Modeling of a micro-diaphragm Biosensor for Human Artery Pulse Wave Detection

K. Hasikin[1], F. Ibrahim[1], *Member IEEE*, and N. Soin[2]
[1]Department of Biomedical Engineering, Faculty of Engineering, University of Malaya
[2]Department of Electrical Engineering, Faculty of Engineering, University of Malaya
50603, Kuala Lumpur, Malaysia
email: eishahasikin@gmail.com

Abstract – **The analysis of the behavior of the micro-diaphragm biosensor for human artery pulse wave detection has been presented in this paper. This includes the study of the effect of the diaphragm structural parameters on the static and dynamic performances such as sensitivity and natural frequency. It can be concluded that the modeled micro-diaphragm with a radius of 175μm and thickness of 4μm respectively has satisfied the maximum allowable deflection and operates in optimum frequency response.**

I. Introduction

The arterial pressure waveform can be assessed noninvasively by using the technique of pulse wave analysis. Pulse wave analysis is a noninvasive method that measures small vessel and large vessel compliance derived from the radial artery. The shape of the arterial pressure waveform provides a measure of the stiffness of the artery [1]. Therefore, the pulse pressure waveform can be used to diagnose atherosclerosis. Atherosclerosis is the buildup of fatty deposits (plaque) on the inside walls of the arteries. Plaques will reduce the blood's flow through the artery [2].

Most of the atherosclerosis diagnosis method, regardless of their cost and invasiveness conditions, can present only the percentage of arterial occlusions. There is no information about the degrees of sclerosis and stiffness of the arteries can be directly achieved by them. [3,4]. The study of arterial pulse wave analysis has shown its potential to indicate physiological changes due to the atherosclerosis or peripheral vascular disease (PVD) [4,5]. The peripheral vascular disease is a condition similar to the coronary artery disease. People with PVD often have fatty buildup in the arteries of the heart and brain [5].

Because of correlation between atherosclerosis and PVD [5], some noninvasive methods have been focused on blood pressure and structures of peripheral arteries were reviewed in [6]. The methods can partly inform physicians about atherosclerosis conditions. For severe atherosclerosis, the duplex ultrasonography, which is a combination of Doppler ultrasound and real-time brightness-mode imaging is more accurate [5,6]. However this technique is depended on operator and location of diseased.

Angiography technique is also used in diagnosis of the atherosclerosis. The angiography is used to look inside the arteries to see if there is any blockage in the wall of the arteries [5]. This is the most accurate way to assess the presence of severity of vascular diseases [5]. However angiography is invasive and has relatively high cost.

Nowadays, most of the sensor is designed by using Micro-electro-mechanical- system (MEMS) technology [6,7]. Sensing principles such as capacitive [6], piezoresistive [7], and optical [8,9] MEMS have a good potential in biomedical application. The ability to guide signals to and from a measurement site has made the optical MEMS technology attractive in designing of a biosensor.

In this paper, the radius and thickness of the diaphragm were varied in order to investigate their effect on natural frequency, deflection, stress and sensitivity.

II. Methodology

Light emitting diode (LED) will be used as a light source. Light from an LED will be transmitted via optical fibers and reflected back from a fixed surface of human wrist. A Sensor consists of an elastic metal-coated silicon diaphragm is fitted onto the end of a fiber optic

 1-4244-2561-7/08/$20.00

cable. This silicon diaphragm sensor will deflect under applied pressure [10].

The sensor is demodulated by detecting the shift of the reflected or transmitted spectrum or change in intensity of the light spectrum which both results from changes in optical path length [10,11]. The diffused components of the reflected light will strike a diaphragm which is in contact with the skin on a superficial artery.

Light source spectrum and reflected interference pattern can be extracted from this sensor [12]. From the reflected spectrum, the locations where the interference is minimum, will be used to calculate the cavity length of the sensor and thereby the diaphragm deflection and corresponding pressure [13]. The reflected waveform would produce the information about the stiffness and elasticity of the wall of the artery.

