Highly Sensitive Capacitive Pressure Sensor

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Outline

- Relevant Capacitor Equations
- Current Capacitive Pressure Sensors
- Initial Proposed Sensor Concept
  - Theory
  - Results
- Revised Sensor
  - Results
- Conclusion
Parallel Plate Capacitor

Plate Area (A)

Dielectric thickness (d)

Figure 1: Parallel Plate Capacitor

Deriving Capacitance Equation [7]

\[ V = \int_0^d E \, dz = \int_0^d \frac{\rho}{\varepsilon} \, dz = \frac{\rho d}{\varepsilon} = \frac{Qd}{\varepsilon A} \]  

(1)

V is Voltage  
E is the Electric Field  
\( \varepsilon \) is Permittivity of the Dielectric  
\( \rho \) is the Charge Density  
Q is the Charge  
A is Plate Area  
d is Separation Distance

C is Capacitance  
Q is Charge  
V is Voltage  
\( \varepsilon \) is Permittivity of the Dielectric  
d is Separation Distance  
A is Plate Area

\[ C = \frac{Q}{V} = \frac{Q \varepsilon A}{Qd} = \frac{\varepsilon A}{d} \]  

(2)
Existing Capacitive Pressure Sensors

Advantages:
- Low Temperature Hysteresis
- Low Pressure Hysteresis
- Low Power Consumption

Disadvantages:
- Poor Resolution

Figure 2: Typical Capacitive Pressure Sensor [4]
Inspiration

A golf ball striking steel at 150 mph [5]
Initial Proposed Capacitive Pressure Sensor

Figure 3: Diagram of Proposed Pressure Sensor [2]

Figure 4: Components of Sensor
Input(Pressure) -> Displacement -> Radius -> Wetting Area -> Output(Capacitance)

\[ P_{int} = P_{atm} + \frac{2\gamma}{R} \]  \hspace{1cm} (3)

- \( P_{int} \) is Internal Pressure
- \( P_{atm} \) is Atmospheric Pressure
- \( \gamma \) is Surface Tension (Mercury – 487 dyn/cm)
- \( R \) is Radius of Drop

Figure 5: Pressure vs Displacement for Test Diaphragm

Figure 6: Simplified Diagram of Mercury
Relating Applied Pressure to Change in Internal Pressure

\[ P = P_{\text{int}} - (P_{\text{int}})_0 \]  \hspace{1cm} (4)

Replacing \( P_{\text{int}} \) with (3)

\[ P = P_{\text{atm}} + \frac{2\gamma}{R} - \left( P_{\text{atm}} + \frac{2\gamma}{R_0} \right) = 2\gamma \left( \frac{1}{R} - \frac{1}{R_0} \right) \]  \hspace{1cm} (5)
Wetting Area Equation [2]

\[ A = \pi \left[ \sqrt{\frac{\pi^2 R^2}{16} + \frac{2R_0^3}{3R} - \frac{\pi}{4} R} \right]^2 \]

- \( A \) is Wetting Area
- \( R \) is Radius of Deformed Mercury
- \( R_0 \) is Initial Radius of Mercury

Parallel Plate Capacitor Equation

\[ C = \frac{\epsilon A}{d} \]

- \( C \) is Capacitance
- \( \epsilon \) is Permittivity of the Dielectric
- \( A \) is Plate Area
- \( d \) is Separation Distance
Initial Experimental Results

Figure 7: Sensor Capacitance vs Pressure

Low Pressures: Excellent Agreement
High Pressures (7-10kPa): up to a 7% difference

Dynamic Range: 2500pF
High Sensitivity: 250pF/kPa
Revised Pressure Sensor

Significant Differences:
- Dielectric -
  Thickness: 2mm to 1μm
  Constant: 1,200 to 12,000

- Mercury –
  Drops: 2 to 1
  Drop Diameter: 5mm to 3mm

Figure 8: Revised Pressure Sensor Diagram

Figure 9: Revised Pressure Sensor Physical Assembly
Figure 10: Capacitance vs Pressure

Low Pressures: Excellent Agreement
High Pressures (2-3kPa): about 3% difference

Revised Sensor:
High Dynamic Range!: 6μF
High Sensitivity: 2.24 μF/kPa

First Sensor:
Dynamic Range: 2500pF
High Sensitivity: 250pF/kPa
Effects of Temperature

Equation for Thermal Expansion of Mercury

\[
\frac{\Delta A}{A} = 3\lambda \Delta T
\]

A is the Original Wetting Area
\(\Delta A\) is the Change in Wetting Area
\(\lambda\) is the Expansion Coefficient (Mercury – 9.1x10\(^{-5}\)°C\(^{-1}\))
\(\Delta T\) is the Change in Temperature

Figure 11: Error in Pressure from +10°C to +40°C
Temperature and Pressure Hystereses

Figure 12: Temperature Hysteresis at 3kPa

Varies about 1.5%

Figure 13: Pressure Hysteresis at -10°C

Maximum error < ±0.05%
Figure 14: Recovery Time vs Applied Pressure

Max ~50ms
Significantly Less as Pressure Increases
Table 1: Comparison of New Sensor to Existing Pressure Sensors

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity</th>
<th>Linearity</th>
<th>Pressure Hysteresis</th>
<th>Temperature Hysteresis (For temp. range of -10 °C to +80 °C)</th>
</tr>
</thead>
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<tr>
<td>Piezoresistive</td>
<td>Up to 25 mv/kPa</td>
<td>Generally linear</td>
<td>Up to ±1% FSO</td>
<td>Up to ±2% FSO</td>
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<td>pressure sensors</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Capacitive pressure</td>
<td>Up to 0.2 nF/kPa</td>
<td>Generally non-linear</td>
<td>Up to ±0.1% FSO</td>
<td>Up to ±0.5% FSO</td>
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<td>sensors</td>
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<td></td>
</tr>
<tr>
<td>New sensor</td>
<td>2.24 µF/kPa</td>
<td>Non-linear</td>
<td>Less than ±0.05% FSO</td>
<td>Up to ±1.5% FSO</td>
</tr>
<tr>
<td>(uncompensated)</td>
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Additional Notes:
Dynamic Range: ~6µF
Inductive Pressure Sensor

Figure 15: Diagram of Inductive Pressure Sensor [8]

Figure 16: Components of Inductive Sensor
References


[5] British Broadcasting Corporation


[7] http://hyperphysics.phy-astr.gsu.edu/hbase/electric/pplate.html#c2

Questions