Development of Strain Gauge Pressure Transducer up to 2000 bar

Thesis submitted in partial fulfillment of the requirements for the award of
degree of

Master of Engineering
in
Electronics Instrumentation and Controls Engineering
by

ANUJ KUMAR
(Roll. No. 800851003)

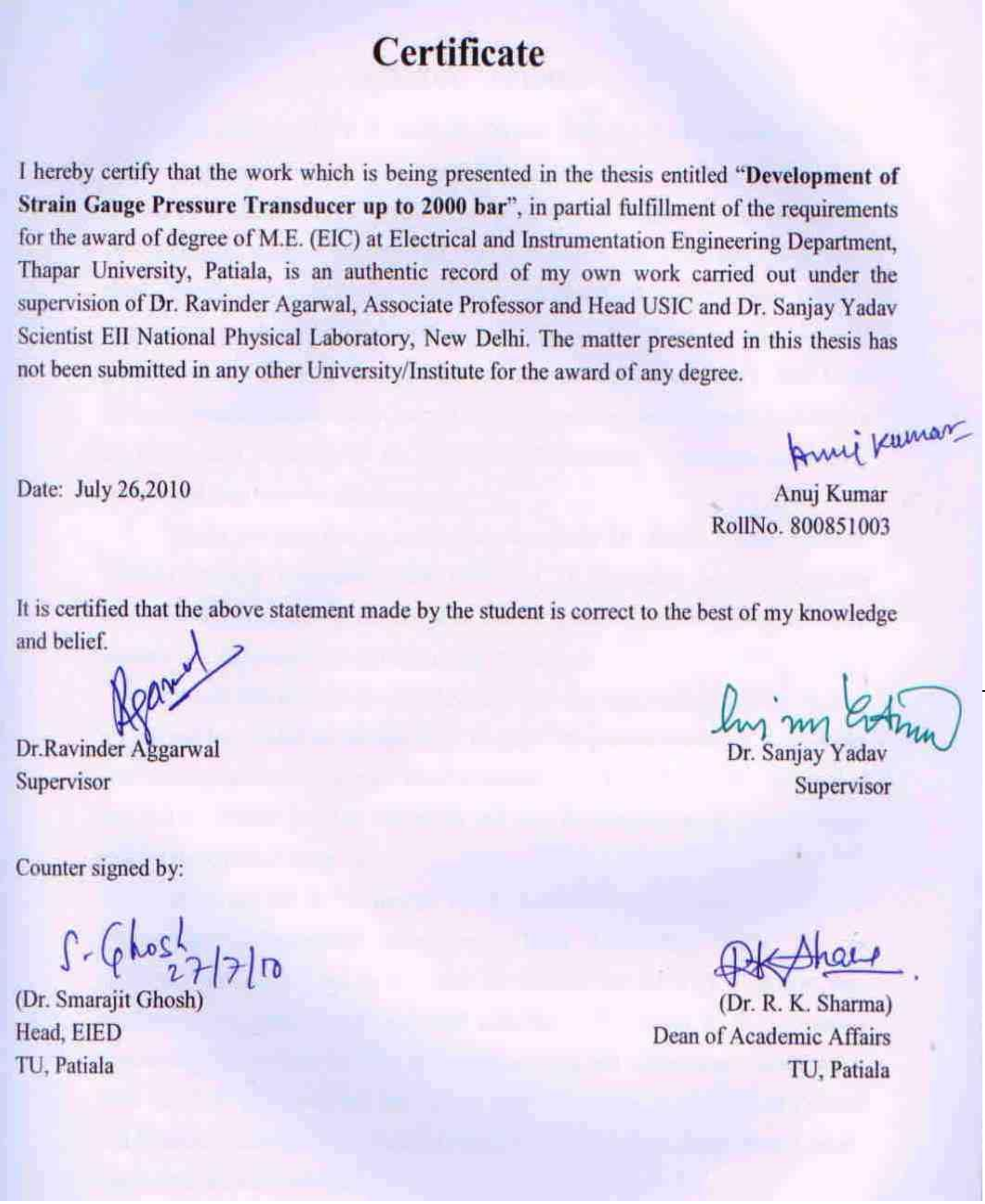
Dr. Ravinder Aggarwal
Associate Professor, EIED
Thapar University
Patiala

Dr. Sanjay Yadav
Scientist EII
National Physical Laboratory
New Delhi

DEPARTMENT OF ELECTRICAL AND INSTRUMENTATION ENGINEERING

THAPAR UNIVERSITY, PATIALA – 147004

July 2010



Certificate

I hereby certify that the work which is being presented in the thesis entitled "**Development of Strain Gauge Pressure Transducer up to 2000 bar**", in partial fulfillment of the requirements for the award of degree of M.E. (EIC) at Electrical and Instrumentation Engineering Department, Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of Dr. Ravinder Agarwal, Associate Professor and Head USIC and Dr. Sanjay Yadav Scientist EII National Physical Laboratory, New Delhi. The matter presented in this thesis has not been submitted in any other University/Institute for the award of any degree.

Anuj Kumar

Date: July 26,2010

Anuj Kumar
RollNo. 800851003

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Dr.Ravinder Aggarwal
Supervisor

Dr. Sanjay Yadav
Supervisor

Counter signed by:

S. Ghosh 27/7/10

(Dr. Smarajit Ghosh)
Head, EIED
TU, Patiala

(Dr. R. K. Sharma)
Dean of Academic Affairs
TU, Patiala

ACKNOWLEDGEMENT

I am grateful to Dr. R. C. Budhani, Director, National Physical Laboratory, New Delhi, for his permission to carry out this work. Thanks are also due to Dr. Rajeev Chopra, Head, Human Resources and Development Group, National Physical Laboratory for his valuable suggestions, encouragement and support. Dr. A. K. Bandhyopadhyay, Head, Vacuum and Pressure Standards, National Physical Laboratory, New Delhi is thanked for constructive contribution and discussions. I express my deep sense of gratitude towards Dr. T. K. Saxena, Scientist, National Physical Laboratory, New Delhi for his invaluable guidance, keen interest, useful suggestions, moral support, and making the environment conducive for the completion of the project. Without his support, the work would have been the statement only.

Thanks are also due to my project supervisors Dr. Sanjay Yadav, Scientist, National Physical Laboratory, New Delhi and Dr. Ravinder Agarwal, Associate Professor, Thapar University for their keen interest, guidance, encouragement, continued interests, intelligent criticism and stimulating discussions. I would like to thank the almighty God, who has been with me in every walk of my life and has guided me through every obstacle. My greatest thanks are to my father who bestowed ability and strength in me to complete this work. I am deeply indebted to him and my friends for their inspiration and ever encouraging moral support, which enabled me to pursue my studies. Thanks are also to Dr. Smarajit Ghosh, Head of the Department of Electrical & Instrumentation Engineering department, Thapar University, Patiala for his encouragement, support and for providing the facilities for the work. I am also very thankful to the entire faculty and staff members of Electronic & Instrumentation Engineering Department for their direct–indirect help and cooperation. Contributions from Mr. B. V. Kumaraswami, Mr. Sameer Swaroop and Mr. V. K. Gupta of Pressure and Vacuum Standards Group, National Physical Laboratory, New Delhi are also greatly appreciated and acknowledged.

Anuj Kumar

ABSTRACT

A number of pressure transducers, based on strain gauge, capacitance / inductance type, frequency resonators, are commercially available and are being used for sensing and producing an electrical output proportional to applied pressure. These sensors have their own advantages and limitations due to operational ease, linearity, hysteresis error, measurement uncertainty and the costs. Strain gauge type transducers are now well established devices for accurate and precise measurement of pressure within measurement uncertainty up to 0.1 % of full scale. In the present thesis work, an indigenous strain gauge pressure transducer has been designed, developed, tested and calibrated for pressure measurement up to 200 MPa or 2000 bar. The measurement uncertainty estimated using the pressure transducer is found better than 0.1 % of full scale. This transducer is developed using four foil type strain gages, bonded two in axial direction while other two in radial direction, to the controlled stress zones of a tubular maraging steel active cylinder working also as diaphragm. The strain gages are then connected to a Wheatstone bridge arrangement to measure stress generated strains. The pressure is applied through matching connector designed in the same tubular transducer active element. The treaded unique design in a single piece through collar, ferule and tubing arrangement provides leak proof pressure connections with external devices without using additional seals. The calibration and performance checking of the pressure transducer is carried out using dead weight type national pressure standard using the internationally accepted calibration procedure.

PREFACE

The last few decades have witnessed the growing need of the industrial utilization of pressure metrology day by day. Different principles and techniques are employed in pressure measuring devices for pressure measurements. Generally, a mechanical device provides a direct response to a pressure change, for example, change in the length of the column of mercury or change in the area of piston cylinder assembly or some times change in the mechanical stresses or change in the resistance of a coil etc. Thus the response function of a pressure-induced change can be monitored and quantitative information is possible. These sensors have their own advantages and limitations due to operational ease, zero shift, linearity, repeatability, long term stability and hysteresis in the measurement, uncertainty and the costs and sometime some of these limitations limit their practical applications as pressure standards.

The strain gauge type pressure transducers have been used in past as pressure standard. Such sensors are easy to design and cost effective. One of the features of such transducers is that they can be designed with extremely sharp resistance changes with the help of quality electronic circuitry and hence it is possible to detect very small changes in the resistance as a function of applied pressure. In order to avoid an effect of pressure transmitting media on the gauge characteristics, the guage is not directly exposed to the pressure transmitting media but is behind or embedded in the deflecting component. Based on our literature and product survey, it is evident that no indigenous pressure sensor is commercially available beyond 1500 bar within reasonable measurement uncertainty up to 0.1 % of full scale or better. In the present thesis work, an indigenous strain gauge pressure transducer has been designed, developed, tested and calibrated for pressure measurement up to 200 MPa or 2000 bar. The measurement uncertainty estimated using the pressure transducer is found better than 0.1 % of full scale.
The step by step procedure for the completion of the present developmental works is described in this thesis. The thesis is divided in to five Chapters as follows.

Chapter 1 gives brief introduction of concept of pressure, applications of accurate pressure measurements, its units and their conversions, pressure measurement techniques and the motivation of the present work.

Chapter 2 describes the details of strain gauge pressure transducers, literature survey and state of the art in the development of strain gauge pressure transducer. The details of strain gauge pressure transducers include basic design considerations, types, salient features, theoretical aspects, Wheatstone bridge balancing operations and its types.

Chapter 3 highlights the developmental activity of the strain gauge transducer developed in the present work. The details of the mechanical design considerations of the active element, diaphragm and casing, specifications of the strain gauges used, bonding of strain gauges with active element and electronics circuitry for power supply, amplification and signal conditioning are given.

Chapter 4 describes the calibration procedure of the developed transducers against dead weight pressure standard, results obtained and discussion.

Chapter 5 summarizes the conclusions, significance of the present work and future recommendations.

TABLE OF CONTENTS

Contents **Page No.**

Lists of Figures

Lists of Tables

CHAPTER- 1: INTRODUCTION

1.1. PRESSURE CONCEPT

What is fluid pressure? A container full of gas contains innumerable atoms and molecules that are constantly bouncing of its walls. The pressure would be the average force of these atoms and molecules on its walls per unit of area of the container. Fluid pressure can be defined as the measure of force per-unit-area exerted by a fluid, acting perpendicularly to any surface it contacts (a fluid can be either a gas or a liquid, fluid and liquid are not synonymous). Moreover, pressure does not have to be measured along the wall of a container but rather can be measured as the force per unit area along any plane. Air pressure, for example, is a function of the weight of the air pushing down on Earth. Thus, as the altitude increases, pressure decreases. Similarly, as a scuba diver or submarine dives deeper into the ocean, the pressure increases.

As mentioned above **pressure** is defined as force per unit area exerted by a fluid on the containing wall of a vessel with respect to a pressure, which is also usually known as **barometric pressure**. When the pressure is measured as force per unit area exerted by a fluid on the containing wall with respect to local ambient pressure then it is called **gauge pressure**. Gauge pressure can be either positive or negative and conveniently negative gauge pressure is also called as **'vacuum'**. If a vessel contains no molecules whatsoever, the force per unit area or pressure on containing wall would be zero. The pressures measured on the scale that uses this zero pressure as its reference point, are called **absolute pressure**. The absolute pressures are always positive. In some of the applications, the knowledge of pressure difference between two systems is required. In such cases, the reference pressure may not necessarily be either zero or atmospheric pressure but some other value. These pressures are known as **differential pressures**. The measurement of gauge, absolute and differential pressures is categorized as measurement of pressure in gauge, absolute and differential modes, respectively. These pressure modes are clearly illustrated in Fig. 1.1. The reference line of gauge pressure is not illustrated as straight line because of the changeable nature of atmospheric pressure.

The physical quantity "pressure" is a derived unit from base units of mass, length and time, dimensionally represented by p [$M L^{-1} t^{-2}$], as shown in Fig. 1.2. Pressure being an intensive, thermodynamic and mechanical quantity can not be added up but is realized by mechanical definitions or thermodynamic phenomenon (phase transitions in substance) for different pressure scales. The pressure is extremely important in fluid for its hydrostaticity principle and is defined as tensor for pressure applied to solids. The concepts are graphically represented in Fig. 1.2.

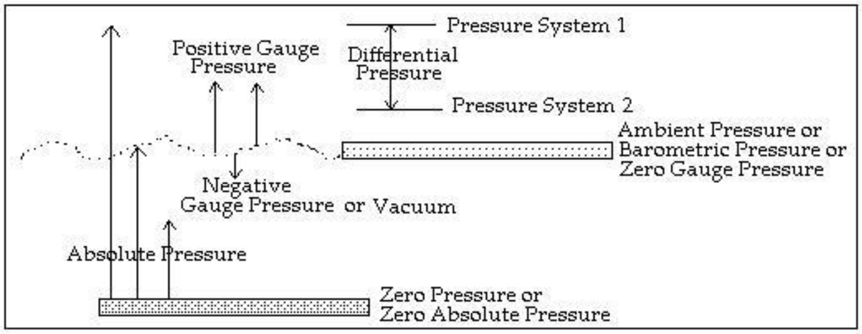


Fig.1.1: Different modes of pressure measurements

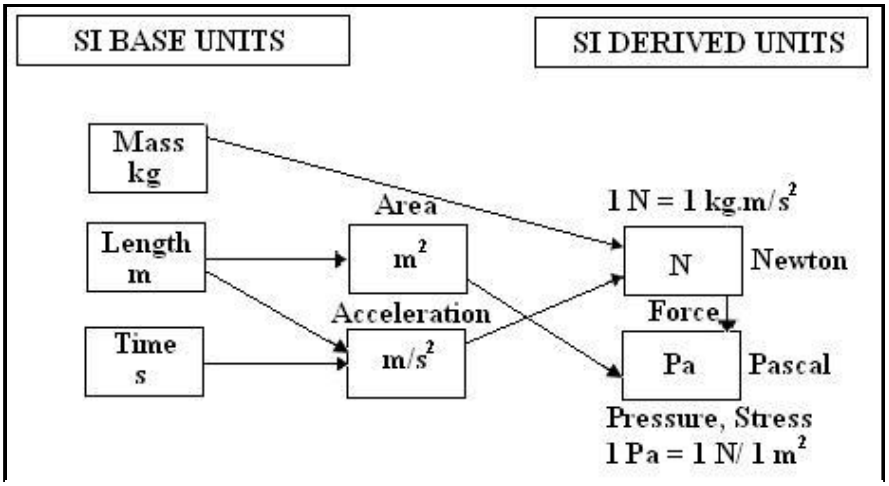


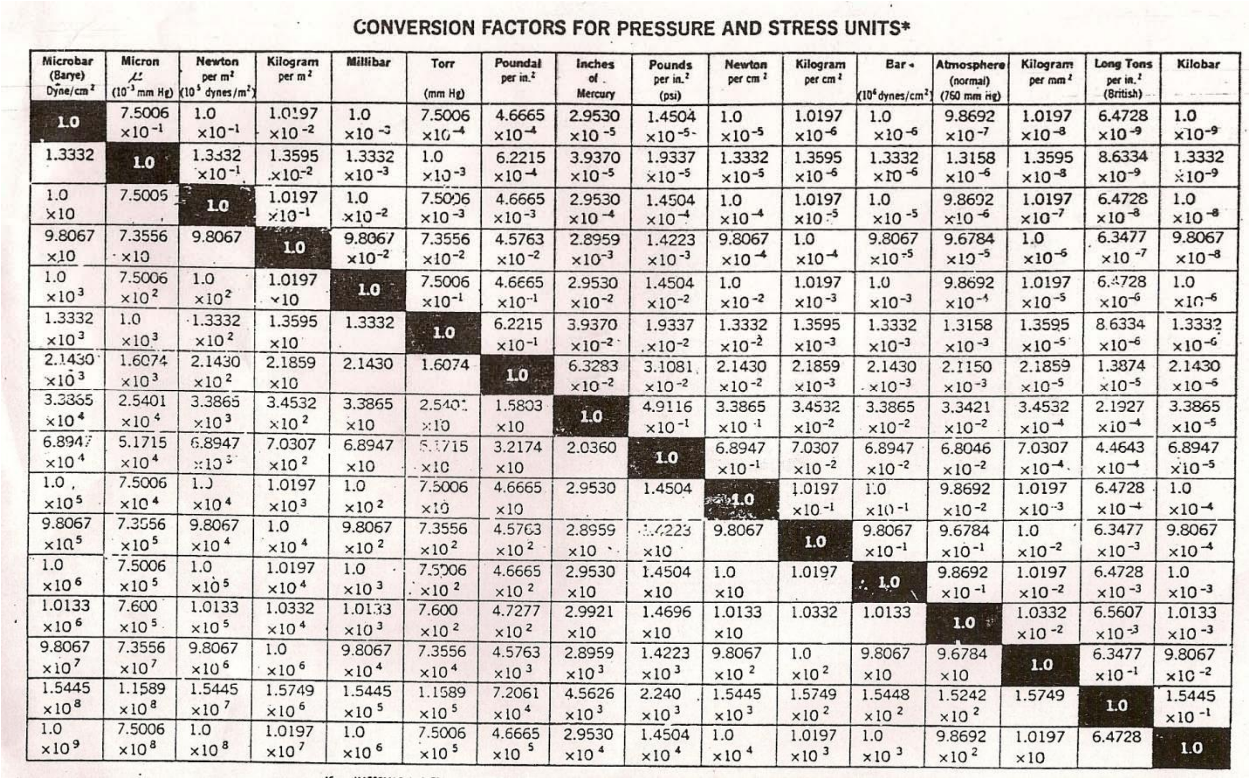
Fig. 1.2: Pictorial view of pressure as derived unit from base units

1.2. APPLICATIONS

Pressure is an important thermodynamic parameter and often called as the controlling parameter in the industry and must therefore be measured for control and optimization in many industrial applications. These applications include high pressure hot extrusion, cold forging of the metals, synthesis of the super hard materials, synthetic diamonds, geothermal applications, transport of fluid, automobile engines, tyros, refrigerators, furnaces, aircraft industry. In the absence of facilities for accurate measurement of pressure, certain processes cannot be used and optimized. The accurate pressure measurement is not only critical for the different processes in industries such as power generation, fertilizers, chemical, petrochemical, automobiles, aviation etc. but it is also essential for the human safety against hazards. Even a small-unnoticed thing i.e. the slight deviation from the optimum value of the tire pressure in automobiles or the pressure of the LPG cylinder for domestic cooking would affect the nation's economy. Oxygen monitoring gauges in the air-cabin, if not accurate, can create an unbearable atmosphere and cause irreparable image. If the pressure dial gauges at petrol pumps are not properly calibrated, then either the excess or less tire pressure would not only affect the fuel consumption and hence the national economy and loss to the individual but the driving would also not be comfortable and would lead to more wear and tear of the vehicles. The measurement of differential pressure at high line pressure is of increasing industrial importance especially in the field of fluid flow measurements and control. Important applications also include the metering of the flow of petroleum products from oil well to the refinery, control of coolant in nuclear power stations and the control of boiler feed water flow in electrical power generation etc.

