MEMS oscillating squeeze-film pressure sensor

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Abstract. This work reports on an oscillating pressure sensor that converts pressure into frequency using the squeeze-film effect. A feedback loop, consisting of a laser Doppler vibrometer (LDV), a phase shifter and an automatic gain control circuit, brings the sensor element into sustained oscillation. The frequency stability of the pressure sensor is investigated by measuring its Allan deviation and is compared to the performance of a quartz oscillating pressure sensor. In addition, the pressure resolution of this novel type of oscillating pressure sensor is compared to conventional sensors.

1. Introduction
Pressure sensing has been one of the first commercial applications of micro-electro-mechanical systems (MEMS) technology [1]. Recently, production volumes have increased by the introduction of MEMS pressure sensors in mobile devices for indoor navigation, weather forecasting and altitude measurement [2], [3]. Most conventional sensors determine pressure by capacitive or piezoresistive measurement of the static deflection of a suspended membrane caused by a difference between the ambient pressure and the pressure in a reference cavity [4]. In addition to these static sensors, several dynamic or resonant pressure sensors have been reported that detect a stress induced change in resonance frequency [5], [6], [7]. The fabrication of all these devices is however complicated by the need for a sealed reference cavity. In order to keep the pressure in the reference cavity constant, the hermetic seal needs to be leak tight for many years and the cavity needs to be very clean to prevent pressure changes due to outgassing effects.

In contrast, squeeze-film pressure sensors do not require a reference cavity, since instead of measuring the force exerted by a gas pressure difference, they determine the force needed to compress the gas. Even if the gas is not hermetically sealed, it can be compressed at high frequencies if the escape time of the gas is much longer than the compression period.

This work demonstrates an oscillating squeeze-film pressure sensor which consists of a squeeze-film pressure sensor element that is brought into sustained oscillation by a feedback loop. Operating the sensor in an oscillator loop has two major advantages: firstly it increases the immunity of the signal to external disturbances and secondly it facilitates analog-to-digital conversion (ADC) by counting periods [8]. After the frequency has been determined, it is straightforward to determine the pressure from the known frequency-pressure relation. Due to noise in the the oscillator’s output signal, the resolution of the sensor is limited. The Allan
variance [9] is used to characterize the oscillator’s stability and benchmark the performance of the pressure sensor against quartz oscillating pressure sensors and state-of-the-art piezoresistive and capacitive pressure sensors.

2. MEMS squeeze-film and quartz resonant pressure sensor
This section introduces the two resonant pressure sensors discussed in this work. The MEMS squeeze-film pressure sensor shown in Figure 1a-c consists of a circular 4 µm thick perforated SiGe membrane that is covered by a 2 µm SiN layer. The diameter of the membrane is 340 µm. The suspended membrane is separated by a 1 µm gap g from a SiGe bottom electrode that is covered by a SiC dielectric and that is used for electrostatic actuation. In the middle of the membrane, a small (< 1 µm diameter) hole is etched which ensures pressure equalization on both sides of the membrane. Figure 1a shows a device cross-section and top view optical micrographs are shown in Figures 1b and 1c. Figure 1d shows an equivalent electrical network of an electromechanical resonator.

A commercial EuroQuartz MH32768 quartz crystal tuning fork is used as a benchmark device to investigate the effect of the feedback loop on the oscillator performance (Fig. 1e). The quartz crystal can be actuated by piezoelectric force. In order to use the quartz crystal as a gas pressure sensor, the hermetic metal package of the tuning fork is removed.

![Figure 1.](image)

The fundamental resonance of both MEMS and quartz sensor is studied by measuring their open loop response at 1 bar using an HP4191A impedance analyzer. The resonance curves are fit using the equivalent model in Figure 1d and the extracted parameters are given in Table 1. The resonance frequency \( \omega_0 = 2\pi f_0 \) and Q-factor \( Q \) of the resonators are calculated using \( \omega_0 = \frac{1}{\sqrt{L_m C_m}} \) and \( Q = \frac{1}{R_m} \sqrt{\frac{L_m}{C_m}} \).
Figure 2. Open loop characterization of MEMS and quartz pressure sensors in ambient conditions with an AC voltage \( V_{ac} = 100 \text{ mV} \). A capacitive bias voltage \( V_{dc} = 10 \text{ V} \) is used for the actuation and capacitive readout of the MEMS sensor.

