A Bio-Inspired Artificial Whisker for Fluid Motion Sensing with Increased Sensitivity and Reliability

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***Abstract*—Biological hair fluid motion sensors are found in a variety of animals such as arachnids and marine mammals. These sensors display a wide range of geometrical sizes and dynamic characteristics affecting their sensitivity. We report design revisions to improve sensitivity, wake detection capabilities, and reliability in a biologically inspired fluid motion/wake detection sensor. The design implements a cone-in-cone capacitance based sensing mechanism for monitoring fluid motion fluctuations in the wake of an object in four directions. The improved sensor design shows a gain range (the difference between peak output voltage amplitude divided by the peak input voltage amplitude) of up to 0.27 between whisker compression and deflection, a 300X increase relative to prior art. Improvements to the sensor include adjusting the deflection measurement modality, increasing the inner cone size, using silver epoxy for plating, shielding signal wires, and reducing parasitic capacitance that dampens the output voltage range.**

I. INTRODUCTION

A number of species have demonstrated an ability to monitor their surroundings by detecting hydrodynamic stimuli independent of acoustic or visual clues. Such a capability has the potential to play an important role in surveillance and tracking applications. These applications require the ability to monitor and track wakes while maintaining operational silence. We turned to biologically inspired designs for signal detection, in particular the vibrissae of harbor seals (Phoca vitulina). Previous work by Denhardt et al. showed that blind-folded, acoustically masked harbor seals are able to use only their whiskers to detect fluid velocities as low as 245 μm/s in the 10-100 Hz range [1]. A following study demonstrated a trained harbor seal's ability to detect and track a hydrodynamic wake even after a delay of up to 20 seconds [2]. Prior work by Barbier et al. demonstrated the feasibility of using a parallel plate capacitance based sensor to measure deflections of an artificial whisker [3]. Stocking et al. built upon the capacitance sensing methodology developing a cone-in-cone based design [4]. Limitations in the signal strength and reliability in the prior art sensor led to design improvements resulting in a 300X increase in signal resolution and improved repeatability. This paper discusses the revisions of the whisker-like sensor, explains the sensor's sensing modality, details the circuit model of the sensor, and presents results illustrating the sensor improvements.

II. PRIOR ART WHISKER SENSOR DESIGN

The ability to sense fluid motion speed and direction is vital to numerous critical tasks. Many animals use specialized hairs and whiskers to detect fluid movements in order to track prey, evade predators, and identify conspecifics. Autonomous underwater vehicles (AUVs) rely on fluid speed measurements to aid in navigation. Many commercial and military applications would benefit from fluid flow information to monitor target movements at sea, to track environmental pollution, and to locate natural resource reserves. The whisker-like sensor captures a combination of directional and speed information in a single device making it useful for many wide-ranging applications.

The artificial whisker sensor from Stocking et al. [4] utilizes a cone-in-cone design, in which the sides of the cones facing each other are plated with copper and sealed with epoxy to create a parallel plate capacitor. This design maximizes the surface area of the capacitor plates to increase signal magnitude, especially when multiple sensors are arrayed around a cylindrical vessel, as well as provides for a more durable sensor construction. The copper plates on the outer cone are divided into four quadrants to provide directional information for the flow, and insulating silicone oil floods the gap to produce a dielectric constant of about two. The metal plating on the base and cone is protected by a thin epoxy layer. In order to provide an appropriate damping and restoring force, the cone-in-cone base is covered by a thin membrane of polydimethylsiloxane (PDMS), approximately 200 μm in thickness. Fabrication of the sensor is further described in Stocking et al. [4].

The prior art sensor suffers from two important problems. First, the output capacitance range as measured in [4] was limited to 9 pF. The limited capacitance measurements were caused in part by the epoxy waterproofing layer generating additional parasitic capacitances in series with the desired sensor capacitance. This layer also failed to protect the copper plates and led to further signal degradation (Fig. 1). The range was also limited by the measurement process. Difficulties

Figure 1. Corrosion of the copper plate due to distilled water seeping through the protective layer in the prior art sensor. Initial (left); after 2 weeks (right).

arose measuring the capacitance alone as a means of monitoring whisker deflections. The signal was small, inconsistent, could not capture frequency information, and could not measure capacitance with other fluids such as water in the sensor gap. Second, the thin wires connecting the sensor to measurement devices were unshielded and prone to electromagnetic noise. The previous results inspired design changes to improve the signal performance by increasing its discriminatory ability and better understanding of the electrical system.

III. Sensor improvements

A. *Improved Whisker Sensor Design*

The limited signal resolution led to several design changes (Fig. 2). The small 9 pF range was difficult to measure accurately in [4]. To improve the signal range over the range of whisker deflection and to resist corrosion, the copper plates were replaced with a layer of the same silver epoxy used on the inner cone. The silver epoxy showed none of the corrosion previously observed on the copper plates. The epoxy waterproof layer on the base was replaced with a layer of commercial grade plastic wrap that was thinner and more uniform in thickness. The waterproofing still creates parasitic series capacitances in the sensor, but the thinner layer increased the value of this parasitic capacitance reduced its dampening effects. The diameter of the inner cone was increased by 5%. This limited the overall distance the whisker could deflect, but increased the surface area of all the capacitor plates resulting in a higher total capacitance.