1.3. PRESSURE UNITS AND CONVERSIONS

The standard SI unit of pressure is the **Pascal (Pa)** which is equivalent to one Newton per square meter (**N/m**^{2}) i.e. **1 Pa = 1 N/m**^{2}where N (newton) is the name of the unit for force. Pressure can be expressed in many different units including in terms of a height of a column of liquid. The special name pascal was adopted by the 14th Conférence Général des Poids et Mesures (CGPM) in 1971 for the SI unit newton per square metre [1]. The pascal unit can be used with multiples (daPa, hPa, kPa, MPa, GPa and TPa) and submultiples (dPa, cPa, mPa, µPa, nPa). Another commonly used and internationally accepted non - SI unit is **bar**, 1 bar = 10^5 Pa = 100 kPa = 0.1 MPa = 1000 hPa. The bar and its symbol are included in resolution n.7 of the 9th CGPM of 1948 and this choice was essentially made for practical use and was not changed at the time of the adoption of the pascal in 1971. In the English system, pressure is usually expressed in pounds per square inch (psi). Other non – SI units in use having wide applications are torr (1 torr = 133.3223 Pa), atm (standard atmosphere), kg/cm^2, mmHg, mmH_2O. The conversion of different pressure units is shown in Fig. 1.3.



CONVERSION FACTORS FOR PRESSURE AND STRESS UNITS*

Microbar (Barye) Dyne/cm^2	Micron μ (10^{-3} mm Hg)	Newton per m^2 (10^5 dynes/m^2)	Kilogram per m^2	Millibar	Torr (mm Hg)	Poundal per in.^{2}	Inches of Mercury	Pounds per in.^{2} (psi)	Newton per cm^2	Kilogram per cm^2	Bar (10^6 dynes/cm^2)	Atmosphere (normal) (760 mm Hg)	Kilogram per mm^2	Long Tons per in.^{2} (British)	Kilobar
1.0	7.5006×10^{-1}	1.0×10^{-1}	1.0197×10^{-2}	1.0×10^{-3}	7.5006×10^{-4}	4.6665×10^{-4}	2.9530×10^{-5}	1.4504×10^{-5}	1.0×10^{-5}	1.0197×10^{-6}	1.0×10^{-6}	9.8692×10^{-7}	1.0197×10^{-8}	6.4728×10^{-9}	1.0×10^{-9}
1.3332	1.0	1.3332×10^{-1}	1.3595×10^{-2}	1.3332×10^{-3}	1.0×10^{-3}	6.2215×10^{-4}	3.9370×10^{-5}	1.9337×10^{-5}	1.3332×10^{-5}	1.3595×10^{-6}	1.3332×10^{-6}	1.3158×10^{-6}	1.3595×10^{-8}	8.6334×10^{-9}	1.3332×10^{-9}
1.0×10	7.5005	1.0	1.0197×10^{-1}	1.0×10^{-2}	7.5006×10^{-3}	4.6665×10^{-3}	2.9530×10^{-4}	1.4504×10^{-4}	1.0×10^{-4}	1.0197×10^{-5}	1.0×10^{-5}	9.8692×10^{-6}	1.0197×10^{-7}	6.4728×10^{-8}	1.0×10^{-8}
9.8067×10	7.3556×10	9.8067	1.0	9.8067×10^{-2}	7.3556×10^{-2}	4.5763×10^{-2}	2.8959×10^{-3}	1.4223×10^{-3}	9.8067×10^{-4}	1.0×10^{-4}	9.8067×10^{-5}	9.6784×10^{-5}	1.0×10^{-6}	6.3477×10^{-7}	9.8067×10^{-8}
1.0×10^{3}	7.5006×10^{2}	1.0×10^{2}	1.0197×10	1.0	7.5006×10^{-1}	4.6665×10^{-1}	2.9530×10^{-2}	1.4504×10^{-2}	1.0×10^{-2}	1.0197×10^{-3}	1.0×10^{-3}	9.8692×10^{-4}	1.0197×10^{-5}	6.4728×10^{-6}	1.0×10^{-6}
1.3332×10^{3}	1.0×10^{3}	1.3332×10^{2}	1.3595×10	1.3332	1.0	6.2215×10^{-1}	3.9370×10^{-2}	1.9337×10^{-2}	1.3332×10^{-2}	1.3595×10^{-3}	1.3332×10^{-3}	1.3158×10^{-3}	1.3595×10^{-5}	8.6334×10^{-6}	1.3332×10^{-6}
2.1430×10^{3}	1.6074×10^{3}	2.1430×10^{2}	2.1859×10	2.1430	1.6074	1.0	6.3283×10^{-2}	3.1081×10^{-2}	2.1430×10^{-2}	2.1859×10^{-3}	2.1430×10^{-3}	2.1150×10^{-3}	2.1859×10^{-5}	1.3874×10^{-5}	2.1430×10^{-6}
3.3865×10^{4}	2.5401×10^{4}	3.3865×10^{3}	3.4532×10^{2}	3.3865×10	2.5401×10	1.5803×10	1.0	4.9116×10^{-1}	3.3865×10^{-1}	3.4532×10^{-2}	3.3865×10^{-2}	3.3421×10^{-2}	3.4532×10^{-4}	2.1927×10^{-4}	3.3865×10^{-5}
6.8947×10^{4}	5.1715×10^{4}	6.8947×10^{3}	7.0307×10^{2}	6.8947×10	5.1715×10	3.2174×10	2.0360	1.0	6.8947×10^{-1}	7.0307×10^{-2}	6.8947×10^{-2}	6.8046×10^{-2}	7.0307×10^{-4}	4.4643×10^{-4}	6.8947×10^{-5}
1.0×10^{5}	7.5006×10^{4}	1.0×10^{4}	1.0197×10^{3}	1.0×10^{2}	7.5006×10	4.6665×10	2.9530	1.4504	1.0	1.0197×10^{-1}	1.0×10^{-1}	9.8692×10^{-2}	1.0197×10^{-3}	6.4728×10^{-4}	1.0×10^{-4}
9.8067×10^{5}	7.3556×10^{5}	9.8067×10^{4}	1.0×10^{4}	9.8067×10^{2}	7.3556×10^{2}	4.5763×10^{2}	2.8959×10	1.4223×10	9.8067	1.0	9.8067×10^{-1}	9.6784×10^{-1}	1.0×10^{-2}	6.3477×10^{-3}	9.8067×10^{-4}
1.0×10^{6}	7.5006×10^{5}	1.0×10^{5}	1.0197×10^{4}	1.0×10^{3}	7.5006×10^{2}	4.6665×10^{2}	2.9530×10	1.4504×10	1.0×10	1.0197	1.0	9.8692×10^{-1}	1.0197×10^{-2}	6.4728×10^{-3}	1.0×10^{-3}
1.0133×10^{6}	7.600×10^{5}	1.0133×10^{5}	1.0332×10^{4}	1.0133×10^{3}	7.600×10^{2}	4.7277×10^{2}	2.9921×10	1.4696×10	1.0133×10	1.0332	1.0133	1.0	1.0332×10^{-2}	6.5607×10^{-3}	1.0133×10^{-3}
9.8067×10^{7}	7.3556×10^{7}	9.8067×10^{6}	1.0×10^{6}	9.8067×10^{4}	7.3556×10^{4}	4.5763×10^{3}	2.8959×10^{3}	1.4223×10^{3}	9.8067×10^{2}	1.0×10^{2}	9.8067×10	9.6784×10	1.0	6.3477×10^{-1}	9.8067×10^{-2}
1.5445×10^{8}	1.1589×10^{8}	1.5445×10^{7}	1.5749×10^{6}	1.5445×10^{5}	1.1589×10^{5}	7.2061×10^{4}	4.5626×10^{3}	2.240×10^{3}	1.5445×10^{3}	1.5749×10^{2}	1.5448×10^{2}	1.5242×10^{2}	1.5749	1.0	1.5445×10^{-1}
1.0×10^{9}	7.5006×10^{8}	1.0×10^{8}	1.0197×10^{7}	1.0×10^{6}	7.5006×10^{5}	4.6665×10^{5}	2.9530×10^{4}	1.4504×10^{4}	1.0×10^{4}	1.0197×10^{3}	1.0×10^{3}	9.8692×10^{2}	1.0197×10	6.4728	1.0

Fig. 1.3: Conversion factors for different pressure units

1.4. PRESSURE MEASUREMENT

The precise and accurate measurement of pressure is of important in many applications including process industries. During the last few decades, the importance of pressure in science and technology has brought with it a need for improved accuracy in measurement over a wide range. These days accurate pressure measurement system based on smart sensor are widely used. The accurate pressure measurement is not only critical for the different process industries such a power generation, fertilizer, chemical, petrochemical, automation, aviation etc. but it is also essential for the human safety against hazards. Even a small unnoticed thing i.e. slight deviation from the optimum value of the tire pressure in automobile or then pressure of the LPG cylinder for domestic cooking would affect the nation’s economy. Pressure is an important parameter in most manufacturing processes and must there for be measured for control or optimization. It is critically necessary to measure accurate pressure for numerous applications, having direct bearing on safety, scientific and technological development and economic growth in the country etc. To name a few, pressure cooker, high pressure hot extrusion, cold forgoing of the metals, synthesis of the super hard materials, synthesis diamonds geothermal applications, transport of fluid, automobile engine tyros, refrigerators, furnaces, aircraft industry etc. [1-20]. In the absence of such facilities certain process can not used and optimized.

One of the prime benefits derived from pressure measurements is human safety, most familiar example being provided by the high pressure generated in a pressure cooker or a LPG cylinder. Oxygen monitoring gauge in the air cabin, if not accurate, can create an unbearable atmosphere and cause irreparable image. Each automobile owner keeps his tires properly inflated to optimum the value. If the pressure dial gauge at petrol pumps are not properly calibrated, then either the excess or less tire pressure would not affect the fuel consumption and hence the national economy and loss to the individual but the driving would also not be comfortable and would lead to more wear and tear of the vehicles. The measurement of differential pressure at high line pressure is of increasing industrial importance especially in the field of fluid flow measurement and control. Important applications include the metering of the flow of petroleum products from oil well to the refinery, control of coolant in nuclear power stations and the control of the boiler feed water flow in electrical generation etc.

Inaccuracy in the pressure measured by the gauges installed boilers, process chambers, storage tanks in heavy chemical industry and petrochemical complexes may cause complete shutdown of the process plants and hence would affect the magnitude of production and the quality of products. Measurement of pressure is also applied in the measurement of temperature, flow, and liquid level. Piston gauge and liquid column manometer are used as primary standard. Pressure neglects the property of fluid such as state, flow, force. Pressure measurement in liquid or gases is common particularly in process control and in engine control.

1.5. TECHNIQUES FOR PRESSURE MEASUREMENTS

Researchers and technologists have continuously placed frequently concentrated efforts to measure pressure in a simple, cost effective and precise way. A pressure measurement can be described as either static or dynamic. The pressure in cases where no motion is occurring is referred to as *static* pressure. Examples of static pressure include the pressure of the air inside a balloon or water inside a basin. Often times, the motion of a fluid changes the force applied to its surroundings. Such a pressure measurement is known as dynamic pressure measurement. For example, the pressure inside a balloon or at the bottom of a water basin would change as air is let out of the balloon or as water is poured out of the basin.

A wide variety of different applications are around atmospheric pressure i.e. 10^5 Pa to few GPa where the most accurate and precise measurement of pressure is possible by using **primary standards**. Primary standards establish the practical pressure scale in terms of fundamental units of mass, length, temperature and time etc. through metrological characterization in an independent way i.e. without calibration. For this purpose, liquid column manometers (LCM) and piston manometers (PM) are regarded as primary standards. These techniques for pressure measurements are fundamental in character such as measuring the height of a liquid column of known density i.e. mercury manometer and measuring the force acting on a piston of known cross-sectional area, rotated into a cylinder of matched dimension i.e. piston manometer. The use of LCM is limited around atmospheric pressure measurements while the bulky sizes, high costs, highly skilled operations and difficulties in transportation of piston manometers limit their use in National Metrological Laboratories and Reference Pressure Laboratories.

The use of pressure instrumentation techniques based on secondary principles addresses such problems and have overcome such difficulties. These techniques for pressure measurements are regarded as **secondary standards** where pressure is measured in terms of some other suitable physical parameters whose relation to pressure is established by calibration, that is, in comparison with primary pressure standards. Therefore, the use of secondary standards such as mechanical gauges and electronic transducers and sensors would be limited to detecting changes in pressure and recording repeated unstandardized values in the absence of suitable correlation with primary standards. It is therefore obvious by that reason that the accuracy of secondary standard is limited to the accuracy of primary standard against which it is directly or indirectly calibrated and by its own metrological characteristics. Therefore, it is essential for users to know the factors affecting the metrological characteristics of secondary standards.

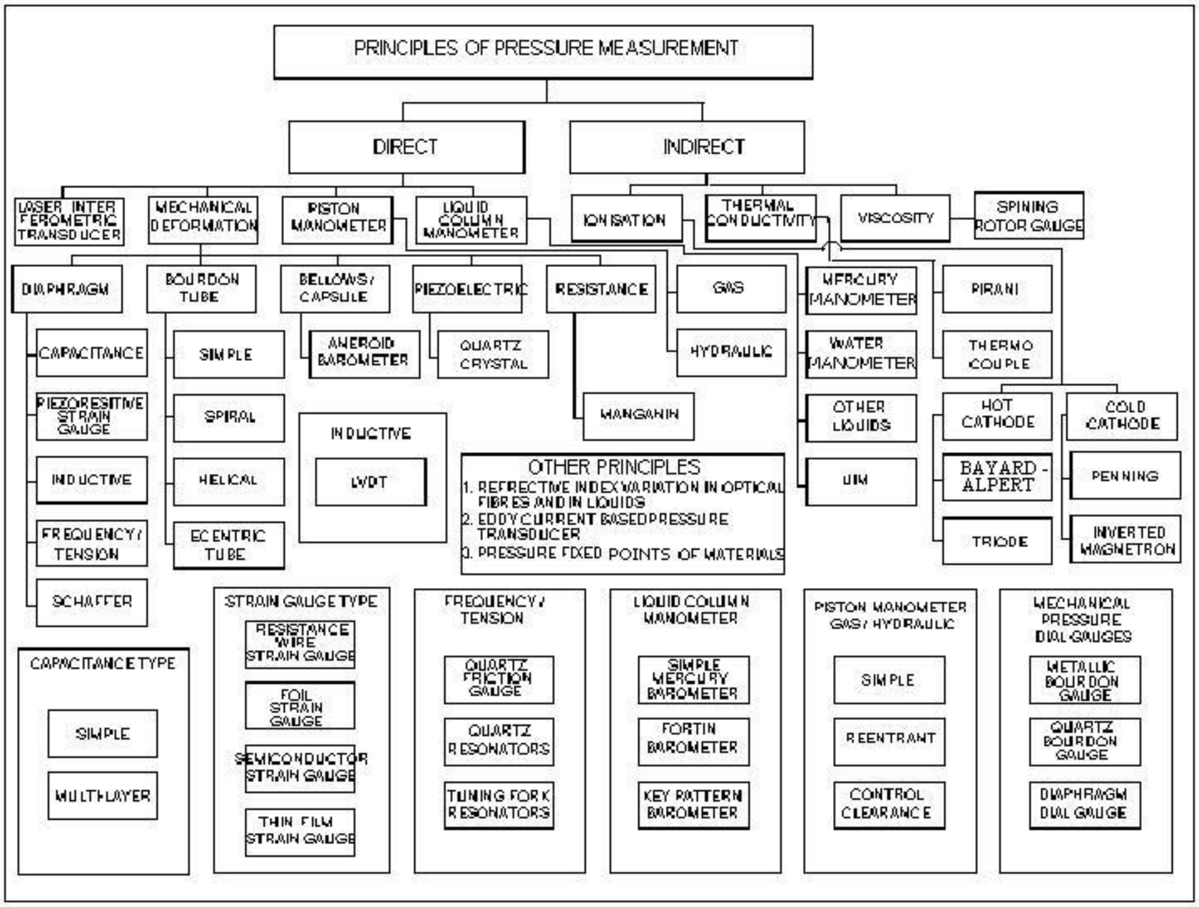


Fig. 1.4: A broad classification of pressure measurement techniques

Pressure instrumentation techniques utilize a number of quite different principles for pressure measurement. They are categorized as direct pressure measurement and indirect pressure measurement. Based on direct pressure measurement principle, generally, a mechanical device provides a deformation in response to a pressure change. This, in turn, is translated into an electrical signal by means of a displacement transducer interfaceable to a personal computer, which makes it suitable for use in modern computer controlled systems. The mechanical deformation can be both implemented and sensed in a number of ways; a series of mechanical levers to give a direct display of the deformation, **resistance measurement in strain gauge**, capacitance measurement, change in frequency of a resonating element under tension and compression and so on. In case of indirect pressure measurement principle where mechanical deformation is too small to be measured, indirect means are used to measure a physical quantity such as thermal conductivity, ionization and viscosity that is dependent on the number of gas molecules. The techniques thus used are summarized in Fig. 1.4 [20].

1.6. MOTIVATION FOR PRESENT WORK

As highlighted above, a number of pressure transducers, based on strain gauge, capacitance / inductance type, frequency resonators, are commercially available and are being used for sensing and producing an electrical output proportional to applied pressure. These sensors have their own advantages and limitations due to operational ease, linearity, hysteresis error, measurement uncertainty and the costs. No doubt, the Quartz based pressure sensors are the most accurate and best available commercially in the market but are not used beyond 2000 bar and are very expansive. The capacitance type pressure transducers are though used up to 5000 bar but active elements are in direct contact with the pressure transmitting fluids and hence pressure sealing becomes very difficult for such a high pressure. Although, the special mechanical designs are used but make them again very expensive and some time more than the Quartz based pressure sensors. Strain gauge type pressure transducers address these problems amicably and are easy to design and very cheaper. Further, the designs allow to use strain gauges separately with pressure transmitting fluids. Therefore, the strain gauge type transducers are now well established devices for accurate and precise measurement of pressure up to 14000 bar within measurement uncertainty up to 0.1 % of full scale or better. To the best of my knowledge, no indigenous pressure transducer is commercially available beyond 1500 bar within reasonable measurement uncertainty up to 0.1 % of full scale or better. In the present thesis work, an indigenous strain gauge pressure transducer has been designed, developed, tested and calibrated for pressure measurement up to 200 MPa or 2000 bar. The measurement uncertainty estimated using the pressure transducer is found better than 0.1 % of full scale.

CHAPTER-2: STRAIN GAUGE PRESSURE TRANSDUCERS

2.1. LITERATURE SURVEY

A variety of sensing devices are used in pressure transducers (PT) to provide an electrical output proportional to applied pressure. The sensing devices employed in the PT under discussion are bonded, metal foil type strain gauges. Such devices operate via a plurality of foil strain gauges bonded to the controlled stress zones of a pressure responsive diaphragm or a relatively thin wall. The strain gauges are then connected to a Wheatstone bridge arrangement. As the fluid pressure is applied into to the fluid medium cavity or channel the pressure is transferred through a thin preferably metal diaphragm to the sensing diaphragm or wall. The strain gauges, connected in a Wheatstone bridge circuit, provide an electrical transfer function proportional to the applied fluid cavity pressure. Strain gauge pressure transducers have an established reputation and outstanding record in the great many applications requiring an accurate measurement of fluid pressure.

In **1856,** Lord Kelvin [21], (England) first discovered that the resistance of the copper and the iron wires changes when they are subjected to mechanical strain. He observed that the change in resistance was very small and was very difficult to be measured accurately using voltage and current measuring devices. In **1908,** S. Landeck [22], (Germany) described a pressure measurement technique using Manganin wire wrapped around a copper tube as shown in Fig. 2.1.