Table 1. Extracted motional parameters at 1.02 bar from Figure 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MEMS</th>
<th>Quartz</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_m )</td>
<td>3.6 M( \Omega )</td>
<td>213 k( \Omega )</td>
</tr>
<tr>
<td>( L_m )</td>
<td>46.72 H</td>
<td>12.8 kH</td>
</tr>
<tr>
<td>( C_m )</td>
<td>1.26 fF</td>
<td>1.84 fF</td>
</tr>
<tr>
<td>( C_0 )</td>
<td>3.4 pF</td>
<td>36 pF</td>
</tr>
<tr>
<td>( f_0 )</td>
<td>657 kHz</td>
<td>32.763 kHz</td>
</tr>
<tr>
<td>( Q )</td>
<td>50</td>
<td>12,500</td>
</tr>
</tbody>
</table>

3. Pressure sensitivity

Before operating the sensors as oscillators, their pressure sensitivity is investigated. The resonance frequency and Q-factor of both MEMS and quartz resonator is measured at varying pressures in a vacuum chamber at room temperature, using an HP 4191A impedance analyzer, as is shown in figure 3. The dependence of the sensor’s resonance frequency on pressure is called its sensitivity \( S = \frac{df}{dp} \). The pressure sensitivity of the MEMS resonator (95 kHz/bar) is caused by the squeeze-film effect. At low frequencies the squeeze-film effect is causing an increased damping [11], but at high frequencies it mainly affects the spring constant of the resonator [10]. Because the hole in the membrane is very small, the gas enclosed in the space under the membrane does not have enough time to escape within the vibration period of the resonator [12]. Therefore, at a constant ambient pressure \( p \), the number of gas molecules in the enclosure is constant, but the volume decreases when the membrane moves downward. According to Boyle’s law the gas is compressed to a pressure \( p + \Delta p \). The position dependent force on the membrane that is related to this squeeze pressure, can be described as a spring with a squeeze-film spring constant \( k_{sq} \) that effectively causes an increase in the spring constant \( k_{eff} = k_0 + k_{sq} \). Because the amount of gas molecules trapped below the membrane depends on pressure \( p \), the value of \( k_{sq} \) also depends on pressure. In the high frequency and small gap limit, it can be assumed that no gas leaves the cavity and \( k_{sq} \) can be derived from Boyle’s law\([10], [12],[13]\). In \([14]\), it has been reported that the trapped gas is compressed isothermally such that according to Boyle’s law \( (p + \Delta p)(V - \Delta V) = pV = \text{const} \). For small center deflection \( \Delta x \), it follows that
\[ V \frac{k_{sq} \Delta x}{A} - p \alpha A \Delta x = 0. \] Thus the squeeze film spring constant is found to be:

\[ k_{sq} = \frac{pA}{g} \]

(1)

\( A \) is the area of the membrane and \( \alpha = \frac{\Delta V}{V_{g} \Delta x} \) relates the membrane center displacement \( \Delta x \) to the volume change of the cavity \( \Delta V \). From the analytic equation for the fundamental resonance mode of a circular plate, a value \( \alpha = 0.31 \) is derived. Using the equation \( k_{eff} = m_{eff} \omega_{0}^{2} \), the sensitivity \( S \) is found to be:

\[ S = \frac{df_{0}}{dp} = \frac{\alpha A}{8\pi^{2}m_{eff}f_{0}g} \]

(2)

Where \( m_{eff} \) is the effective mass of the fundamental resonance mode of a circular plate [15], which is given by \( m_{eff} = m/4 = \frac{1}{4} \rho h \pi r^{2} \). Combining these equations with the device parameters from Tables 1 and 2, an estimated pressure sensitivity of \( S_{MEMS,est} = 1.1 \times 10^{2} \) kHz/bar is calculated in good agreement with the measured sensitivity of \( S_{MEMS} = 95 \) kHz/bar.

