

Review on Pressure Sensors for Structural Health Monitoring

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Abstract: This paper reports the state of art in a variety of pressure and the detailed study of various matrix based pressure sensors. The performances of the bridges, buildings, etc. are threatened by earthquakes, material degradations, and other environmental effects. Structural health monitoring (SHM) is crucial to protect the people and also for assets planning. This study is a contribution in developing the knowledge about self-sensing smart materials and structures for the construction industry. It deals with the study of self-sensing as well as mechanical and electrical properties of different matrices based on pressure sensors. The relationships among the compression, tensile strain, and crack length with electrical resistance change are also reviewed.

Keywords: Strain; crack detection; self-sensing; smart materials; cement; pressure sensor

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1. Introduction

The process of implantation of damage detecting device and making a strategy for engineering structures from damages is termed as structural health monitoring (SHM) [1]. Here damage is defined as the degradation of the building material and changes observed in its geometrical structures. It can also be defined as changes introduced into a system that adversely affects its current or future performance. It also changes the boundary conditions and system connectivity, which in turn affect the system's performance. The SHM involves the process under which the observation of the system and its periodically dynamic response measurements from an array are analyzed. SHM is used for rapid condition screening and aims to provide in near real-time analysis. The extremely worst condition of the earthquake and many other environmental disasters which are able to damage

the buildings, bridges etc. may be pre-detected by SHM. Since the beginning of the 19th century, railroad wheel-tappers have used the sound of a hammer striking the train wheel to evaluate if the damage was present but after revolution and advancements in science and technology, a process of SHM was developed [2]. Especially when damages to structures are concerned, there are various problems which are given as below:

- (1) Detecting the presence of the damage on the structure;
- (2) Locating the damage;
- (3) Identifying the types of damage;
- (4) Measuring the severity of the damage.

So, to overcome these problems, SHM is addressed in the context of its paradigm which can be broken into four parts. The first part is the operational evaluation, which begins to set the limitations on what will be monitored and how the monitoring will be accomplished. Then, it undergoes

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through the data acquisition, normalization, and cleansing, which involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware. Feature extraction and data compression are also valuable steps after data acquisition, which is based on correlating the response quantities of the measured system, such as vibration amplitude or frequency, with the first-hand observations of the degrading system. The portion of SHM process ends with the last attention of statistical model development in which the damaged and undamaged structures are discriminated. The structural health monitoring system can be made much advanced by the use of piezo-optic based sensors.

2. Structural health monitoring

It is necessary to test structures and materials, in some vulnerable stage of construction when verifying theoretical calculations. Analysis of certain desired parameters took place in the field of civil engineering in the latest century. Steel strains, rock stresses, concrete curing temperature, shrinkage and stresses, pressure of the concrete in form of vibrations, and many other phenomena that engineers felt unconfident about due to the lack of knowledge or experience were measured and recorded. When monitoring the arch of the old Traneberg bridge during retrofitting, it was found that several monitoring activities took place in the 30s (Anger 1935) [3]. The arch was, at the time of its completion, the largest and longest ever built, and monitoring was used to increase the understanding that was needed in order to build a bridge with the quality that still stands today. Static field tests on bridges were performed before opening in the early 20th century with loads simulating actual traffic on them. If the bridge did not collapse or show extreme deflection under the test loads, it was judged to be safe for traffic. Dynamic field tests have been performed on bridges since the late 19th century. These early tests were mostly conducted as part of the safety inspection. When Tacoma Narrows bridge

collapsed in 1940 [4], engineers had to face the problem with long-span bridge aerodynamics. The dynamic monitoring has grown meaningfully in the following decades. These activities in the early 20th century were thought in small scale and mostly considered as part of construction phase rather than organized structural monitoring. The monitoring technology was not yet well developed in terms of automation and data handling. The amount of data was held in small portions in order to be able to handle and use it in a decent way. Intelligent structural systems, as well as smart materials and structures, were also the concepts in use before the statement of SHM became more common. Health monitoring accordingly may be defined as: “the monitoring of the operating and loading environment and the critical responses of a structure to follow and evaluate the characteristics of operational incidents, irregularities, and/or degradation or damage indicators that may affect the operation, functionality, or safety reliability.”

