2012 2nd International Conference on Environment and Industrial Innovation
IPCBEE vol.35 (2012) © (2012) IACSIT Press, Singapore

Magnetoelastic Sensor Array for Tracking Personal Exposure to Atmospheric Environmental and Industrial Pollutants

Ee Lim Tan, Andrew Curriston, Andrew DeRouin, Rupak M. Rajachar and Keat Ghee Ong [+]

Department of Biomedical Engineering, Michigan Technological University, Houghton, MI 49931, USA.

Abstract. Monitoring personal exposure to atmospheric environmental and industrial pollutants such as volatile organic compounds and mercury vapour is critical to ensure health of individuals who are likely of such exposures. In this work, a wireless, passive atmospheric pollutant monitoring system based on the magnetoelastic sensor technology was developed for tracking elemental mercury vapour in workplaces. The system is consisted of dosimeters that can be worn by the user, and a detector installed by the doorway that automatically monitors the dosimeters when the user passes through. Instead of determining the total pollutant exposure at intervals of weeks or months, this system is able to record day-to-day exposure rate by measuring the dosimeter response every time the user passes through the detector, thus providing a complete exposure profile for ongoing surveillance to protect the user's health. The advantages of such a technology are the low dosimeter cost, and the fact that the user does not need to take any action, besides wearing a badge, to track exposure to pollutants, thus eliminating human errors. The feasibility of this technology was demonstrated with the fabrication of a mercury dosimeter, which is ideal for many manufacturing plants and mines where workers have long-term exposure of low-to-medium concentrations of mercury vapour.

Keywords: Magnetoelastic sensor, dosimeter, mercury vapour, environmental and industrial pollutants.

1. Introduction

Atmospheric environmental and industrial pollutants, which can be present in both indoor and outdoor, may come from multiple sources such as static emitters, mobile sources, or consumer products. Personal exposure to these pollutants not only depends on the sources, but also highly relies on the individual's social economic background, as well as lifestyle and behaviour [1]. Therefore, pollution exposure assessment techniques that focus on ambient air monitoring and emission tracking may not accurately reflect the actual exposure of a population group. In fact, studies have indicated that monitoring techniques based on static-location tracking provide poor correlation to the actual personal exposures [2]. An alternative to the static-location monitoring techniques is to use personal exposure tracking devices to directly quantify the levels of pollutant exposure by an individual. To be effective, however, such personal exposure tracking devices have to be lightweight, passive (battery-less), and require minimal or no additional operational procedure.

This work focuses on the development of a wireless, passive dosimeter for tracking personal exposure to environmental and industrial pollutants. The dosimeter was based on the passive, wireless magnetoelastic sensor/dosimeter technology [3, 4], which is made of magnetoelastic strips that can be worn by the user. Under the excitation of a magnetic AC field, the magnetoelastic strip resonates, generating a secondary field that can be remotely detected through a coil antenna. Pollutant detection is achieved by functionalizing a chemical-responsive coating that changes its mass or elasticity in response to the specific pollutant, causing a shift in the resonant frequency of the magnetoelastic strip. In practice, a detector installed by the doorway automatically monitors the dosimeter when the user passes through. Instead of determining the total pollutant exposure at an interval of weeks or months (most dosimeters can only determine the total chemical exposure

---

[+] Corresponding author. Tel.: +19064872749; fax: +19064871717.
E-mail address: kgong@mtu.edu.

when they are sent for analysis, which may be on a weekly or monthly basis), this system is able to record day-to-day exposure by measuring the response of the dosimeter every time the user leaves and enters a specific path such as a doorway, thus providing a complete pollutant exposure profile with ongoing surveillance to protect the user's health. The advantages of such a technology are the low dosimeter cost, and the fact that the user does not need to take any action (besides wearing the dosimeter) for his or her pollutant exposure level to be monitored, thus eliminating human errors. To track the user's identity, the dosimeter also features an array of magnetoelastic strips that can provide digital identity of the dosimeter.

