A New Method to Design Pressure Sensor Diaphragm

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ABSTRACT

Over the last decade, silicon pressure sensors have undergone a significant growth. In most cases, these MEMS (Microelectromechanical System) devices are manufactured from rectangular or circular diaphragms whose thickness is constant and in the order of some microns. The development of high-performance diaphragm structure is of critical importance in the successful realization of the devices. In particular, diaphragms capable of linear deflection are needed in many pressure sensors. In order to increase the sensitivity, the diaphragm thickness should be thin to maximize the load-deflection responses. On the other hand, thin diaphragm under high pressure may result in large deflection and nonlinear effects that are not desirable. It is therefore important to characterize the relationship between diaphragm thickness, deflection, and sensitivity, both analytically and experimentally in order to establish the design guidelines for micro pressure sensors.

Keywords: resonant frequency, thickness, diaphragm, deflection

INTRODUCTION

The load-deflection method is a well-known method for the measurement of elastic properties of thin films. In this technique, the deflection of a suspended film is measured as a function of applied pressure. The load-deflection relation of a flat square diaphragm is given by [1]:

$$\frac{Pa^4}{Eh^4} = \frac{4.2}{(1-\nu^2)}\left[\frac{y}{h}\right] + \frac{1.58}{(1-\nu)}\left[\frac{y}{h}\right]^3 \qquad (1)$$

Where
P applied pressure (Pascal),
y the center deflection of the diaphragm
a the half side length,
E young's modulus,
h the diaphragm thickness,
v Poisson's ratio of the diaphragm material.

The deflection range is divided into two regions: a small deflection region and (deflection less than 25% of the diaphragm thickness) described by the linear term in Equation 1 and a large deflection region described by the non-linear, cubic term in Equation 1.

As a general rule, the deflection of the diaphragm at the center must be no greater than the diaphragm thickness; and, for linearity in the order of 0.3%, should be limited to one quarter the diaphragm thickness.

For Linear Part

$$y = \frac{Pa^4(1-\nu^2)}{4.2Eh^3} \qquad (2)$$

For a diaphragm clamped on its edges, from a mathematical point of view, the diaphragm can be viewed as a thin plate and the exact solution for the differential equation that describes its oscillation is given in [1]. Assuming that the deflection of the diaphragm is small compared to its thickness. The Reyleigh-Ritz method [2] was used to find the frequency of the lowest mode of vibration. The relationship for fundamental frequency for a square plate having density ρ_d and osculating in a medium (ρ_m) with was found to be:

$$f_1 = \frac{10.21}{a^2\sqrt{1+\beta}}\sqrt{\frac{gD}{\rho_d h}} \qquad (3)$$

Where g is acceleration of gravity, and β and D is given by:

$$\beta = 0.6689\frac{\rho_m}{\rho_d}\frac{a}{h}$$

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

SIMULATION

Figure 1 shows the relationship among side length, thickness, and natural frequency. With a given side length, the resonant frequency increases with thickness. With a given thickness of diaphragm, the frequency decreases with side length. Figure 1 also shows us that thickness has more effect on resonant frequency than side length.

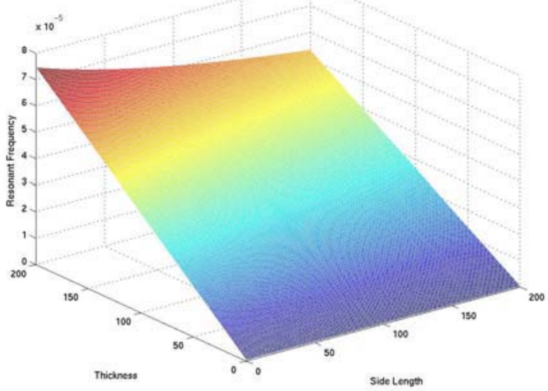


Figure 1 Relationships among side length, thickness and resonant frequency

According to Equation [2]

$$a = \left(\frac{4.2Eh^3 y}{(1-\nu^2)P} \right)^{1/4} = \left(\frac{50.4Dy}{P} \right)^{1/4}$$

Given E 150 GPa and ν 0.25, Equation [3] becomes

$$f_1 = 4.5 \left(\frac{P}{y \left(\rho_d h + 0.6689 \rho_m \left(\frac{y}{P} \right)^{1/4} h^{3/4} \right)} \right)^{1/2}$$

Where ρ_d is 2330 kg/m^3 and ρ_m 1.25 kg/m^3.

