Micro-diaphragm Performance Analysis for Polyimide Diaphragm

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Abstract – **This paper presents a micro-diaphragm performance analysis for optical sensor for human pulse pressure detection. The effect of diaphragm radius and diaphragm thickness on the static and frequency responses were investigated. It can be concluded that the polyimide micro-diaphragm with a radius of 90µm and thickness of 4µm has achieved the optimum performance in term of the sensitivity, flexural rigidity and resonance frequency.**

I. Introduction

A micro-diaphragm is a common element in a diaphragm based sensors. These sensors have been widely used in biomedical applications [1-4]. Among all the elastic plates, the micro-diaphragm is not only simple to construct, but it is also suitable for use in high vibration environment [5]. Moreover, the micro-diaphragm is a flexible plate which undergoes elastic deflection when lateral pressure is applied onto it.

Deformation of the loaded micro-diaphragm will determine the performance and sensitivity of the complete sensor system. The vibration of micro-diaphragm structure is detected either through deflection or through strain induced in the micro-diaphragm. In recent work [6-9], both of these methods have been considered for designing appropriate mechanical elements for optical sensor. Numerous researchers have investigated the performance of micro-diaphragm for an optical sensor [10,11].

Findings by other researchers have shown that the performance of the micro-diaphragm become less sensitive when it is thick [10,11]. Analysis presented by [12] showed that a micro-diaphragm with high sensitivity is desirable since it measures how sensitive the micro-diaphragm deforms with the applied pressure.

Resonance frequency of the diaphragm is another important parameter to be considered in any micro-diaphragm performance analysis. High sensitivity micro-diaphragm reduces its resonance frequency [10-12]. Thus, it is crucial to select design parameters which give the highest sensitivity without affecting diaphragm resonance frequency.

In addition, the selection of the most suitable material for the micro-diaphragm is also a crucial part in designing an optical sensor. The polymer-based materials have potential to be used in designing the micro-diaphragm for an optical sensor [2, 3, 13-15].

In this paper, micro-diaphragm has been developed using a polyimide. The polyimide is a high performance polymer material which has a good thermal stability. In addition, it has low linear coefficient of thermal expansion [16]. The performance of the micro-diaphragm is analyzed in terms of its sensitivity, diaphragm stiffness and resonance frequency.

II. Methodology

Circular micro-diaphragm and its fabrication process were constructed and modelled using MEMS design software, Intellisuite™. The micro-diaphragm has been designed in “Intellifab” module. The micro-diaphragm was coated with chromium and titanium to enhance reflection off the diaphragm [10].

Further analysis on the performance of micro-diaphragm has been conducted in “Thermoelectromechanical” module. Design parameters namely diaphragm’s radius and thickness were varied to investigate the performance of micro-diaphragm. In this paper, the micro-diaphragm is specifically designed to detect the human’s radial artery pulse pressure. Thus, the micro-diaphragm must have an appropriate dynamic range and sensitivity for small pulse pressure measurement. The summarized micro-diaphragm design specifications are presented in Table 1.

TABLE 1
Diaphragm Design Specifications

Parameter	Value
Pressure range	0-300mmHg
Frequency range	0-50kHz
Maximum Deflection	≤1µm

The performance of micro-diaphragm is analyzed using the load-deflection method [5]. The micro-diaphragm is loaded with the lateral pressure and its sensitivity is investigated. The sensitivity of the micro-diaphragm is a ratio of the changes in the diaphragm deflection to pressure difference [5,10,11]. The diaphragm pressure sensitivity is investigated as in equation (1) [5,10,11]:

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$$S = \frac{\Delta y}{\Delta P} \quad (1)$$

where y is diaphragm deflection and P is the applied pressure.

Based on this equation, it is shown that diaphragm deflection is closely related to diaphragm pressure sensitivity. In more specific, the higher the deflection increases the sensitivity.