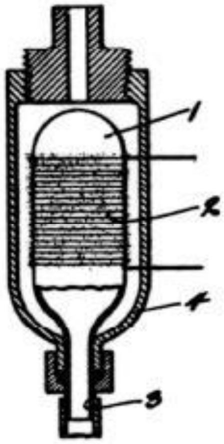


Fig. 2.1: An early bonded strain gage pressure transducer developed by S. Landeck, (Germany)

B. W. Bridgman, (America) in **1911** verified Kelvin results using wires under hydrostatic pressure [22-23]. The first engineering application appears to have been designed about **1930** by R.W. Carlson (Statham Laboratories of Los Angeles) who developed an unbounded type of gauge for the measurement of strain in concrete [24]. A refinement of this principal was developed about **1945** by Meyer [25]. Unbounded gauge is used to give an electrical output signal proportional to a very small displacement of a body relative to another body. Figure 2.2 shows the principle applied to an accelerometer. Very fine wire forming the strain gauge resistance is stretched between insulating pegs on the two bodies, one as seismic mass of the accelerometer and the other one as casing around it. He reported that the tension in the wire must be sufficient to ensure that some tension still remains at maximum displacement of the seismic mass in either direction. Thus unbounded strain gauge can only be seen by taking the transducer apart-that is not the case for modern day sensors. Modern sensors are always part of the transducer usually an accelerometer or extensometer. The four wire resistance elements were wound between eight posts and were insulated from them. Four posts were mounted on the frame and the other four on armature. One end of each element was fixed to a frame post, the other to an armature post. When the armature moved within the frame, the tension of the four elements was found to be varied which resulted in to change in their resistance. The four elements were then connected in a Wheatstone bridge with all four arms as active element.

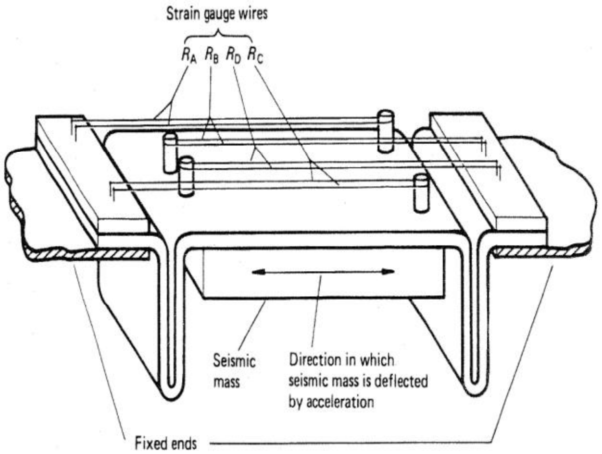


Fig. 2.2: An unbounded strain gauge accelerometer developed by Mayer (1945)

Early 1930s, Charles Kearns made the first notable use of bonded resistance strain gauges to measure vibratory strains in high performance propeller blades [26]. He used carbon composite resistors (as used in standard electronic instruments) ground flat and mounted on an insulating strip. These were then cemented onto the propeller blades, and were able to indicate the dynamic strains experienced by the blades. However, these gauges were not very accurate, and due to the resistance stability with variations in time and temperature being poor, the gauges were unable to measure slowly changing or static strains. In **1938,** the idea of bonding the resistance element directly to the body under test was first conceived at the California Institute of Technology by Simons and reported by Clark and Datwlyer [26]. In **1937-38,** Arthur Ruge and Edward Simmons (working independently of each other), co-invented the bonded wire strain gauge and transducer [26-29]. Both discovered that small diameter wires made of electrical resistance alloys can be bonded to a structure to measure surface strain. This type of gauge had the advantage of responding well to static strains. Following this breakthrough, strain gauge measurements were adopted for use in aircraft development programme during World War II.

It was due to the demands of this rapidly growing industry that the important advances into foil strain gauges were made. In **1952,** The Saunders-Roe Company (UK) improved the performance of the bonded wire gauges to enable their use in more demanding environments [30]. At this time, printed circuits were emerging, and Saunders-Roe developed the idea of making a strain gauge by etching the pattern for the gauge from a thin foil. These foil gauges had some distinct advantages, most notably a reduction in size and production costs. This allowed much more extensive use of electrical resistance strain gauges, and they are the most common type in use today.

Semiconductor strain gauges are also in use today, and these are different in many aspects from the metallic wire and foil strain gauges. Most importantly, they produce much greater sensitivity (10 to 50 times), which was at one time thought to herald the downfall of metallic gauges. But, semiconductor gauges are very limited as a general purpose gauge, and so there is a place for both types in modern strain measurement. Around **1970,** the first semiconductor (silicon) strain gauges were developed for the automotive industry. As opposed to other type of strain gauge, semiconductor strain gauge depends on the piezoresistive effect of silicon or germanium and measure the change in resistance with stress as opposed to strain.

Early **1980,** E. E. S. Simmons and A. C. Ruge described the famous investigation of development of thin film strain gauge pressure transducers [31]. They also investigated the development of smart sensor based pressure transducers. Development of various smart sensor based pressure transducers belonging to piezoresistive and piezoelectric categories are reported in the last two decades. The smart pressure transducer gives fast, accurate, reliable and automatic measurement of pressure.

Since **1992,** foil strain gauges were being replaced by thin film strain gauges in pressure transducers [32]. Thin film strain gauges offer number of advantages over the conventional foil strain gauges. The major advantage is that thin film strain gauge can be directly deposited on the transducer diaphragm. Hence it eliminates the need to use adhesive material which may cause error due to the adhesive bonding. Thin film strain gauges can be deposited on the diaphragm by simple evaporations technique or by sputtering. It appears promising that thin film pressure transducer can be made to have better characteristics in comparison with conventional transducers in respect of their behavior namely, linearity, hysteresis, output, stability, repeatability and temperature behavior.

During last decade, G. F. Molinar (Italy) and his co-workers [33-34] developed the hexagonal shape free-cylinder strain gauge pressure transducer for pressure measurement in liquid medium up to 0.5 GPa. They further designed a pressure transducer with cylindrical elastic element. Since than such transducers are widely used for a long time now in scientific research or in industry, for a pressure range of up to 1.4 GPa [35-36]. The design of 1.4 GPa pressure transducer originates from their previous patented version in which the active element was cylindrical and contained two concentric cups. Pressure was applied in the internal part of the cylinder and also on its open end in order to realize a symmetrical load distribution. The new active cylinder was assembled coaxially to a pair of sealing cups which were intended to limit friction between the active element and the main external body of the transducers when pressure was applied. The hexagonal shaped active element was placed in its central part which allowed a flat surface for bonding strain gauges circumferentially and longitudinally in respect of the cylinder axis. As the strain gauges were bonded on a flat surface of an hexagonal prism, the circumferential strain was considered as transversal. Transducer of this type is useful as transfer standard considering hysteresis effects carefully. The sealing effects were minimized in this design. The same design was used for the construction of the other pressure transducers having improved resolution than those described above, in the pressure ranges from 0.1 GPa to 0.7 GPa.

In **2001,** Patrik Melvas (Royal Institute of Technology, Stockholm, Sweden) developed a free-hanging H-shaped strain-gauge pressure sensor for ultra miniaturized pressure sensors (Fig. 2.3) [37]. The first entirely surface was micro machined. A free-hanging strain gauge pressure sensor element of size 80µm is bonded to H-shaped force beam supported at both ends. The H-shape enables strain-gauge to be a part of beam without the need for additional layers. The beam was attached to a polysilicon diaphragm at one end to the cavity edge at other end. The diaphragm of the fabricated sensor was 2µm thick and had a side length of only 100µm. This type of design enables a combination of high pressure sensitivity (5µV/V/mmHg) and miniature chip size as well as good environmental isolation.

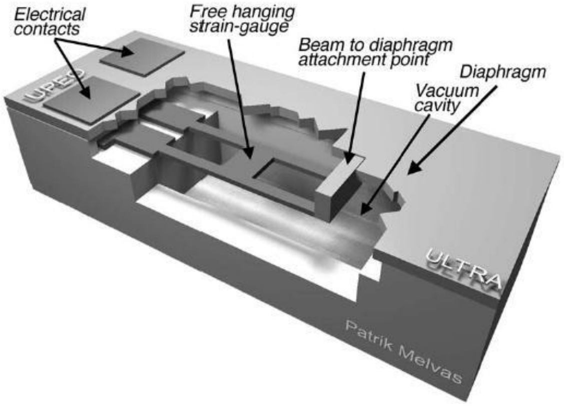


Fig. 2.3: Schematic drawing of the free-hanging strain gauge pressure sensor

In **2003,** Andre Schafer (Germany) designed a transducer for accurate dynamic pressure measurement up to 1500 bar using foil strain gauges [38]. In **2008,** Falk L. Tegtmeir (Germany) designed an important element for construction industry for precise and continuous measurement of stress conditions [39]. For this purpose, an encapsulated measuring sensor which encloses and protects the sensitive strain gauges was inserted into measurement boreholes. The mechanical adaptation was effected by optimizing the process of deformation of two conical bodies such that the envisaged measuring range covers the range of elastic deformation of construction steels. Suitable calibration procedures, as well as measurement methods for the early detection of structural damage in buildings, were developed for this adaptation model. A strain gauge layout adapted to the specific local conditions was devised for the sensor, and the strain gauge was protected by a plastic seal. In order to assess the lifetime of the sealing materials, which in part were being employed for the first time, the chemical/climatic building environment was simulated under forced conditions in the laboratory. This strain gauge was protected with a new type of plastic capsulation. In the future, the sensor and its encapsulation will have to prove their worth in applications in real buildings.

In **2009,** U. Heckmann (Germany) development material for sputtered thin films with a high gauge factor and negligible temperature coefficient of resistivity (TCR) [40]. The object for self compensated sensor materials was the combination of a semiconducting material (negative TCR) with high gauge factor and a metal (positive TCR) leading to a TCR close to zero. With nickel containing diamond like carbon films (Ni-DLC) compound, the zero crossing in TCR and gauge factors higher than 10 were achieved.

In **2009,** Valerio Tomarchio, Max Planck Institute for Plasma Physics Greifswald (Germany) described that the strain gauge working with superconducting coils in the field of fusion engineering [41]. Later on Barlian et al published a review of micro force measurement systems based on the strain gauges [42]. In the micro world (the world of very small components), signal to noise ratio is very low due to weak amplitude of the signals. Such problems were amicably addresses by these inventors.

In **2010,** H. M. Kalpana and R. John Stephen described the development of thin film strain gauge sensor for strain measurement using Lab View [43]. The strain gauge designed were deposited on either side of the cantilever of beryllium copper (Be-Cu) using DC magnetron sputtering technique. Lab View version 7.1, signal conditioning connector block with half bridge type II, strain gauge input module SG03 and data acquisition board 6221 were utilized. The developed devices were used in aerospace and biomedical applications for the measurement of micro strain. The Lab View measurement platform has dramatically reduced test times as results were automatically collected.

The recent trends in strain gauge pressure transducers are focused on miniaturization, fast response, higher sensitivity, much higher pressure ranges, improved accuracy and communication with modern instrumentation and controls using USB cables connectivity [44-50]. As an effort in this direction, we have designed and developed an indigenous strain gauge based tubular pressure transducer for pressure measurement up to 2000 bar within the measurement uncertainty of 0.1 % of full scale.

2.2. STRAIN GAUGE

Strain gauge is one of the most important tools of the electrical measurement technique applied for the measurement of mechanical quantities. As indicated, they are used for the measurement of strain. Strain gauges are designed to convert mechanical motion into an electronic signal. Therefore, strain gauge is an electrical sensor which is used to measure strain accurately in a test piece. Strain gauges are usually based on a metallic foil pattern. The gauge is attached to the test piece with a special adhesive. As the test piece is deformed, so the adhesive deforms equally and thus the strain gauge deforms at the same rate and amount as the test piece. It’s for this reason that the adhesive must be carefully chosen. If the adhesive cracks or becomes detached from the test piece, the test results will be useless. Strain gauges are metal or semiconductor elements whose electrical resistance is sensitive to strain. They are very versatile and usually bonded on a surface of an elastic body, which deforms in response to force, pressure, temperature, etc. As a technical term ‘*strain*’ comprises of tensile and compressive strain, distinguished by a positive or negative sign. Thus, strain gauges are used to pick up expansion as well as contraction. Strain gauges are used not just with metals but they have also been connected to the retina of the human eye, insects, plastics, concrete and indeed any material where strain is under investigation. Modern composite materials like carbon fiber when under development are often constructed with strain gauges between the layers of the material.

2.3. STRAIN GAUGE: DESIGN CONSIDERATIONS

A typical layout diagram of a strain gauge is shown in Figure 2.4. Strain gauge is often designed in the serpentine shape. Strain gauges have small mass and size, high sensitivity, and suitable for static and dynamic applications. Foil element are available with unit resistance, generally, from 120 to 5000 ohm.

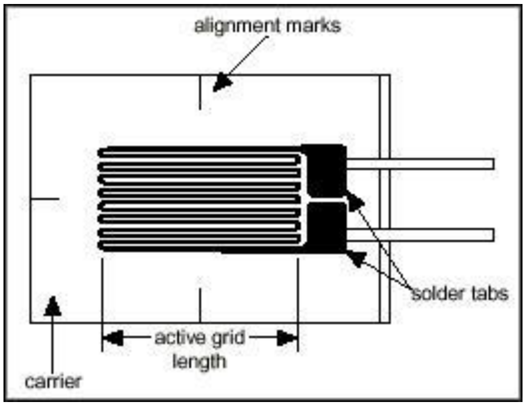


Fig 2.4: A typical layout diagram of a strain gauge

2.3.1. TYPES OF STRAIN GAUGES

The electrical strain gauges, commonly used in pressure transducers are classified as follows;

2.3.1.1. Resistance Wire Strain Gauge

Resistance wire strain gauges are used in two basic forms, unbounded and bonded type. The former consists of a fine wire stretched in an insulating medium between two points fixed over the force summing element whereas the later contain a fine wire looped back and forth on carrier cement to the force summing element. The effective length is increased by having several wire loops. In the bonded type, the resistance wire is configured to have the form of a grid, rosette, helical, or torque type strain gauge

2.3.1.2. Foil Strain Gauge

Foil strain gauges have a much larger dissipation capacity than resistance wire strain gauges on account of their larger surface area for the same volume and hence they are used at higher temperature and better bonding is achieved. These strain gauges are fabricated on a mass scale and in different shapes.

2.3.1.3. Semiconductor Strain Gauge

The action of a semiconductor strain gauge depends upon piezoelectric effect. The change in resistance of the semiconductor is due to change in resistivity and its dimensions. The silicon and germanium are the most commonly used semiconductor strain gauges in fabricating the pressure transducers.

2.3.1.4. Thin Film Strain Gauge

In last two decades, the foil strain gauge pressure transducers have been replaced by thin film strain gauge type pressure transducers because the latter show better characteristic such as linearity, hysteresis, repeatability, temperature compensation and stability. The thin film strain gauge pressure transducers are deposited either by simple evaporation technique or by sputtering directly on the diaphragm surface thereby eliminating the use of adhesives.

The most common strain gages are of the bonded type where the gage consists of metal foil, which is thin film cut into a grid structure by a photo-etching process, and a resin film base on which the foil is mounted. The film backing is attached to the structure to be measured with suitable adhesive such as nitrocellulose, cyanoacrylate, phenolic and quick setting cement. The gage is usually positioned in such a way that its active (sensitive) axis is along the direction of the strain to be measured. Active part of the gauge is made from a thin metal foil which is electrically conducting. Comparatively larger areas at the ends of the grid are suitable for easy connections. Separate layers of the gauge are bonded together. The plastic carrier helps to handle the gauge and protects the active grid against mechanical damage. Most of the gauges in commercial production employ a metallic filament made of 45/55 copper-nickel alloy generally 0.001 in. diameter. For specific applications, staybrite, nichrome and iso-elastic wire are also used.

2.3.2. SALIENT CHARACTERISTICS

The salient characteristics of resistance wire strain gauges as strain measuring device are summarized as follows:

2.3.2.1 The fractional change of resistance against strain is a linear function for strain value.

2.3.2.2 The gauge has negligible weight, and hence exerts negligible influence on the member to which it is attached. It is flexible, and is cemented in position, it can be attached to curved surface as easily as to plain surface.

2.3.2.3 Such gauge is equally suitable for both tensile and compressive strains, the accuracy is of the order of 1% and strain of the order of 10 can be indicated.

2.3.2.4 The gauge is subjected to temperature change but these can be effectively compensated.

2.3.2.5 The output from several gauges can be added, subtracted average, or combined electrically, to give direct reading of average stress, bending moments, shear, torsion and direction of principal stress.

2.3.2.6 The impedance is relatively low, and the output can thus be observed or recorded remotely.

2.3.2.7 The measuring equipment for static strain is very simple, needing, in the most elementary form, only a battery and galvanometer. For dynamic work, the cathode ray oscilloscope will fill many requirements. Strain gauge a most effective instrument, not only for measuring strain as such, but also for measuring any other physical quantities that can conveniently be related to the strain in an appropriately designed mechanical structure.

2.4 WHEATSTONE BRIDGE AND BALANCING OPERATION

These small resistance changes are very difficult to measure. So, in a practical sense, it is difficult to measure a strain gauge, which is just a long wire. Whatever is used to measure the strain gauges resistance will itself have its own resistance. The resistance of the measuring device would almost certainly obscure the resistance change of the strain gauge. The solution to this problem is to use a Wheatstone bridge to measure the resistance change. A Wheatstone bridge is a device used to measure an unknown electrical resistance. It works by balancing two halves of a circuit, where one half of the circuit includes the unknown resistance. Fig. 2.5 shows a classical Wheatstone bridge where R_x represents the strain gauge. Resistors R_2, R_3 and $R_4$are known resistances. Normally, 120 Ω, 350 Ω Or 1000 Ω are used depending on the application. Knowing the supply voltage and the returned signal voltage, it's possible to calculate the resistance of Rx very accurately. For example if R_2, R_3 and R_4 are 350 Ω and if the measured signal voltage between measurement points A and B is 0 then the resistance of R_x is given by;

$$\frac{R_3}{R_4} = \frac{R_X}{R_2} \text{ or } R_X = \frac{R_2 \cdot R_3}{R_4} \qquad [2.1]$$

For example, we get;

$$R_x = \frac{350\Omega \cdot 350\Omega}{350\Omega} = 350\Omega \qquad [2.2]$$

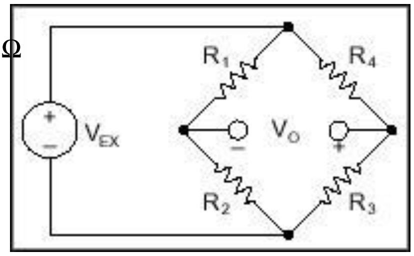


Figure: 2.5 Simple Wheatstone bridge circuit

This is the condition of a perfectly balanced bridge. In practice, the strain gauge undergoes through different strain levels i.e. its resistance changes. It is necessary to know the relationship between resistance and voltage. The measured voltage is related to a resistance and, hence, a strain value. Fig. 2.6 shows the addition of another resistor *R*s, called the shunt resistor.

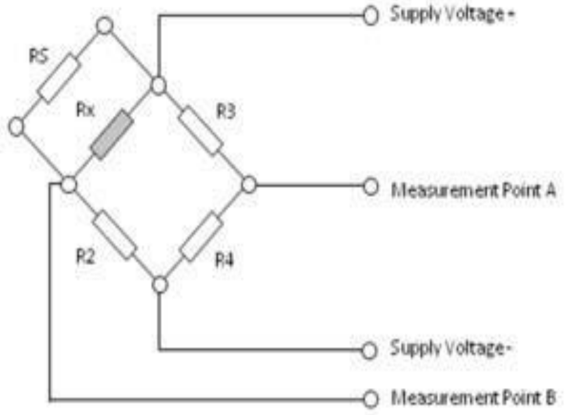


Fig. 2.6: Wheatstone bridge with shunt resistor

The shunt resistor is a known fixed value. The Shunt resistor is added for calibration purposes and is a very high precision resistor. By measuring the voltage between measurement points A and B with the shunt resistor across R_x, a voltage with the shunt resistor is known. Then by removing the shunt resistor and measuring the voltage between measurement points A and B again, it's possible to relate the measured voltage change to a known resistance change. Therefore the Ω∇value is known for this particular bridge.