The magnetoelastic dosimeter was applied to track personal exposure to elemental mercury vapour. Mercury is a major environmental pollutant in air, soil and groundwater. Among the many mercury species, elemental mercury vapours are the most common source for human exposure through inhalation, which represents about 90-99% of atmospheric mercury [5]. Current techniques for mercury vapour monitoring such as cold vapour-atomic absorption spectrophotometer [6], colorimetric dosimeter, and piezoelectric dosimeter [7] have limitations preventing them from use to track personal mercury vapour exposure. For example, piezoelectric dosimeters and calorimetric dosimeters need to be sent to a laboratory for analysis, increasing the turnaround time to at least a few days. Conversely, colorimetric dosimeters are easy to use and relatively inexpensive, but its accuracy is relatively low since the user needs to compare the individual dosimeter colour with a chart. A dosimeter based on the resistance of a thin gold film was developed to instantaneously monitor personal exposure to elemental mercury vapour [8]. Although this dosimeter can provide real-time continuous, mobile monitoring, the unit cost of each dosimeter is too high to be cost effective for high-volume use since the electronics are embedded to the sensor. Alternatively, the presented system is truly passive and low cost, thus is ideal for many manufacturing plants and mines where workers have long-term exposure to low-to-medium concentrations of mercury vapour.

2. Experiments

2.1. Dosimeter Fabrication

An array of magnetoelastic strips was used to monitor mercury vapour and providing identity of the dosimeter. Magnetoelastic ribbon (Metglas 2826MB) obtained from Metglas Inc. was mechanically sheared into different lengths and widths to control their resonant behaviours. Table 1 lists the dimensions, resonant behaviors, and functions of these magnetoelastic strips.

Table 1: Dimensions and functions of the magnetoelastic strips.

Strip	Length (mm)	Width (mm)	Frequency Range (kHz)	Function
1	24	5.0	94	Mercury
2	27	5.0	81	Control
3	28-29	5.0	74-78	ID1
4	30-32	5.0	70-74	ID2
5	32-34	5.0	66-70	ID3
6	34-36	5.0	62-66	ID4
7	37-39	5.0	58-62	ID5

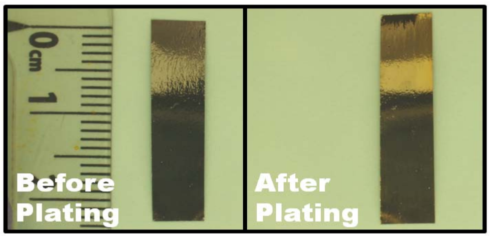
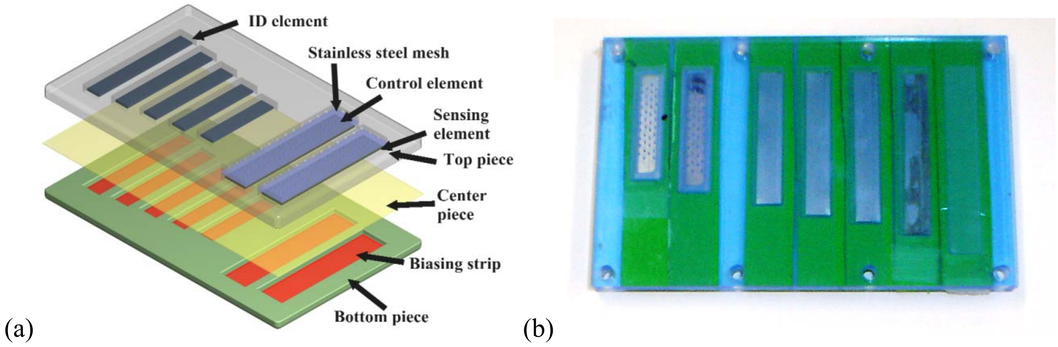


Fig. 1: The magnetoelastic strip following the gold electroplating process.

The mercury sensing magnetoelastic strip was functionalized with a gold coating. The strip was used as the cathode, and a stainless steel plate was used as the anode. Both electrodes were immersed in a gold plating solution obtained from Caswell Inc. and were introduced to a current density of 37.5 mA/cm^2 for a plating duration of 30 seconds. The outcome of the coating is illustrated in Fig. 1.

2.2. Dosimeter Packaging

The design of the dosimeter package is shown in Fig. 2a and the actual package is in Fig. 2b. The dosimeter package was consisted of mercury-sensing strip, control strip, ID strips and biasing elements. The package was made of three polycarbonate pieces: the top piece held the magnetoelastic strips, the centre piece was a separator, and the bottom piece held the biasing elements. The biasing elements were permanent magnetic strips (Arnokrome III) that used to provide DC magnetic fields to maximize the resonance of the magnetoelastic strips. The dimension of these biasing elements was determined by systematically changing their length and width until a large resonance from the magnetoelastic strips was found.



