO3]	45.91

Gokaraju Rangaraju Institute of Engineering & Technology
(Autonomous)

Summation of Teacher Appraisal by Student
Academic Year 2018-19

Name of the Instructor	U. Vijaya Lakshmi
Faculty ID	692
Branch	EEE
Class and Semester/Section	III / II / A
Academic Year	2018-19
Subject Title	Sensors&Transducers
Total No. of Responses/class strength	11/71

Average rating on a scale of 4 for the responses considered:

S. No	Questions of Feedback	Average
1	How do the teacher explain the subject?	3.5
2	The teacher pays attention to	3.6
3	The Language and communication skills of the teacher is	3.4
4	Is the session Interactive?	3.3
5	Rate your teacher’s explanation in clearing the doubts	3.1
6	Rate your teacher’s commitment in completing the syllabus	3.4
7	Rate your teacher’s punctuality	3.3
8	Rate your teachers use of teaching aids	3.1
9	Rate your teacher’s guidance in other activities like NPTEL, Moodle, Swayam, Projects.	3
10	What is your overall opinion about the teacher?	3.2

Net Feedback on a scale of 1 to 4: 3.29

Remarks by HOD:

____

Remarks by Principal:

____

Remarks by Director:

____