Solid circular diaphragm and fabrication process diaphragm were constructed and modeled using MEMS design software, (Intellisuite). The solid circular diaphragm has been designed in "Intellifab" module. The diaphragm was coated with chromium and titanium to enhance reflection off the diaphragm [10]. Silicon nitride has been chosen as the material for the diaphragm since it is transparent in optical range [13]. Further analysis on the behavior of the diaphragm has been conducted in "Thermoelectromechanical" module. The thickness and radius of the diaphragm were varied to evaluate its behavior.

Load-deflection method is a well known method for the measurement of elastic properties of the diaphragm [14]. In this design, the load-deflection relationship of a circular diaphragm is applied [15]:

$$y_c = \frac{3(1-\mu^2)Pa^4}{16Eh^3} \tag{1}$$

where y_c is deflection, P is applied pressure, μ is Poisson's ratio, E is Young's Modulus, h and a are diaphragm thickness, and effective diaphragm radius respectively.

The Reyleigh-Ritz method is used to find the frequency of the lowest mode of vibration [16]. The frequency of the circular diaphragm used in this study is:

$$f_{mn} = \frac{\alpha_{mn}}{4\pi}\sqrt{\frac{E}{3\rho(1-\mu^2)}}\left(\frac{h}{r^2}\right) \tag{2}$$

where α_{mn} and ρ are constants related to the vibrating modes of the diaphragm and mass density of the diaphragm material, respectively.

III. RESULTS & DISCUSSIONS

Simulation results for deflection, stress, sensitivity and natural frequency of the diaphragm are shown in Figures 1, 2 and 3. Fig. 1 illustrates that when the thickness and the radius of the diaphragm are small and large respectively, the deflection of the diaphragm will increase. This happens due to the relative increase in the diaphragm's stiffness as supported in Eq. (1).

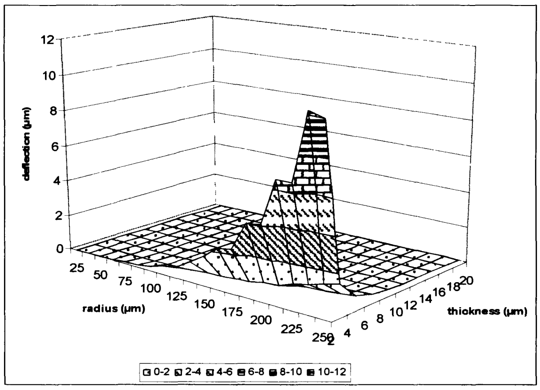

Fig. 1 Relationship between deflection, thickness and radius of the diaphragm.

However, when the size of the diaphragm is increased, the deflection and stress is also increased as shown in Fig. 2. If the radius is larger than 200 µm, the diaphragm will deflect by more than 1µm (Fig. 2). This phenomenon is due to the diaphragm's bending stress which has been increased. Therefore, the range of the radius of the diaphragm must be selected within 150 µm to 200 µm in order to optimize the performance of the diaphragm as shown in Fig. 2.

The result for the relationship between sensitivity, natural frequency and radius of the diaphragm is shown in Fig. 3. The result illustrates that the sensitivity of the diaphragm will be increased whilst the frequency will be reduced when the radius of the diaphragm is increased as in agreement with Eq. (2).