3. Sensors and their types

The sensor is defined as the device which can analyze the events observed in an environment with changes and provides its corresponding output. Typically, the output of the sensor is based on optical or electrical signals. A robust sensor is sensitive to the measurand and insensitive to any other properties likely to be encountered in its applications [5]. It is called as the selectivity of the sensor. Also, a good sensor is not permanently influenced by the measured property.

Pressure is defined as the force applied per unit area in a direction perpendicular to the surface of an object. The formula is commonly written as

$$P = F/A \quad (1)$$

where P is the pressure, F is the normal force, and A is the area of the surface of contact. The unit of pressure in the SI (International System of Units) is the Pascal (Pa). Bar, Torr, Psi, and Atm are also commonly used units.

The pressure sensors vary drastically with the changes in technology, design, performance, application suitability, and cost. Pressure sensor is a kind of device which measures pressure, typically of gases or liquids or any solid materials in terms of mechanical force [6]. It is usually a transducer which generates a signal as a function of the pressure imposed. Nowadays, pressure sensors are basically used for controlling and monitoring the various kinds of measurements like fluid/gas flow, speed, water level, and altitude. Alternatively, they are also called pressure transducers, pressure transmitters, pressure senders, pressure indicators, piezometers, and manometers [7]. There are various types of pressure sensors, among them some are shown in Fig. 1 and discussed as below:

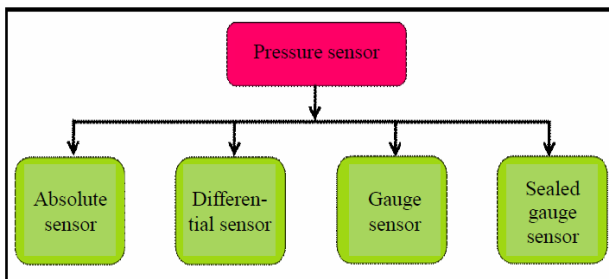


Fig. 1 Block diagram of the types of pressure sensors.

(1) An absolute pressure sensor, which relates with a perfect vacuum. It is also called vacuum pressure sensor as it measures the difference between the vacuum and atmospheric pressure;

(2) Differential pressure sensor, which measures the difference between two pressures;

(3) Gauge or relative pressure sensor, which relates to atmospheric pressure [8];

(4) Sealed pressure sensor, which relates the measured pressure to some fixed pressure rather than the ambient atmospheric pressure.

An absolute pressure sensor as shown in Fig. 2 measures dynamic, static or total pressure by taking vacuum as a reference. The name absolute pressure sensor is due to its measurement against vacuum. A special kind of absolute sensor is the barometric sensor. As is well known, the vacuum must be high to prevent disturbing effects by different temperatures in the “almost” vacuum chamber [9].

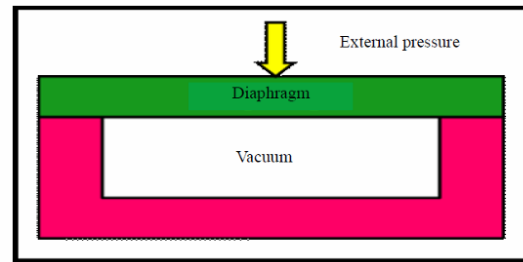


Fig. 2 Schematic representation of absolute pressure sensor.

A differential pressure sensor as shown in Fig. 3 measures a dynamic, static, or total pressure P_1 with reference to an unspecified variable pressure P_2 . The differential sensor has inputs to each side of the membrane, one being positive while the other one being the negative pressure input. The bending of the membrane is related to the difference of the pressure on each side [10].

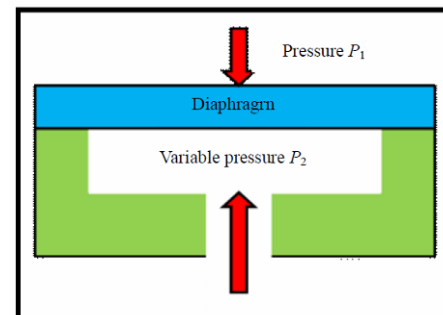


Fig. 3 Schematic representation of differential pressure sensor.

A gauge pressure sensor or a relative pressure sensor as shown in Fig. 4 records the static, dynamic, or total pressure by taking ambient atmospheric pressure as a reference. As by principle, one side of the membrane is pressurized by liquid or gas type medium that has to be measured, and the other side of the membrane is open to the atmosphere. As an example, the car tire pressure equipment is a typical gauge type pressure sensor [10].