The micro-diaphragm should possessed high sensitivity to detect small changes of pressure. Thus, micro diaphragm with high deflection and sensitivity needs to be constructed as a pressure transducer for the optical sensor.

The load-deflection relationship of a circular diaphragm is analyzed using equation (2) [5,10,11]:

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

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.

Thus by rearranging equation (2) and solving it for polyimide diaphragm, the diaphragm pressure sensitivity is given by:

$$Y_c(polyimide) = 2.194\times10^{-11}\frac{a^4}{h^3}(\mu m/mmHg) \quad (3)$$

Despite deflection and sensitivity, stiffness of the diaphragm is another important parameter which needs to be studied in designing a micro-diaphragm. The stiffness of the micro-diaphragm can be analyzed by analyzing a flexural rigidity. The flexural rigidity is defined as a force couple required to bend a rigid structure [5] and it is presented in equation (4):

$$D = \frac{Eh^3}{12(1-\mu^2)} \quad (4)$$

For a dynamic measurement, resonance frequency of the micro-diaphragm need to be studied [17]. Therefore it is important to characterize the relationships between the micro-diaphragm dimension, sensitivity and resonance frequency to design the micro-diaphragm.

In the analysis of frequency response of the micro-diaphragm, the diaphragm vibration theory is employed. The micro-diaphragm is assumed to be perfectly elastic and is made of homogeneous isotropic material. The transverse deflection of a circular membrane clamped at its edge is expressed in Hemholtz equation [18,19]. The resonance frequency of the diaphragm was analyzed using the following equation (5) [5,10].

$$f_{mn} = \frac{\alpha_{mn}}{4\pi}\sqrt{\frac{E}{3\rho(1-\mu^2)}}\left(\frac{h}{r^2}\right) \quad (5)$$

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, sensitivity and resonance frequency of the diaphragm are shown in Figures 1, 2 and 3. Fig. 1 illustrates the behaviour of deflection and sensitivity with variation in diaphragm radius. It can be depicted from this figure that both deflection and sensitivity increase when diaphragm radius is large. This finding is in agreement with the analytical formulae presenting in equations (2) and (3).

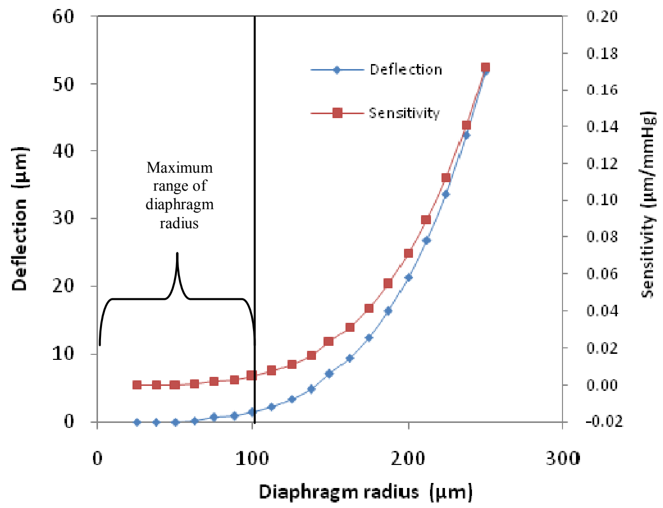

Fig. 1: Behaviour of deflection and sensitivity with variation of diaphragm radius.

As shown in Fig. 1, if the diaphragm radius is larger than 100 µm, the micro-diaphragm will deflect by more than 1µm. This phenomenon is due to the increase of micro-diaphragm bending stress. Therefore, in order to optimize the performance of the micro-diaphragm, the diaphragm radius must be less than 100µm.

The relationship of diaphragm pressure sensitivity and flexural rigidity with diaphragm thickness is illustrated in Fig. 2. Based on the simulation result presented, the flexural rigidity is found to increase as the diaphragm thickness increases. It can be concluded that micro-diaphragm with low flexural rigidity is highly desirable. This is because thin diaphragm decreases the flexural rigidity and thus will increase diaphragm sensitivity.

