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A Review on Application of MEM's Sensors For Structural Health Monitoring

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ABSTRACT

The development of Structural Health Monitoring (SHM) and smart structure concepts in civil engineering field are gathering attention in academic research. Monitoring the structure to know the hidden structural damage due to fatigue, shear cracking, loss of stress, corrosion, earthquake and internal the structure minimize sudden failures. This paper presents the scope and reliability of Micro Mechanical sensors () application for SHM. Fabrication and types of materials used for MEM's sensors with respect to sensitivity range, cost efficiency were also discussed.

Keywords— MEM's, Structural Health Monitoring, accelerometers, MEM's sensors in Civil Engineering, SHM of Prestressed Concrete elements

I. INTRODUCTION

Monitoring the structures with criteria under critical loading conditions definitely reduce or avoids the risk of sudden structural collapse. It also made easy to assess the exact location of failure at early stage of deterioration, further repair and rehabilitation of the structure. Adopting new construction techniques and replacement of basic constituents with various recycled materials like fly ash, blast furnace slag and other alternating materials have been widely increased in construction. Alterations in construction techniques impart variation in material properties and also lead variation in structural behavior of the concrete elements under loading conditions. Although the new trends in construction field would possess beneficial in strength as well as economy, but still there is a necessity to look forward and monitor the performance of the structures. Many methods already exist for monitoring the structure which requires more wring and optical fibers to collect data. After collecting the data one need to analysis and estimate the deterioration and all it takes lots of time, required skilled supervisions. The limitations and difficulties are overcome through wireless sensors and current sensors. Still, there was a requirement for the advance research in the adaptation of smart sensors for SHM with respect to compatibility conditions and sensitivity requirements. Monitoring of the structure under various loading conditions was achieved through pressure sensors which is an application of MEMs. The application of MEM'spressure sensors had adopted widely in the detection and calculation of pressure generating in air craft's, automobiles and also in electrical fields. Very few research studies are held on the application of MEMs in structural industry, effective application of MEMs in structural field demands further more research regards fabrication of sensors, data analysis and monitoring of structural behavior. Particularlythe studies should focus on a) complete monitoring of the structures, b) evaluates development of critical stress due to subjected load combinations, c) alerting when the developed stresses reaches the permissible stress conditions, d) accessing the critical stress developed locations within the structural element. In this paper various types and the materials used for fabrication of MEM's sensors are discussed. Based on literature mechanical properties of various MEMS' sensors were presented. Also, discussed the adaptation of MEM's for pre stressed concrete structure health monitoring.

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II. TECHNICAL BACKGROUND-MEM'S

MEM's are the sensing device with their micro size providing a greater adaptability in various fields. Many types of MEM's sensors are available in the present day with varying features. MEM's are widely applying in automobile, air crafts, medical fields and industrial sector (Ming Zhao, XiaoleiXiong). Their physical dimensions can vary ranging from a size below one micron to several millimetersizes. A MEM's device is a combination of microstructure, micro sensors, micro actuators and microelectronics. Frompast several years many developers gave the evidence on adaptability of micro sensor which had been sensing all possible conditions including temperature, pressure, internal force, magnetic fields etc,. But still research should have done on the basis of how exactly a MEM's sensor work for SHM and also suitable fabrication techniques. Shown in figure-1

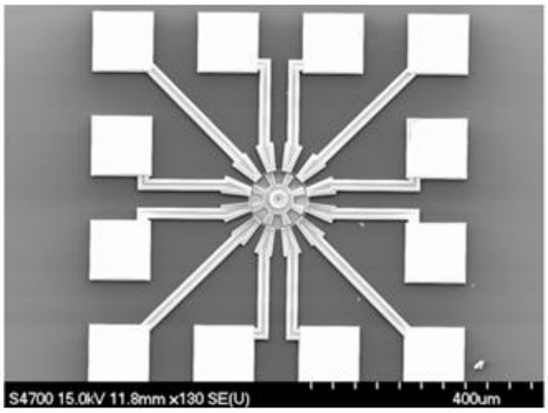

Figure 1. MEM's based micro actuator

MEM's devices are mainly classified into sensors and actuator: Sensors covert the deformations into electrical parameter and conveys in the form of current, voltage etc. An Actuator covert electrical energy into nonlinear parameter in the form of kinetic, potential, thermal etc.(Robert Neal Dean, Jr., Member, IEEE, and Antonio Luque, Senior Member, IEEE). Accelerometers, pressure sensors, optical sensors, chemical sensors, gyroscopes are some of the MEM's sensors. Comparing with other conventional electromechanical systems MEM's have more advantages by their feature like miniaturizing and integrating of sensors with electronics, also low cost with mass fabrication, resistance to high temperature conditions, less weight and low power consumption (D.Ozevin, university of Illinois at Chicago, USA). In civil engineering MEM's accelerometer are applied which will convert the displacement of the static structures in the form of frequency dampers. For large civil structures like long span bridges pre stress or post stressed concrete elements the overall eigenfrequency is below 10 Hz (Ming Zhao, XiaoleiXiongTongji University). So we can comfortably adopt MEM's sensors for health monitoring of structures.