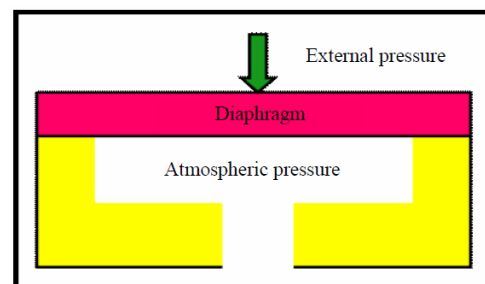


Fig. 4 Schematic representation of gauge or relative pressure sensor.

A sealed relative or gauge pressure sensor is shown in Fig. 5. It measures dynamic, static, or total pressure with reference to ambient atmospheric pressure, sealed at the time of manufacture of the sensor [11].

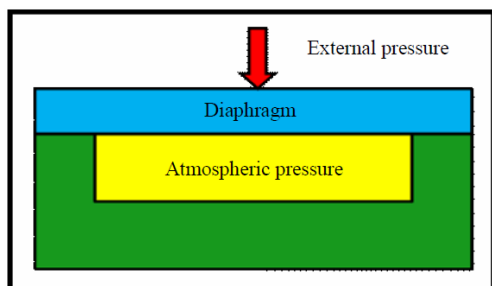


Fig. 5 Schematic representation of sealed gauge or relative pressure sensor.

4. Piezo effect and its types

The word “piezo” is derived from the Greek word “piezein”, which means to squeeze or press or push. Piezo effect is the ability of certain materials to generate different physical parameters in response to applied mechanical stress.

4.1 Piezoelectric pressure sensor

The principle of piezoelectric based pressure sensor can measure the changes in pressure, acceleration, temperature, strain, or force by applying an electrical charge. A piezoelectric sensor is a versatile tool that reacts to compression [11]. This kind of pressure sensor is having applications in medical, aerospace, nuclear instrumentation, and as a tilt sensor in consumer electronics or a pressure sensor in the touch pads of mobile phones.

Fig. 6 shows the piezoelectric pressure sensor in which the sample is compressed under the pressure, and the output variation in terms of capacitance or resistance is calculated by a voltmeter connected to the sample. Table 1 shows the comparison of piezo sensor materials vs. other types.

A piezoelectric transducer is proportional to the voltage source and filter network and has very high direct current output impedance. The voltage variation is directly proportional to applied force, pressure, or strain.

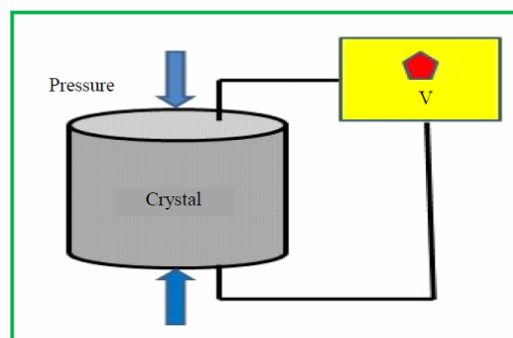


Fig. 6 Set-up of piezoelectric based pressure sensor.

Table 1 Characteristics of piezo sensor materials vs. other types [11].

Principle	Strain sensitivity (V/ $\mu\epsilon$)	Threshold ($\mu\epsilon$)	Strain to threshold ratio
Piezoelectric	5.0	0.00001	100 000 000
Piezoresistive	0.0001	0.0001	2 500 000
Inductive	0.001	0.0005	2 000 000
Capacitive	0.005	0.0001	750 000
Resistive	0.000005	0.01	50 000

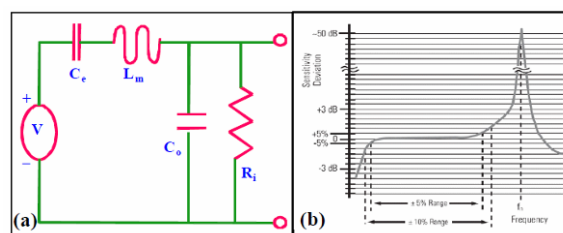


Fig. 7 Schematic symbol of (a) piezoelectric sensor and (b) frequency response of sensor [10].

From Fig. 7(a), the output variation V of the voltage along with the capacitance C_o and resistance R_i can be determined. It can also be observed that the charge source is parallel to the capacitance, with the charge directly proportional to the applied force. The mechanical structure of the piezoelectric based pressure sensor imposes a high-frequency limit. The sensitivity begins to rise rapidly as the neutral frequency of the sensor is approached as illustrated in Fig. 7(b).