In order to go one step further and calculate the strain from the resistance, the gauge factor must be known. This is a calibrated number provided by the manufacturer of the strain gauge. With this information the sensitivity of the whole sensor can be calculated. That is, the volt per strain is known. Strain gauge readings can be affected by variations in the temperature of the strain gauge or test piece. The wire in the strain gauge will expand or contract as an effect of thermal expansion, which will be detected as a change in strain levels by the measuring system as it will manifest itself as a resistance change. In order to address this situation, most strain gauges are made from constantan or karma alloys. These are designed so that temperature effects on the resistance of the strain gauge cancel out the resistance change of the strain gauge due to the thermal expansion of the test piece. Different materials have different thermal properties or different thermal expansion. So, the temperature change during the test is an issue and temperature compensating strain gauges can be used. However this requires correctly matching the strain gauge alloy with the thermal expansion properties of the test piece and the temperature variation during the test. In certain circumstances temperature compensating strain gauges are neither practical nor cost effective. Another more commonly used option is to make use of the Wheatstone bridge for temperature compensation.

When using a Wheatstone bridge constructed of four strain gauges, it is possible to attach the four gauges in a fashion to remove the changes in resistance caused by temperature variation. This requires attaching the strain gauge R_x in the direction of interest and then attaching the remaining strain gauges, R_2, R_3 and R_4, perpendicular to this. The piece under test, however, must only exhibit strain in the direction across R_x and not in the perpendicular direction. It's important to understand that the R_2, R_3 and R_4

strain gauges should not be under strain, hence their direction. This means the whole bridge is subject to the same temperature variations and therefore stays balanced from a thermal expansion point of view. As the resistance changes due to temperature, all the resistances in all four gauges change by the same amount. Only the strain in the desired direction, across Rx, in the test piece affects the measured voltage readings. The main configurations in which that strain gauges are used in a bridge is described as follows;

2.4.1 QUARTER BRIDGE

The quarter bridge is the one of the most common strain gauge configurations and it is depicted in Fig. 2.7. It is actually a three wires configuration which allows measurement of actual voltage.

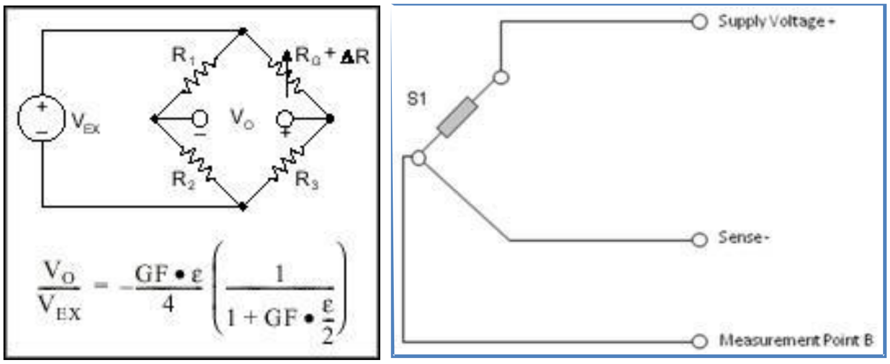


Fig. 2.7: Quarter bridge

2.4.2 HALF BRIDGE

The half bridge is not often used strain gauge configuration (Fig. 2.8). It is actually a five wire configuration. The main advantage of the half bridge configuration is that both the strain gauges S1 and S2 can be attached to the test piece, but perpendicular to each other which as previously discussed allows the temperature compensation.

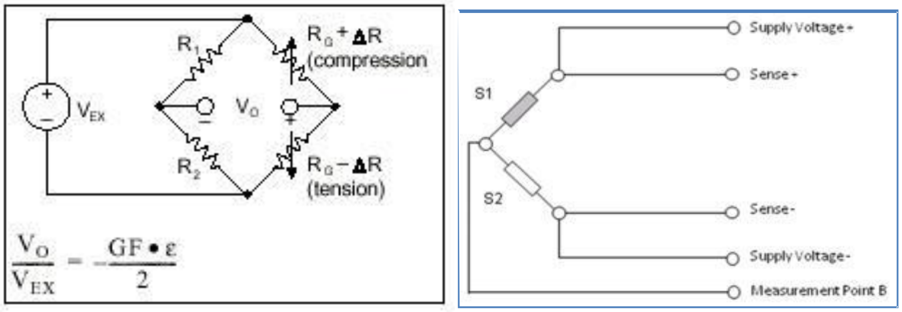


Fig. 2.8: Half bridge configuration

2.4.3 FULL BRIDGE

The full bridge is used for situations where the fullest degree of accuracy is required. The full bridge configuration is a six wire system as shown in Fig. 2.9. The full bridge configuration is the most accurate in terms of temperature variation because two strain gauges can be used as active gauges. The gauges can be configured with S1 and S4 in the direction of interest on the test piece and S2 and S3 perpendicular to this. Further the voltage sense lines have no effective current flow and therefore have no voltage drop, therefore the voltage measured by the system is the actual voltage that is exciting the bridge. The reason for this requirement is that strain gauges are often of long wires and all wires have their own resistances.

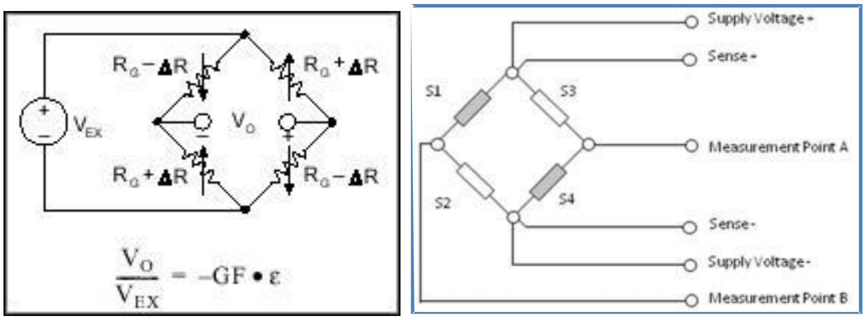


Fig. 2.9: Full bridge configuration

CHAPTER- 3: DESIGN AND DEVELOPMENT OF A STRAIN GAUGE PRESSURE TRANSDUCER

3.1. DESIGN CONSIDRATIONS

The strain gauge pressure transducer is essentially consisting of a transducer casing, diaphragm (may or may not be the part of transducer casing), strain gauges, electronics (power supply, amplifier etc.) and measuring / display device.

3.1.1 TRANSDUCER ACTING ELEMENT, DIAPHRAGM AND CASING

A typical layout diagram of the transducer casing of the presently developed pressure transducer is shown in Fig. 3.1. The transducer acting element (A) is basically a single piece of tubular maraging steel cylinder having external diameter of 12 mm and internal bore diameter of 2 mm. The maraging steel is thermally aged at $490 + \underline{5}^{0}$C for 5 h and cooled in air to achieve a measured hardness value of 53 HRC and an expected yielding stress of 1.77 GPa. Other properties of the maraging steel are Young's modulus E = 189 GPa, Poisson ratio $\mu = 0.3$, linear thermal expansion coefficient $\alpha = 1 \times 10^{-5}{}_{0C-1}$ and thermal conductivity 21 $mW^{0}C$.   The Its one end (7) is closed while other end (8) is used to make standard threading (3) with cone, collar and ferule arrangements with pressure tubing to provide leak proof and required pressure (2) sustainable connections. The cylinder wall (1) has been used to attach strain gauges and it works as acting diaphragm to avoid pressure leakage for such a high pressure.

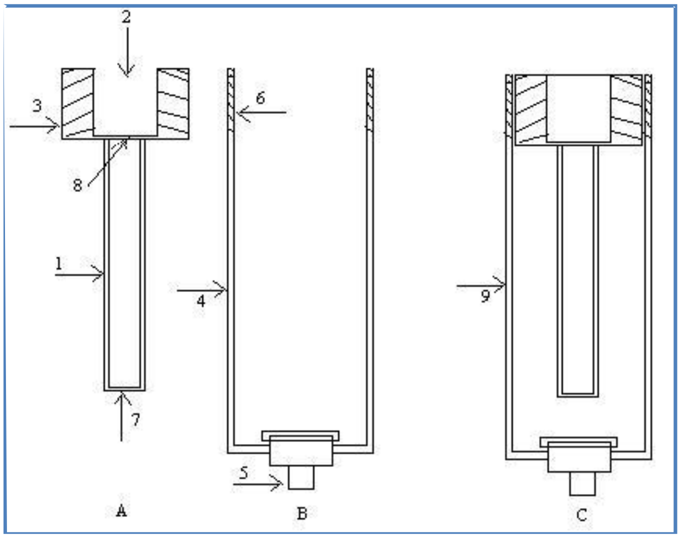


Fig. 3.1: (A) Acting element, (B) Outer casing and (C) Complete transducer assembly

The maraging steel used, density 8000 kg/m^3, is commercially known as inox steel or inox**.** It is an alloy with a minimum of 11% chromium content by mass. This particular material is used due to its several advantages i.e. it does not stain, corrode, or rust as easily as ordinary steel. Also its thermal conductivity is about 40 to 50 % less than that of plain carbon steel. The outer casing (B) is again a hollow cylinder made of same material. Its one end (6) has internal threads which are tightened to house the whole acting element (A). The other end of (B) is closed but having BNC / rotation free lead through arrangements for electric connections. The complete acting element (A) is fitted in to (B) to make complete assembly of pressure transducer (C).

The following points are important and taken in to consideration while designing diaphragm or acting element. The actual design and development process involves arriving at the best compromise of sensitivity, linearity, and pressure response which are primarily determined by the diaphragm diameter and thickness. The mathematical computations used herein are based upon the following assumptions;

Uniform diaphragm thickness or cylindrical bore and outer diameters.

Small deflections

Infinitely rigid clamping around the diaphragm periphery

Perfectly elastic behavior

Negligible stiffening and mass effects due to the presence of the strain gage on the diaphragm

3.1.1.1 Sensitivity

The strain distribution in a rigidly clamped diaphragm under uniform pressure distribution is shown Fig. 3.2. The strain distribution in clamped diaphragm is computed using the relationship as follows;

$$\varepsilon(\ )\ (\ )_{T} = -{}^{3}{}_{0}\ \frac{pR^{2}(\ )_{y2}}{{}^{2}\ .\qquad 8t\ \ E} \qquad [3.1]$$

where ε ( ) and ε ( ) are the radial and tangential strains**,** p is the pressure in psi, is the diaphragm radius in mm, t is the diaphragm thickness in mm, is the Poisson ratio which is a dimensionless quantity and E is the modulus of elasticity in psi. The radial strain decreases rapidly as the radius increases, becoming negative, and (at the edge) equal to twice the center strain. The tangential strain decreases to zero at the periphery of the diaphragm. Thus, the radial and tangential strains at the center of the diaphragm are identical, and expressed by;

$$\varepsilon\left(\;\right)_0 = \frac{3pR_0^2\left(1-y^2\right)}{4t^2 E},\ \varepsilon\left(\;\right)_0 = 0 \qquad [3.2]$$

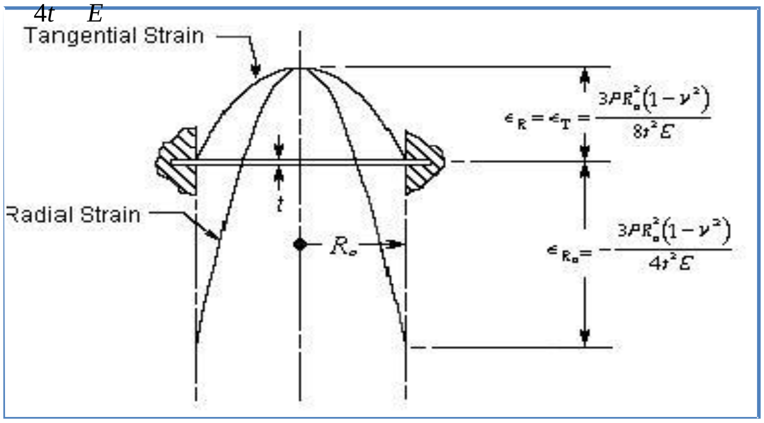


Fig. 3.2: Computation of radial and tangential strains in a diaphragm

For our design, the sensitivity or the total gage output ( ) in mill volts per volt is computed using linear strain gauge pattern, averaging, the strain over the region covered by each sensing element (having a gauge factor of 2.1), and averaging the outputs of all sensing elements by the following formula;

$$\varepsilon_0 = \frac{0.75\,pR_0^2\left(1-y^2\right)}{t^3 E}\cdot 10^3\left(\;\right)V/ \qquad [3.3]$$

The gauge factor (GF) or strain factor of a strain gauge is the ratio of relative change in electrical resistance to the mechanical strain *ε*, which is the relative change in length. The resistance is also dependent on temperature. The total effect is given by;

$$\frac{\Delta R}{R} = GF\cdot\varepsilon + \alpha\cdot\varphi \qquad [3.4]$$

where $\varepsilon = \Delta L / L$ is the strain, ΔR is the change in strain gauge resistance, R is the unstrained resistance of strain gauge, α is the temperature coefficient and φ is the temperature change. A fundamental parameter of the strain gage is its sensitivity to strain, expressed quantitatively as the gauge factor (*GF*). Gauge factor is defined as the ratio of fractional change in electrical resistance to the fractional change in length (strain):

$$GF = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon} \qquad [3.5]$$

The gauge factor for metallic strain gauges is typically around 2. However, for a single active gauge and three dummy resistors, the output v from the bridge is given by;

$$v = \frac{V}{4} \cdot GF \cdot \varepsilon \qquad [3.6]$$

where V is the bridge excitation voltage. Foil gauges typically have active areas of about 2-10 mm^2 in size. With careful installation, the correct gauge, and the correct adhesive, strains up to at least 10% can be measured.

3.1.1.2 Linearity

The preceding equations for diaphragm strain and output indicate that the output is proportional to the applied pressure. This precise linearity applies, however, only for vanishingly small deflections. In the case of finite deflections, the diaphragm pressure transducer is inherently, and becomes more so, as deflection increases.

3.1.1.3 Construction

For maximum accuracy and minimum hysteresis, it is common practice to design pressure transducers so that the diaphragm is an integral part of the transducer body. In our design, the cylindrically bore tube itself is used as diaphragm. It is neither necessary nor desirable to try to machine the body of the transducer to a sharp internal corner at the junction with the diaphragm. The presence of the fillet radius, however, is merely one of the ways in which practical transducer construction differs from the idealized concept corresponding to the earlier assumptions and the equations given here. Because of this and the other differences, the transducer behavior will necessarily differ from the ideal; and experimental development will obviously be required to optimize the performance.

3.1.2 SPECIFICATIONS OF THE STRAING GAUGES USED

The strain gauges used in the present work were procured form M/s Hytech Micro Measurements, New Delhi (model AP2-3-5SD-C6-EL). The gauges are manufactured by them from specially treated constantan alloy. The backing carrier is a specially selected polyimide film or glass matrix impregnated with low creep epoxy formulation. All encapsulated gauges are soldered with tipped tabs. All the gauges used are of (350 ± 0.6) ohms, gauge length 5 mm (grid length), thickness < 0.04 mm, overall dimension (11.5 x 6.5) mm and gauge factor 2.1. The gauge power dissipation is from minimum 0.007 mW to maximum 71.84 mW for minimum excitation voltage as 0.1 V to maximum excitation voltage as 10 V.

3.1.3 STRAIN GAUGE BONDING

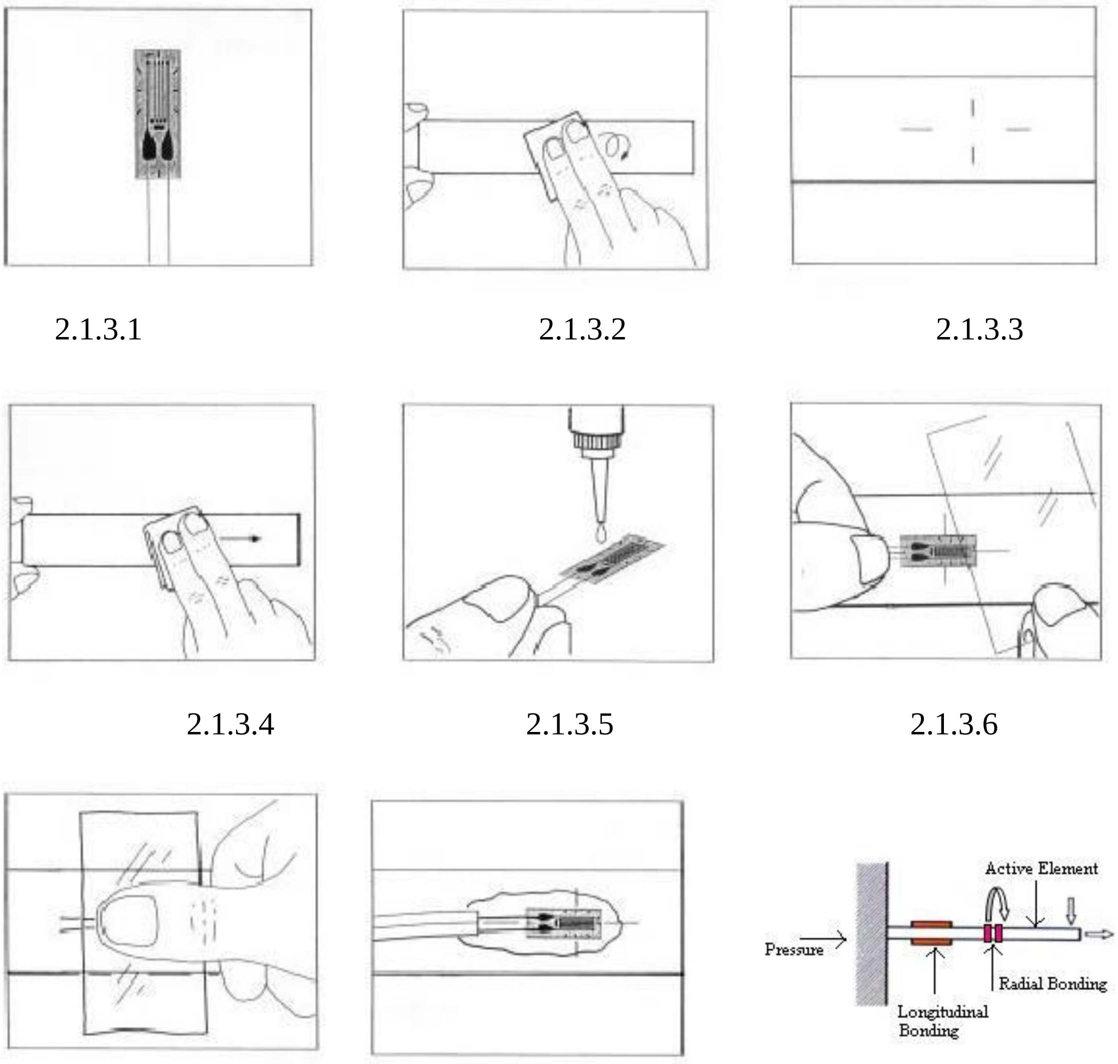
Bonding of strain gauges with diaphragm is one of the most important, critical and skilful job in the development of strain gauge pressure transducers. Small negligence and carefree attitude would damage the expensive strain gauge while cementing with diaphragm. The strain-gage bonding method differs depending on the type of the strain gage, the applied adhesive and operating environment. In the present case, for the purpose of strain gauge mounting at normal temperatures in a room, the bonding procedure is described for a typical lead wire gauge to a mild steel specimen using commercially available TT3300 quick-curing adhesive. TT3300 cement is a heat-cured, 2-part epoxy adhesive that can be used to bond polyimide-backed strain gages for strain measurement up to 200 °C (392 °F). Each TT300 kit includes 2 bottles of resin and hardener that are pre-measured to ensure proper mixing proportions. Before use, one bottle of hardener is mixed with one bottle of resin and shaken for a minute or so. The mixture of one bottle each of hardener and resin produces approximately 125 – 150 ml of adhesive. The life of the resin hardener mixture is about 6 weeks at room temperature. However, the life of the unmixed components is indefinite provided bottles are kept tightly sealed. Each TT300 kit also includes 50 ml of acetone, acid primer, neutralizer, and resin solvent for cleaning and preparing the surface, as well as 2 funnels and 2 cap brushes.