A. MEM's sensors

Micro Electro Mechanical sensors are the device at micro scale in a range of 1µ- 100µ. The integration of micro sensors, actuators and electronics into one single microchip would leads to greater application of MEM's devices in various fields including industrial, engineering and medical fields. These sensors collect the required data through measuring physical, mechanical, chemical, thermal, optical and magnetic parameters and allow the micro system for controlling or alerting under specified conditions. MEM's sensors with their reliability, esteemed functionality, integrality and accuracy have been widely applicable in all fields of research both in application and fabrication methods.
MEM's sensors are classified as:
Ø Based on engineering properties: a) Accelerometers b) Pressure sensors c) Humidity sensors d) Gas sensors e) Force sensors.
Ø Based on material used: a) Silicon sensors b) Polysilicon c) Silicon carbide d) stratified layered e) Insulators.
Ø Based on Micro matching methods: a) Bulk Micro matching b) Surface Micro matching
c) LIGA.

MEM's accelerometers are most suitable for SHM. MEMsaccelerometers are the sensors which measures the force and acceleration. They are divided based on which type of force static or dynamic force, in which capacitive type accelerometer is used mostly in general. A capacitive accelerometer is having more sensitivity with low range which can be suitable for SHM.

B. Materials used for fabrication of MEM's sensors

To design mechanical and electrical structure in MEM'ssensors a vast range of materials could be used with micromachining methods. In general MEM's sensors can be fabrication using material like silicon, polysilicon, steel, nickel etc., for SHM. Major criteria go for the material that can be fabricated in micron size and should resist temperature and atmospheric conditions. The mechanical properties of the MEM's sensors are governed by the size in which they are fabricated (Spearing, 2000). MEM's sensors fabricated with silicon would be more effective for mechanical applications. The sensors fabricated with silicon carbide would be used for high temperature trough bulk micromachining method and with poly silicon through surface micromachining method are suitable for microstructure design (D. OZEVIN, University of Illinois at Chicago, USA). The mechanical property of these materials used for the fabrication of MEM's sensors yields higher values than that of structural steel properties.

- **Silicon:** Silicon fabricated sensors could be usedin SHM due to stability, resisting capacity under anyatmospheric conditions and machinability. Silicon may use as semiconductor for subtract the materials in fabrication process due to their potential to combine sensors and electronics through one subtract. Circular silicon wafers are used as subtract, the crystal orientation of silicon commonly <100> and <110> directions are used in manufacturing process as shown in figure- 2 number indicates Miller indices (Madou, 2002).

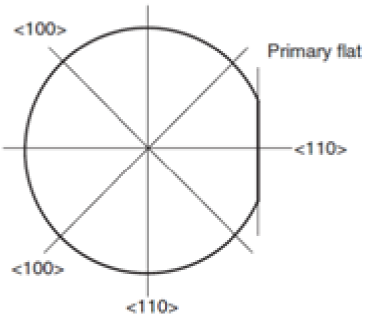

Figure 2. Crystal orientation of silicon

The use of silicon had been extensive in the sensor designing only after the demonstration of smith in 1954. Such that the resistivity changes approximately linear with stress, as follows

$\frac{\Delta\rho_{ij}}{\rho} = \sum_{k,l} \pi_{ijkl} T_{kl}$ With I, j, k= 1, 2, 3

Where $\pi$is the coefficient of piezo resistivity and T is the Stress. Coefficient of Piezo resistivity depends on orientation of silicon crystals.

- **Poly silicon:** Surface micro machining device is generally designed in poly silicon materials which are having properties similar to single crystal silicon. Using low pressure chemical vapor deposition technology (LPCVP) thin layers of poly silicon are deposited to form a micro structure. With increasing thickness of film, ploy silicon grains also increases their size during manufacturing process involves with high temperature. Leads to surface roughness and affects both the mechanical and electrical properties. Manufacturing of thick poly silicon films needs a chemical polish and the thickness is limited to 2-5 µm.

- **Silicon Carbide:** Exhibits excellent mechanical properties and physical stability with high thermal resistivity greater than 30000C. It is a semiconductor material having bang gap 2.3-3.4eV. For SiC bulk micro machining, laser ablation etching technique and for SiC surface micromachining plasma based dry etching were used in general (Jiang and Cheung, 2009).

