A BIO-INSPIRED SENSOR FOR FLUID MOTION DETECTION

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Abstract

Biological hair fluid motion sensors can be found in a variety of animals such as arachnids, insects, crustaceans, fish, and mammals\(^1,2,3\). These sensors display a wide range of geometrical sizes and dynamical characteristics affecting their sensitivity depending on their purpose. This paper examines a novel capacitance based sensor designed to detect fluid motion. The sensor was experimentally subjected to a variety of input signals to develop a theoretical model of the sensor response.

Introduction

A bio-inspired whisker-like sensor is currently in development for detecting and tracking hydrodynamic wakes. The sensor is based on a harbor seal's recognition of fluid motion by picking up vibrations of its mystacial vibrissae at the base. The ability of the harbor seal to detect minute hydrodynamic signals in water was first documented by Denhardt et al\(^4\). A male harbor seal could detect velocity stimuli generated by a small oscillating sphere. The sight and hearing of the animal were blocked leaving the vibrissae to detect the signal.

The ability of a harbor seal to track the wake of a vehicle in water was first documented by Denhardt et al\(^5\). In this landmark study a blindfolded harbor seal with head phones adapted for acoustical masking was able to detect and accurately track the hydrodynamic wake of a miniature submarine. The submarine was powered along a predetermined straight or curved path for up to 5 s at speeds up to 2 m/s before being turned off and coming to a rest at the bottom of the pool afterwards the seal was able to track the path taken by the submarine with final object detection of close to 80%.

This paper illustrates tests conducted to examine the signal output of the bio-inspired sensor for a variety of input frequencies in order to characterize the sensor. Measurements were also made of the electrical properties of the sensor and compared to theoretical approximations to develop an electronics circuit model of the whisker-like sensor.

Sensor Design

Building from the inspiration found in the harbor seal’s abilities and work by Barbier et al\(^6\) a whisker-like sensor was developed to capture fluid motion.
Whereas the Barbier sensor relied on two circular flat capacitor plates attached to the base of a whisker-like post, the current effort utilizes a cone-in-cone design to capture the fluid motion (Figure 1).

![Diagram](image)

**Figure 2.** Schematic drawings of cone-in-cone sensor showing side and top views. The four quadrants of parallel plate capacitors generate directional information.

A vertical post (whisker) is attached to the base of a cone coated in a silver epoxy followed by a layer of plastic for waterproofing. This cone rests in a hollowed out conical base of slightly larger diameter. The base has four equal quadrants of silver epoxy also coated in a thin plastic layer. The cone with the attached whisker is held in place by a thin layer of polydimethylsiloxane (PDMS), effectively sealing the resulting gap caused by the difference in the two cone diameters. This gap may be filled with any fluid. The opposing metal surfaces create four capacitors (Figure 2). As fluid strikes the post, the force causes the cone to pivot, resulting in a change in the gap between the two cones. This generates a measurable change in the capacitance of the four quadrants providing information on the fluid motion, including direction, striking the sensor. The mechanical response of the sensor has been documented by Stocking et al.\(^7\).

**Capacitance Model**

Each silver epoxy quadrant and the silver epoxy coated cone is an individual capacitor. For the purposes of this paper these capacitors are considered to be parallel plate capacitors. The angle between each of the two plates is small and the gap change due to the difference in cone diameters is negligible to the calculations. Additional parasitic capacitors (labeled \(C_E\)), in series with the gap capacitance (\(C_{\text{Gap}}\)), occur from the plastic waterproofing layers. The resulting circuit for an individual pair of plates is shown in Figure 3. \(R_{\text{Fluid}}\) is the resistance of the dielectric medium filling the gap in the sensor. The gap capacitance and medium resistance change as the sensor deflects, while the edge capacitances remain constant regardless of the surrounding fluid motion.

