MEMS Application in Pavement Condition Monitoring – Challenges

by

Nii O. Attoh-Okine*
Stephen Mensah#

ABSTRACT

Although the universal definition of MEMS product possesses a number of distinctive features, they are miniature systems involving one or more micro-mechanical components or structure. Infrastructure assessment has recently addressed an important field for MEMS application. For example, satisfactory laboratory experiment in the area of concrete monitoring has been developed. Although the experiment is at an infant stage, it demonstrates the enormous potential of MEMS application in civil infrastructure systems. This paper proposes to develop a framework for the application of MEMS technology in pavement condition monitoring and evaluation. Some difficulties which may be encountered, especially in asphaltic medium and loading condition of the pavement will be discussed.

Keywords: devices, evaluation, microelectromechanical, monitoring, non-destructive, pavement, system

1. INTRODUCTION

Pavement condition monitoring and evaluation is important in many areas of pavement engineering, especially in pavement management. The in-service performance of the pavement depends on consistent, cost-effective and accurate monitoring of condition for early scheduling of repair and maintenance. For the past decade, nondestructive evaluation (NDE) testing has played a major role in pavement condition monitoring, assessments and evaluation. The NDE evaluation methods include seismic evaluation such as wave propagation, vibration methods, acoustic and ultrasonic methods, electromagnetic method and electrical resistivity methods.

The accuracy and repeatability of the interpretation of these NDE techniques are dependent on the limitations imposed by the operating conditions and material properties. For example, the use of acoustic methods is well established in water but in a dense material, especially concrete pavements, specially developed sensors are required [1].

Researchers from diverse disciplines especially electrical, computer and mechanical engineering, have been drawn into vigorous efforts to develop sensing technologies and nano-technology in infrastructure condition assessment [2], crack detection [3] and building monitoring [4]. Recently, MEMS have been proposed as a tool in infrastructure condition monitoring. Researchers over the years have developed microfabricated sensors for measuring position, acceleration, pressure, force, torque, flow, magnetic field, temperature, gas composition, himidity, and biological gas/liquid molecular concentration [5]. Its miniature size has enabled widespread use in the medical field and the automotive industry. MEMS have had a tremendous impact on our modern society: it has led to creation of jobs; it has a significant leverage factor enabling the production of sensor-based systems exceeding sensor cost by several orders of magnitude; and in some instances have even become critical components that determine the feasibility of new products [6]. While the success of MEMS continues to grow, it appears its use in civil infrastructure monitoring is yet to make any impact.

This paper delves into the potential application of MEMS in infrastructure monitoring and some of the technological as well as technical issues to grapple with.

2. MICROELECTROMECHANICAL SYSTEMS (MEMS)

MEMS can generally be characterized as miniature systems involving one or more micro-machined components or structures. The inherently small size of MEMS enables high-level functions by virtue of the large-scale integration process. This permits multiple functions or capabilities integrated on the same silicon chip or package for greater utility.

While MEMS devices are typically on the scale of a few microns in dimension, the small size of a device does not automatically qualify it as a MEMS device. The distinctive features are [8]: miniaturization, micro-electronic and multi-plicity. Also the device consists of components which act together in a systematic fashion for a desired purpose.

MEMS technology will have an impact on engineering in the following ways [9]:

- By causing orders of magnitude increase in the number of sensors and actuators
- By enabling the use of very large-scale integration (VLSI) as a design and synthesis approach for electromagnetics.
- By becoming a driver for multiple, mixed and emerging technology integration.
- By being both a beneficiary of and a driver for information systems.

In addition to the potential economic benefits MEMS has the ability to integrate mechanical (or chemical, biological and environmental) functions. It will also allow for consideration of concepts such as the highly distributed networks for the condition monitoring of large civil infrastructure systems. The fundamental technological issues in MEMS include:

- Materials
- Machining process
- Micro-mechanical devices
- Application

2.1 Materials

Silicon has been used extensively however there have been advances in new materials exploration and the study of material properties for microsensors and actuators has opened up new frontiers of materials. The progress of microactuator technology depends critically upon the development of actuation forms that are compatible with the materials and processing technologies of silicon microelectronics [5]. Mechanically, silicon is an elastic and robust material whose characteristics have been well studied and documented. Furthermore silicon as a material exists in three forms: crystalline, polycrystalline or amorphous. Each of the forms has unique properties which make them useful for different applications. Another important property of silicon is its ability to integrate with electronic circuits and sensors. Three important material properties which are of great interest to MEMS are:

- Piezoresistivity – the phenomenon where a material's resistivity changes with mechanical strain.
- Piezoelectricity – when crystals exhibit the peculiar property of producing an electric field when subjected to external force.
- Thermoelectricity – the interaction between electricity and temperature.

The choice of material depends on its compatibility with the current fabrication process as well as other materials to be used in the device fabrication. A material property of significance cannot be exploited if this compatibility is not met.

2.2 Micromachining

Three fabrication routes or methods account for the majority of MEMS devices: surface micromachining, bulk micromachining and molding. Surface micromachining [10] uses the CMOS (complementary metal oxide semiconductor) process to fabricate VLSI (very large scale integration) devices. In the surface micromachined MEMS, the layers are patterned and etched to yield electromechanical elements to allow motion of the mechanical layers. Bulk micromachining involves etching features directly into the silicon wafers, it is an important consideration in MEMS where higher mechanical power or force levels are desired [11]. Molding is the third prevalent manufacturing process used for MEMS. It is the creation of the mechanical elements of the device by the deposition of material into a microfabricated model.

