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A silicon micromachined resonant pressure sensor

Zhangyang Tang^{1,2}, Shangchun Fan^{1,2}, Chenguang Cai¹

¹School of Instrumentation Science & Opto-electronics Engineering, Beihang University, Beijing, 100191, China

²State Key laboratories of transducer technology, Shanghai, 200050, China

Email: tangzhangyang1@163.com

Abstract. This paper describes the design, fabrication and test of a silicon micromachined resonant pressure sensor. A square membrane and a doubly clamped resonant beam constitute a compound structure. The former senses the pressure directly, while the latter changes its resonant frequency according to deformation of the membrane. The final output relation between the resonant frequency and the applied pressure is deducted according to the structure mechanical properties. Sensors are fabricated by micromachining technology, and then sealed in vacuum. These sensors are tested by open-loop and close-loop system designed on purpose. The experiment results demonstrate that the sensor has a sensitivity of 49.8Hz/kPa and repeatability of 0.08%.

1. Introduction

Pressure is one of the most important parameters in the aircraft measurement and control. Among various kinds of pressure sensors, the resonant pressure sensor is attractive because of its digital and high performance. The vibrating cylinder pressure sensor is a typical one which has been successfully used on the aircrafts. However, as the development of modern aircraft manufacture technology, the demand for smaller, lighter and better pressure sensors is emerged [1]. The maturation of silicon micromachining technique guarantees the fabrication of this minized sensor. As far, there are a few companies selling their products on the market as the Druck in U.K. and the Yokogawa in Japan [2,3]. For China, the research on this field started since last ten years and is still in the stage of laboratory.

This paper presents the design and realization of a compound structure silicon micromachined resonant pressure sensor, and the test results by the open-loop and closed-loop system designed on purpose.

2. Design and theory

2.1. Working principle

The compound structure of this silicon resonant pressure sensor is illustrated by figure.1. The square membrane is the direct pressure sensing component, and is deformed under the measured pressure. A doubly clamped beam is suspended on the surface at the center of the membrane. Its axial stress is changed as the membrane deformed, and accordingly its resonant frequency is changed. Consequently, the measured pressure can be obtained through the resonant frequency. Figure.2 shows a fabricated sensor.

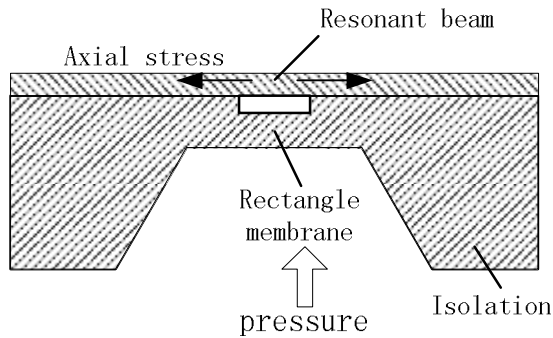


Figure.1 compound structure of the pressure sensor

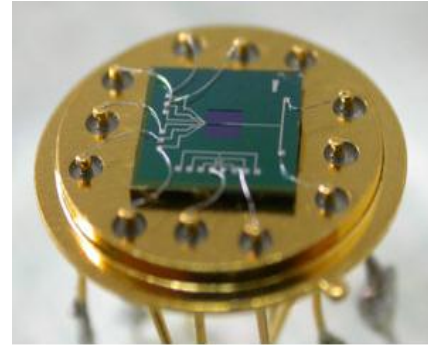


Figure.2 the fabricated sensor photo

2.2. Theory calculation

Assuming that the membrane side length is A , thickness is H , and the direction along the beam axis is x direction. Then, the displacement along x direction on the surface of the membrane $u(x)$ is as in equation (1).

$$u(x) = \frac{-49P(1-m^2)}{96E} \left(\frac{A}{H}\right)^2 \left(\frac{x^2}{A^2} - 1\right)x \quad (1)$$

Where E is the Young modulus of the material, and m is the Poisson ratio of the material [4].