III. CHARACTERISTICS OF MEM'S SENSOR

MEM's sensors are characterized with the effect of their manufacturing methods for SHM they can build using transduction principles.Stiction and collapse voltage, squeeze film damping, thin film residual stress and packing are involved in fabrication process. Sensors suitable for SHM are designed based on the

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transduction principles likepiezoresistivity, piezoelectric and capacitance. The stiction is one of the manufacturing methods of sensors, in which two parallel conductive layers design the capacitive sensor on an insulator layer. The sacrificial layer was removed by means of wet etching later (Song et al., 2007). Shown in fig-3

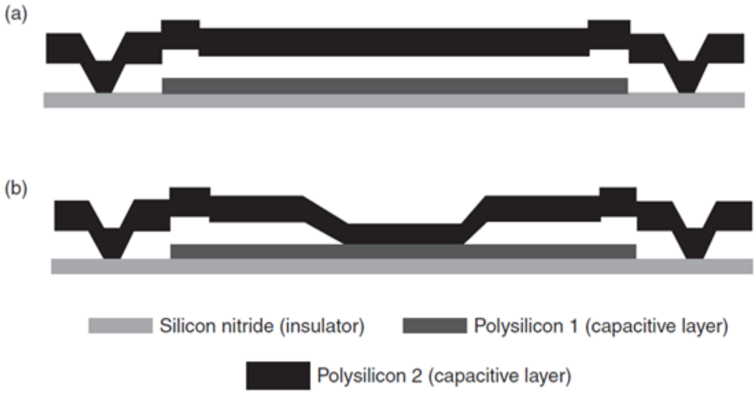

Figure 3. Stiction process a) intended microstructure
b) consequence of stiction

Squeeze film damping caused by the air resistance under the vibration of freely moving layer due to air velocity. Using Reynolds lubrication theory damping between two plants also done by squeezing fluid (Oppenheim et al., 2003). Due to the mismatch in thermal expansion coefficient of deposited layers, non-uniform plastic deformation, interstitial impurities and deposition process residual stress may induce in micro structure layers (Madou, 2002). Packing would have most criteria for the MEM's sensors in SHM; they have to attach to the structural elements and may expose to atmosphere. So there by the packing of MEM's sensor issuch that it would allow the sensor to measure the required quantities and also should resist the climatic conditions. Die adhesive and the density of potting materials affects the sensitivity of MEM's accelerometers (LI et al., 2013).

IV. APPLICATION OF MEM'S SENSORS

A. Fault detection in machinery using MEM's sensors

MEM's sensors are widely used in many fields for the detecting the faults, measuring the vibrations, as a processing units in industrial sectors and service sectors, for SHM of long span bridges, etc. MEM's accelerometers are used for detecting the faults of machinery. From the laboratory experiment done by Jong-Duk Son, Byung-Hyun Ahn, Jeong-Min Ha, Byeong-Keun Choi concluded that MEM's based sensors may substitute commercial accelerometers and current sensors for fault detection. They conducted the test on both accelerometers and current sensors shown in figure -4 for the fault detection in machinery and demonstrated that accelerometers are the best performers than current sensors. The accuracy is differing at least 38% more performance of accelerometers than current sensors.

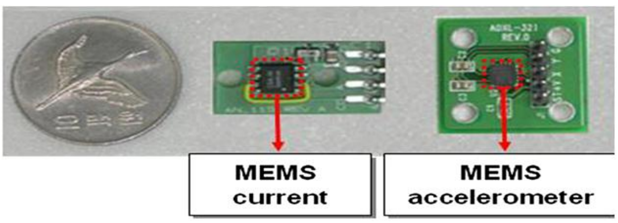

Figure 4. MEM's Current sensors and accelerometer

The test was conducted on both MEM's based accelerometers and current sensors which are applied for machinery fault detection and analyzed the suitability through frequency. Specifications for MEM's based accelerometer are so consider like measurement range is _18g, frequency range 0-2500 Hz, sensitivity 57mV/g, shock range 10,000g power 2.4-6 VDC, operating temperature is between -20Oc to 70oC. The accelerometers

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with polysilicon surface micro machined sensor outputs analog voltages proportional to the acceleration sensing. Sensor converts the capacitance acceleration into voltage. The performance of the accelerometer for the periodic excitation was found and compared with conventional current sensors and piezoelectric sensor at a calibrated frequency of 159.2 Hz and amplitude of 1 g rms. MEM's accelerometer measuring range(g) is of _18 whereas current sensors shows a range of _10. The experiment was held on five defected machines using MEM's accelerometer as a result deflection of about 0.2 mm, unbalanced mass of 20g, bearing fault results in cracking on outer surface and broken bars was found. This experimental evidence concludes that using MEM's accelerometers under some constrains, may measure the deflection of the elements, internal stress and strains of the elements. So therefore MEM's accelerometers may also use for measuring the deflection in the structures and also internal stress and strain due to loading on the structure.