Other commonly used adhesives for strain gauges, SG496 and SG401, are general purpose cold curing, 1-part glues. They cure in a minute but require 24 hours to set. The SG496 is an ethyl-based cyanoacrylate while SG401 is a methyl-based cyanoacrylate. They have generally one year shelf life at room temperature but may be used for longer period at cold places. Their working temperature range is -54 to 82 °C (- 65 to 180 °F).

The pictorial view of the step by step bonding procedure is shown in Fig. 3.3 for which all the steps are given below;

3.1.3.1 Select the suitable strain gauge model with appropriate gauge length as per requirement and measuring purpose.

3.1.3.2 The active element bonding sites are then polished with the help of sand cloth, especially # 200 to 300 having much higher areas then required for bonding to accommodate the gauges appropriately. All the paint, rust and plating, if any, are wiped off with the help of a grinder o r sand blast before polishing.



2.1.3.1 2.1.3.2 2.1.3.3

2.1.3.4 2.1.3.5 2.1.3.6

2.1.3.7 2.1.3.8 Complete bonded assembly

Fig. 3.3: Step by step procedure for bonding of strain gauges

3.1.3.3 The measuring site is then properly marked off in the strain direction using a lead pencil or a marking-off pin. Appropriate care is taken while marking not to scratch strain gauge bonding surface deeply.

3.1.3.4. The strain-gage bonding site is then cleaned using an industrial tissue paper dipped in acetone. The surface is then wiped off, strongly in a single direction to collect dust and then remove dust by wiping in the same direction. Reciprocal wiping causes dust to move back and forth and do not ensure cleaning.

3.1.3.5 The few drops of TT3300 adhesive is then applied to the back of the strain gauges. The proper care is taken not to spread the adhesive for unwanted places. The unwanted spreading of adhesive adversely affects the curing process thereby lowering the adhesive strength.

3.1.3.6 After applying a drop of the adhesive, the strain gauges are placed on the measuring site while lining up the center marks with the marking off lines. Two strain gauges are bonded on the measuring surface in longitudinal direction while other two are placed in radial direction.

3.1.3.7 The strain gauges are then covered with the accessory polyethylene sheet which is pressed over with a thumb for a minute or so. The lifting of strain gauges is not required to adjust the position, once the strain gage is placed on the bonding site because it would extremely lowered the adhesive strength.

3.1.3.8. After pressing with thumb process is over, the polyethylene sheet is removed and it is ensured that the strain gauge is properly cemented. The gauges are then kept for at least 2/3 hours for complete curing of the adhesive. After following of these steps, the gauges are ready for electrical connections and for other electronics.

3.1.4 POWER SUPPLY

Power supply is designed and developed to convert high voltage AC mains to a suitable low voltage supply for electronic circuits and other devices. The Power supply thus developed is a combination of series of blocks, each of which performs a particular function. The block diagram, circuit diagram and photograph of the Regulated DC Power Supply are shown in Figs. 3.4, 3.5(a) and 3.5(b), respectively.

Transformer steps down the high voltage AC mains to low AC voltage. The rectifier converts this AC voltage into DC but the DC output obtained is varying. The smoothing circuit smoothes the DC from varying greatly to a small ripple. The voltage regulator eliminates the ripples by setting up DC output to a fixed voltage.

The digital board is powered by this dual power supply and it produces regulated DC supply of +12V, -12V. A 15-0-15 V centre tap transformer is used to step down the 230 V AC voltage. Full bridge rectifier is formed by four BRI4A diodes, which convert AC voltage to DC voltage. Voltage regulator 7812 converts the DC voltage obtained from full bridge rectifier to +12 V regulated DC voltage. Several capacitors are used as filters of DC voltage at various stages. Since, a supply of 10 V was needed for the sensor, it was achieved through a voltage divider circuit shown in right hand side of Fig. 3.5 (a). In order to use supply in future works for the digitization of the transducer output, this special design of the power supply was made to have there outputs of 5 V, 10 V and 12 V. The 12 V power supply would be used for microcontroller design for future works.

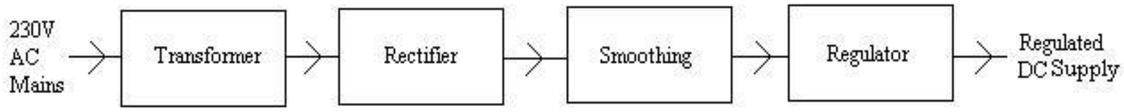


Fig. 3.4: Block diagram of a the regulated power supply

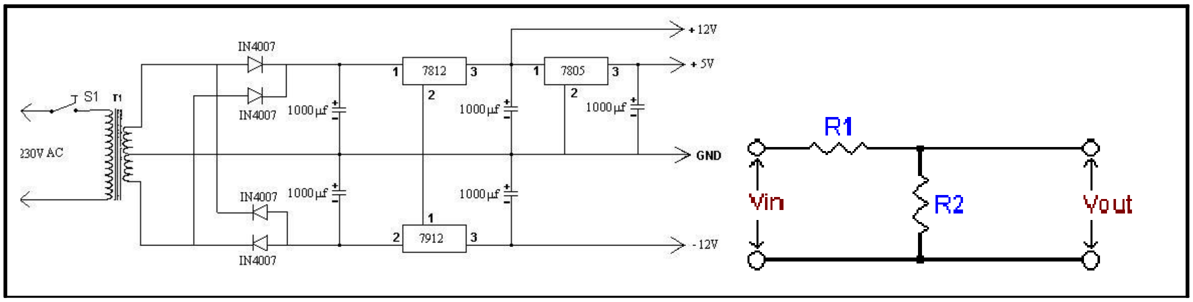


Fig. 3.5: (a) Circuit of a regulated power supply

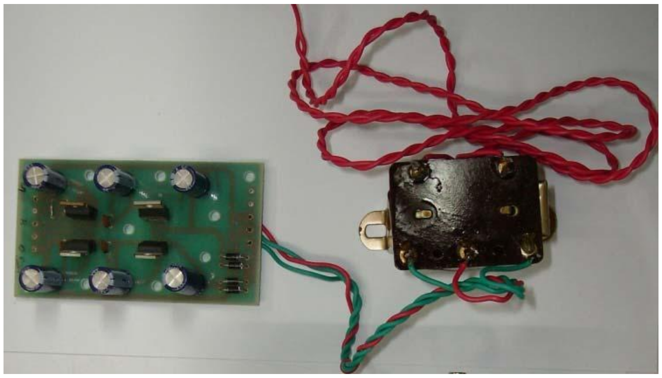


Fig. 3.5: (b) Photograph of the 12 V power supply

3.1.5 SIGNAL CONDITIONING AND AMPLIFICATION

In electronics, signal conditioning means manipulating an analogue signal in such a way that it meets the requirements of the next stage for further processing. The processing of the form or mode of a signal so as to make it intelligible to, or compatible with, a given device. Signal conditioner is a device placed between a signal source and a readout instrument to change the signal. Examples are attenuators, preamplifiers, charge amplifiers, and sophisticated level-translating devices that can compensate for non-linearity in the sensor or amplifier. The signal conditioner coverts a signal that may be difficult to read by a conventional instrumentation amplifier into a more easily format following several functions which include filtering, conversion, excitation and electric isolation. The various signal conditioning stages of the present developmental work are shown in Fig. 3.6. The electrical output (in mV) of the transducer is amplified using an instrumentation amplifier, INA114. It is a low cost, general purpose instrumentation amplifier offering excellent accuracy.

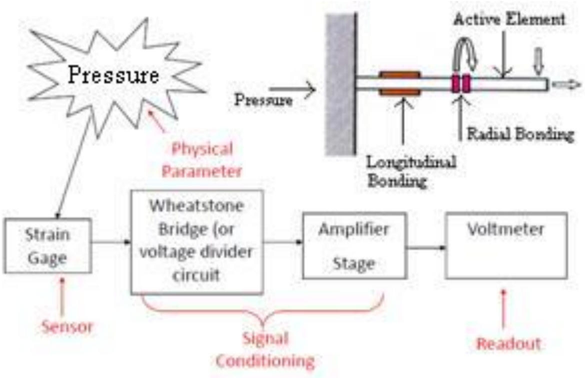


Fig. 3.6: Signal conditioning stages for the present pressure transducer

Its versatile 3-op amp (operational amplifier) design and small size make it ideal for a wide range of applications. A single external resistor sets gain from 1 to 10,000. Internal input protection can withstand up to ± 40 V without damage. The INA114 is a laser trimmed for very low offset voltage (50 mV), drift (0.25 mV/°C) and high common mode rejection (115 dB at G = 1000). It operates with power supplies as low as ± 2.25 V, allowing use in battery operated and single 5 V supply systems. Quiescent current is 3 mA maximum. The INA114 is available in 8-pin plastic and SOL-16 surface-mount packages. Both are specified for the – 40°C to + 85 ° C temperature ranges. A layout diagram of the pin arrangement is shown in Fig. 3.7.

Applications with noisy or high impedance power supplies may require decoupling capacitors close to the device pins. The output is referred to the output reference (Ref) terminal which is normally grounded. This is a low-impedance connection to assure good common mode rejection. A resistance of 5 Ω in series with the Ref pin will cause a typical device to degrade to approximately 80 dB CMR (G = 1). The gain of the INA114 is set by connecting a single external resistor, ;

$$G = 1 + \frac{50\,K\Omega}{R_G} \qquad [3.4]$$

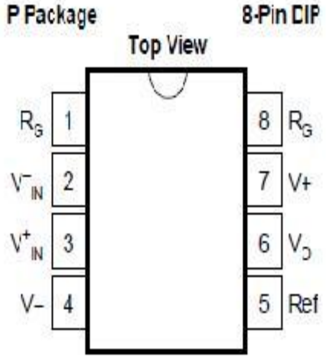
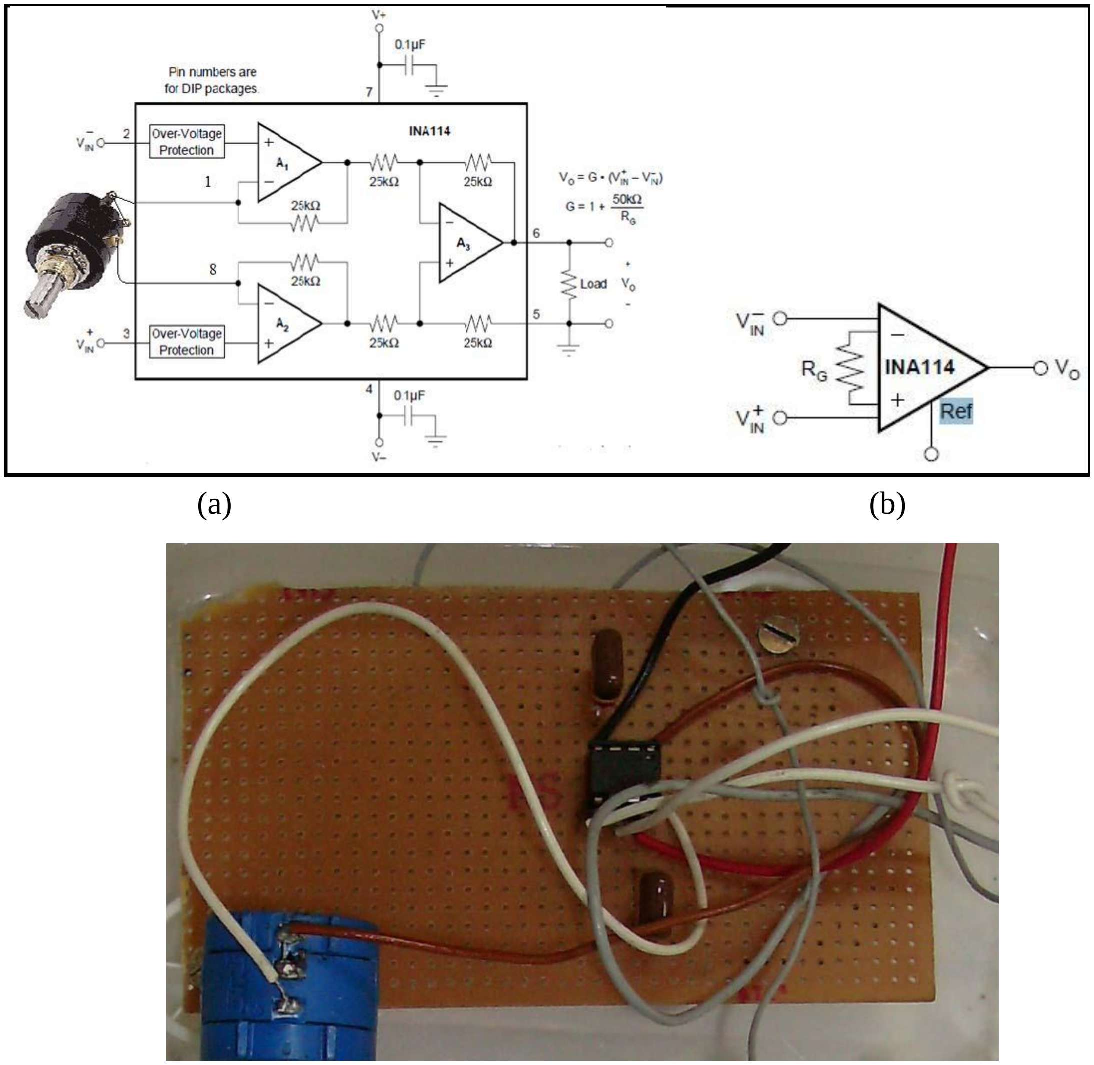


Fig. 3.7: The pin configuration of INA114

The full circuit diagram showing resistor values is shown in Fig. 3.8. The 50 KΩ term in eq. (3.4) is derived from the sum of the two internal feedback resistors. These are on-chip metal film resistors which are laser trimmed to accurate absolute values.



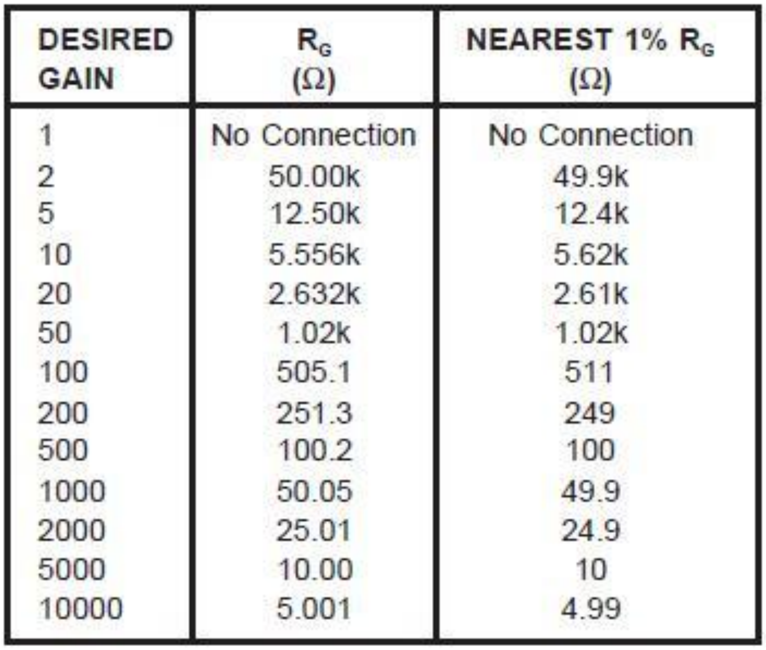
(a) (b)

(c)

Fig. 3.8: (a) The circuit diagram of instrumentation amplifier (INA114) used in the present work, (b) Pin configuration of INA114 and (c) photograph of INA114

The accuracy and temperature coefficient of these resistors are included in the gain accuracy and drift specifications of the INA114. The stability and temperature drift of the external gain setting resistor, R_G, also affects gain. The contribution of R_G to gain accuracy and drift is directly inferred from the eq. (3.4). Sockets attached to the wiring resistance contribute additional gain error (possibly an unstable gain error) in gains of approximately 100 or greater. The INA114 provides very low noise in most applications. Low frequency noise of the INA114 is approximately 0.4 mV peak to peak measured from 0.1 Hz to 10 Hz. This is approximately one-tenth, the noise of ‘low noise’ chopperstabilized amplifiers. The most commonly used gains and resistor values for INA114 are shown in Table 3.1. The full connection arrangements of INA114 with bridge circuit and power supply are depicted in Fig. 3.9. A photograph of the complete assembly of the transducer and electronics is depicted in Fig. 3.10.

Table 3.1: The amplifier gain and register values



DESIRED GAIN	R_G (Ω)	NEAREST 1% R_G (Ω)
1	No Connection	No Connection
2	50.00k	49.9k
5	12.50k	12.4k
10	5.556k	5.62k
20	2.632k	2.61k
50	1.02k	1.02k
100	505.1	511
200	251.3	249
500	100.2	100
1000	50.05	49.9
2000	25.01	24.9
5000	10.00	10
10000	5.001	4.99

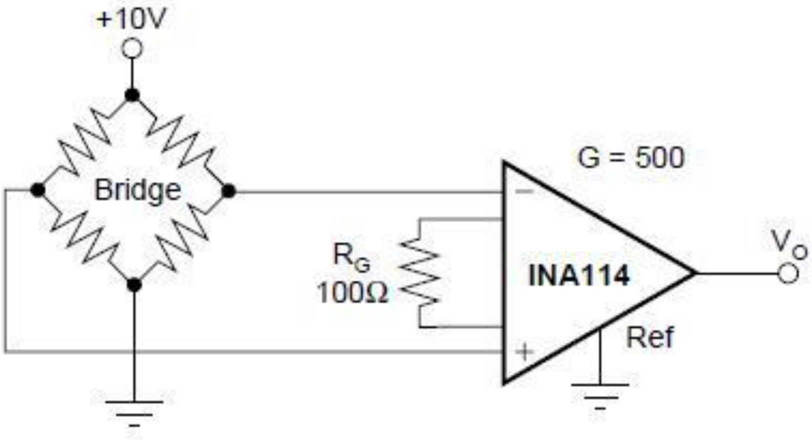


Fig. 3.9: Connection arrangements of power supply, bridge and INA114

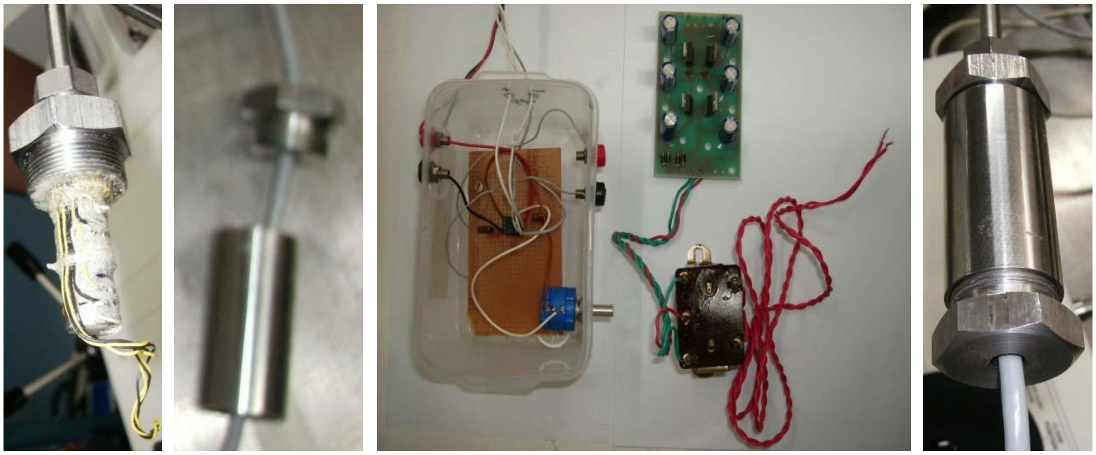


Fig. 3.10: A photograph showing the pressure transducer developed and its electronics

CHAPTER-4: CALIBRATION, RESULTS AND DISCUSSION

4.1. CALIBRATION OF THE PRESSURE TRANSDUCR

The calibration is a method for comparing measurements taken by measuring equipment against a standard, whose accuracy is known and is traceable to National or International Standards. Traceability is a concept of establishing a valid calibration of a measuring instrument or a measuring standard by a step-by-step comparison with better Working Standards or National Standards.