Assuming that the beam length, width and thickness are l , b and h . As b and h is relatively small than A , the axial strain of beam e_x is merely determined by the displacement of the two suspended points as in equation (2).

$$e_x = [u(\frac{l}{2}) - u(-\frac{l}{2})] / l \quad (2)$$

From the solution of the vibrating partial differential equation for the resonant beam, the vibrating shape and resonant frequency under the axial force N of each modes can be obtained. To working at the lowest energy point, the first resonant frequency is chose as the working frequency, expressed by equation (3).

$$f_1(N) = f_{n1}(0) \left(1 + g_1 \frac{Nl^2}{Ebh^3}\right)^{\frac{1}{2}} \quad (3)$$

Where, $f_{n1}(0) = \frac{a_1^2 h}{2pl^2} \left(\frac{E}{12r}\right)^{\frac{1}{2}}$ is the nature frequency of the beam when $N = 0$, and

$g_1 = 0.295$, $a_1 = 4.730$, which are constants related with the order of mode [5].

Substituting $N = bhe_x$ into equation (3), the relation between the measured pressure and the first order resonant frequency can be obtained by equation (4).

$$f_1(P) = f_{n1}(0) \left[1 + \frac{49g_1 l^4}{96Eh^2} (1-m^2) \left(\frac{A}{H}\right)^2 \left(1 - \frac{l^2}{4A^2}\right) \cdot P\right]^{\frac{1}{2}} \quad (4)$$

As for the relatively small pressure range, equation (4) is approximately linear, the sensitivity of resonant frequency to pressure is expressed by equation (5).

$$S_{pf} = \frac{1}{P} \frac{f_1(P) - f_{n1}(0)}{f_{n1}(0)} \approx 0.075 \frac{(1-m^2)}{E} \left(\frac{Al}{Hh}\right)^2 \left[1 - \left(\frac{l}{2A}\right)^2\right] \quad (5)$$

3. Experiment analysis

3.1. Test system

As the dimension of the resonant beam and the vibration amplitude is very small, the pickup signal is very weak and is submerged in the strong background noise [6]. To extract the weak vibrating signal, an detection circuit system is designed based on the lock-in amplify principle. Tests for the pressure sensor characteristics are realized by it. Figure.3 is the block diagram of the circuit system.

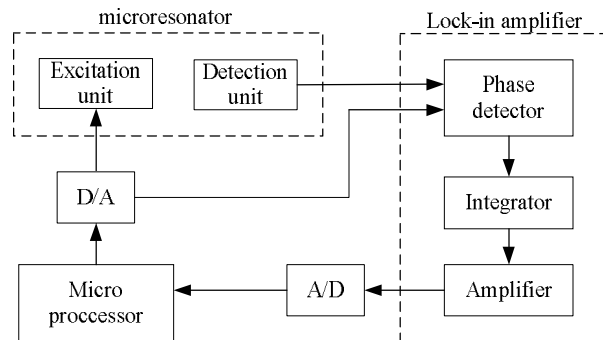


Figure.3 the block diagram of the detection circuit system

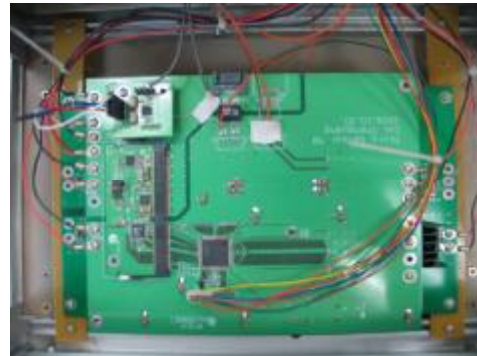


Figure.4 the detection circuit board

The vibration is transformed to voltage. This electrical signal is input to the phase detector and further to the low pass filter, which fulfill the lock-in function together. After appropriate amplifying, the preprocessed signal is transformed to digital values for the microprocessor. Open-loop and closed-loop algorithms are carried out to complete the characteristic test. The open-loop test flow consists of the large scale frequency scanning and the samll scale frequency scanning. The former is to determine the approximate range of the resonant sensor, and the latter adjust the frequency step to locate the resonant frequency precisely. Finally, the resonant peak value, phase shift and Q value are calculated and displayed. Based on these characteristics, the closed-loop judges the present frequency by its responding vibration amplitude. Through the feedback, the control logic tracks and maintains the resonant state. The control model is based on the relation between the frequency and the amplitude differential. Figure.4 is the photo of the circuit board.