**Table 2.** Device parameters of the MEMS squeeze-film pressure sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness</td>
<td>6 µm</td>
</tr>
<tr>
<td>Radius</td>
<td>170 µm</td>
</tr>
<tr>
<td>Air gap</td>
<td>1 µm</td>
</tr>
<tr>
<td>Average density</td>
<td>3.57 \times 10^{3} kg/m^{3}</td>
</tr>
</tbody>
</table>

Since the quartz tuning fork is resonating in free space, the gas is not compressed and the squeeze-film effect does not play a role. Nevertheless, due to a different principle the resonance frequency of the tuning fork also depends on pressure as is observed in figure 3 (\( S_{quartz} = -5.85 \) Hz/bar). This is caused by the fact that the gas that surrounds the quartz tuning fork needs to be accelerated. This effect causes an increase in the effective mass of the resonator that leads to a pressure dependent decrease in the resonant frequency. The acceleration force on the gas surrounding an oscillating sphere is evaluated in [16]. These equations are used to evaluate the inertial force on gas surrounding the quartz resonator by approximating the tuning fork by a string-of-spherical beads [17]. The result is that the force needed to accelerate the gas surrounding the tuning fork is equal to that needed to accelerate an object of the same volume but with a density of half the density of air. The effective mass \( m_{eff,air} \) of the tuning fork in the presence of gas therefore becomes \( m_{eff,air} = m_{eff}(1 + \frac{1}{2}\frac{\rho_{air}}{\rho_{quartz}}) \). Taking the Taylor expansion of \( \omega_{0} = \sqrt{k/m_{eff,air}} \) the pressure sensitivity of the tuning fork is found to be [18]:

\[ \frac{df_{0}}{dp} = -\frac{1}{4} \frac{d\rho_{air}}{dp} \frac{1}{\rho_{quartz}} \omega_{0} = -\frac{1}{4} R_{air} T \rho_{quartz} \]

(3)

where \( R_{air} \) is the specific gas constant of dry air (287.058 J/kg.K), \( \rho_{quartz} \) is the density of quartz (2660 kg/m^{3}) and \( \rho_{gas} = pR_{air} T \). Thus a theoretical pressure sensitivity of \(-3.6 \) Hz/bar is calculated. For the quartz sensor a sensitivity \( S_{quartz} = -5.8 \) Hz/bar is measured which is higher than the theoretical sensitivity of \(-3.6 \) Hz/bar. In [18] the experimental value of \( d\omega_{0}/dp \) for quartz tuning forks is also found to be about twice the theoretical value obtained from string-of-bead model, which is attributed to differences between the string-of-bead model and the actual shape of the tuning fork.

After having established the dependence of the resonance frequency on pressure, both sensors are operated in an oscillator circuit in order to create oscillating pressure sensors.
4. Oscillating pressure sensors

4.1. MEMS oscillating squeeze-film pressure sensor

For continuous pressure monitoring and to facilitate analog to digital conversion, a feedback loop is used to bring the resonating element into oscillation. As shown in Figure 4, the feedback loop consists of an electrical amplifier and 2 transducers between the mechanical and electrical domain and of an electrical amplifier. The amplifier compensates energy losses of the resonator. The MEMS resonator is actuated by electrostatic force \[19\]. For transduction from the mechanical to electrical domain of the MEMS sensor, the motion is sensed optically using a laser Doppler
A novel aspect of this paper is the implementation of a Laser Doppler Vibrometer (LDV) as a transducer and amplifier in an oscillator loop. Laser Doppler Vibrometry extracts the velocity of an object using the Doppler shift of a reflected laser beam. A main advantage of using LDV readout instead of capacitive readout is that crosstalk via the capacitor $C_0$ in Figure 1d is eliminated because the actuation voltage of the MEMS is optically isolated from the output voltage of the LDV. A large value of $C_0(\gg C_m)$ can otherwise make it impossible to reach the Barkhausen [21] oscillation condition in the Pierce topology [22] (Figure 7). Moreover, optical readout improves immunity to electrical noise sources and does not load the oscillator (input impedance of the LDV is virtually infinite). The LDV can also be used to scan a full wafer of devices fast, without need for assembly. Disadvantages of the LDV include noise caused by vibrations in the optical elements and the signal processing electronics that causes additional delay time.

The LDV used in this work is a Polytec MSA 500 Doppler Vibrometer. The optically measured velocity of the vibrating membrane is converted into electrical signals with a sensitivity of 20 mm/s/V. The overall experimental setup is shown in Figure 5.

The gain of LDV is so large that no additional electric amplifiers are needed. However, without gain control no stable oscillation could be obtained. To stabilize the LDV feedback loop an automatic gain control (AGC) circuit is used. The AGC contains an operational amplifier whose gain is controlled by a JFET. The rectified oscillator voltage is fed into the JFET, after subtracting a reference voltage, to control the gain of the operational amplifier (inset Figure 5). The AGC thus stabilizes the oscillator voltage amplitude and reduces amplitude noise. A tunable all-pass filter is used as a phase shifter to tune the oscillator to the point where it oscillates at a minimum value of $V_{dc}$ (Figure 5).

