International Journal of Advance Research in Science and Engineering
Volume No.06, Special Issue No.(01), Nov 2017
www.ijarse.com
IJARSE
ISSN: 2319-8354

A SURVEY ON FORCE SENSORS AND IT'S APPLICATIONS

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ABSTRACT

Force sensor is one of the most important sensors in the field of instrumentation and measurement. This paper attempts to review the major developments in force sensor technologies which play important role in fault detection and maintenance of monitoring systems. Force sensor has an immense research interest due to the demand of high sensitivity, stability and fast response for environmental monitoring. Force sensors are categorized into different types according with their sensing mechanisms such as capacitive, inductive, piezoelectric, piezoresistive so on. This paper analyzes various force sensor technologies and its applications together with their sensing principle.

Keyword: *Force Sensor, Capacitive Type, Inductive Type, Piezoelectric Type, Piezoresistive Type, Sensor Applications*

I. INTRODUCTION

The technology of force sensing material was invented in 1977 by Franklin Eventoff; the sensing technology consists of a conductive polymer whose resistance changes in a predictable manner when force is applied to its surface. Later, several force sensing technologies were invented for small and large force measurements. In physics, force is the capacity to do work or cause physical changes and it is measured either in The English system or in the international system of units (SI). The unit of force in SI is Newton (N) and in The English system is the Pound (LB). Force is a vector quantity, which has both magnitude and direction.The equation (1), (2) shown the relationship between newton and the pound.

Newton (N), 1N=0.255 lb (1)

Pound (LB), 1LB=0.488N (2)

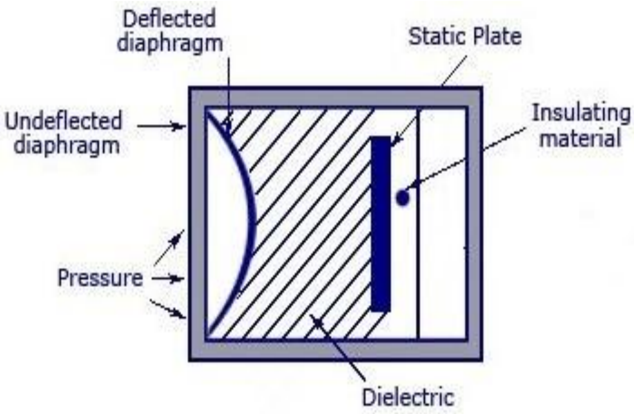
The necessity of measuring the force exerted on a body would have some technical importance while considering a particular field of application. In the electronic era, force sensing technology has adequate usages in many fields, are listed as instrumentation and measurement, smartphones, medical devices, safety systems, industrial controls etc.

II. FORCE SENSING TECHNOLOGIES

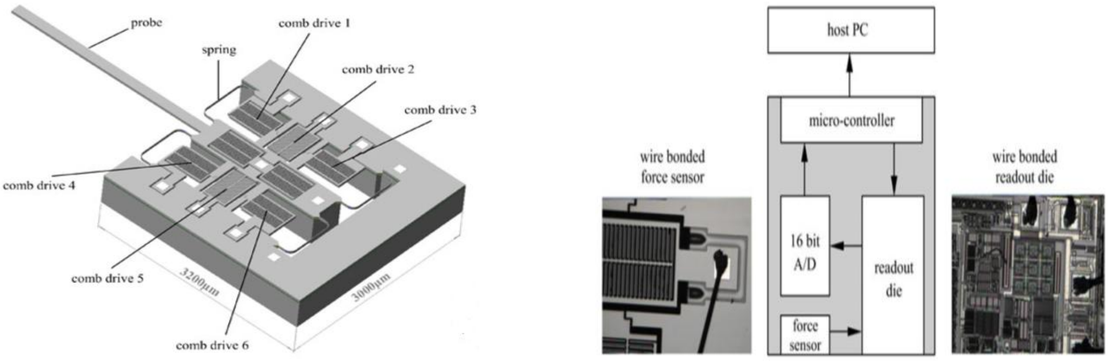
The force sensing technologies are mainly categorized into four types according with the behavior of the sensing element. These force sensing techniques are capacitive, inductive, piezoelectric and piezoresistive and are satisfactorily operating in different environmental conditions

2.1 CAPACITIVE FORCE SENSOR

A capacitive force sensor is a device its capacitance is varying with varying force or pressure applied. It consists of two parallel metal plates that are separated by a dielectric; when a force is applied to the outer plate could reduce the distance between the two plates and is leading a change in capacitance. The capacitive sensor is extensively used for displacement and pressure measurements is shown in figure 1.David C. Catling et al [1] developed a prime experimental setup for measuring gas pressure. In the experimental prototype, a silicon diaphragm and a silicon substrate as two plates were combined to act as a pressure sensitive capacitor; where design features of the sensor, theoretical pressure resolution, capacitance versus pressure response and strength of the silicon capacitive sensor were discussed. Enikov. E.T et al [2] fabricated a fiber chip coupled three-dimensional capacitive force sensor; the peculiar technique was applied in process of sensor fabrication was the complementary use of wet anisotropic etching with deep reactive iron etching.