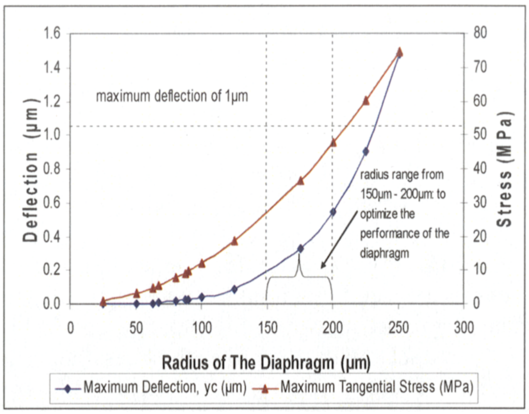

Fig. 2 Deflection and stress versus radius of the diaphragm

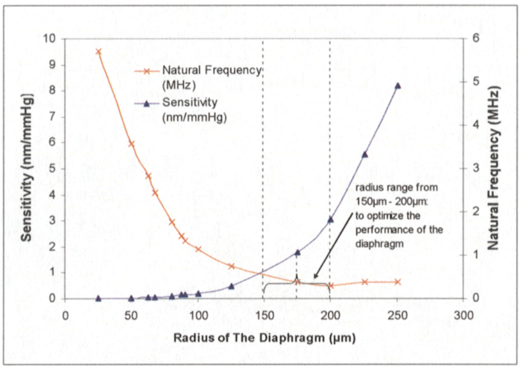

Fig. 3 Sensitivity and natural frequency of the diaphragm versus radius of the diaphragm

In this study, the thickness and radius of the diaphragm are selected depending upon the pulse pressure range (less than 300mmHg). According to [17,18], the diameter of normal human artery is between 2.5mm to 3mm. Since the sensor will be attached externally to the surface of human's wrist, the sensor must be smaller than the size of human artery. As a result, the pressure will not cause any deflection to the diaphragm by more than 1μm [19].

Therefore, referring to Figures 2 and 3, the diaphragm with a thickness of 4μm and radius of 175μm were selected. Previous research findings by [20] has also shown that the diaphragm achieved high sensitivity when these dimensions (thickness and radius of 4μm 175μm respectively) were selected. This diaphragm must be capable to deflect linearly [14]. In order to ensure the diaphragm operates in a linear range, the natural frequency of the diaphragm should be at least 2.5 times larger than the applied frequency [15]. Since the sensor is designed for biomedical application, the diaphragm should be able to operate in frequency range up to 50 kHz. Therefore, the diaphragm should have a minimum natural frequency of 0.1MHz (2.5 times larger than 50kHz). Due to these requirements, the diaphragm with a thickness of 4μm and radius of 175μm was found to be the optima and selected. These radius and thickness of the diaphragm give maximum deflection and sensitivity of 0.32μm and 1.08nm/mmHg respectively. It also shows that the stress and frequency of the diaphragm are 36.5MPa and 0.63 MHz, respectively (as shown in Figures. 2 and 3).

IV. CONCLUSIONS

The analysis of the behavior of the micro-diaphragm biosensor has been presented in this paper. It was found that the deflection, stress and sensitivity of the diaphragm increased when the thickness and radius of the diaphragm are small and large, respectively. However, any increased in deflection and sensitivity of the diaphragm will decrease the natural frequency of the diaphragm. With the diaphragm's radius of 175μm and thickness of 4μm, the sensitivity and the frequency of the diaphragm achieved and optimized are 1.08nm/mmHg and 0.63MHz, respectively. Thus, this modeled micro-diaphragm satisfied the maximum allowable deflection and operates in optimum frequency response.

ACKNOWLEDGEMENT

Our greatest appreciation goes to Prime Minister's Department for encouraging and funding of this research.

REFERENCES

1. I.B.Wilkinson, I.R. Hall, H. MacCallum, I.S. Mackenzie, C.M. McEniery, B.J. Van der Arend, S. Yae-Eun, L.S. Mackay, D.J. Webb, J.R. Cockcroft. "Pulse Wave Analysis Clinical Evaluation of a Noninvasive, Widely Apllicable Method for Assessing Endothelial Function". *Arterioscler Thromb Vasc Biol*. 147-152. (2002).
2. F. Latifoglu,, S. Sahan, S. Kara, S. Gunes, "Diagnosis of atherosclerosis from carotid artery Doppler signal as a real world medical application of artificial immune systems". *Expert Systems with Applications*. 33. 786-793. (2007).
3. M. Pouladian, M.R.H. Golpayegani, "Noninvasive detection of a atherosclerosis by

Arterio-Oscillo-Gram". *Proceedings of the 25th Annual International Conference of the IEEE EMBS*. September 17-21, (2003).