(a) (b)

Fig. 2: (a) Illustration and (b) photograph of the package that house the magnetoelastic strips and biasing elements.

2.3. Development of the Detector

A detection system was assembled and interfaced with a computer. The system consisted of a function generator (Fluke 271), an amplifier (Tapco J-1400), and a lock-in amplifier (Stanford Research System 810). The function generator generated a frequency-agile sinusoidal wave to excite the magnetoelastic strips. The amplifier increased the strength of the AC signal. The instruments were interfaced with the computer via IEEE 488.2 (GPIB) interface. A program, coded using Visual Basic 6.0, allowed the user to perform the interrogation process, which first controlled the function generator to send a frequency-changing signal and then recorded the measurements captured by the lock-in amplifier.

The excitation coils consisted of a circular 60 turn coil with a diameter of 25 cm. The receiving coils consisted of two 150-turn rectangular coils (8 cm × 12 cm) with opposite winding directions. This configuration canceled out the excitation signal thus increasing the signal-to-noise ratio.

2.4. Monitoring of Personal Exposure to Mercury Vapour

The mercury absorption rate of the coating was determined by examining the changes in the magnetoelastic strip's resonant frequency. The dosimeter was placed in a customized test chamber, connected to a mercury source and an outlet that connected to activated carbon to remove remaining mercury vapour before releasing into a fume hood. Compressed air with flow rate of 2 standard cubic feet per minute was introduced to the chamber followed by heating the liquid mercury at 50°C. At time points of 12, 24, 48, 72, and 96 hour, the strip was retrieved and the resonant frequency and mass were measured.

3. Results and Discussion

3.1. Simultaneous Detection of Multiple Magnetoelastic Strips

The resonant frequency range of the mercury-sensing and the control magnetoelastic strips was set to span from 80 to 100 kHz. The resonant frequency of each ID strip was set within a frequency span of 4 kHz, which was equally divided into 4 possible states of a quaternary numeral system. Shown in Fig. 3a is an array with the mercury-sensing and control strips configured to exhibit resonant frequency at 81-82 kHz and 94-95 kHz, respectively. The ID strips were each divided into 4 different states (0, 1, 2, and 3) and dependent on where the resonant peak was located, an identity to the dosimeter was obtained. From Fig. 3a, the identity of the dosimeter was determined as $0\times4^0 + 1\times4^1 + 1\times4^2 + 1\times4^3 + 2\times4^4 = 596$. Another example is shown in Fig. 3b where the dosimeter's identity was $3\times4^0 + 1\times4^1 + 1\times4^2 + 1\times4^3 + 2\times4^4 = 599$.