In order to start the oscillator, the DC bias voltage $V_{dc}$ across the MEMS sensor is applied via a bias tee. The bias voltage is increased until the circuit starts oscillating due to the associated decrease of the motional impedance $R_m$. The higher the pressure is, the lower the Q factor and the higher the minimum $V_{dc}$ needed to start the oscillator. The opto-mechanical oscillator output at atmospheric pressure $P = 1.02$ bar, at a DC bias of 3.8 V is measured using an oscilloscope and spectrum analyzer as shown in Figures 6a,b. The output frequency as a function of pressure is determined using a Fluke 6681 frequency counter, based on the number of zero crossings detected within a certain time interval $\tau$. Figure 6c shows the pressure dependent oscillator frequency determined at $\tau=0.1$ ms.

The pressure dependence of the oscillator frequency is found to be equal to 97 kHz/bar, which is close to the measured open loop value (Figure 3).
4.2. Quartz oscillating pressure sensor

In addition to the opto-mechanical MEMS oscillator, a quartz oscillating pressure sensor is studied. The quartz crystal is operated in 2 oscillator circuits to study the effect of the feedback loop on the oscillator performance. The first oscillator circuit uses an LDV, like for the MEMS squeeze film pressure sensor. The second oscillator circuit is an electrical Pierce oscillator topology (Figure 7). For direct comparison at the same pressure, two quartz oscillators are operated in the same vacuum chamber as shown in Figure 7. The Pierce oscillator uses a transistor amplifier to compensate for the losses associated with $R_m$. Two large capacitors at the input and output ports ensure zero total phase shift in the loop and minimize noise spikes. The output of both oscillators and the pressure dependence of their output frequency are shown in Figure 8. For the LDV a velocity decoder with a sensitivity of 50 mm/s/V is used and the Pierce oscillator supply voltage is $V_{DD}=3.95$ V.

For direct comparison of the two feedback loops, the quartz oscillator was operated without AGC and phase shifter circuits. The absence of the AGC caused non-linearities in the output of the Pierce oscillator (Figure 8b). Figure 8c shows the pressure dependent oscillation frequency as measured by the frequency counter. The pressure sensitivity of the device is similar to that measured in the open-loop measurements.

5. Stability and resolution

Since the resonance frequency is observed to be approximately a linear function of pressure, the resolution of the pressure sensor is directly proportional to the frequency stability of oscillator output. Here, the frequency stability of the oscillating pressure sensors is characterized by
measuring their (two-sample) Allan deviation $\sigma_A$ as a function of averaging time $\tau$ [9]. The Allan deviation is determined using a gated frequency counter Fluke PM6881 that determines frequencies $f_1$ and $f_2$ averaged over two adjacent time intervals each having a duration of $\tau$. This measurement is repeated 50 times and the Allan deviation is determined using the equation:

$$
\sigma_A = \frac{1}{f_0} \sqrt{\frac{1}{2} \langle (f_1 - f_2)^2 \rangle} \quad (4)
$$

Where $f_0 = (<f_1> + <f_2>) / 2$ and the brackets indicate averaging over 50 measurements. The Allan deviation as a function of averaging time $\tau$ of the MEMS optomechanical pressure sensor is shown in Figure 9. The data is fit by a function $\sigma_A = a_0 \tau^{a_1}$ with $a_1 = -1.01$. The slope of the Allan deviation in a log-log plot can be used to identify the type of noise source. A slope $a_1 = -1$ corresponds to white (frequency independent) phase modulation of the oscillator. At longer averaging times, the data deviates from the $1/\tau$ fit, and $\sigma_A$ starts to increase due to frequency drift.

Figure 10 compares the Allan deviation of the two feedback methods (electromechanical Pierce and optomechanical LDV) as determined using the quartz pressure sensor. For the Pierce topology $a_1 = -0.94$, whereas for the quartz oscillator with optical feedback $a_1 = -0.80$ was found. Although the Allan deviation of both MEMS and quartz optomechanical oscillators increased significantly at longer averaging times, the quartz-based Pierce oscillator had several orders of magnitude lower absolute $\sigma_A$. Moreover the Pierce oscillator was stable within $\pm 0.3$
Figure 7. Two quartz oscillators were measured in the same vacuum chamber allowing a direct comparison of optical and electrical feedback. The optical feedback circuit used an LDV, whereas the electrical Pierce oscillator circuit is shown in the inset.

ppm during a measurement period of 2 hours, whereas the MEMS and quartz optomechanical oscillators show large frequency drifts of ±900 ppm and ±300 ppm respectively.