Yu Sun et al [3] developed a technology of multi-axis capacitive cellular force sensor for micro robotic cell manipulation; where the sensor could provide a real-time force feedback during cell manipulations, and also, a transverse comb drive movement could improve the sensitivity of the sensor by overlapping sensor area. The multi-axis force sensor shown in figure 2 was bonded on a circuit board and a microcontroller program for the capacitance readout IC MS3110 with a resolution of 4.0 aF $Hz^{-1/2}$ to covert capacitance change in voltage.



(a) (b)

Fig.2.(a) Solid model of the multi-axis force sensor; (b) Readout circuit design.

MEMS (Micro-Electro-Mechanical Systems) capacitive force sensors are suitable for a wide range of biological studies due to their high performance and are capable of measuring forces from mN(millnewton) low to pN(piconewton) [3, 4]. But the main disadvantage of capacitive type sensor is that, it is temperature sensitive.

2.2 INDUCTIVE FORCE SENSOR

The inductive force sensor is working on the principle of inductance change when a quantity to be measured. Some of the inductive sensors change their properties such as self-inductance, mutual inductance or Eddy current production for measure a force. Inductive force sensors are suitable mainly for low force measurements and displacement measurements. The introduction a bi-directional inductive force sensor technology was enhanced to measure both amplitude and direction of the force in a plane [5]. John C. Butler et al [6] invented a wireless inductive strain sensor consisting of an embedded LC tank, where the resonant frequency of the LC circuit changes with strain. Therefore the sensor can be used as a structural monitor for composite material under stress condition.

Sneha M. Djuric et al[7] introduced a planar inductive displacement sensor which is used to measure the normal and tangential component of the applied force. The sensor could applied in the robotic field for implementing humanoid foot of the robot. The sensor was composed with two sensor elements; one element detects the horizontal displacement and the other element detects the vertical displacement. And a new simulation tool in MATLAB was developed for evaluating the input inductance of the sensor, also, the sensor elements were electrically tested with the help of an impedance analyzer HP4194A at 1MHz frequency. Li Du et al [8] demonstrated a multiplexed inductive force sensor for measuring normal force and shear force on diabetes patient’s foot. The sensor consists of three mini-sized sensing coils simultaneously measure the normal force and shear force on foot during walking. The schematic sketch of inductive force sensor is shown in figure 3. When an AC excitation is applied to each sensing coil to generate a magnetic field as a results an eddy current is induced inside the steel plate, which generate an opposite magnetic field that causes a decrease in the inductance of the sensing coil. Heng Chung Chang et al [9] studied features of magnetostrictive type inductive pressure sensor. The pressure sensor technology consists of a planar coil, CoFeB (Cobalt Iron Boron)magnetic films and a Si diaphragm; a pressure load will be changing the permeability of the magnetic films due to the inverse magnetostriction effect that also results in a change in the inductance of the planar coil.

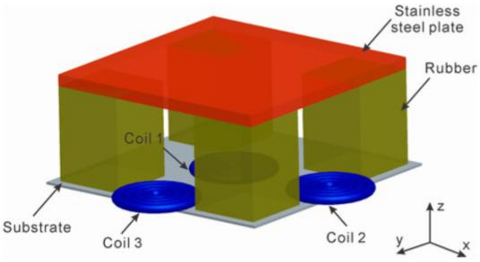


Fig.3.schematic of a three-coil inductive force sensor for foot monitoring

2.3 PIEZOELECTRIC FORCE SENSOR

The piezoelectric force sensor is a device that work on the principle of piezoelectric effect.When mechanical stress or forces are applied to some materials along certain planes, they produce an electric voltage. A Schematic diagram of a piezoelectric force sensor is shown in figure 4. The fundamental properties of a piezoelectric strain sensor have been investigated by Jayant Sirohi et al [10]; wherein the output of a calibrated piezoelectric force sensor was compared with the output of a conventional foil strain gauge sensor, also, the transfer function of both sensors was compared over a frequency range of 5-500 Hz. An experimental setup of dynamic beam bending was used to calibrate the piezoelectric sensor. The investigation shows, properties of all piezoelectric materials vary with temperature; but the output of the sensor needs no temperature correction over a moderate range of operating temperature.