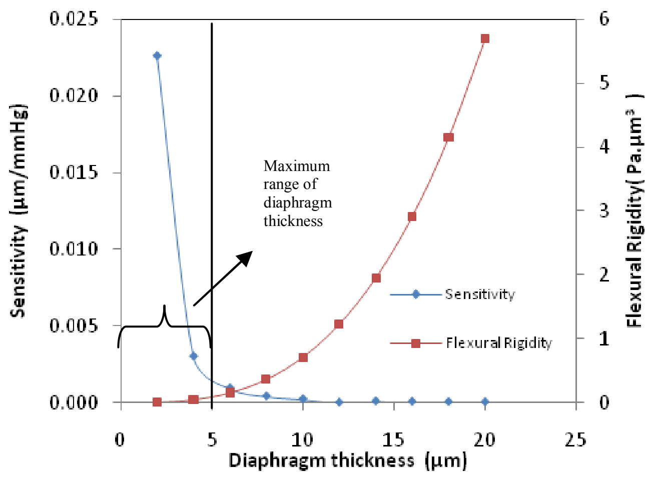

Fig. 2: Sensitivity and flexural rigidity in relation with diaphragm thickness

The result of flexural rigidity and resonance frequency in relation with diaphragm thickness is presented in Fig. 3. The micro-diaphragm was found to achieve a high resonance frequency when the flexural rigidity was increased.

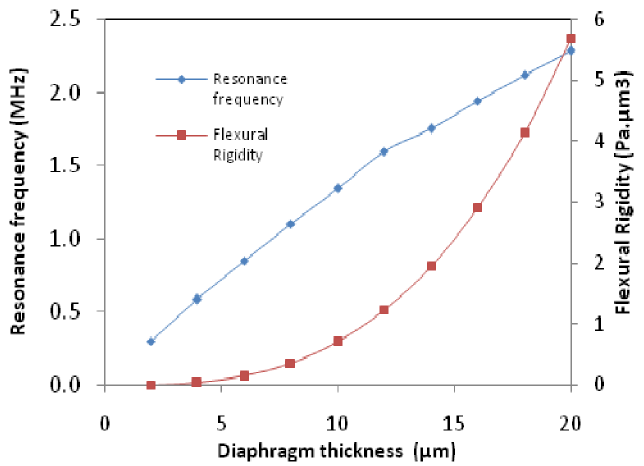

Fig. 3: Resonance frequency and flexural rigidity in relation with diaphragm thickness.

The increment in this flexural rigidity is related to the increased in the diaphragm stiffness. It is found that thicker diaphragm requires higher vibration frequency in order to attain a maximum deflection and thus increases the resonance frequency. In other words, higher flexural rigidity will cause the micro-diaphragm to be less sensitive.

In this study, diaphragm thickness and diaphragm radius are selected depending upon the pulse pressure range (less than 300mmHg). Therefore, referring to Figures 1 to 3, the diaphragm with a thickness of 4µm and radius of 90 µm was selected. Previous research findings by [22,23] have also shown that the diaphragm achieved high sensitivity when these dimensions were selected.

The selected dimension was found to give maximum deflection and sensitivity of 0.9µm and 0.003µm/mmHg respectively. It also shows that the resonance frequency of the micro-diaphragm is 0.58 MHz (Figure 3).

IV. Conclusions

The micro-diaphragm performance analysis for optical sensor has been presented in this paper. It was found that the deflection and sensitivity of the diaphragm increased when the diaphragm radius is large. However, any increased in deflection and sensitivity of the diaphragm will decrease the resonance frequency of the micro-diaphragm. Thus, by selecting the diaphragm radius of 90 µm and diaphragm thickness of 4µm, the sensitivity and resonance frequency of the diaphragm achieved its best performance Therefore, this modelled micro-diaphragm satisfied the maximum allowable deflection and operated in optimum frequency response.

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