4.2 Piezoresistive pressure sensor

The piezoresistive pressure sensor is also called strain sensor or strain gauge. These are the devices which are used to measure how much a component distorts under loading [12]. In this kind of pressure sensor, the electrical resistance of a sensing material changes as a result of applied strain [13]. It is a

conductor or semiconductor material that can be directly fabricated on the sensor itself or bonded with the sensor.

The piezoresistive pressure sensor is a kind of sensor which can change the electrical conductivity and resistivity as a result of crystal lattice deformation. The strain causes the shape of energy band curves to change, therefore, changing the effective mass, m^* which in turn changes the electrical conductivity σ as follows:

$$m^* = \frac{h^2}{d^2 E / dk^2} \quad \text{and} \quad \sigma = \frac{q\bar{t}}{m^*} .$$

Spot-weldable strain gauges are used with strain gauge sensors and a vibrating wire indicator or data logger to monitor strain in steel members. Typical applications of piezoresistive pressure sensor include:

- (1) Monitoring structural members for pre and post construction;
- (2) Determining the load changes at various places;
- (3) Measuring stress and strain in tunnels.

The failure condition is reached when the strain in the material exceeds the fracture strain. Therefore, it is important not only to design the mechanical structure accurately but also to leave safety margins [14]. The other one is fatigue as if the repeated cycle of force is applied to a mechanical member, with the induced strain much lower than that of the fracture strain; the structural member may fail after repeated cycles. Its mechanism depends on microscopic defects (bubbles and dislocations) amplifies over time and causes stress concentration (re-distribution of stress). The defects are often hidden underneath the surface of the material [15]. The relationship between stress and strain along with the fractional resistance changes has been studied. It was found that tensile strain increases linearly with tensile stress while with changes of fractional resistance, and it increases slowly and later drastically during static tensile testing up to failure for a cement matrix composite with very less vol.% of carbon fibers [14].

Also, the abrupt increase in resistance at high

strain is accompanied by a decrease in modulus attributed to fiber breakage. So the variation of changes in resistance during loading and unloading for various stress amplitudes is shown in Fig. 8.

At higher strains, the modulus is decreased, and the resistance is increased with strain abruptly, due to fiber breakage.

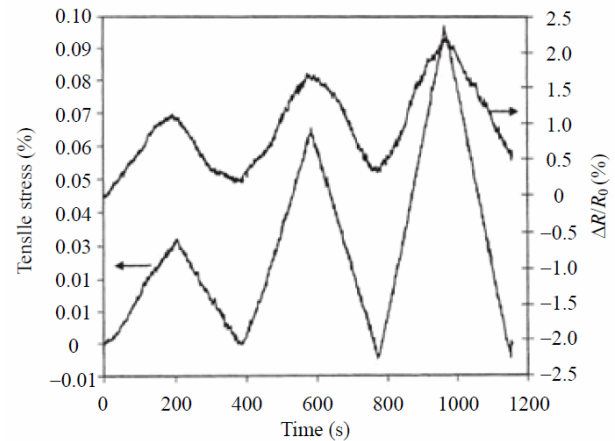


Fig. 8 Variation of changes in resistance during loading and unloading for various stress amplitudes within the linear portion of the stress-strain curve for a cement matrix composite with 2.60 vol.% carbon fibers. Reprinted with permission from [14].

4.3 Piezo-optic pressure sensor

In a piezo-optic pressure sensor, the laser is taken as the input light source, and the beam is passed through the fiber embedded matrix sample [15]. The pressure is applied on the sample using the hydraulic pressing machine, and the corresponding variation in output is recorded at the detector. Curves for loading and unloading the pressure are obtained [16], and sensitivity is calculated from these curves. The block diagram of the experimental setup is shown in Fig. 9 in which laser is taken as input. The beam is coupled to the sample through fiber coupler at both the ends. Pressure is applied to the sample using the hydraulic pressing machine. The variation of the power with the pressure is recorded at the output using detector.

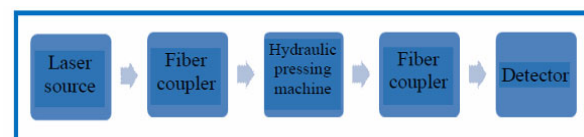


Fig. 9 Block diagram of the experimental setup of piezo-optic pressure sensor.