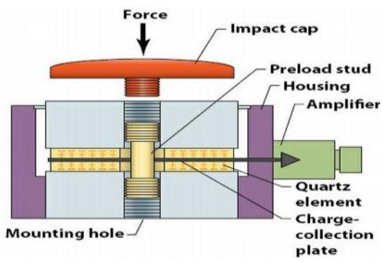


Fig.4. piezoelectric force sensor

It is known that, electricity has become a lifeline of human population and its demand is increasing day by day; while Kiran Boby et al [11] implemented a footstep power generator using piezoelectric transducers. The implemented piezo tile is capable of generating power corresponding to the weight applied to it. To analyze the capacity of piezo tile, people whose weight varied from 40 kg to 75 kg were made to walk on the tile; thus a maximum voltage of 40V is obtained across the tile when a weight of 75 kg is applied to the tile. Yang Jingfang et al [12]developed a force sensor based tire dynamic balance detection system; where the piezoelectric force sensor, converted the vibration signal generated by the imbalance in a vehicle tire into corresponding electrical voltage. The hardware components of the tire balance detection system are shown in figure 5. In order to achieve vibration measurement in vehicle tire,a piezoelectric quartz sensor technology was adopted because of its favorable properties such as good linearity, high stiffness, high insulation resistance and outstanding stability.

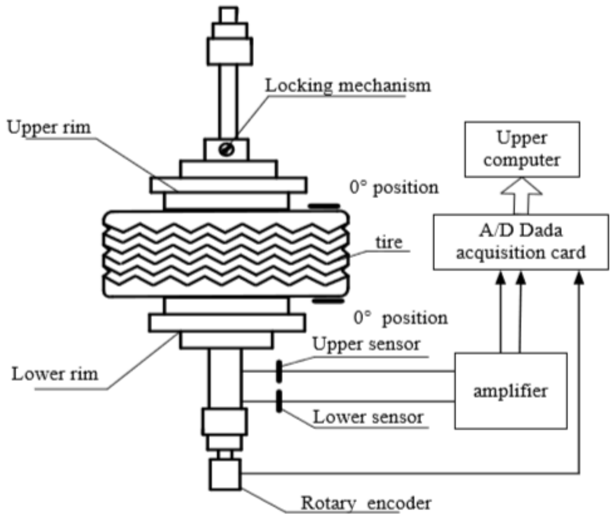


Fig.5.hardware components of tire balance detection system.

Hyonyoung Han et al [13] proposed a sensor based stiffness estimation system would provide human muscle analysis while muscle contraction; where, a resonance based active muscle stiffness sensor made by piezoelectric probe was capable to measure the stiffness change in muscles. The developed sensor was validated using silicon phantoms with different stiffness levels. But thermal drift was one challenging issue in piezoelectric sensing results variations in the sensor output. Piezoelectric force sensors have vast applications in the many fields due to its outstanding features. Jon Lu et al [14] addressed a new method of sensor design to develop a six axis piezoelectric force sensor. And Jon Lu was constructed a structural model of the six axis force sensor and also technically analyzed the operating measures of the sensor. The uses of the device include external force measurement, detection of position information of the force functional point, and, collection of spatial force information from three force and torque components.

Piezoelectric transducers offer several advantages such as high frequency response**,** high transient response**,** and small in size and have rugged construction. But, the output obtained from the piezoelectric transducers is low and it is very difficult to give the desired shape to the piezoelectric crystals with sufficient strength, also, piezoelectric crystals have high impedance create impedance matching problems while connecting with auxiliary circuits.

2.4 PIEZORESISTIVE FORCE SENSOR

Resistive type force sensors are devices that change their resistance and also generating appropriate output while monitoring environments such as force, strain, pressure so on. A strain gauge used a force sensing material that can be directly fabricated on the sensor itself or bonded with the sensor. The sensing mechanism of a resistive force sensor is that, an external force is applied to the sensor, the resistive element is deformed against the substrate. And air from the spacer opening is pushed through the air vent in the tail, the conductive material on the substrate comes into contact with the active area; conduction is possible as result resistance of the material decreases. The different layers of a resistive force sensor are shown in figure 6. H. E Elgamel et al [15] studied about the various influencing factors of piezoresistive pressure sensor and how they mutually related. These factors are stress, resistance change and diaphragm deflection. A simple quasi-analytical technique was implemented for stimulates the performance of silicon pressure sensor. The quasi-analytical method is simple, accurate and gives a clear understanding about the basic response mechanisms of the pressure sensor.