4.1.1 CALIBRATION PROCEDURE

The calibration of the presently developed pressure transducer in gauge mode is carried out using dead weight tester as pressure standard. A layout diagram and photograph of the experimental setup used are shown in Figs. 4.1(a) and (b), respectively. The sensor of the transducer detects the pressure-induced stress by means of changes in the resistance of the strain gauge. The sensor produces output in mV. The output changes from 0 mV to 0.022 mV within the pressure range 0 to 2000 bar. The output is then amplified using instrument amplifier (INA114). The amplified output is then measured / monitored using a 6-1/2 HP34401A Digital Multimeter.

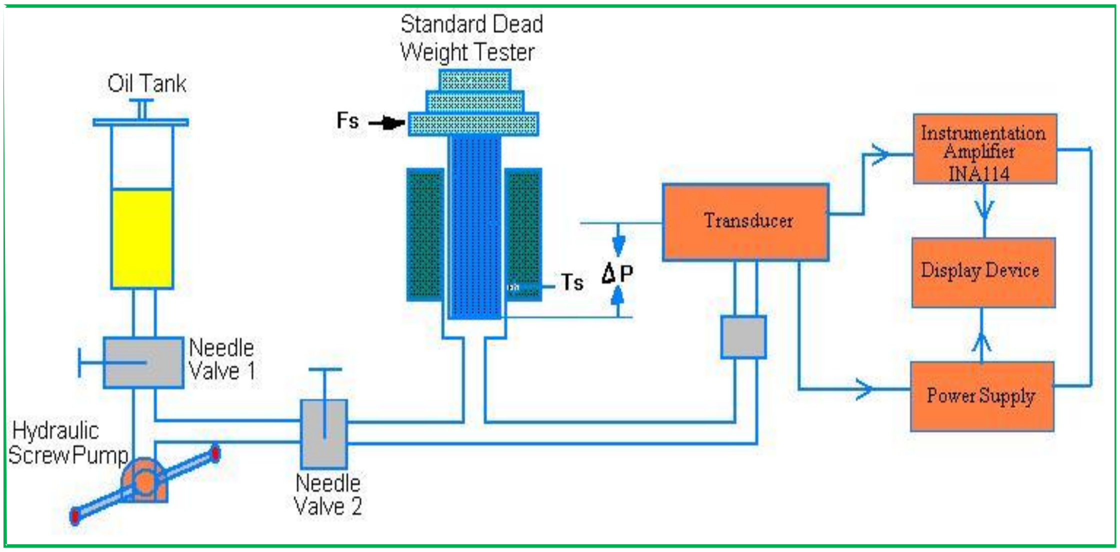


Fig. 4.1(a): Experimental setup for calibration of the developed pressure transducer using dead weight tester as standard instrument

Fig. 4.1(b): Photograph of the experimental setup for calibration of the developed pressure transducer

In present work, the electronic circuitry has also been designed and developed for measuring the direct digital pressure output. Although I have completed the electronics for direct digital pressure measurement and associated software, but due to lack of sufficient time, the electronic circuit could not be used for calibration purpose. Since it takes at least one-month time to calibrate the instruments against national secondary standard to validate the repeatability and reproducibility of the data, the output was measured using a 6-1/2 HP34401 Digital Multimeter in order to understand the whole calibration procedure and acquire calibration expertise. Both the sensor and INA114 were excited by a regulated DC power supply of 10.0 V developed in the present work. The standard instrument used in the present study is a simple type dead weight tester, a national hydraulic secondary pressure standard, designated as NPL200MPA herein thereafter, make DH Instrument, USA, capable to measure high hydrostatic pressure up to 200 MPa. The relative uncertainty associated with pressure measurement using this standard is 37 x 10^{-6} x p at a coverage factor k = 1 and its compatibility and traceability is established through CCM sponsored international key comparison and in-house intercomparison exercises [51-57].

4.1.2 PRELIMINARY OPERATIONS AND PRECAUTIONS

Both the instruments, the standard used (DWT) and pressure indicating transducer under calibration referred as (Test) herein thereafter are placed on strong rigid table in the calibration room, which has stainless steel sheet having thickness of 15 mm as the top of the working table to isolate the vibrations. The calibration room is always maintained as very neat, clean and dusts free. The DWT and Test were cleaned with soft cloth or tissue paper or cotton. Being electronic equipments, Test gauges are generally very delicate instruments and therefore are used with utmost care. The Test was switched on and warming time of at least half an hour was given. The free movement of piston of DWT was checked by moving it up and down by hand. The piston-cylinder assembly should be free from any dust particles. The free rotation of the screw hydraulic pump handle and valves were checked. Clean mineral oil (Sebacate oil) was then poured in the oil reservoir. Valve-1 was opened and Valve-2 was closed. The screw pump was fully turned anticlockwise for sucking transmitting fluid from the oil reservoir. Then valve-1 was closed and valve-2 was opened and screw pump handle was turned clockwise to create and transmit generated pressure in to the DWT and Test. The sprit level was placed on the pressure carrier of DWT. DWT was leveled with the help of leveling screws. The leveling screws were locked by tightening lock nuts on the legs. After leveling the instruments, calibration of the gauge was started.

The calibration of the Test starts with leak testing, zero adjustment and the selection of a reference or datum level. **For leak testing**, both the DWT and Test were pressurized up to full scale pressure of the Test with the help of hydraulic screw pump and needle valves and waited for at least 5 minutes. Thereafter, the pressure was released slowly to zero. This process was repeated at least three times to ensure that there were no leaks in the system. In this way compressibility of the transmitting oil, packing of the valves, pump plunger and O-ring seals were stabilized to reach an optimum level. The test should not be pressurized for more than 1.2 time of its full-scale pressure. The over pressure would damage the sensor. It is strongly suggested to avoid over pressurizing the system. A good quality pressure dial gauge was used in between pump and the Test to keep watch on the applied pressure.

Zero adjustment of the Test was then performed. Since zero adjustment knob was not made in electronics, the initial bias in the measurement was recorded and necessary corrections were applied at appropriate level. A precise **reference or datum plane** is then established for both the gauges for the hydrostatic head correction. Usually, reference or datum plane is marked on the DWT and Test or noted in the operational manuals. The center point of the quartz sensor was considered as the reference or datum plane.

Before taking the observations, the full-scale pressure of the transducer was divided into 11 equally spaced pressure points. The NPL200MPA was then pressurized up to the pressure point to be calibrated and brought to the floating position at the datum plane and the corresponding output of the transducer was recorded. Observations were repeated in a similar way to reach the full-scale pressure. Total number of 24 observations, 12 each in increasing as well as decreasing orders of pressures, were taken in one pressure cycle to evaluate the hysteresis in the pressure measurements. After reaching full-scale pressure in increasing order of pressure, 10 minutes were allowed to pass before repeating the observations in decreasing order of pressure. Sufficient time of at least 15-20 minutes was given between two successive observations to allow the system to reach thermally equilibrium state. Three pressure cycles were employed so that the minimum number of observations at each pressure point was 6 and there were total 72 observations as a whole.

All the values of the measured pressure by the DWT are corrected for temperature at 23^{0}C, and using thermal expansion coefficient of the piston – cylinder assembly using standard equations. The measured pressure by the DWT was then computed after applying all corrections i.e. temperature correction, hydrostatic head correction and unit conversion using eq. (4.1) with the help of a computer software developed by the Pressure & Vacuum Group for this purpose [58] using the well established theory of pressure balances [1-10, 20, 59-65].

$$P_{DWT} = \frac{\sum_i m_i \cdot g_L \cdot (1 - \rho_{air}/\rho_{mi}) + \gamma \cdot C}{A_0(1 + bP)\cdot[1 + (\alpha_p + \alpha_c)\cdot(T - T_r)]} \pm \Delta P \qquad [4.1]$$

where $\Sigma_i m_i$ is the mass of the dead weights acting on the piston, g_L is the local acceleration of gravity, ρ_{air} is the density of air, ρ_{mi} is the density of the weights, γ is the

surface tension of the fluid, *C* is the circumference of the piston where it emerges from the cylinder, A_{0P} is the area of the piston at the reference temperature T_r [23^{0}C] and at atmospheric pressure, *b* is the distortion coefficient for the piston, α_p and α_c are the linear thermal coefficients for the piston and cylinder, respectively, *T* is the measurement temperature of the piston cylinder and Δp is the head correction in terms of pressure. The **head correction** term $\Delta P = [(\rho_f - \rho_{air}).\ g_L.\ H]$, is a very important correction term and contributes significantly, where H is the difference in height between the reference levels of the DWT and the Test, g_L is the local acceleration of gravity in m/s^2 and (ρ_f) is the density (in kg/m^3) of the pressure transmitting fluid used in the measurements. If H is in meter, g_L in m/s^2 and ρ_f in kg/m^3 then ΔP will be in Pa. ΔP will be positive, if the reference level of the DWT is above the reference level of the Test and will be negative for the reverse case.

4.1.3 SPECIFICATIONS OF THE INSTRUMENTS

4.1.3.1 Specification of the Test

Pressure range:	0 - 2000 bar
Output range:	0 – 0.00095 mV/V (before amplification), 0 – 2.75 mV/V (after amplification)
Resolution:	0.001 mV/V
Hysteresis:	0.002 mV/V
Accuracy:	0.1 % of full scale
Over pressure range:	2400 bar

4.1.3.2 Specification of the DWT

Pressure range:	0.4 - 200 MPa
Measurement uncertainty:	$37 \times 10^{-6} \times p$ (at $k = 2$)

4.1.4 ESTIMATION OF MEASUREMENT UNCERTAINTY

The operational integrity of any measuring instrument is determined by the measurement error evaluated by calibration. Therefore, a well established, readily implemented, easily understood and generally accepted procedure for characterizing the quality of measurement i.e. uncertainty of measurement has been brought out by BIPM as ISO document [66]. The measurement uncertainty is estimated as per ISO guidelines [66] and other literature available on this subject [66-75].

The output pressure of the transducer can be defined by a curve that has been fitted to experimental data by method of least square [66]. In pressure metrology, a curve of the reading made by a gauge under calibration versus the applied reference pressure is generally a straight line, if device is working properly. Let (x_i, y_i) be a set of n ordered pairs, obtained experimentally. If we wish to fit a polynomial of degree m to n experimental points, $n > m$, then we would get n equations and m+1 normal equations after differentiating the sum of squares of the residuals. The corrected pressure y is related to indication of the device x_i by a simple polynomial as follows [70];

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + ... + a_m x^m \qquad [4.2]$$

where m is the order of fitting for n sets of observations having m+1 constants to be evaluated. In case of direct pressure indicating devices, the simplest form of modeling is linear regression. For a linear relationship, the eq. (4.2) reduced to;

$$y = a_0 + a_1 x \qquad [4.3]$$

For the linear relationship, the constants a_0 and a_1 and their associated standard deviations are computed using the following equations;

$$a_0 = \frac{\sum y \sum x^2 - \sum x \sum xy}{n \sum x^2 - \left(\sum x\right)^2} \qquad [4.4]$$

$$a_1 = \frac{n \sum xy - \sum x \sum y}{n \sum x^2 - \left(\sum x\right)^2} \qquad [4.5]$$

$$\sigma(\;) = \sqrt{\frac{\{s^2 \sum x^2\}}{n \sum x^2 - \left(\sum x\right)^2}} \qquad [4.6]$$

$$\sigma(\;) =$$

$n \quad x$

$\{ns^2\}$

$$\square$$

$$\square [4.7]$$

$$\square \sum{}^2 - (\ ) x^2 \square$$

$n \quad x$

where $\sigma(\ )$ and $\sigma(\ )_1$ are the standard deviations of constants a_0 and a_1, respectively and s^2 is expressed as sum of squares of residual errors divided by number of degree of freedom.

$$s^2 = \left[\sum \{y - (a_0 + a_1 x)\}^2\right] / n - 2 \qquad [4.8]$$

The standard uncertainty associated with constants a0 and a1 is then computed using;

$$u(a_0) = \sigma\left(\ \right) \qquad [4.9]$$

$$u(a_1) = \sigma\left(\ \right)_1 \qquad [4.10]$$

Further, the covariance $V\left(a_0, a_1\right)$and correlation coefficient $r\left(a_0,a_1\right)$of both the constants are estimated by;

$$V\left(a_{0}, a_{1}\right) = -\frac{s^2\sum x}{\left[\sum\ \left(\ \right)^2\ \right]} \qquad [4.11]$$

$$r\left(a_0, a_1\right) = -\frac{V\left(a_0, a_1\right)}{\left[\sigma\left(\ \right)\left(\ \right) a_1\right]} = -\frac{\sum x}{\sqrt{\left[n\sum x^2\right]}} \qquad [4.12]$$

The standard deviation of residual errors between experimental and fitted values is one of the important contributions. This is an optional contribution to be included in the uncertainty budget and is computed using the following relationship;

$$\sigma\left(\ \right)_c = \sqrt{s^2} \qquad [4.13]$$

Finally, the standards uncertainty associated with estimate y for a given value x by linear curve fitting is estimated following the ISO Guide as follow;

$$u\left(\ \right) = \sqrt{\left(\frac{\delta y}{\delta a_0}\right)^2 \cdot u\left(\ \right)^2 + \left(\frac{\delta y}{\delta a_1}\right)^2 \cdot u\left(\ \right)^2 + 2\left(\frac{\delta y}{\delta a_0}\right)\cdot\left(\frac{\delta y}{\delta a_1}\right)\cdot u\left(\ \right)\left(\ \right)\left(\cdot r\, a_0, a_1\right)} \qquad [4.14]$$

where ($\delta y/\delta a_0$) and ($\delta y/\delta a_1$) are the sensitivity coefficients of a_0 and a_1, evaluated by partial derivations of eq. (4.14).

4.2. CALIBRATION RESULTS

The calibration results are shown in Table 4.1 at the end of this Chapter.

4.2.1 EVALUATION OF TYPE A UNCERTAINTY

Since $u(y_c)$ is estimated by statistical means through linear curve fitting, its contribution is considered to be evaluated through Type A method. Therefore;

$$u_A = \max\{u(y_c)\} = 0.55 \text{ bar} \tag{4.15}$$

Although, $u(y_c)$ is function of pressure but as it is observed that $u(y_c)$ is almost constant, therefore, we have taken maximum value for computation purposes. This condition may not apply for all the calibrations. If there is a considerable change in $u(y_c)$ as a function of pressure, the linear relationship may be taken to represent the u_A uncertainty in the calibration.

4.2.2 EVALUATION OF TYPE B UNCERTAINTY

The other uncertainty contributions due to zero setting, resolution, hysteresis and uncertainty of the standard used in the measurements are considered uncertainty contributions evaluated through Type B method and their uncertainty contributions are evaluated as follows.

4.2.2.1 Zero Setting

Generally zero setting knob / adjuster is provided with transducer. The zero is set before each measurement cycle. If such knob / adjuster is not provided (as in present case) then zero offset value is recorded at the beginning and end of measurement cycle, both in increasing as well as decreasing orders of pressure, with zero pressure / load. Therefore, zero error is calculated using the formula;

$$\delta P_0 = \max \{ |Z_{2,0} - Z_{1,0}|, |Z_{4,0} - Z_{3,0}|, | Z_{6,0} - Z_{5,0}|, \ldots\ldots\ldots\ldots |Z_{n,0} - Z_{n-1,0}| \} \qquad [4.16]$$

where, $Z_{1,0}$, $Z_{3,0}$, $Z_{5,0}$, $Z_{n-1,0}$ are the zero pressure values recorded at the beginning of each pressure cycle while $Z_{2,0}$, $Z_{4,0}$, $Z_{6,0}$, $Z_{n,0}$ are the zero values recorded after reaching full scale pressure in each pressure cycle. This implies that the maximum difference of zero offset recorded at the beginning and reaching full scale pressure of the pressure cycles (three pressure cycles in the present case) is the zero setting error. The uncertainty contribution to the pressure measurement due to zero setting error is estimated as follows assuming rectangular distribution;

$$u(\delta P_0) = \delta P_0 / \sqrt{3} = 0.00115 \text{ bar} \qquad [4.17]$$

4.2.2.2 Resolution

The resolution is the smallest measure / digit step of an electromechanical pressure transducer. During pressure release or loading of device, the indication does not vary by more than one digit step. If '*r*' is the resolution of the device, the error due to resolution and its associated uncertainty contribution are given by eqs. (4.18) and (4.19), respectively, assuming a rectangular distribution.

$$\delta P_{res} = a = r / 2 \qquad [4.18]$$

$$u(\delta P_{res}) = a / \sqrt{3} = 2.88 \text{ x } 10^{-4} \qquad [4.19]$$

where, ‘*a*’ is semi range of the device.

4.2.2.3 Hysteresis

The difference between corresponding values in increasing and decreasing orders of pressure in a pressure cycle is called hysteresis or reversibility in the measurement. The hysteresis at a particular pressure point, j, is determined by:

$$\delta P_{hys} = \frac{1}{n} \{ |X_{2,0} - X_{1,0}|, |X_{4,0} - X_{3,0}|, | X_{6,0} - X_{5,0}|, ... |X_{n,0} - X_{n-1,0}| \} \qquad [4.20]$$

The maximum value of $\delta P_{hy,j}$ is then selected to estimate the uncertainty contribution as follows;

$$\delta P_{hys} = \max \{| \delta P_{hys}|\} \qquad [4.21]$$

$$u\,(\delta P_{hys}) = \delta P_{hys} /\sqrt{3} = 0.298 \text{ bar} \qquad [4.22]$$

4.2.2.4 Combined Type B Standard Uncertainty

Therefore, the combined Type B standard uncertainty is computed as follows;

$$u_B = \sqrt{(\;)\,(\;)\,(\;)_{B1}B2^{2} + u_{B3}22} \qquad [4.23]$$

$$= \sqrt{(0.00115)^2 + \left(2.88x10^{-4}\right)^2 + (0.298)^2} + 19x10^{-6} \cdot p = 0.2981bar + 19\,x\,10^{-6} \cdot p$$

4.2.3 COMBINED STANDARD UNCERTAINTY

Finally, the combined standard uncertainty associated with pressure measurement is then computed using the following relationship;

$$u(P_{Test}) = \{(u_A)^2 + (u_B)^2\}^{1/2} = 0.625 \text{ bar} + 19 \text{ x } 10^{-6} \text{ x } p \qquad [4.24]$$

4.2.4 EXPANDED UNCERTAINTY

Using the Student's table, *k* = 2 for a confidence level of approximately 95.45 %, the expanded uncertainty is then computed as follows;

$$U = k \text{ x } u(P_{Test}) = 1.25 \text{ bar} + 38 \text{ x } 10^{-6} \text{ x } p \qquad [4.25]$$

4.3. REPORTING OF RESULTS

For the pressure range of 0 - 2000 bar, the uncertainty associated with pressure measurements using the strain gauge pressure transducer under reference is + (1.25 bar +

38 $\times 10^{-6}p$) (where p is pressure in bar) at a confidence interval defined by an expanded uncertainty $U = k \times u\,(p_{Test})$ and a coverage factor $k = 2$ based on Student's distribution for $\upsilon_{eff} = 524$ degree of freedom, and is estimated to a level of confidence of 95.45 %. The plots showing the relationship between transducer output, measured pressure and calculated pressure are shown in Fig. 4.2 (a) along with deviations between measured and calculated pressure while the hysteresis in the measurement and measurement uncertainty & accuracy of the transducer are depicted in Figs. 4.2 (b) and (c), respectively.