5. Piezo-resistive based cement matrix composites used for SHM

The advancements in SHM tools make the scientists work on piezo-resistive based sensor due to its cost-effective nature. Chung *et al.* studied electrical and mechanical properties of cement matrix composites whereas Han *et al.* investigated the piezoresistivity of nickel powder reinforced cement composite under compression [17] through the point of advancement in self-sensing smart materials and structures for the construction industry. Egemen Teomete *et al.* worked on the measurement of crack length sensitivity and strain gauge of carbon fiber reinforced cement matrix composites [18]. He took cement matrix composed of carbon fiber, which may resist the resistance in the structure. Finally, three tests namely bending test, split tensile test, and notched bending test were performed. Five different carbon fiber reinforced cement composites with a fiber length of 13 mm were designed. From each mixture, six cubes of $5 \times 5 \times 5 \text{ cm}^3$ samples and three cuboids of $4 \times 4 \times 16 \text{ cm}^3$ prismatic samples were cast and tested by compression, split tensile, and notched bending tests. 45 tests were conducted, and the correlations among various parameters were obtained. The results obtained from compression were:

(1) Compressive strain reduced the carbon fibers, closed the micro voids and cracks, and hence decreased the electrical resistance;

(2) A strong linear relationship between electrical resistance and strain was obtained with the gauge factor of 76 (~ 40 times that of commercial foil strain gauges);

(3) As the fiber volume % increased, the percent of fiber-fiber and matrix fiber contacts were disrupted by the strain decreased which ended up a decrease in the gauge factor. At percolation threshold of 0.5% fiber volume fraction at which few direct electron conduction paths formed which were further disrupted; the system shifted from post-percolation to pre-percolation situation, and the

highest gauge factor was obtained.

Apart from the above results, the split tensile test gave the following results:

(1) The tensile strain caused elongation of the fibers, opening of micro cracks, and voids which resulted in an increase in the electrical resistance;

(2) A sharp linear relationship between the tensile strain and electrical resistance change (%R) was observed [19].

5.1 Piezo-optic cement matrix composites

Many researchers of science and technology are working experimentally for developing smart materials or self-sensing materials. Wang *et al.* worked on a fiber optic crack sensor for concrete structures [20]. Experiments were performed for monitoring single and multiple flexural cracks under static loading, crack monitoring under cyclic loading as well as for shrink crack under restraint. The optical power loss with respect to crack opening relations was found experimentally, which was in good agreement with the theoretical results. Based on the results of the present investigation, the potential of the sensor for various practical applications is demonstrated. Pandey *et al.* [21] worked on a fiber optical pressure sensor based on microbending losses of fiber embedded in araldite matrix. The linear decrease in the output intensity of light with the respective increase in pressure on the embedded structure shows that the sensor can be reliably used to constantly check the pressure ($3.0 \times 10^6 \text{ Pa}$) and to perceive the damage created because of high-pressure cyclic operations. The results show an average reproducibility of 3.3%.

In another work, Pandey *et al.* [22] created the pressure-induced microbends of 5 mm in silica clad graded index multimode optical fiber, plastic clad PCS200 and plastic clad PCS600 optical fibers and embedded them in the araldite matrix. The maximum pressure measured with PCS600, PCS200, and silica clad fibers were 3.0 MPa, 1.8 MPa, and 1.6 MPa, respectively among which PCS600 optical

fiber embedded structure was found most linear and reliable.

Further, Pandey *et al.* demonstrated [23] another experiment in which he created pressure induced microbends in 50 μm graded index multimode optical fiber with spatial periodicity $\Lambda = 4.5$ mm embedded in the araldite-aniline matrix. The results showed that it was most suitable for monitoring the high pressure (1.6 MPa) with reproducibility within $\pm 5\%$ of the measurand. He combined the embedded sensor and microbend sensor to get an average sensitivity (5.3/MPa) with remarkable durability.

6. Advantages of piezo-optic pressure sensor over other pressure sensors

Basically, the materials used for the pressure sensor is of quartz crystals and polycrystalline ceramic which are made up of natural piezoelectric material and artificially polarized (manmade material) whereas another pressure sensor is dependent on manmade materials. As in terms of sensitivity, the piezoelectric pressure sensor has high voltage sensitivity, and the piezoresistive pressure sensor has high charge sensitivity whereas other pressure sensors are less sensitive [24]. Electric based pressure sensor is large in stiffness quality in comparison to others. They exhibit excellent long-term stability and operate at high temperature. Their characteristics vary with temperature whereas for others it does not [25].

