MEMS based pressure sensor for detection of negative pressure wave in subsea pipelines

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Abstract
Design analysis and simulation of a MEMS based capacitive pressure sensor for detection of a negative pressure wave (NPW) has been presented for leak detection in subsea pipelines. A capacitive pressure sensor measures the change in pressure through a calibrated circuit due to displacement of the membrane. Capacitive pressure sensor involves two coupled physics, namely Electrostatics and Solid mechanics. COMSOL Multiphysics was used to simulate the sensor behavior under various conditions. A negative pressure wave, modeled in MATLAB, was imported as an input load to study the change in impedance and its sensitivity to different parameters. The parameters chosen for sensitivity analysis were (a) the material of the capacitor membrane and (b) the gas-filled in the cavity. Simulation study showed that the maximum displacement occurred at the center of the sensor membrane and reduced radially outwards; also a change in the capacitance due to the change in membrane material is also observed. While the same deflection and capacitance was observed when the cavity was filled with air and noble gases, there was improved total capacitance when the cavity was filled with Nitrogen. We conclude that a change in the dielectric material of the cavity and membrane material has a positive effect on the sensitivity of the sensor.

Introduction

Oil and gas industry has one of the largest contributions in the world economy through supply of oil barrels and different gases. These pipelines travel very long distances through deep seas and lands, leakages in these pipelines could cause disastrous consequences as they carry hazardous substances and can cause damages to sea life and also to habitats nearby. Subsea pipelines are designed in such a way to sustain harsh environments.

It is very important to develop a reliable system to detect leakages in these pipelines. When there is a leak in the pipeline there is a sudden change in the density of gas, resulting in creation of a negative pressure wave. This negative pressure wave travels upstream and downstream. Detection of a negative pressure wave by sensors can be used to calculate the location of leak. Detection of negative pressure waves using pressure sensors based on Fiber Bragg Grating (FBG) has been reported in [1]. Rao et al [2] presents design and simulation of MEMS capacitive pressure sensors in harsh environments. Material selection for the design of sensors plays an important part, this has been reported in [3]. Pressure wave behaviour and leak detection has been reported in [4]. In harsh environments like the sea, MEMS based pressure sensors [2] are more reliable than pressure transducers. The work in this paper uses negative pressure waves for an approximate estimation of the location of the leak in a pipeline by improving sensitivity of the MEMS based pressure sensor.

Leak Detection

Figure 1 shows a pipe with two pressure sensors at a distance L. If a leak happens, the negative pressure wave is divided into two damping waves flowing in opposite directions. The amplitude of the damping wave and the time difference between two consecutive peaks can be used to detect the location of the leak.Consider the velocity of the fluid is u and the pressure wave velocity is V: Then,V-u and V+u are the upstream and downstream velocities respectively. Let t_1 (t_2) be the time at which the upstream (downstream) sensor detects pressure change. The location of the leak, x can be derived using equation (1)

$$x = (t_1 - t_2)\frac{V^2-u^2}{2V} + L\frac{V-u}{2V} \qquad (1)$$

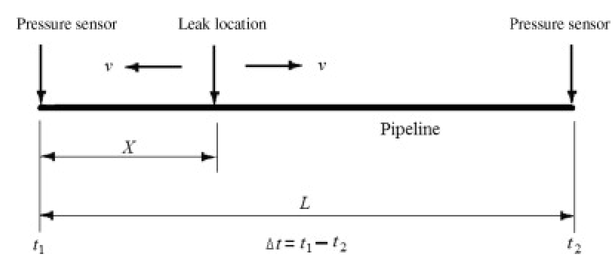

Fig.1 Sketch of the pipe with pressure sensor and leak location

Design Methodology of the Sensor

The sensor uses two capacitors, where one capacitor is fixed and the other is variable, which provides detectable leak. A simple schematic diagram of the MEMS based pressure sensor used is shown in Figure 2. It has a pressure membrane, anchors to hold and clamp the membrane onto the substrate, a cavity, two electrodes, and a dielectric layer. The two electrodes and the dielectric makes one of the capacitors whose capacitance (C_1) is constant (capacitance $C = \mathcal{E}\frac{A}{d}$). Another capacitor results from the membrane, upper electrode and the cavity shown by the air gap, which is a variable capacitor (C_2) as the distance between the plates varies due to change in pressure subjected by the membrane. Using COMSOL multiphysics a parametric study is performed to check the effect of change in the material in the cavity and the change in membrane material on the sensitivity of the sensor. The substrate, membrane, electrodes and dielectric are circular in shape. The cross-sectional view of the model is shown in Figure 3.