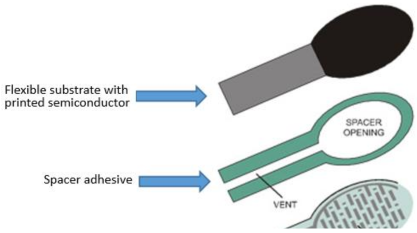


Fig.6. different layers of a resistive force sensor

For medical application, T. Chu Duc et al [16] invented a two dimensional force sensing cantilever shown in figure 7 could adopts the features of piezoresistive force sensing technology. For sidewall implantation, two piezoresistors are placed on both sides of the cantilever; where its bending was related the applied force. The cantilever was made with silicon wafer which would capable of detecting both lateral and vertical bending. Dzung Viet Dan et al [17] described the fabrication, design and calibration of piezoresistive silicon based micro force-moment sensor. The silicon chip was a single crystalline silicon crossbeam with two terminals and four terminal piezoresistior diffused on the surface was able to detect the three components of force as well as moment in simultaneously. The sensing chip was fabricated by micromachining processes and calibrated it by a computer-controlled ultra-small load indenter. The designed sensor chip could be applied to different integrated force-based micro devices, such as tactile sensors, and micro multi-axis accelerometers. Dazhong Jin et al [18] was developed a high-mode resonant pizoresistive cantilever sensor for tens-femtogram resoluble mass sensing in the air. The cantilever sensor circuit includes a piezoresistive bridge and a metal coil for not only signal sensing but also measure the Lorentz force resonance excitation; Wherein Jin was introduced an optimized electromagnetic exciting method to measure the resonant force and these optimally excited resonant cantilever sensors with piezoelectric sensing element could improve quality factor of the measurement.

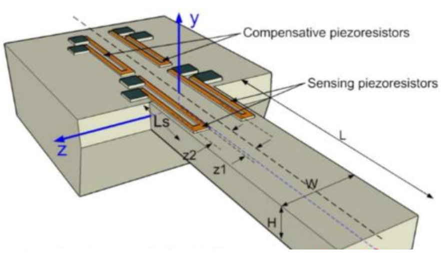


Fig.7. schematic diagram of a two dimensional piezoresistive force sensing cantilever

The pioneer investigation by C. Pramanik et al [19] encountered a design optimization of high performance conventional silicon based pressure sensor for biomedical applications. The peculiar improvement on sensing technique has been achieved by optimizing the doping concentration as well as the geometry of conventional piezoresistors. Other hands, the sensitivity of the conventional piezoresistor has been improved by thinning the diaphragm thickness of the sensor. The developed high sensitive pressure sensors are ideal for biomedical applications such as ventilators, spirometers, respirators and blood pressure measurement. A. Tibrewala et al [20] designed and fabricated a miniaturized three axis piezoresistive force sensor using with 16 p-type piezoresistors. The p-type diffused layer changes their resistivity when they were subjected to strain. A boss membrane test structure was developed using silicon micromachining would capable to measure the 3D coordinates of force. Where, 16 p-type piezoresistors were arranged in four different ways could improve the sensitivity of the device. Force sensors are widely used in smart skin applications. Thomas V. Papakostas et al [21] introduced a tactile sensor used as a force sensitive artificial skin in robotic applications. The smart skin sensor system has been used for the measurement of real time pressure profiles on flat, curved, soft and rigid surfaces.The trimmed smart skin could insert in the sole of the shoe could help to analyze the comfort level of the shoe. And, the measurement of pressure distribution of feet would help for the diagnosing diabetic ulcers in patients.

2.4.1 Flexiforce Force Sensor Technology

A commercial force sensor works on the principle of piezoresistve sensing technology is called FlexiForce force sensors [22]. These sensors are ultra-thin, flexible printed circuits can be acted as a force sensing resistor in an electrical circuit. These sensors can measure the force between any two surfaces and are durable enough to stand up to most environments. When the force sensor is unloaded, the resistance of the sensor is very high. But, the resistance of the sensor decreases with applied force. Flexiforce load sensor can manufacture in different shapes shown in figure 8, is for the need of its application. These sensors carry many advantages,including superior linearity, high accuracy, output is not area- dependent, suitable for high temperature force measurements and user-friendly. These FlexiForce can work on a PSOC (Programmable embedded System-On-Chip) background.

Fig.8.flexiforce force sensors in different shape

System-On-Chip (SoC) is an integrated circuit that integrates all components of an electronic circuit in a single platform. These components include digital, analog, mixed-signals, processor, memory, GUI, radio frequency functions and other application related options. The latest SoC is configurable is called PSoC, family of microcontroller integrated circuits by Cypress semiconductor.

III. CONCLUSION

Force sensing technology have immense research interest due to its necessity for force measurements in divergent fields includes instrumentation, robotics, medical, artificial intelligence, automobiles, wireless transmission etc. Moreover, force sensing is a challenging task because the measurand force have been in different scale range and are influenced by external parameters such as noise, surrounding medium, material properties etc. In this paper, various force sensing technologies and its optimization techniques were successfully presented, and various force sensor applications in different fields were analyzed.

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