7. Choice of materials

The choice of materials for the SHM system is basically dependent on the sensitivity of the material after applying any pressure or some kind of force on them [26]. Cement matrix composites for smart structures include cement and sand. Also, they contain short carbon fibers which have applications in sensing strain, damage and temperature, for thermal control and electromagnetic radiation and reflection. These structures also contain short steel fibers (for sensing temperature and for thermal control) and silica fumes basically for vibration

reduction. The less cost of carbon fiber provides it a special importance in cement-matrix composites [27, 28]. We can also give a surface treatment of carbon fiber as it may improve the bond between the fiber and the matrix, thereby improving the properties of the composite [29]. By this, the volume fraction increases, and negated content becomes terribly high [30]. In terms of structural properties, carbon fibers are used due to its superior ability to increase the tensile strength, modulus, and ductility [31]. Mainly polyacrylonitrile (PAN) based carbon fibers are used [32].

One of the materials used for the SHM is araldite composed of epoxy and resin. Araldite is a two-component, room temperature curing paste adhesive which gives a resilient bond [33]. Also, it is thixotropic and non-sagging upto 10mm thickness. Basically, it is suitable for SMC (sheet moulding compound) and GRP (glass-reinforced plastic) bonding. It is a white colour paste having 1.4 specific gravity and thixotropic viscosity at 25°C [34]. The strength and durability of a bonded joint are dependent on the proper treatment of the surfaces to be bonded. At the very least, joint surfaces should be cleaned with a good degreasing agent such as acetone, iso-propanol, or other proprietary degreasing agents in order to remove all traces of oil, grease and dirt. Through chemically etching or mechanically abrading process, the strongest and most durable joints are obtained. Araldite has various applications like long open time, high shear and peel strength, ease to apply, good resistance to static and dynamic loads, and electrically insulated in different fields. Some of the areas are given below:

- (1) Metal;
- (2) Ceramics;
- (3) Wood;
- (4) Vulcanized Rubber;
- (5) Foams;
- (6) Plastics.

8. Applications of pressure sensor

Pressure sensors are widely used in various sectors of household and industrial monitoring. Few of them are depicted below:

(1) Pressure sensing

Pressure sensing is useful in weather instrumentation, aircraft, automobiles, and any other machinery that has pressure functionality implemented [35].

(2) Altitude sensing

Altitude sensing is useful in aircraft, rockets, satellites, weather balloons, and many other applications, as all these applications make use of the relationship between changes in pressure relative to the altitude. This relationship is calculated by altimeter up to 36090 feet. In navigation applications, altimeters are used to distinguish between stacked road levels for car navigation and floor levels in buildings for pedestrian navigation [36].

(3) Flow sensing

This is the kind of measure flow with the venturi effect using pressure sensors. Differential pressure is measured between two segments of a venturi tube that has a different aperture.

(4) Level/depth sensing

This is the technique commonly used to measure the depth of a submerged body (such as a diver or submarine), or level of contents in a tank (such as in a water tower). A pressure sensor may also be used to calculate the level of a fluid.

(5) Leak testing

In the leakage test, the leak is compared to a known leak using differential pressure, or by means of utilizing the pressure sensor to measure pressure change over time.

Some other applications are:

1) Cracks in buildings and bridges may also be detected by using its opto-electronic version;

2) Useful in altimetry, barometry, process

monitoring, safety, etc., laboratory instrumentation, in static barometry, aerospace, transport, and energy (liquefied gases);

3) Useful in harsh mechanical or thermal environment, anemobarometry in aircraft, and digital avionics;

4) Useful in harsh environments, e.g. in oil industry, energy industry, refineries, engines, etc. and measurements of static pressures [37–42].

9. Experimental setup of piezo-optic sensor

Piezo-optic is the study or use of devices in which a mechanical input produces an optical output. Opto-electronic sensors are more advantageous over their electrical counterparts as they have fast dynamic response, miniaturized size, light weight, low cost, easy installation, and immunity to electromagnetic interference (EMI), which make them a better candidate for sensor application. These advantages benefit this type of sensor with a wide range of industries [43]. The piezo-optic sensors are the systems that use optical fiber technology to transport a light input signal that is modulated according to a measured object magnitude and then collected by a detector, conditioned, and processed [44]. Fig. 10 shows the block diagram of opto-electronic sensor. Here opto-electronic unit contains the luminescent input source, and the optical channel comprises of the path (sample) through which optical wave travels. The optical transducer consists of the device which collects the signal.