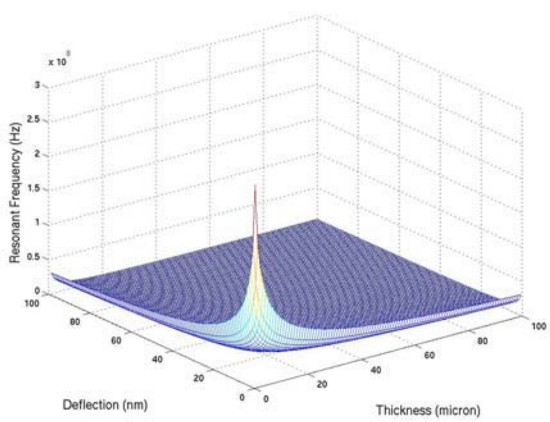


Figure 2 Relationships among deflection, thickness and resonant frequency

When the fixed pressure (1 Pa) is applied to the diaphragm, the relationships among natural frequency, deflection and thickness of diaphragm are shown in Figure 2. Figure 2 tell us that in order to get large natural frequency and large deflection at the given pressure, the thickness should be thin.

According to Equation [2],

$$h = \left(\frac{Pa^4(1-\nu^2)}{4.2Ey} \right)^{1/3}$$

Then Equation [3] becomes

$$f_1 = \frac{467.5P^{1/3}}{a^{2/3} y^{1/3} \left(\rho_d + 5863 \rho_m \left(\frac{y}{aP} \right)^{1/3} \right)^{1/2}} \tag{4}$$

When the fixed pressure (1 Pa) is applied to the diaphragm, the relationship among natural frequency, deflection and diameter of diaphragm is shown in Figure 3. Figure 3 tells us that in order to get large natural frequency and large deflection of diaphragm at given load, the side length need to be small. Figure 2 and 3 tell us in order to get the large deflection and large resonant frequency of the diaphragm at the same times, both the side length and thickness of the diaphragm should be small.

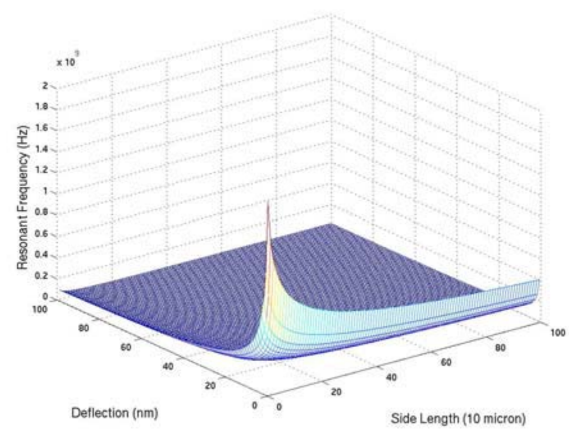


Figure 3 Relationships among deflection, side length and resonant frequency

Based on the understanding that partial discharge acoustic signal can occur at frequencies up to 100 kHz, and the fact that our proposed optical interrogation method should be capable of measuring displacements as low as 0.1 nm for 1 Pa sound pressure amplitudes, we found that many thickness/diameter combinations could be used to achieve a 200 kHz natural frequency, but the diameter must be less than ~1.4 mm in order to achieve the required displacement/pressure specifications according to equation 4. These results are illustrated in Figure 1, which shows that the curve denoted by triangles (1.4 mm diameter, 30 micron thickness) achieves 0.1 nm deflection for 1 Pa pressure. Smaller and thinner membranes can also be used, but these are less practical to fabricate.

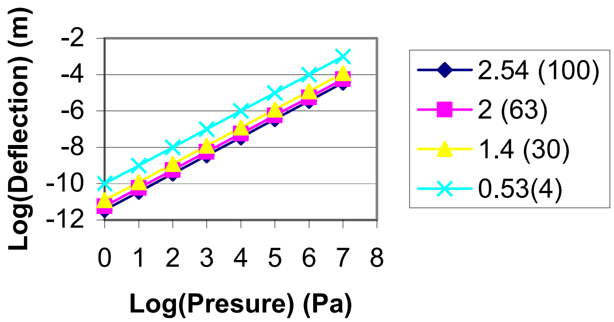
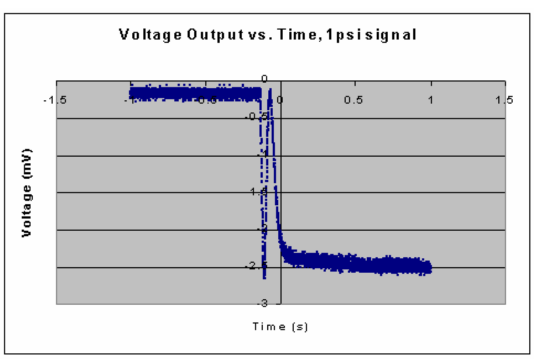