2.3 Microelectromechanical Devices

Microelectromechanical devices generally comprise of microsensors, microactuators, and electronic circuits or signal processing units integrated on a single chip. The miniaturization of the devices makes them inherently smaller, lighter and faster than their macroscopic counterparts and are usually more precise. The microsensors sense or collect information from the environment whereas microactuators alter the state of the environment. This process essentially involves the conversion of a mechanical force or physical effect in the environment (such as change in pressure or temperature) into electrical signals and vice-versa. This is possible by taking advantage of peculiar material properties such as piezoresistive, piezoelectric and thermoelectric effects to convert the change in the environment to electricity. The signal processing unit or electronics will then process the information and provide inputs to the actuators. The actuators in turn can manipulate the environment for a desired purpose or trigger another action to compensate for the change. Microactuators are the key devices allowing MEMS to perform physical functions. They are categorized in two perspectives: one based on driving forces and the other based on mechanisms.

2.4 Application

Microdevices are being embedded in structures to enhance their performance. Such structures are called smart structures or smart materials. Smart materials and structures technology is a new field of study that is finding its way into many applications in civil infrastructure systems. The applications include structural control, condition health monitoring, damage assessment, structural repair and integrity assessment. More recently and extension has been made to cover asset management and preservation and operation of civil infrastructure. The drawback to extensive MEMS application is that there are no generic MEMS products but rather they are application specific. The vast majority of applications require unique solutions that often necessitate the funding a completion of an evaluation or development program. This process could take several years, typically 2-5years, and it impacts directly on the performance of MEMS devices on the market [5].

3. PAVEMENT CONDITION MONITORING

3.1 Infrastructure maintenance is undertaken based on the perceived health of the infrastructure based on information gathered from the performance indicators. The need to collect data reflective of the true state of health of the infrastructure is therefore crucial for an efficient management of the system. Condition based maintenance (CBM) or on-demand maintenance are gaining currency due to the superior advantage they afford. Microsensors can be embedded unobtrusively and inconspicuously in structures to monitor parameters critical to the safe operation and performance. Bennet et al. [12] developed a wireless monitoring system for highways. The system consists of a retrofitted instrumented asphalt core, which is bonded into the pavement structure. The core contains all of the electronics necessary to record two pavement temperatures (surface and base) and two strains (longitudinal and transverse). The data when collected is transmitted via low power radio link to a receiver and data logger positioned by the side of the road. Also Sackin [13] proposed a new laboratory approach for the feasibility of embedded microdevices for infrastructure monitoring in concrete. This microdevice will be termed as “smart aggregate”. One of the objectives of the work is to investigate how an embedded device will behave under real working and environmental conditions. Although the laboratory test was successful, most questions vital to the MEMS application in infrastructure systems were not adequately considered. Some of these will be highlighted in the subsequent paragraph. Table 1 summarizes the potential application of MEMS based on condition deterioration mechanism.

3.2 Important Considerations

It is envisaged that MEMS devices can be embedded in the road infrastructure to monitor the condition at all times. The information collected can then be relayed via wireless technology into a database. Or MEMS devices with remote query capability can be interrogated at any given time to assess the condition of the pavement system as mentioned earlier. For the successful application and implementation of MEMS in pavement for continuous monitoring, some issues need to be addressed. Some of these issues are listed below:

- The effect of asphaltic medium on MEMS.
- How many MEMS devices are to be installed per 1km of pavement
- Where will the designer install or embed the microdevices (MEMS) in the pavement?
- Pavements have a life span of 20-30 years, will MEMS devices be able to perform throughout this period?
- How will environmental conditions affect the performance of MEMS in pavement condition monitoring?
- How will the effects of chemical medium such as corrosion in reinforced concrete structures, affect the performance of MEMS.
- Although the cost of MEMS is predicted to be reasonable, will it be a cost-effective method of collecting continuous data?

Some of these considerations have been addressed in other fields. For example, MEMS has been used in various chemical media in bioengineering applications [14].

4. CONCLUSIONS

The paper presents some challenges that need to be addressed for a successful implementation of MEMS technology in pavement monitoring. For example, laboratory investigation on the behavior of embedded MEMS in asphaltic material medium under dynamic loading needs to be addressed. Finally, it is required to test and track the field behavior of the pavement to establish both repeatability and long-term behavior of MEMS embedded in the pavement.

5. REFERENCES

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Table 1. Potential application of MEMS based on condition deterioration mechanism.

Condition deterioration	Deterioration mechanisms		Potential use of MEMS
	Load/usage, environment, material degradation, construction quality, interaction	Other	
1. Surface defects	Primary (environment, material degradation) Secondary (load/usage, poor construction quality) Interaction (material/environment and extended by load)	Man-made defects, maintenance patches	Fair
2. Deformation	Primary (environment, material degradation) Secondary (load/usage, poor construction quality) Interaction (material/environment/load)	Loss of support, inadequate maintenance	Excellent
3. Cracking, disintegration	Primary (environment, material degradation) Secondary (load/usage, poor construction quality) Interaction (load /environment/ material degradation)	Accidents, inadequate maintenance	Very good to excellent
4. Failure (a) Aging/inadequate structural capacity or retirement	The facility is structurally deficient because the limiting threshold values of (1) surface defects (2) deformation (3) cracking and disintegration are exceeded or the facility is retired because it is functionally obsolescent. Interaction (nature)	Capacity and safety considerations, inadequate maintenance	Good
(b) Catastrophic failure	Primary causes: earthquake, floods, freeze/snow, ice, tornado/cyclones, wind storms, foundation and soil failure and sink holes. Interaction (poor construction quality/design deficiency	Fire, arson, terrorist act or other accident	Poor