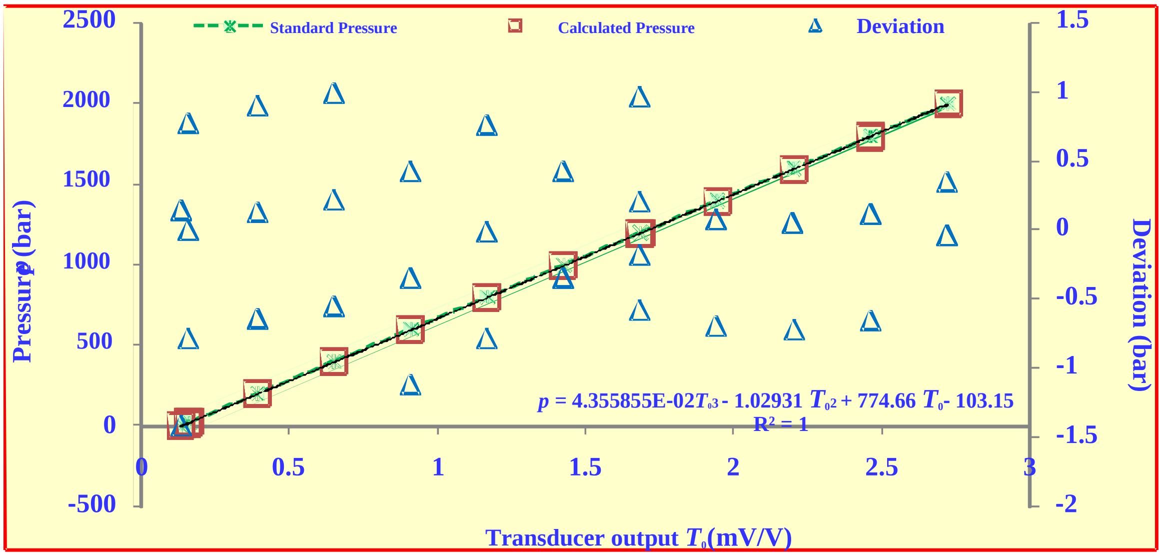


Fig. 4.2(a): Graph between measured pressure and test pressure

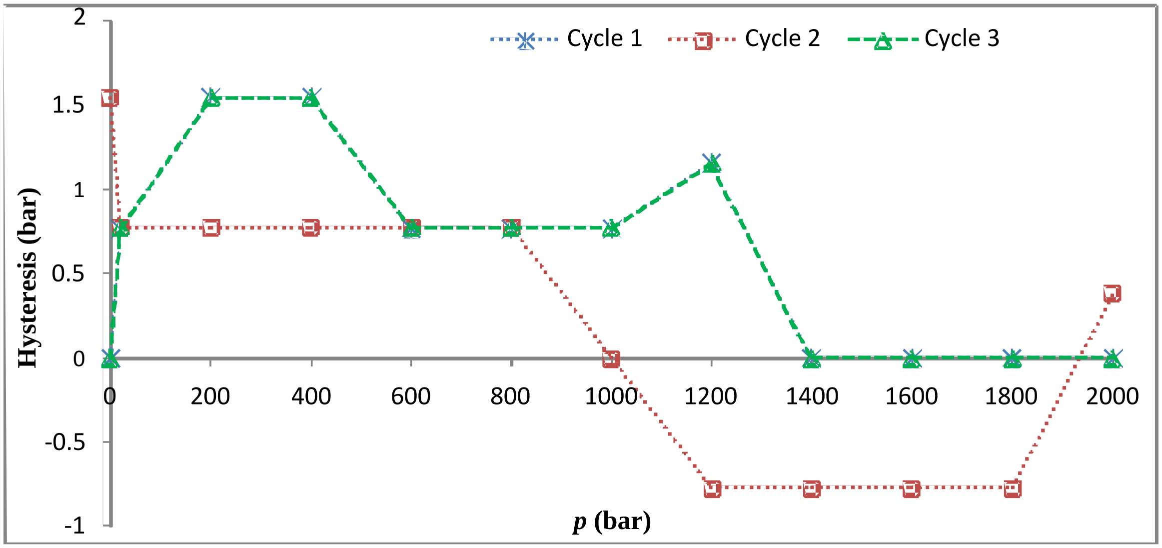


Fig. 4.2(b): Graph showing hysteresis in the measurement for all the 3 pressure cycles

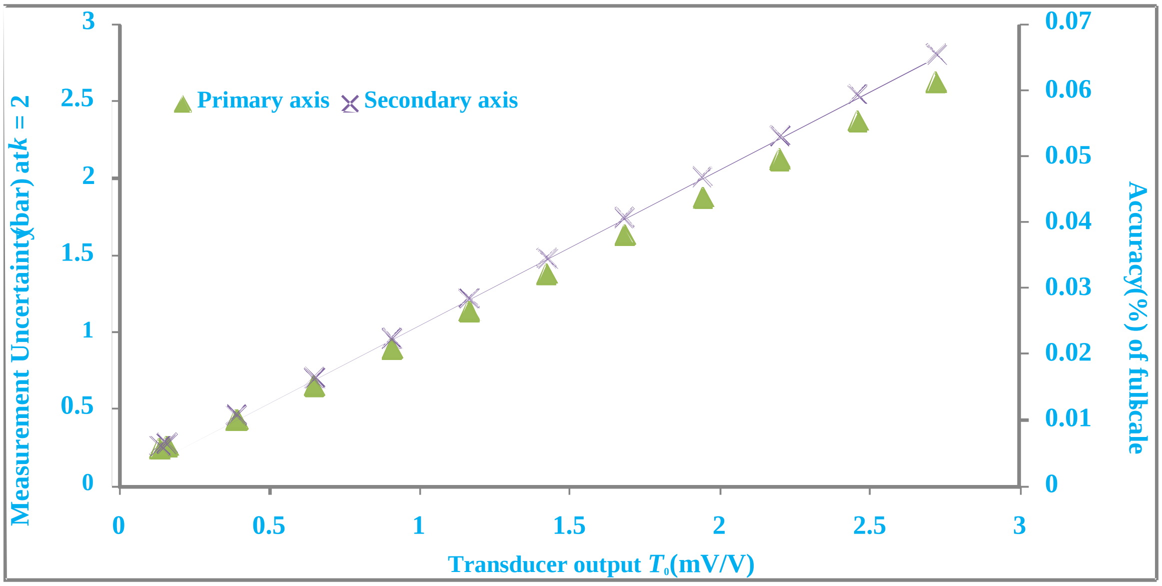


Fig. 4.2(c): Graph showing measurement uncertainty and accuracy of the pressure transducer

4.4. DISCUSSION

It is clearly evident form Fig. 4.2 (a) that there is a perfectly linear relationship between the pressure measured through transducer (calculated pressure) and the pressure measured by the dead weight pressure (standard pressure). The transducer output (T_0) and measured pressure (p) are then list squares fitted using simple polynomial equation of 4th order and the fitting coefficients and the fitting equation thus obtained are shown in eq (4.28) and also in Table 4.2. The pressure calculated values thus obtained are also plotted in Fig. 4.2(a). It is clear from the plots that the experimental pressure values and fitted values are almost superimposed each other within the acceptable deviations shown on secondary y axis. The standard deviation of the fitting is found to be 0.5 bar which is 0.04 % of the full scale pressure value.

$$p = [(-103.1503) + (774.6636) \text{ x } T_0 + (-1.02921) \text{ x } T_{02} + (4.355855E\text{-}02) \text{ x } T_{03}][4.26]$$

The linearity of a curve is generally defined by the value of coefficient of determination (R^2). If the value of R^2 is near or equal to unity, the relationship is considered linear. In the present case, $R^2 = 1$, defines the linearity of the pressure transducer. The zero error and its associated uncertainty computed using eqs (4.16) and

(4.17) are found to be 0.0021 bar and 0.0012 bar, respectively. Similarly, the resolution error and its uncertainty contribution computed using eqs (4.18) and (4.19) are found to be 0.0005 bar and 0.00028 bar, respectively. The hysteresis in the results for any measuring instrument is a major source of error. The maximum uncertainty contribution computed using eqs (4.20) to (4.22) is found to be 0.29 bar is equivalent to 0.0145 % the full scale pressure in relative terms. However, the accuracy of the instrument is found to be better than 0.07 % of the full scale pressure.

The unique design of the single piece active element achieved by extensive theoretical computations of the design parameters. One of the most important parameters is designing of adequate wall thickness with sufficiently measurable output signal. The wall thickness t is calculated using Lame's equation as follows;

$$t = r \cdot \left(\sqrt{\frac{\sigma_{\max} + p}{\sigma_{\max} - p}} - 1 \right) \qquad [4.27]$$

where maximum allowable stress, $\sigma_{\max}$ is calculated from outer diameter, R, inner diameter, r and maximum pressure p = 2000 bar as follows;

$$\sigma_{\max} = \left(\frac{r^2 \cdot p}{R^2 - r^2} \right) \cdot \left(1 + \frac{R^2}{r^2} \right) \qquad [4.28]$$

At a pressure of 2000 bar, the $\sigma_{\max}$ is found to be 2214 bar. Although, the calculated measurable signal is much higher at wall thicknesses ranging from 1 to 3 mm but the values of maximum allowable stress, $\sigma_{\max}$ are smaller than that of the maximum pressure of 2000 bar. Therefore, such designs are assumed to be not working safely at such a high pressure. The values of $\sigma_{\max}$ are higher than p at t > 3 mm. For keeping the goal of achieving the burst pressure, $p_b = 1.2 * p = 2400$ bar, we have focused our design at a wall thickness t = 5 mm. The theoretical computations of V_o as a function of t are depicted in Fig. 4.3.

As reported earlier, two strain gauges are bonded in axial direction and two in radial direction. The design of the transducer includes a theoretical stress – strain analysis of the active element of the transducer. Radial strains are calculated because they are crucial for machining tolerance values. The stress – strain analysis was made at the highest and pressure value of 200 MPa. The change in the outer and inner diameters, ΔR *and* Δr, of the active element due to applied pressure, p are given by Molinar et al [35];

$$\Delta R = \frac{p \cdot R \cdot \mu}{E} \qquad [4.29]$$

$$\Delta r = \frac{p \cdot r \cdot \mu}{E} \qquad [4.30]$$

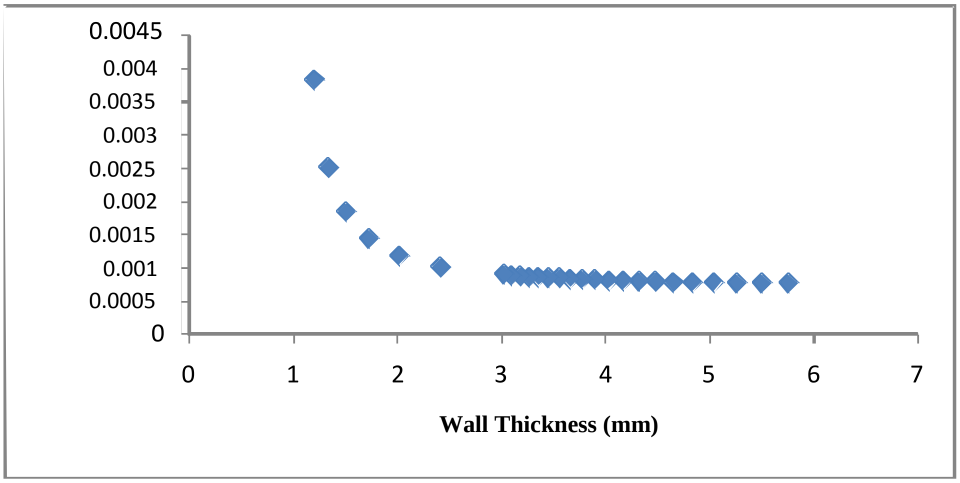


Fig. 4.3: V_o as a function of t

Further, the axial and radial strains, ε_a and ε_r, and the measurement signal $\Delta V/V$ (expressed in mV/V) of the full Wheatstone bridge for the case of cylindrical free cylinder are calculated using the following formulae;

$$\varepsilon_a = -\frac{p}{E}\left(1+\frac{2\mu}{\varpi^2-1}\right) \qquad [4.31]$$

$$\varepsilon_r = \frac{p}{E}\left(\mu+\frac{2}{\varpi^2-1}\right) \qquad [4.32]$$

$$V_{out} = \frac{GF \cdot \varepsilon_r \; \varepsilon_a}{4} \qquad [4.33]$$

All the values thus calculated are shown in Table 4.2. The resolution of the strain measurements ranges form 17 – 60 ppm of full scale signal. The stability, in case of full bridge configuration and over 15 days time is found to be better than 0.2 bar. The repeatability is calculated over 3 consecutive calibration pressure cycles. Typical repeatability is found to be better than 0.05 bar. The zero shift of the transducer is found well within the measurement resolution of 0.1 bar. The transducer sensitivity is evaluated at maximum pressure 2000 bar by putting fractional masses on the pressure balance and it

V_0 (mV/V)

is found to be well within 50 x 10^{-6} of full scale pressure. The transducer linearity is observed well within 60 x 10^{-6} of full scale pressure.

Table 4.2: Characteristics of the pressure transducer

Description Value	
Outer Diameter R (mm)	12
Inner Diameter r (mm)	2
Wall Thickness t (mm)	5
Length l (mm)	15
Young's Modulus E (GPa)	189
Yield Strength Y (GPa)	1.77
Maximum Allowable Stress σ_{max} (GPa)	0.22
Poisson Ratio μ	0.3
Change in Outer diameter ΔR(mm)	3.84E-03
Change in Inner diameter Δr (mm)	6.67E-04
Axial Strain ε_a ($\mu\varepsilon$)	-1.08E-03
Radial Strain ε_r ($\mu\varepsilon$)	3.83E-04
Calculated Measurement Signal V_o(mV/V)	0.00077
Experimental Measurement Signal (mV/V)	0.000955
Measurement Signal after Amplifications (mV)	0.135 -2.75

Table – 4.1: Calibration results and fitting parameters of the transducer

Sl. No.	COEFFICIENTS	STD. DEV.	STD. UNC.
1	-103.1503	.2100048	.2100048
2	774.6636	.7243276	.7243276
3	-1.02921	.6164728	.6164728
4	4.355855E-02	.1449878	.1449878

STD DEV = .5074648 STD UNC = .5074648

X MIN = .133 X MAX = 2.722

Y MIN = 0 Y MAX = 1998.703

Sl. No.	X(mV/V)	MEAS. Y(bar)	CALC. Y(bar)	DEVIATION(bar)
1.	.133	0	-.1381998	.1381998
2.	.133	0	-.1381998	.1381998
3.	.133	0	-.1381998	.1381998
4.	.135	0	1.410665	-1.410665
5.	.133	0	-.1381998	.1381998
6.	.133	0	-.1381998	.1381998
7.	.158	19.99006	19.22097	.7690923
8.	.159	19.99006	19.99527	-5.206518E-03
9.	.159	19.99005	19.99532	-5.267553E-03
10.	.16	19.99006	20.76965	-.7795873
11.	.158	19.99006	19.22097	.7690923
12.	.159	19.99006	19.99527	-5.206518E-03
13.	.39	199.7151	198.8145	.9006402
14	.392	199.7153	200.3622	-.6469346
15	.391	199.715	199.5884	.1265962
16	.392	199.7152	200.3623	-.6470567
17	.39	199.7151	198.8145	.9006402
18	.392	199.7153	200.3622	-.6469346
19	.648	399.4039	398.4113	.9925942
20	.65	399.4041	399.9581	-.5539888
21	.649	399.4035	399.1847	.2187831
22	.65	399.404	399.9581	-.5541108
23	.648	399.4039	398.4113	.9925942
24	.65	399.4041	399.9581	-.5539888
25	.907	599.0866	598.6553	.4312505
26	.908	599.0871	599.4282	-.3411438
27	.908	599.0861	599.4282	-.3421203
28	.909	599.0868	600.2012	-1.114351
29	.907	599.0866	598.6553	.4312505
30	.908	599.0871	599.4282	-.3411438
31	1.165	798.7635	798.0048	.7587445
32	1.166	798.7642	798.7772	-1.300718E-02
33	1.166	798.7627	798.7772	-1.453306E-02
34	1.167	798.7639	799.5497	-.7857844
35	1.165	798.7635	798.0048	.7587445

36	1.166	798.7642	798.7772	-1.300718E-02
37	1.424	998.4353	998.0095	.4258423
38	1.425	998.4362	998.7814	-.3451813
39	1.425	998.4343	998.7814	-.3470734
40	1.425	998.4357	998.7814	-.3456696
41	1.424	998.4353	998.0095	.4258423
42	1.425	998.4362	998.7814	-.3451813
43	1.682	1198.101	1197.129	.9715324
44	1.6835	1198.102	1198.287	-.184724
45	1.684	1198.099	1198.672	-.5735393
46	1.683	1198.102	1197.901	.2011232
47	1.682	1198.101	1197.129	.9715324
48	1.6835	1198.102	1198.287	-.184724
49	1.942	1397.76	1397.684	7.605185E-02
50	1.942	1397.761	1397.684	7.702842E-02
51	1.943	1397.758	1398.455	-.6969761
52	1.942	1397.761	1397.684	7.702842E-02
53	1.942	1397.76	1397.684	7.605185E-02
54	1.942	1397.761	1397.684	7.702842E-02
55	2.201	1597.415	1597.363	5.215887E-02
56	2.201	1597.416	1597.363	5.313543E-02
57	2.202	1597.412	1598.134	-.7215747
58	2.201	1597.415	1597.363	5.215887E-02
59	2.201	1597.415	1597.363	5.215887E-02
60	2.201	1597.416	1597.363	5.313543E-02
61	2.46	1797.063	1796.943	.1205421
62	2.46	1797.064	1796.943	.1215187
63	2.461	1797.06	1797.713	-.6527358
64	2.46	1797.063	1796.943	.1205421
65	2.46	1797.063	1796.943	.1205421
66	2.46	1797.064	1796.943	.1215187
67	2.722	1998.702	1998.737	-3.481356E-02
68	2.722	1998.703	1998.737	-.033837
69	2.7215	1998.699	1998.352	.3470867
70	2.722	1998.703	1998.737	-.033837
71	2.722	1998.702	1998.737	-3.481356E-02
72	2.722	1998.703	1998.737	-.033837

Y CALC. MIN = -.1381998	Y CALC. MAX = 1998.737
MAX POS. DEV. = .9925942	MAX NEG. DEV. = -1.410665
No. OF POS. DEV. = 38	No. OF NEG. DEV. = 34
No. OF DEV. SIGN REVERSAL = 43	

Corrected pressure can be computed using the following equation:

$$p = [(-103.1503) + (774.6636) \times T_0 + (-1.02921) \times T_0^2 + (4.355855E-02) \times T_0^3] \quad [4.34]$$

where, p = (Y CALC.) is the corrected pressure of the pressure transducer in bar, Y Meas. is the pressure measured by the standard and T_0 = (X) is the pressure transducer's reading in mV/V.

CHAPTER- 5: CONCLUSIONS, SIGNIFICANCE AND FUTURE RECOMMENDATIONS

5.1. CONCLUSIONS

From the project work carried out and reported here in this dissertation, the following conclusions are drawn;

5.1.1 A digital strain gauge pressure transducer has been designed and developed for the pressure measurement up to 2000 bar i.e. 200 MPa.