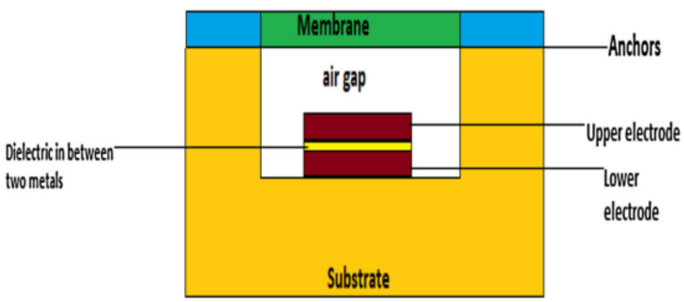

Fig. 2 Schematic diagram of the MEMS sensor

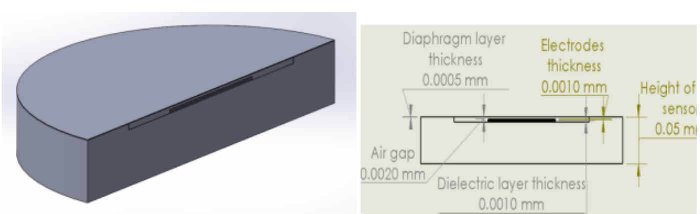

Fig 3. CAD model and its dimensions.

Results and Discussions

The simulation was conducted for coupled electrostatics and solid mechanics simultaneously. A dynamic convergence criteria was used by COMSOL. Applied pressure in the NPW model was 120kPa. Figure 4 shows displacement of the membrane varied from maximum at the center to no displacement as we moved away from the center. With Si_3N_4 dielectric, the capacitance of the fixed capacitor C_1 = (8.85E-12) * (7.5) * (7.85E-09) / (1.00E-05) = 5.21E-14 F. Table 1 and 2 provide displacement and variable capacitance (C_2) for varying cavity gas and membrane material.

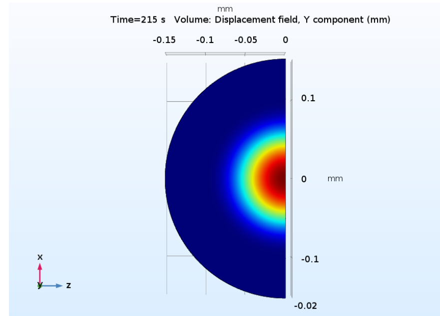

Fig 4. Displacement of the membrane

Table.1 Displacement and Capacitance for different gases

Membrane Material	**Cavity Filled**	**Displacement (m)**	**Capacitance (C_2) F**	**Total Capacitance**
Silicon	Air	7.99E-08	3.62E-14	8.84E-14
Silicon	Nitrogen	8.06E-08	4.16E-14	**9.38E-14**
Silicon	Krypton	7.99E-08	3.62E-14	8.84E-14
Silicon	Argon	7.99E-08	3.62E-14	8.83E-14
Silicon	Helium	7.99E-08	3.62E-14	8.83E-14

Table.2 Displacement and Capacitance for membrane

Membrane Material	**Displacement of membrane(m)**	**Cavity Remaining (m)**	**Variable Capacitance (C_2)(F)**	**Total Capacitance (F)**
Silicon	7.99E-08	1.92E-06	3.62E-14	8.83E-14
Aluminum	1.20E-07	1.88E-06	3.70E-14	**8.91E-14**
Polysilicon	1.10E-07	1.89E-06	3.68E-14	8.89E-14

Conclusion

With silicon membrane and different gases in the cavity, nitrogen provides the highest displacement and capacitance. When the cavity gas is fixed and varying membrane material, aluminum membrane provides better displacement and capacitance thereby increasing sensitivity of the sensor.

References

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