3.2. Experiment result

The standard pressure is generated by DHI PPC3 pressure calibrator and the constant temperature is supplied by GDS-50L temperature controllor. The open-loop test undergoes in the pressure of 100kPa and temperature of 25°C. The pressure values are 10kPa, 30kPa, 50kPa, 70kPa, 90kPa, 110kPa, 130kPa for closed-loop test and repeats 3 times in the constant temperature of 25°C. The results are presented by figure.5 and figure.6.

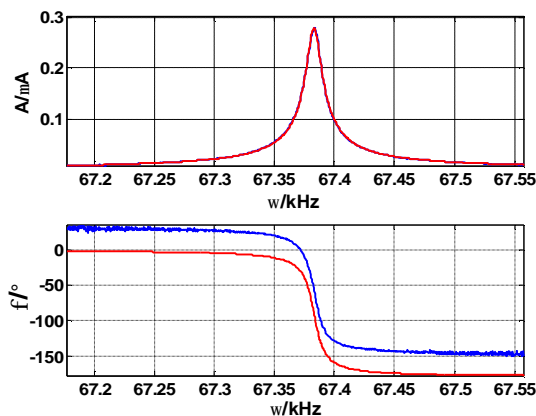


Figure.5 open-loop test result, the blue and the red refer to the actual value and the theory value, respectively.

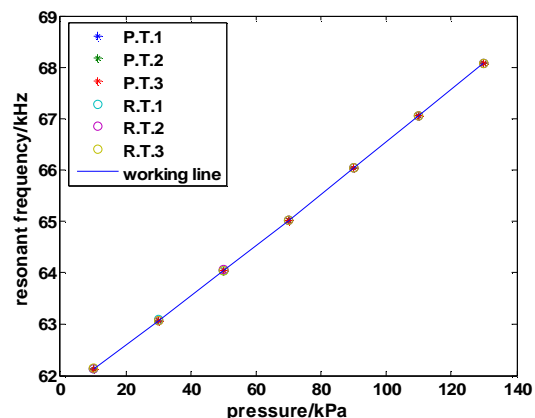


Figure.6 close-loop test result, the note 'P.T.' and 'R.T.' refers to positive travel and reverse travel, respectively.

The open-loop test result shows that, the resonant frequency of the silicon micromachined resonant pressure sensor is 67.3829kHz, the Q value 5195, the resonant peak value 0.278uA and phase shift 35.5° . The blue curve is the actual value, while the red one is the calculation value according to the theory formula. The amplitude characteristics accord with the theory very well. The phase characteristics has a constant deviation from the theory, which is result from the error of the analog device.

The close-loop test result shows that, in the pressure range of 10kPa to 130kPa, the full output is 5.972kHz, and the sensitivity is 49.8Hz/kPa, and the repeatability is 0.08%, the hysteresis is 0.15%, and the total error is 0.17%.

4. Conclusion

The resonant pressure sensor presented in this paper is fabricated by silicon micromachining technique. It has a compound structure, which consists of a square membrane and a doubly clamped resonant beam. A detection circuit system based on the phase-lock amplifier principle is designed. With the pressure and temperature controller, the experiment platform is setup to fulfill the open-loop and the close-loop test. The experiment results demonstrate that the sensitivity of the sensor is 49.8Hz/kPa, the repeatability is up to 0.08%, and the total accuracy is 0.17%.

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