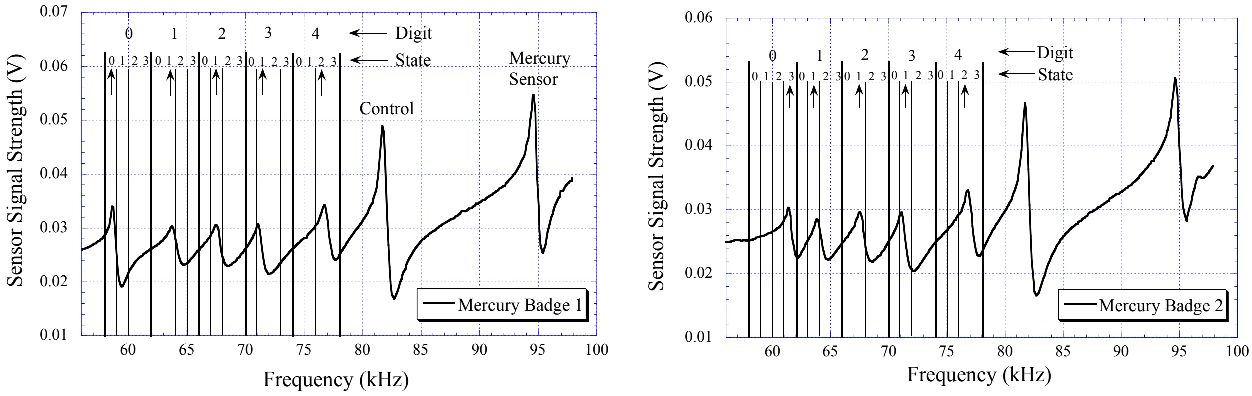
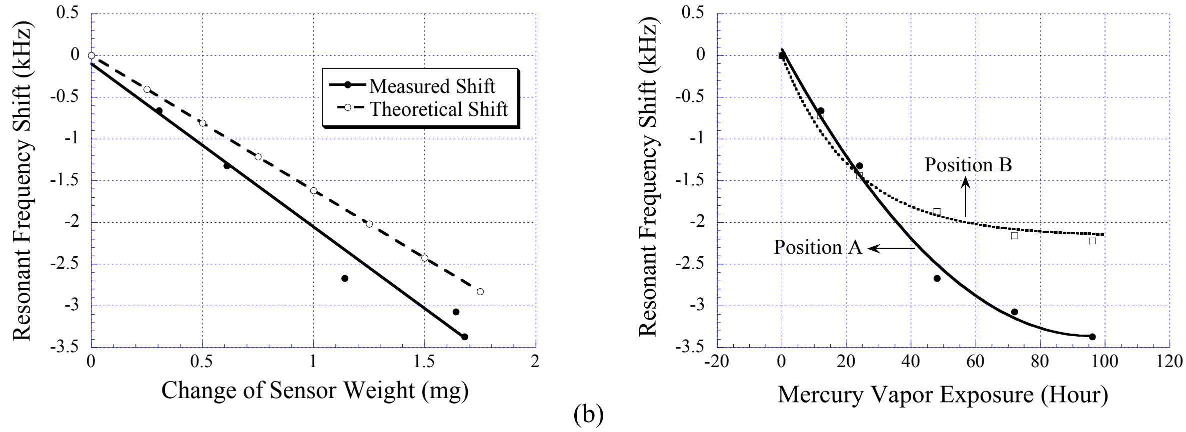


Fig. 3: The identification of Mercury Dosimeter Badges. The identity shown on the left (a) is $0\times4^0 + 1\times4^1 + 1\times4^2 + 1\times4^3 + 2\times4^4 = 596$. The identity shown on the right (b) is $3\times4^0 + 1\times4^1 + 1\times4^2 + 1\times4^3 + 2\times4^4 = 599$.

3.2. Performance Evaluation

Shown in Fig. 4a is the relationship between the resonant frequency shift and the weight of the magnetoelastic strip. As shown, the resonant frequency was decreased when the weight of the strip increased linearly. Fig. 4b demonstrates that the resonant frequency shift was correlated to the duration of mercury vapour exposure in an inversely exponential function. Not shown here is the change of the mass of the strip as a function of mercury exposure duration, which was correlated in an inversely exponential fashion. When the gold-coated magnetoelastic strip was initially exposed to the mercury vapour, the gold-mercury interaction was rapid due to the large area of gold-coated surface. Subsequent exposure to mercury vapour was expected to result in lower rate of amalgam formation due to limited exposed gold surface.

Also shown in Fig. 4b is the effect of relative distance to the liquid mercury source. It was demonstrated that as the gold-coated magnetoelastic strip was positioned further from the mercury source (Position B), the gold-amalgam formation rate was lower, resulting in a lesser sensitivity in terms of the resonant frequency shift. As the magnetoelastic strip was positioned closed to the mercury source (Position A), the sensitivity of mercury vapour detection was notably increased.



(a)

(b)

Fig. 4: (a) The magnetoelastic strip experienced a shift in resonant frequency when gold was deposited on its surface. (b) The effect of mercury exposure duration. Position A is when strip was 5 cm from the mercury source while Position B is when the strip was 6 cm from the mercury source.

3.3. System Performance Evaluation

The effect of relative distance and alignment between the magnetoelastic strip and detection coil was investigated. Fig. 5a plots the change in the resonant frequency when the dosimeter was moved away from the detection coil. As shown, when the sensor was moved away, the amplitude of the signal reduced significantly. Fig. 5b indicates the dosimeter exhibited highest signal strength when it was positioned at 0° because the length of the magnetoelastic strip was parallel to the direction of the applied excitation field.