B. MEM's sensors in civil engineering

MEM's sensors applications are been wide in civilengineering, with some characteristics like reliability, sensitivity range and cross axis sensitivity ratio; an experimental investigation done by Ming Zhao, XiaoleiXiong. A new type of MEM's accelerometer was applied that is produced by VTI technologies, SCA610 MEMS chip mounted in accelerometer. The measuring range of the MEM's sensors lies from 0-0.5g and frequency of the chip varying from 0-20Hz. The laboratory test was conducted to study the sensitivity and accuracy of the MEM's sensor using shaking table as vibration actuator with desired frequency range. The accelerometer gave some output voltage signal proportional to acceleration of the table. The signals from the sensor are transmitted to the operated system and converted into digital signals. This data is saved and later through the analysis of the digital signals and on the basis of permissible values of the accelerations corresponding alerts would be programmed. Further researches are needed to study the digital signals an also requires standard protocols for decision-making and alerting process. The performance of the MEM's accelerometer was studies at low frequency.

The results were obtained such that MEM's accelerometer possess high precision in the identification of vibration frequencies greater than 0.1Hz. With this experimental evidence it is shown that the MEM's accelerometer are capable of detecting very small frequency of 0.1Hz and above with negligible errors of 2.5% along with high precision (or) accuracy. Though it is a laboratory experiment done by using a shaking table as vibration actuator, MEM's accelerometers may apply for satisfactory performance in the real time structure for the detection of deflection and monitoring with time. Further research would be done with the exact application of the MEM's sensors corresponding to the real time problems in SHM.

C. MEM's sensor for SHM

MEM's sensors like accelerometer may use for measuring deflection, internal stresses and strains. The possible applications of MEM's sensors in SHM may be as follows:

- Complete monitoring of the structure could be possible by embedding the sensors in the fresh concrete in suit (or) while casting of pre-casted concrete elements. But supplying power to the sensors for lifetime is the challenge in order to send output signals to the system. At the early ages of hardened concrete, sensor may use to monitor the strength gain and process of hydration such that monitor the curing requirements may achieved. Further, long term SHM of the concrete elements may be done through motoring the deflection, monitoring the load impacts on structure, monitoring the state of reinforcement provided in concrete.
- For pre-stressed concrete elements the possibleapplication of sensors for SHM would be done by the implantation of the accelerometers to the tendons at the points where the max deflection and stress are expected for the loading conditions. Initial pre-stress loss immediately after releasing the stress at the ends may detected. Later for lifetime monitoring the pre stress loss may be achieved also internal stress and deflection would be monitored. Adaptability of MEM's sensors involves development of such sensor which may use at any environmental condition and with effective output values corresponding to the constrain changes.

- MEM's sensors may apply for long span bridges SHM. It may be achieved through monitoring the displacements of the spans under moving wheel loads and winds loads, monitoring the transit joints of the rigid pavement segments. MEM's sensor for monitoring the long span bridge requires the development of the sensors majorly measures the deflections and internal stress developed due to the moving loads. Thus there is a necessity for the further research to develop the suitable MEM's based sensors, applied for SHM of Civil structures. In the present day using MEM's accelerometer, monitoring of the structures may be done with required satisfactory performance. It is understood that the application of sensor devices for monitoring the structures, with high satisfactory levels throughout the lifetime, was a possible vision.

V. Cost efficiency of MEM's

MEM's have been recognized as cost effective device forthe SHM in civil engineering. An investigation done by M.K Jah and A. B Davy form Morgan state university; on the cost benefits in using MEM's sensors in monitoring the transportation infrastructure through Fuzzy logical approach.
Fuzzy logical approach was selected as it is adopting for the monitoring of structures. Fuzzy logical approach is not like whether the result is true or false, it lies in between like partially true. The developed fuzzy beneficial cost procedure for MEM's application is much satisfactory with high precision.

VI. Conclusion

In this review paper criterion given to look forward in theapplication of MEM's sensors for SHM of pre stressed concrete elements, an attempt to adopt the MEMs device in civil domain to extensive level of possibilities. Form the studies of laboratory experiments done prior it is proven that MEM's sensors have the capability to measure the deflection, internal deterioration, developed internal stress and strains.

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