5.1.2 The hardware and electronics thus developed are very compact, noise free and sagaciously designed.

5.1.3 The resolution of the measured pressure is equivalent to 0.005% of the full scale reading.

5.1.4 Zero shift and repeatability are always lower than 0.05 bar.

5.1.5 The unique mechanical design of a single tubular cylindrical active element made of stainless steel and used as diaphragm is a big advantage to make the transducer perfectly leak proof. Also, the strain gauges and any of the electronic components are not in direct contact with pressure transmitting fluid.

5.1.5 The flexibility in adjusting the gain of the amplifier form 1 to 10000 by changing the resister value from 5 KΩ to 5 **Ω** is also very useful. This would enable user to use the electronics for much wider low and high pressure ranges.

5.1.6 The calibration of pressure transducer is carried out using dead weight tester as pressure standard having measurement uncertainty better than $37 \times 10^{-6} \times p$ at $k = 2$.

5.1.7 The calibration results show that there is a very small difference between calculated pressure of the transducer and the pressure measured by dead weight pressure standard which is within the standard deviation of ≤ 0.5 bar. This is equivalent to 0.04 % of the full scale pressure value.

5.1.8 It is evident from the study that this pressure transducer can be used as a reliable transfer pressure standard for the accurate and precise hydrostatic pressure measurements and for the calibration of pressure measuring instruments having accuracy ± 0.08% or coarser in the pressure range from atmospheric pressure to 200 MPa.

5.1.9 Excellent linearity, repeatability, low hysteresis and higher resolution in the pressure values are obtained when the digital multimeter is used as display device.

5.2. SIGNIFICANCE AND SCOPE OF FUTURE WORK

There is no indigenous pressure transducer or pressure dial gauge is available commercially beyond 1500 bar having measurement uncertainty $+ \underline{0}.1$ % or better. The imported pressure dial gauges and transducers are very expensive. For a pressure dial gauge of this accuracy class, the cost is in lakhs of Indian rupees and it is much higher in case of transducers. Further, the readout of a pressure dial gauge can not be digitized. In modern era, emphasis is always placed on the development digital measurement system. At present, the electronics for the present transducer gives analogue output but it would easily be converted in to a digital output. Being a digital device, the electronics developed would be interfaced with computer using RS232 for automatic data acquisition, computation and storage. The electronics developed is compact, noise free and cheaper. The electronics developed has made complete system user friendly. The automated system will be of great help in reducing the time required for calibration and also the physical work. Being digital device and interfacing with computer using RS232 for automatic data acquisition, computation and storage, it would now be possible to develop some remote pressure calibration system through internet.

For the pressure generation, generally, manual screw type mechanical hydraulic pump is used which is very tedious, time consuming, cumbersome and involves large physical work. It is possible to drive mechanical screw type piston pump mechanism through a stepping servomotor with the help of suitable mechanical arrangements, electronic circuitry, controls and appropriate software. All the mechanical, electronics and control systems can be embedded into a single unit which can be used as digital pressure calibrator for the calibration of pressure measuring instruments in the pressure range up to 200 MPa in gauge mode. The calibrator can also be used as transfer standards for the intercomparison and proficiency testing exercises.

REFERENCES

1. Buonanno G., Ficco G., Giovinco G. and Molinar G. F., “Ten Years of Experience in Modelling Pressure Balances in Liquid Media up to Few GPa”, Edizioni Universita Degistudi Di Cassino, CASSINO FEBBRAIO, 2007
2. Heydemann P. L. M. and Welch W. E., “Experimental Thermodynamics” Volume II, edited by B. Leneindre and B. Voder, Butterworths, London, p 147, 1975
3. Dadson R. S., Lewis S. L. and Peggs G. N., “The Pressure Balance: Theory and Practice”, Published by Her Majesty’s Stationary Office, London, 1982.
4. Pavese F. and Molinar G. F., “Modern Gas Based Temperature and Pressure Measurements”, Plenum Press, New York, 1992
5. Yadav Sanjay, “Hydraulic pressure measurements from atmosphere to 1.4 GPa at NPL”, in “Trends in Pressure Metrology”, edited by A. K. Bandyopadhyay and A. C. Gupta, Metro Designers and Printers, New Delhi, 44-55, 1997
6. Yadav Sanjay, “Pressure measurements: fundamental aspects”, in “Proceedings of Seminar on Pressure Measurements and Calibration - It’s Relevance to ISO 9000”, Nov. 21, Bombay, 1-11, 1997
7. Brombacher W. G., Johnson D. P. and Cross J. L., “Mercury Barometers and Manometers”, National Bureau of Standards Monograph 8, Gaithersburg, 1960.
8. Brombacher W. G., “Survey of Micromanometers”, National Bureau of Standards Monograph 114, Gaithersburg, 1970
9. Guildner L. A. and Terrien J., “Mercury Absolute Manometers”, in “Experimental Thermodynamics”, edited by B. Leneindre and B.Voder, Butterworths, London, Volume II, 1975
10. “Guide to the Measurement of Pressure and Vacuum”, Published jointly by National Physical Laboratory, U. K. and The Institute of Measurement and Control, U. K., 1998
11. “Pressure Measurement: Instruments and Apparatus”, Published by American Institute of Mechanical Engineers: ASME/ANSI PTC, U.S.A, 1988

12. Tilford C. R., “Pressure and Vacuum Measurements”, in Physical Methods of Chemistry, edited by Rossiter B. W., Hamilton J. F. and Baetzold R. C., V-VI, Published by Interscience, New York, 1991
13. Comings E. W., “High Pressure Technology”, McGraw Hill Book Co. Inc., New York, 1956
14. Robb D. N., “A New Piston Gauge Manometer”, National Engineering Laboratory, Report No. 79, U.K., 1963
15. “High Pressure Measurement”, edited by Giardini A. A. and Lloyd E. C., Published by Butterworths, Washington, U.S.A., 1963
16. “High Pressure Science and Technology”, edited by Timmerhaus K. D. and Barber M. S., Published by Plenum Press, New York, 1979
17. “High Pressure Measurement Techniques”, edited by Peggs G. N., Published by Applied Science Publishers, London, U.K., 1983
18. Tsiklis D. S., “Handbook of Techniques in High Pressure Research and Engineering”, Translated from Russian and published by Plenum Press, New York, 1968
19. Torricelli, Evanglista, Opere, Edited by Loria G. and Vassura, Frenza, 1919.
20. Yadav Sanjay, Agarwal Ravinder, Sharma D. R., Bandyopadhyay A. K. and A. C. Gupta, “Modern instrumentation techniques in pressure metrology under static conditions”, Mapan: J. Metrology Soc. India, 18, 57-82, 2003
21. www.rampantscotland.com/famous/blfamkelvin.htm
22. Bridgeman P. W., “Measurement of hydrostatic pressures up to 20000 kilogram per square centimeter”, Proc. Amer. Acad. Arts Sci., 47, 321-343, 1911
23. Bridgeman P. W., Proc. Amer. Acad. Arts Sci., 48, 309, 1912
24. Carlson R. W., “Five year improvement of the elastic wire strain meter”, Engineering News Record, 114, 1945
25. Meyer. R. D., “Application of unbounded type resistance gauge”, Instruments, 19, 3, 1946
26. Stein, P. K., “The early strain gage accelerometers: the inventors and their times,” The Shock and Vibration Bulletin – Part II, Shock and Vibration

Information Analysis Center (SAVIAC), 67th Shock and Vibration Symposium, Monterrey, CA, November 1996

27. Peter K. Stein, “Strain gauge history and the end of the twentieth century”, Experimental Techniques, March-April, 15 – 16, 2001
28. Peter K. Stein, “A brief history of bonded resistance strain gauges from conception to commercialization”, Experimental Techniques, 14, 13 – 19, 2008
29. http://en.wikipedia.org/wiki/Arthur_Claude_Ruge
30. Thompson J.L., “Wire strain gauge transducers for the measurement of pressure, force, displacement, and acceleration”, Journal of the British Institution of Radio Engineering, 291, 583-597, 1954
31. Simmons E. E. and Ruge A. C., “Development of thin film strain gauge pressure transducers”, U.S. Patient. Serial No. 320, 327, 1980
32. Nayak M. M., Gunasekaran N., “The strain gauge pressure transducer- an overview”, IETE Technical Review, 19, 170-177, 1992
33. Molinar, G. F., Bianchi, L., Sharma, J. K. N. and Jain, K. K., “Intercomparison of pressure standards using pressure transducers up to 500 MPa between NPL (India) and IMGC (Italy)”, High Temp. High Press., 18, 241, 1986
34. Molinar G. F. and Bianchi L., “Stability and metrological characteristics of manganin gauges up to 1.0 GPa”, in “High Pressure Metrology”, edited by Molinar G. F., BIPM Monographie 89/1, 147-156, 1989
35. Molinar G. F., Bray A., Wisniewski R., Maghenzani R. and Nespolil, “Pressure transducer for measurement in liquid up to 0.5 GPa”, Measurement, 24, 161-172, 1998
36. Molinar G. F., “A review of strain gauge pressure transducers on free-cylinder structures up to 2 GPa”, Advances in High Pressure Science and Technology, National Physical Laboratory, New Delhi, 2001

37. Patrik Melvås, Edvard Kälvesten, Peter Enoksson and Göran Stemme, “A free-hanging strain-gauge for ultraminiaturized pressure sensors”, Sensors and Actuators A: Physical, 97-98, 75-82, 2002

38. André Schäfer, “Force, strain and pressure transducer based on Foil type strain gauges as well as the piezoelectric prinziple for the use in industrial applications”, *www.automation.com/pdf_articles/Schaefer_pressure-force-strain.pdf, 2003.*

39. Falk L. Tegtmeier, “Strain gauge based microsensor for stress analysis in building structures”, Measurement, 41, 1144-1151, 2008

40. Heckmann U., Banorf R., Gerdes H., Lubke M., Schnable S. and Brauer G., “New material for the sputtered strain gauge”, Procedia Chemistry, 1, 64-67, 2009

41. Valerio Tomarchio, Konrad Risse and Holger Viebke, “Data analysis of the strain gauges system of the W7-X superconducting coils”, Fusion Engineering and Design, 84, 1852-1856, 2009

42. Barlian A. Alvin, Park Woo-Tae, Mallon Joseph R., Jr, Rastegar Ali J. and Pruitt Beth L., “Review: semiconductor piezoresistance for microsystems”, Proc IEEE Inst Electr. Electron Eng. 97, 513–552, 2009

43. Kalpana H. M. and Stephen R. J., “Development of thin film strain gauge sensor for strain measurement and indication using LabVIEW”, J. of Instrum. Soc. of India, 40, 1, 65-66, 2010

44. Dinger, “Sensitive element for use in a strain sensor and a sensor comprising such an element’’, U. S. Patent #4,498,344, Feb. 12, 1985

45. Jager J., “Use of strain gauge pressure transducers as a transfer standards up to 1.0 GPa at the 0.1% uncertainty level”, in “High Pressure Metrology”, edited by Molinar G. F., BIPM Monographie 89/1, 142-146, 1989

46. Ann Arbor, “Programmable miniature strain gage amplifiers”, Sensors & Transducers e-Digest, 104, 5, 2009

47. Nomura T., Kawasaki K. and Saitoh A., “Wireless passive strain sensor based on surface acoustic wave devices”, Sensors & Transducers Journal**,** 90, 61-71, 2008

48. Tarikul Islam, Shakeb A. Khan, Sheikh S. Islam and Harsh, “Sensitivity enhancement of Wheatstone bridge circuit for resistance measurement”, Sensors & Transducers Journal, 6, 92-104, 2009

49. “FUTEK models available with *USB* output (pressure sensors)”, http://www.futek.com/search.aspx?ws=0&q=pressure

50. “Miniature Titanium Pressure Sensor Available with USB Output”, http://www.pr.com/press-release/148807

51. Yadav Sanjay, Bandyopadhyay A. K., Dilawar Nita and Gupta A. C., “Re-establishment of measurement uncertainty in pressure measurement through in-house laboratory intercomparison of national hydraulic pressure standards up to 500 MPa”, Mapan – Journal of Metrology Society of India, Suppl. Issue No. – 1, 170-177, 2001

52. Yadav Sanjay, Bandyopadhyay A. K., Dilawar Nita and Gupta A. C., “Intercomparison national hydraulic pressure standards up to 500 MPa”, Measurement + Control, UK, 35, 47-51, 2002

53. Kobata Tokihiko, Bandyopadhyay A. K., Moore Ken, Eltawil Alaaeldin A. E., Woo Sam Yong, Chan T. K., Jian Wu, Man John, Con Nguyen Ngoc, Fatt Chen Soo, Permana Wenda, Aldammd Mohamad, Sabuga Wladimir, Changpan Tawat, Hung Chen-Chuan and Pengcheng., “Final report on Key comparison APMP.M.P-K7 in hydraulic gauge pressure from 10 MPa to 100 MPa”, Metrologia, 42,2005, 07006

54. Sabuga W., Bergogilo M., Rabault T., Waller B., Torres J. C., Olson D. A., Agarwal A., Kobata T. and Bandyopadhyay A. K., “Final report on Key comparison CCM.P-K7 in the range 10 MPa to 100 MPa of hydraulic gauge pressure”, Metrologia, 42, 2005, 07005

55. Driver R. G., Olson D. A., Yadav Sanjay, Bandyopadhyay A. K., ”Final report on APMP.SIM.M.P-K7: bilateral comparison between NIST(USA) and NPLI(India) in the hydraulic pressure region 40 MPa to 200 MPa”, Metrologia, France, 43, 07003, 1-15, 2006

56. Bandyopadhyay A. K. and Gupta A. C., “Realization of a national practical pressure scale for pressure up to 500 MPa”, Metrologia, 36, 681-688, 1999

57. Yadav Sanjay, Prakash Om, Gupta V. K. and Bandyopadhyay A. K., “The effect of pressure-transmitting fluids in the characterization of a controlled clearance piston gauge up to 1 GPa”, Metrologia, 44, 222-233, 2007
58. Yadav Sanjay, Vijayakumar D. Arun and Gupta A. C., “Computer software for calibration of industrial and master simple / reentrant type piston gauges”, MAPAN - Journal of Metrology Society of India, 12, 101-104, 1997
59. Yadav Sanjay “Pressure standards and calibration facilities at NPL, India”, Proceedings Spring Meeting of NRLM Forum on Measurements, Tsukuba, 1999
60. Yadav Sanjay, Bandyopadhyay A. K., Gupta V. K. and Gupta A. C., “A reliable quartz digital transfer pressure standard for high pressure measurements up to 275 MPa”, Presented at National Symposium on Instrumentation (NSI-24), Goa University, Goa, Feb 2-5, 2000
61. Yadav Sanjay, Bandyopadhyay A. K. and Gupta A. C., “Characterization of piston gauges using similarity method”, Proceedings V National Conference on High Pressure Science and Technology, Anna University, Chennai, March 1-2, 2000
62. Vijayakumar D. Arun, Yadav Sanjay, Bandyopadhyay A. K. and Gupta A. C., “Evaluation of measurement uncertainty of industrial dead weight testers”, Proceedings V National Conference on High Pressure Science and Technology, Anna University, Chennai, March 1-2, 2000
63. Yadav Sanjay, Vijayakumar D. Arun, Bandyopadhyay A. K. and Gupta A. C., “A proposal for the establishment of measurement uncertainty of pressure dial gauges and transducers”, Cal Lab: The International Journal of Metrology, March/April, 32-43, 2000
64. Yadav Sanjay, “Characterization of dead weight testers and computation of associated uncertainties: a case study of contemporary techniques”, Metrology and Measurement Systems, Poland, XIV, 3, 453-469, 2007
65. Bandyopadhyay A. K., Yadav Sanjay and Dilawar Nita, “Current status of pressure standards at NPLI and our experiences with the key comparison data base (KCDB)”, Mapan- J. Metrology Soc. India, 21, 127-145, 2006

66. “Guide to the Expression of Uncertainty in Measurement”, ISO Document - ISO/TAG/WG 3: (1995) (E)
67. “EA Guidelines on the Calibration of Electromechanical Manometers”, EA-10/17, July 2002
68. “Expression of the Uncertainty of Measurement in Calibration”, European Cooperation for Accreditation of Laboratories”, EAL Document - 2, April, 1997
69. “Guidelines for Estimation and Expression of Uncertainty in Measurement”, National Accreditation Board for Testing and Calibration Laboratories”, NABL Document – 141, Department of Science and Technology, Government of India, New Delhi, 2000
70. Dietrich C. F., “Uncertainty Calibration and Probability: The Statistics of Scientific and Industrial Measurement”, Published by Adam Hilger, Bristol, 1991
71. Yadav Sanjay and Bandyopadhyay A. K., "A proposal for evaluation of associated uncertainties in calibration of direct pressure indicating electromechanical devices", Callab: The International Journal of Metrology, USA, Jan-March, 32-37, 2006
72. Yadav Sanjay, Gupta V. K., Prakash Om and Bandyopadhyay A. K., "Evaluation of associated uncertainties in calibration of direct pressure indicating electromechanical devices", Measurement Science Review, Slovakia, 5, 3, 104-114, 2005
73. Yadav Sanjay, Bandyopadhyay A. K. and Gupta A. C., "Evaluation of associated uncertainties using linear squares best-fit lines for electromechanical transducers", J. Institution of Engineers (ID), 86, 49-53, 2005
74. Yadav Sanjay and Bandyopadhyay A. K., “Calibration of electromechanical type direct pressure indicating devices and evaluation of associated uncertainties”, Mapan- J. Metrology Soc. India, 20, 71-91, 2005
75. Vijayakumar D. Arun, Yadav Sanjay, Bandyopadhyay A. K. and Gupta A. C., “Estimation of measurement uncertainty of dead weight testers”, 3rd CCM

International Conference on Pressure Metrology from Ultrahigh Vacuum to Very High Pressure (10^{-7} Pa to 10^{9} Pa), Torino, Italy, 1999

76. Vijayakumar D. Arun, Yadav Sanjay, Sharma R. K. and Gupta A. C., “Studies on pressure measuring equipments form 100 mbar to 5000 bar both absolute and gauge pressures”, Journal of Instrument Society of India, 27, 269-277, 1998
77. Singh A. P., Yadav Sanjay, Agarwal R. and Gupta A. C., “Recent advances in strain gauge pressure transducers”, Proceedings 2nd International Conference on Metrology, Quality and Global Trade (MQGT-99), New Delhi, Feb. 24-26, 342-349, 1999
78. Singh A. P., Agarwal R., Yadav Sanjay and Gupta A. C., “Trends in electromechanical pressure transducers” , Proceedings National Seminar on Physics, Technology and Sensors, TIET, Patiala, 1-12, 1999
79. Vijayakumar D. Arun, Yadav Sanjay and Gupta A. C., “Quality of measurements: a software for estimation of measurement uncertainty”, Presented during National Symposium on Electronics in Societal Mission, New Delhi, March 29-30, 1997
80. Yadav Sanjay, Bandyopadhyay A. K., Gupta V. K. and Gupta A. C., “On the traceability and stability of a hydraulic transfer pressure standard up to 140 MPa”, Mapan – Journal of Metrology Society of India, 17, 3-10, 2002
81. Yadav Sanjay, Bandyopadhyay A. K., Gupta V. K. and Gupta A. C., “A reliable quartz digital transfer pressure standard for high pressure measurements up to 275 MPa”, J. Instrum. Soc. India, 30, 43-51, 2001
82. Yadav Sanjay, Prakash Om, Gupta V. K. and Bandyopadhyay A.K., “Studies on the stabilities of various types of industrial pressure measuring devices”. J. Sci. Indusl. Res., 65, 721-724, 2006
83. Yadav Sanjay, Kumaraswamy B. V., Gupta V. K. and Bandyopadhyay A. K., “Least squares best fit line method for the evaluation of measurement uncertainty with electromechanical transducers (EMT) with electrical outputs (EO)”, Mapan – Journal of Metrology Society of India, 25, 97-106, 2010