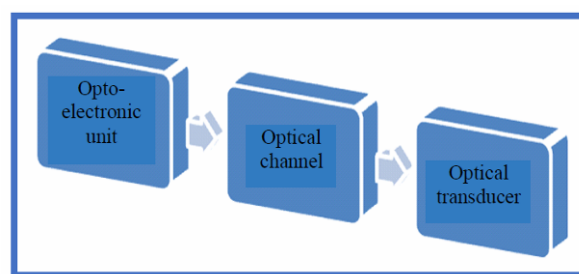


Fig. 10 Block diagram of piezo-optic pressure sensor.

10. Literature survey

We have made a thorough year wise literature survey, regarding the design, fabrication, and application of different types of pressure sensors and have summarized them in Table 2.

11. Conclusions

The design, fabrication, and applications of pressure sensors have been reviewed in detail. Natural disasters are the extremely worst condition for buildings, bridges, etc. Testing and measuring of certain desired parameters including crack detection in these structures at early stages are the need of the hour for structural health monitoring. Different types

of pressure sensors have been studied and concluded that each type of sensor has its own significance. Advances in opto-electronics have lifted this field to a very high level, leading to a broad area of designs with great opportunities. Therefore, araldite based piezo-optic pressure sensor is of much importance due to its flexible and electromagnetic disturbance free nature. The field is matured in many respects and emerging in others and a great progress has been made in a short span of time. From a technological point of view, there hardly seemed harsh limitations in the future.

Applications ranging from structural health monitoring system to onboard aircraft are reviewed.

Table 2 Literature survey of the recent pressure sensors including their construction and working principle.

S. No.	Method used	Author	Material used	Output obtained	Ref. No.
1	Based on a peninsula-structured diaphragm for low-pressure ranges	X. Huang <i>et al.</i>	Peninsula-structured diaphragms	Sensitivity of 18.4 mV/V	[45]
2	Scanned-wavelength-modulation-spectroscopy sensor for CO, CO ₂ , and CH ₄ and H ₂ O in a high-pressure engineering-scale transport-reactor coal gasifier	Ritobrata Sur <i>et al.</i>	CO, CO ₂ , CH ₄ , and H ₂ O	Delayed by 20 min and had a 15 min time response	[46]
3	Based on Strain sensitive Pt-SiO ₂ nano-cermet thin films	H. Schmid-Engel <i>et al.</i>	Pt-SiO ₂	High gauge factors are approx. 40 at% Pt, 20 at% Si, and 40 at% of O	[47]
4	Based on release etching and characterization of MEMS capacitive pressure sensors integrated on a standard 8-metal 130 nm CMOS process	A.D. Sundararajan <i>et al.</i>	Fluorosilicate	0.07 mV/Pa and 0.05 mV/Pa	[48]
5	Based on large-scale textile pressure sensors arrays for activity recognition	J. Cheng <i>et al.</i>	Textile-based surface	pressure dynamic range from 0.25 × 10 ⁵ Pa to 5 × 10 ⁵ Pa.	[49]
6	Based on PZT transducer in LTCC package	A.P. Dabrowski <i>et al.</i>	LTCC (low-temperature Co-fired ceramics) and PZT (lead zirconate titanate) transducer	~6/MPa	[50]
7	Based on double-ended tuning fork resonator using quartz	J. Wang <i>et al.</i>	Quartz	Sensitivity is up to 7.35 Hz/kPa	[51]
8	Capacitance based wearable pressure sensor using E-textiles	A. Arogbonlo <i>et al.</i>	Neoprene and (SAC) plated nylon fabric.	1.65 kg equivalent pressure over a 400 mm ² sensor	[52]
9	Piezoelectric microelectromechanical system acoustic sensor	M. Prasad <i>et al.</i>	piezoelectric zinc oxide (ZnO) thin film	Sensitivity of 382 μV/Pa (RMS) in 30 Hz to 8000 Hz	[53]
10	Piezo-electric	E. Teomete <i>et al.</i>	Reinforced cement-based matrix composites	Sensitivity of 0.98 and 0.99 between resistance and strain and tensile strain, respectively	[54]

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