Figure 4 relationships among thickness, side length and deflection under same resonant frequency

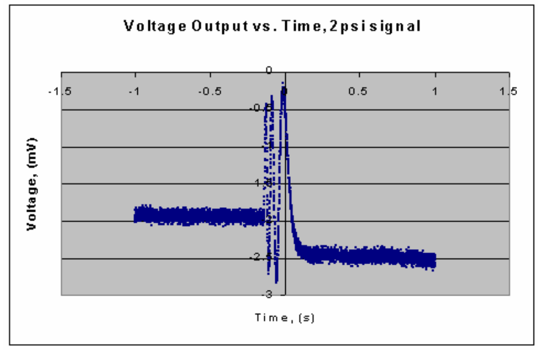
EXPERIMENT RESULTS

A stainless steel housing for the sensor has been designed and fabricated. A finished system is shown in Figure 5. The sensor is placed at the end of a ~7" long tube that can be attached to a drain plug by a compression fitting connection. The end of the housing opposite the sensor has a stainless steel tee fitting for passing the optical fiber and allowing control of the sensor backside pressure and environment, as described above.

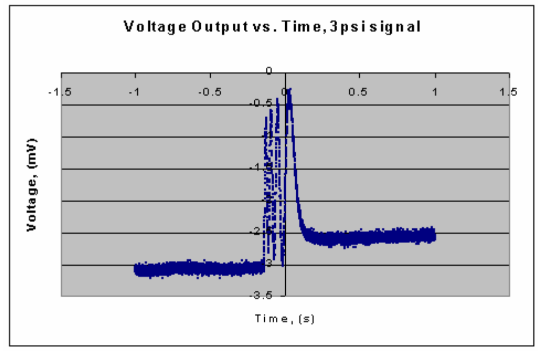
Figure 5 the optical fiber sensor



(I)



(II)



(III)

Figure 6 relationships between load and output

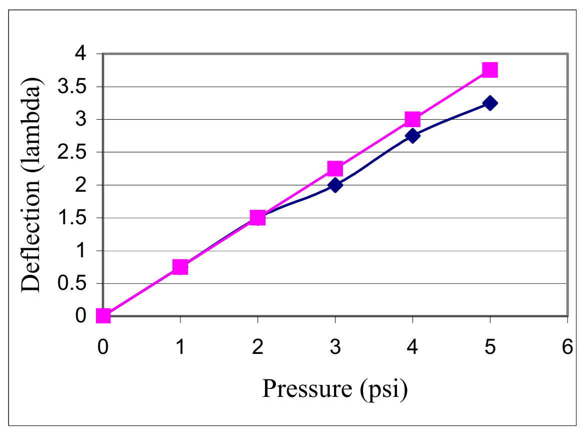


Figure 7 Comparison of the experimental and theoretical results

The frequency analysis of a sensor is important because we may get the resonant frequency of the membrane (actually also is sensor). Figure 8 shows sound response to different frequencies (below 100 kHz). It also shows that one of the resonant frequencies of the membrane is 88 kHz. It agrees with the simulation result.

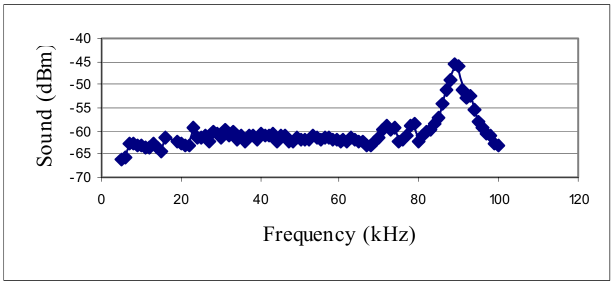


Figure 8 the frequency response of the sensor

CONCLUSIONS

The diaphragm is a very important part for MEMS sensor. The design of the diaphragm is critical to the output of the sensor. The relationships among side length, resonant frequency, deflection of the diaphragm are shown in the paper. According to the design rule, a optical fiber sensor was fabricated and tested. The calculated results agree with the experiments results.

REFERENCES

[1] Gregory T.A. Kovacs, "Micromachined Transducers Sourcebook", McGraw-Hill, 1998

[2] M. Di Giovanni, "Flat and corrugated diaphragm design Handbook", Mercel Dekker Inc., New York, 1982