The much larger Allan deviation of the quartz crystal with optical feedback shows that the stability of the oscillator with optical feedback is much worse than that of the device with electrical feedback. The instability is attributed to drift and phase fluctuations in the optical feedback loop. The laser Doppler vibrometer has a specified signal delay time of 8.9 µs, which was observed by open loop measurements to fluctuate by δt = ±3 ns. The delay fluctuations cause phase fluctuations \( \delta \phi = 2\pi f_0 \delta t \) in the feedback path that are converted into frequency fluctuations by the equation \( 2\delta \omega / \omega = -\delta \phi / Q \) [23]. For the MEMS oscillator this can account for a frequency fluctuations of ±130 ppm. Moreover the velocity decoder has a noise limited resolution of ±0.12 µm/s/√Hz, which is strongly increased by the low reflectivity and roughness of the sample surface. In addition, vibration and other sources of noise in the optical path might play a role. The main conclusion from the quartz oscillator measurements is that the phase noise and Allan deviation of the sensors depends strongly on the feedback circuit. In the next section it is discussed how the pressure resolution of the sensor is related to the Allan deviation and what is the ultimate resolution limit of the MEMS oscillating squeeze-film pressure sensor.

6. Ultimate pressure resolution
The measurement resolution \( \delta p \) of an oscillating pressure sensor with sensitivity \( S \) is related to the oscillators frequency uncertainty by:

\[
\delta p_{\text{res}}(\tau) = \frac{\sigma_f(\tau)}{S}
\]

Where \( \sigma_f(\tau) \) is the standard deviation determined from many frequency measurements each having an averaging time \( \tau \). \( \sigma_\omega = 2\pi \sigma_f \) can be determined from the oscillator’s phase noise.
Figure 8. Closed loop characterization of quartz crystal oscillators. Measured output signal for (a) opto-mechanical oscillator (b) Pierce oscillator using an oscilloscope. (c) shows the pressure dependent output frequency measured using a frequency counter.

spectrum $S_\phi$ [24]:

$$
\sigma^2_\omega(\tau) = \frac{4}{\pi \tau^2} \int_0^{+\infty} S_\phi(\omega) \sin^2(\omega \tau/2) d\omega
$$

Now it is desirable to relate the measured Allan deviation to the pressure resolution. The relation between Allan deviation $\sigma_A(\tau)$ and standard deviation of frequency $\sigma_\omega(\tau)$ depends on the phase noise function $S_\phi$, since the Allan deviation is given by [9]:

$$
\sigma^2_A(\tau) = 2 \left( \frac{2}{\omega_o \tau} \right)^2 \int_0^{+\infty} S_\phi(\omega) \sin^4(\omega \tau/2) d\omega
$$

As a conservative\(^1\) measure, we will use $\sigma_\omega(\tau)/\omega_o = \sigma_A(\tau)$ to convert our measurement data to determine the pressure resolution, such that $\delta p_{res} = \sigma_A(\tau) \omega_o \frac{d\omega}{d\tau}$. This equation is evaluated based on Figure 9 and plotted in Figure 11. As expected, at small $\tau$ it is observed that the

\(^1\) It is found from Equations 6 and 7 that for an oscillator with white frequency noise (such that phase noise follows Leeson’s equation: $S_\phi(\omega) \propto 1/f^2$), it holds that $\sigma_\omega(\tau)/\omega_o = \sigma_A(\tau)/\sqrt{2}$, whereas for white phase noise ($S_\phi(\omega) = \text{const}$), it is found that $\sigma_\omega(\tau)/\omega_o = \sigma_A(\tau)\sqrt{\frac{3}{2\pi}}$. 

Figure 9. Allan deviation as a function of averaging time for the MEMS optomechanical oscillator.

Figure 10. Allan deviation for tuning fork based oscillators vs averaging time.

pressure resolution becomes better if the averaging time is increased. However for times longer than 1 ms the measurement error increases again, probably due to drift in the LDV.