Following the electrical schematic in Figure 3 and solving for the gain of the circuit results in Equation 1. In this equation \(f\) is frequency, \(Z_L\) is the load impedance, and \(H\) is the gain. Here the fluid resistance is in parallel with the gap capacitance. The parasitic capacitances resulting from the water proofing layers covering the silver epoxy are in series.
with the gap portions. The input signal is placed between the plates at points A and B in Figure 3. The sensor output is measured across the resistance load, \( R_L \).

\[
H(f) = \frac{Z_L(f)}{\frac{2}{j2\pi C_E} + \frac{1}{j2\pi C_{\text{Gap}}} + Z_L(f)} \tag{1}
\]

The capacitance of the gap and edges is calculated using the parallel plate capacitor model, Equation 2. In this equation \( C \) is the capacitance, \( k \) is the relative permittivity of the dielectric, \( \varepsilon \) is the permittivity of space, \( A \) is the area, and \( d \) is the separation distance.

\[
C = \frac{k \varepsilon A}{d} \tag{2}
\]

![Figure 3. Electrical schematic illustrating the additional parasitic capacitances.](image)

**Experimental Setup**

The parasitic capacitances were measured directly by pressing a thin sheet of aluminum directly against the plastic waterproofing layer. The aluminum deformed to create a tight fit against the waterproofing layer. The capacitance was measured with a B & K Precision model 890B handheld capacitance meter capable of measuring in the picofarad range.

The circuit model was examined by placing a sinusoidal input signal with an amplitude of 6.6 V across the capacitor plates. This signal was swept from 1 MHz to 80 MHz using an Agilent Technologies function generator. The output was measured across a 330 ohm resistor load. Both the input signal and output signal were measured on a Techtronix oscilloscope to calculate the gain (output voltage divided by the input voltage). For these experiments the sensor gap was filled with air. Sweeps were conducted for three sensor positions (minimal gap, maximum gap, and neutral) across a single quadrant.

**Results**

The parasitic capacitance was calculated using equation 2. The cone dimensions were measured to be 0.018 m in height and 0.0135 m in diameter. The relative permittivity of the plastic waterproofing was approximated as 2 based on values for similar plastics. The waterproofing layer thickness was approximately 0.0005 m. The resulting theoretical parallel plate capacitance was 84 picofarads. Following the method described in the experimental setup section, the measured capacitance of the waterproof lay was found to range between 70 and 90 picofarads for all quadrants.

Using Equation 1, the theoretical response of the sensor was calculated for a frequency sweep. For these results the parasitic and gap capacitances were calculated using Equation 2. In this case the gap is measured as 0.00274 m. The results are shown in Figure 4. The circuit
model predicts the sensor to be a high pass filter with a single pole.

![Figure 4. Bode plot of predicted sensor gain as a function of input frequency.](image)

Gain was measured for a single quadrant with the sensor in ideal positions. The gap was minimized, maximized, and placed in a neutral position with equal gaps between all quadrants. According to capacitor theory, the gain for each frequency should be largest at the minimized gap position and smallest at the maximized gap sensor position. The gain for a frequency sweep between 1 MHz and 80 MHz is shown in Figure 5. The frequency range was limited by the function generator.

![Figure 5. Bode plot of prototype sensor gain as a function of frequency.](image)

The drop in gain at the higher frequencies (above 65 MHz) is attributed to limitations in the frequency range of the cables used to measure the signal. There was little change in the gain between the neutral position and the minimum gap position. The maximum gap position demonstrated a much larger decrease in gain. This is caused by the inverse relation of distance to capacitance shown in Equation 2.

![Figure 6. Bode plot comparison of](image)

A comparison limiting the frequency of the circuit model to that of the experimental results is shown in Figure 6. The sensor illustrates a similar trend to the theoretical circuit model. Dropping the experimental frequencies above 65 MHz, the sensor shows potential to be a high pass single pole filter as predicted.

**Conclusion**

The bio-inspired sensor prototype can be modeled as a single pole high pass filter. There was good agreement between the theoretical frequency sweep and the experimental results for the sensor gap filled with air. Air was an advantageous medium due to its large resistivity effectively removing issues caused by the parallel resistance in the gap.

The parasitic capacitance closely matched the predicted values. These additional capacitors in series limit the response range of the sensor. Further work is needed to understand the full
impact the waterproofing layers have on the sensor output.

Although the sensor model closely matches the experimental results, it is idealized as a parallel plate capacitor. Due to the proximity of the capacitor plates at the base of the cones further investigation is needed to examine how this may affect the overall sensor performance especially when a fluid with a higher dielectric constant is in the gap.

**Ongoing Work**

This research will continue to investigate the influence of the input signal and fluid in the gap. The effort is focused on finding the optimal input signal and sensor parameters to reduce power consumption and provide adequate sensitivity. Work will focus on removing the parasitic capacitors from the sensor and improving the signal quality.

**References**