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Measurement of Vacuum Pressure with Resonators in the Closed-Loop Configuration

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Summary:

This paper proposes a vacuum resonant pressure sensor that is operated in the closed-loop configuration. The damping of MEMS resonator is related to its environment pressure, so the vacuum pressure sensor can be measured by the quality factor or vibration amplitude of resonator. In order to extend the lower limit, a comb-finger actuator is applied to drive the resonator. To enhance the performance, the resonator is operated in closed-loop and the amplitude ratio of detecting and driving signals are used as the output metric. The results show that the sensor can measure the pressure covers from 3.5E−4 Pa to 10 Pa with a repeatability error of ±1.2% RD.

Keywords: Vacuum pressure sensor, damping of MEMS resonator, closed-loop control, piezoresistive strain gauge

Background, Motivation an Objective

Vacuum gauge is widely used in various industrial equipment to monitor the process pressure. The most famous sensor used for high- and medium-vacuum measurement is ionization gauge, and measurement error is about 10% RD. Besides, the volume of their sensing elements is quite large, usually several micrometers, so they are influenced by the direction of installation.

MEMS sensors are famous for their small volume, and a few efforts have been done to achieve the measurement. However, most sensors can only measure low to medium vacuum pressure. For example, Chen et al. have proposed a sensor based on coupled resonators, which can measure the pressure from 9E-5 Pa to 1 Pa. However, the structure is complicated and the sensor is operated in the open-loop configuration, so the accuracy is limited.

In this paper, a simplified resonator is applied and operated in closed-loop configuration. The lower limit and accuracy are optimized with the applied driving / detecting structure and the output metric of amplitude ratio.

Description of the New Method or System

The governing equation is expressed as (1), where ω and x are frequency and the maximum amplitude of the resonator. In addition, F and Q are the driving force and quality factor of the resonator. Since damping monotonically increases with the environment pressure, if F is constant, pressure can be quantified by x. Furthermore, x changes monotonically with F, so if the ratio of x and F is used as the output signal of the sensor, the influence of the fluctuation of detecting and driving signals can be reduced.

$$x = \frac{F}{Q}\sin(\omega t) \Rightarrow \frac{x}{F} = \frac{1}{Q}\sin(\omega t) \qquad (1)$$

The structure of the resonator and closed-loop configuration are shown in Fig. 1. The resonator is a H-type double-ended tuning fork (H-DETF), and works at out-of-phase modes. It is driven by comb-finger actuator to reduce the damping so that Q and x is sensitivity to pressure only when the pressure is small enough. The amplitude is detected by a pair of piezoresistive strain gauge, which has a higher signal-to-noise ratio than capacitive pickup, so it is helpful to obtain a stable signal x_o [2].

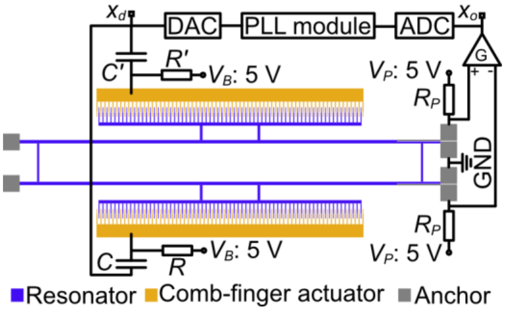

Fig. 1. Structure of the MEMS resonator.

The detecting signal is transformed to digital signal by ADC, then the phase-locked loop (PLL) calculates the frequency and phase, and then the driving signal is generated and transformed to analog signal x_d by DAC. The key point is that the amplitude of the driving signal from DAC is constant. Therefore, the amplitude ratio of x_o and x_d can qualify the pressure according to (1).