4. C.M. Otto, B.K. Lind, D.W. Kitzman, B.J. Gersh, D. Phil, D.S. Siscovick, "Association of aortic-valve sclerosis with cardiovascular mortality and morbidity in the elderly". *The New England Journal*. July 5, 1999, (1999).
5. T.E. Andreoli, J.C. Bennett, C.J. Carpenter, F. Plum, *Cecil Essentials of Medicine*, 50th Edition, Philadelphia, Pennsylvania: Saunders, 155-151. (2001).
6. S. Chatzandroulis, D. Goustouridis, P. Normand, D. Tsoukalas, "A solid-state pressure-sensing microsystem for biomedical applications", *Sensor and Actuators*, A 62, 551-555. (1997).
7. A. Druzhinin, E. Lavitska, I. Maryamova, "Medical Pressure Sensors on The Basis of Silicon Microcrystal and SOI layers", *Sensors and Actuators*, B 58, 415-419. (1999).
8. O. Tohyama, M. Kohashi, M. Sugihara, H. Itoh, "A fiber-optic pressure microsensor for biomedical applications", Sensors and Actuators. A 66, 150-154. (1998).
9. T. Katsumata, Y. Haga, K. Minami, M. Esashi, "Micromachined 125µm diameter ultra miniature fiber-optic pressure sensor for catheter", Trans. Inst. Electrical Eng. Jpn. Part E 120E. 58-63. (2000).
10. Niewczas, P., Dziuda, L., Fusiek, G., Willshire, A.J., McDonald, J.R., Thursby, G., Harvey, D., and Michie, W.C. *Interrogation of Extrinsic Fabry–Pérot Interferometric Sensors Using Arrayed Waveguide Grating Devices*. IEEE Transaction on Instrumentation and Measurements. 52(4). 1092-1096.
11. Xiao-qi, N., Ming, W., Xu-xing C., Yi-xian, G and Hua R., (2006). *An Optical Fiber MEMS Pressure Sensor Using Dual-Wavelength Interrogation*. Measurement Science and technology. Vol. 17. 2401- 2404.
12. Singh, M., Li, J.K-J., Sigel Jr. G.H, Amory, D. (1990). *Fiber Optic Pulse Sensor for Noninvasive Cardiovascular Applications*. IEEE Spectrum.103-104.
13. Hill, G.C., Melamud, R., Declercq, F.E., Davenport, A.A., Chan, I.H., Hartwell, P.G.,
14. J.H.Correia, M. Bartek, R.F. Wolffenbuttel, "Load-deflection of a Low Stress SiN-Membrane/Si Frame Composite Diaphragm". *Technical Proceedings of the 1998 International Conference on Modeling and Simulation of Microsystem* (1998).
15. X. Wang, B. Li, O.L. Russo, H. T. Roman, K.K. Chin, K.R. Farmer, "Diaphragm design guidelines and an optical pressure sensor based on MEMS technique", *Microelectronic Journal*, 37, 50-56. (2006).
16. M.D. Giovanni, *Flat and Corrugated Diaphragm Design Handbook*. Marcel Dekker, Inc. (1982).
17. H.P Le, K. Shah, J. Singh, A. Zayegh, "Design and Implementation of an Optimised Wireless Pressure Sensor for Biomedical Application.", *Analog Interg Circ. Sig. Process*, 48.21-31. (2006).
18. P. Madssen, R. Haere, Wiseth, "Radial Artery Diameter and Vasodilatory Properties After Transradial Coronary Angiography", *.Ann Thorac Surg* , 82.1698-1703. (2006)
19. H. Yamashita, M. Nishimoto, Okuyama, "Diaphragm deflection control of piezoelectric ultrasonic microsensors for sensitivity improvement". *Sensors and Actuators A* (2007). 139.118-123.
20. K.Hasikin, F. Ibrahim, N.Soin. "Determination of design parameters for human artery pulse wave detection", 4th International Conference on Biomedical Engineering, IFMBE, *Springer*, 2008