It is of interest to determine the ultimate pressure resolution that could be achieved by the squeeze-film pressure sensor if thermal-mechanical motion (white frequency noise) of the MEMS membrane would be the only noise source. Then the Allan deviation would be given by [25]:

\[ (\sigma_A^{\text{limit}})^2 = \frac{k_B T}{8P_{in}Q^2 \tau} \]  \hspace{1cm} (8)

Since it is a white frequency noise spectrum, the theoretical limit to the pressure resolution
can then be obtained using the equation:

$$
\delta p_{\text{limit}} = \frac{\sigma_A f_0 \ dp}{\sqrt{2} \ df} = \frac{1}{S} \sqrt{\frac{k_B T f_0^2}{16 P_{\text{in}} Q^2 T}}
$$

(9)

Where \( P_{\text{in}} = \frac{1}{2} m v^2 \frac{\omega_0}{Q} \) is the power required to maintain the output signal amplitude at \( \omega_0 \) due to finite \( Q \). \( P_{\text{in}} \) is determined using the velocity \( v \approx 0.1 \text{ m/s} \) measured by the LDV. This equation is evaluated and Figure 11 shows the value of the pressure resolution determined from experiments compared to the theoretical thermal noise limit based on the equations above. Assuming that drift might be eliminated by proper stabilization of the oscillator, the minimum experimental pressure resolution is taken as the minimum of the \( \delta p_{\text{res}}(\tau) \) curve.

Figure 11. Estimated pressure resolution of MEMS opto-mechanical oscillator.

Thus the experimental resolution of the MEMS squeeze-film pressure sensor is determined to be \( \delta p(1 \text{ ms}) = 4.5 \text{ Pa} \). This resolution is close to that of the commercial pressure sensors based on hermetic membranes that achieve pressure resolutions of 2 Pa at 13 ms (Bosch Sensortec BMP280–pierzoresistive [26]) and 2 Pa at 83 ms (Murata electronics–capacitive [27]). Moreover, since the measured resolution is still three orders of magnitude larger than the thermal noise limited resolution of \( 5.4 \times 10^{-3} \text{ Pa} \), there is still a big margin for improving the oscillator feedback loop (Table 3) and hence improving the performance of this oscillating squeeze-film pressure sensor.

7. Discussion and conclusions
A MEMS oscillating squeeze-film pressure sensor has been investigated. In contrast to most conventional pressure sensors, the device operates without requiring a hermetically sealed cavity. The device has a high pressure sensitivity \( S = df/dp = 97 \text{ kHz/bar} \), which is a factor \( 2 \times 10^4 \) higher than that of quartz resonators and comparable to the best resonant pressure sensors reported in literature [28]–[31]. An LDV vibrometer is used for the first time as a feedback element in a MEMS oscillator. The LDV has the advantage of eliminating crosstalk and electrical noise from the actuation circuit, high gain, high input impedance and simple implementation.
In order to study the effect of the feedback mechanisms an oscillating quartz pressure sensor is studied. It is found that optical feedback using the LDV increased the Allan deviation significantly and showed more drift compared to the same crystal operated in a Pierce oscillator circuit. Furthermore, LDV setup is expensive and too big to integrate in consumer applications. For future work, electrical feedback loops are therefore recommended. The best attained pressure resolution of the sensor is 4.5 Pa at an averaging time of 1 ms, which is close to the performance of current commercial sensors as shown in Table 3. Because the pressure resolution is still far from the theoretical limit based on the thermal noise of the membrane, there is much room for further resolution improvement of MEMS oscillating squeeze-film pressure sensors by reducing noise induced by the feedback method.

Table 3. Comparison of pressure sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Resolution</th>
<th>Measurement time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEMS (Optical feedback, this work)</td>
<td>4.5 Pa</td>
<td>1 ms</td>
</tr>
<tr>
<td>MEMS (Theoretical Limit)</td>
<td>$5.4 \times 10^{-3}$ Pa</td>
<td>1 ms</td>
</tr>
<tr>
<td>Quartz (Optical feedback, this work)</td>
<td>1100 Pa</td>
<td>600 ms</td>
</tr>
<tr>
<td>Quartz (Electrical feedback, this work)</td>
<td>440 Pa</td>
<td>100 ms</td>
</tr>
<tr>
<td>Bosch BMP 280 (Piezoresistive)</td>
<td>2 Pa</td>
<td>13 ms</td>
</tr>
<tr>
<td>Murata Oy. (Capacitive)</td>
<td>2 Pa</td>
<td>83 ms</td>
</tr>
</tbody>
</table>

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References