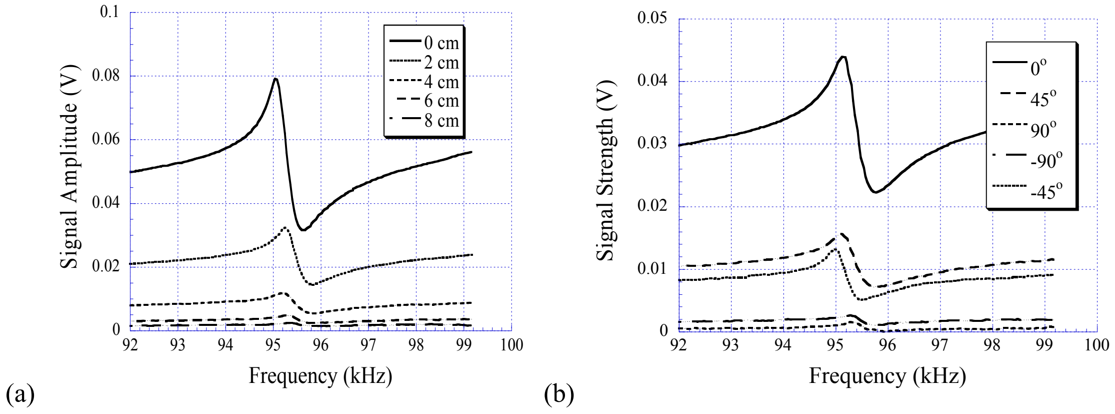


Fig. 5: The effect of (a) relative distance and (b) rotation angle between the sensor and detection coil.

4. Conclusions

A wireless, passive mercury vapour dosimeter system was developed. Particularly, a magnetoelastic strip array was fabricated to monitor mercury vapour accumulation as well as providing identity to the dosimeter. A badge was fabricated to house these strips, and a detection system was assembled using commercial instrumentations. The performance of the system was investigated showing the efficacy of this unique monitoring system that is similar to the anti-theft detection system commonly employed in retail stores.

This technology will be further developed, and eventually a cost-effective commercial device that can play an important role in protecting populations that are at risk to exposure to mercury vapour will be fabricated. In addition, this technology is not limited to mercury vapour. It is relatively easy to adapt the current work to monitor other atmospheric pollutants such as formaldehyde. In the future, it is possible to create a dosimeter that can monitor an array of harmful atmospheric pollutants, all done by user wearing a badge and passing through an entrance where the detector is installed.

5. Acknowledgements

This publication was supported by Grant 1R03OH009312-010A from CDC–NIOSH. Its content are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH.

6. References

[1] P.J. Lioy. Assessing Total Human Exposure to Contaminants - Multidisciplinary Approach. *Environ. Sci. Technol.* 1990, **24** (7): 938-945.

[2] W.R. Ott. Total Human Exposure: Basic Concepts, EPA Field Studies, and Future Research Needs. *J. Air & Waste Manage. Assoc.* 1990, **40** (7): 986-975.

[3] K.G. Ong, J. Leland, K. Zeng, G. Barrett, M. Zourob, C.A. Grimes. A rapid highly-sensitive endotoxin detection system. *Biosensors and Bioelectronics* 2006, **21**: 2270-2274.

[4] C.A. Grimes, C.S. Mungle, K. Zeng, M.K. Jain, W.R. Dreschel, M. Paulose, K.G. Ong. Wireless magnetoelastic resonance sensors: a critical review. *Sensors* 2002, **2**: 294-313.

[5] M. Gochfeld. Cases of mercury exposure, bioavailability, and absorption. Ecotoxicology and Environmental Safety 2003, **56**: 174-179.

[6] E.P. Scheide, J.K. Taylor. A piezoelectric crystal dosimeter for monitoring mercury vapor in industrial atmospheres. *Am. Ind. Hyg. Assoc. J.* 1975, **36** (12): 897-901.

[7] J.J. Caron, R.B. Haskell, P. Benoit, J.F. Vetelino. A surface acoustic wave mercury vapor sensor. *IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Contro*l 1998, **45** (5): 1393-1398.

[8] V. Mattoli, B. Mazzolai, V. Raffa, M.P. Dario. Design of a new real-time dosimeter to monitor personal exposure to elemental gaseous mercury. *Sens. Actuators B* 2007, **123** 158-167.