Results

The testing was conducted at 25±0.5 ℃ and the amplitude ratio against pressure is shown in Fig. 2. The relationship between ratio and pressure is nonlinear which is similar to previous studies [1], and the maximum sensitivity is obtained from 0.1 Pa to 10 Pa, which is about 0.7 /Dec. The singularity around 2 Pa is due to reference gauge is changed from hot ionization gauge to capacitive diaphragm gauge, but they have different zeros. The subgraph shows that it can distinguish the pressure down to approximately 3.5E−4 Pa.

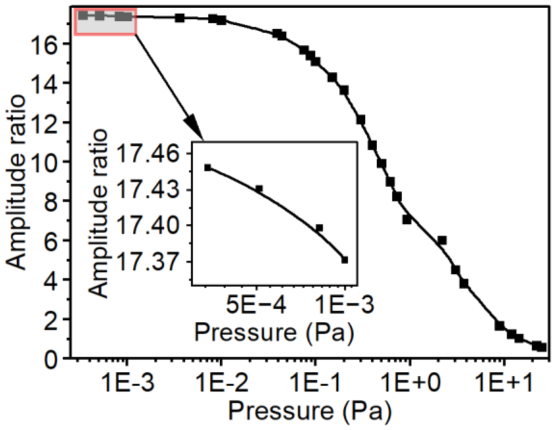

Fig. 2. Sensitivity of the proposed sensor.

The repeatability error was measured at zero pressure, during which the pressure was increased to the upper limit and then down to zero pressure for five times. As shown in Fig. 3, the absolute error is 0.2 and the relative error is calculated as ±1.2% RD.

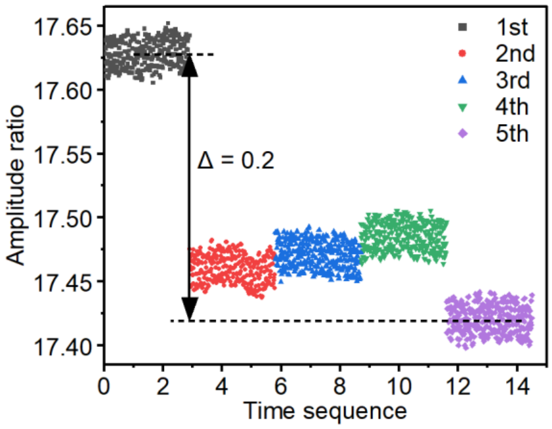

Fig. 3. The repeatability error of the sensor at zero.

The zero drift is continuously monitored for 38 hours, as shown in Fig. 4. The amplitude ratio signals generally show a decrease across the period, which is due to the stress relive and aging. The total variation is about 3% RD, so the drifting rate is about 0.08% RD every day.

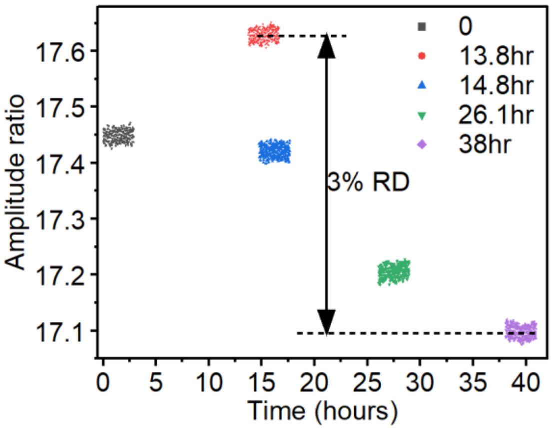

Fig. 4. The zero drift of the sensor.

The results are compared with previous studies as shown in Tab. 1, which shows that it has the advantage of simple structure and low repeatability error.

Tab. 1: Comparison with previous arts

	Principle	Range	Error
Ref. [1]	Damp of coupled resonator/open-loop	9E−5 Pa to 1 Pa	20% RD
Ref. [3]	Damp of diaphragm vibration/open-loop	6E−5 Pa to 11 Pa	<10 % RD
This work	Damp of H-DETF with comb-finger actuator/closed-loop	3.5E−4 Pa to 10 Pa	~1.2 %RD

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