The inert silicone oil filling the gap was unlikely to match the surrounding fluid in any environment where the sensor may be deployed. This would cause unwanted moments on the whisker based upon the sensor's orientation to gravity, e.g. a sensor with a whisker parallel to the ground would deflect downward and provide skewed results. The PDMS layer separating the gap fluid from the environment and providing

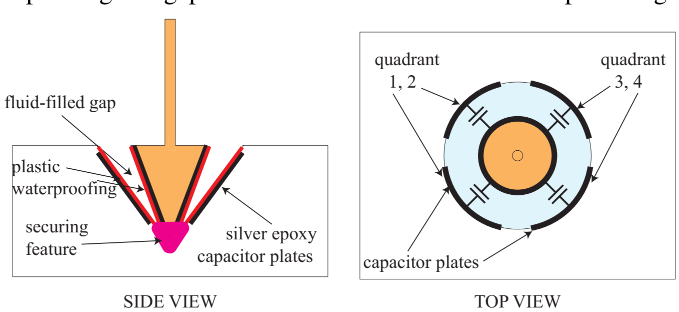

Figure 2. Schematic of improved sensor secured at the base, with larger inner cone, shielded wires, silver plates, and more uniform coating.

to the whisker deflective properties was removed and the whisker cone was held in place by a silicone attachment at the cone tip. This allows the surrounding fluid to fill the gap.

The whisker deflection was previously measured by capacitance. The lack of range, reliability in the results, inability to measure dynamic whisker deflections, and inability to directly measure capacitance in non-inert fluids led to the redesign of the whisker deflection measurement modality. To measure whisker deflection, the whisker cone is excited with a sine wave at a desired frequency, and the output peak-to-peak voltage, corresponding to the whisker's position, is measured across a load resistor. This sine wave sensing modality was used in prior art to measure the capacitance of the sensor directly. The capacitance measurements were limited to a range of 7-16 pF in the silicone oil, a range which is very difficult to sense [4].

Changing the measurement modality helped improve the ability of the sensor to detect whisker deflection. The goal is to maximize the voltage difference detected, with respect to input voltage, between maximum compression and maximum openness to improve sensitivity to whisker position (referred to as gain range) as opposed to the sensor capacitance. A secondary goal is to lower power consumption by choosing the lowest appropriate frequency for the sine wave, which will be generated through the battery-powered backend electronics. Higher frequencies that lead to high output voltages do not necessarily lead to maximum resolution. To identify a new measurement modality and to improve sensing resolution, we developed a model of the sensor's electrical behavior across frequency.

The original sensor design used long, thin wires to connect a capacitance meter to the metal plates. The small diameter prevented the capacitance reading from changing as the wires moved. As the measurement modality changed to a sinusoidal input at high frequencies (>1 MHz), the small unshielded wires acted as antennae. The measured signal would comprise of up 60% electromagnetic interference from the input signal. The wires were replaced with RG-174/U coaxial cable. This reduced the noise observed in the signal output to about 5%. Some interference remains from the unshielded wire between the silver epoxy and coaxial cable (Fig. 3).

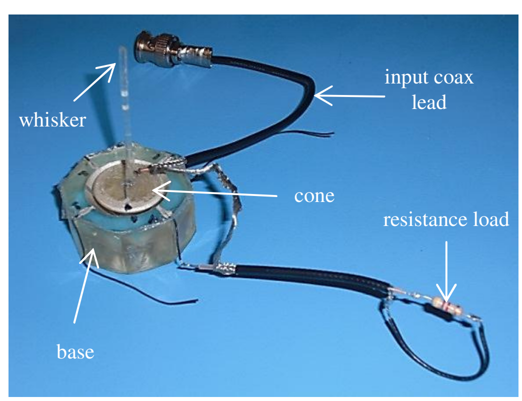

Figure 3. Improved sensor with a resistance load and coaxial cables.

B. Circuit Model

Previous circuit models of the sensor used parallel plate capacitor theory to predict the change in capacitance across the plates as the whisker deflected. The actual capacitor is an inclined plate capacitor conical in shape leading to (1).

$$C_{Air}(\alpha) = \frac{2\pi * \varepsilon_0 * k_{air} * \sin(\alpha) * (b-a)}{\alpha - .5} \quad (1)$$

where k_{air} is the dielectric constant of air, α is the angle of deflection, b is the length of the inner cone, and a is the distance from the inner cone tip to the start of the cone capacitor plate (Fig.4). In a similar manner the total resistance of the fluid in the gap can be calculated from the resistivity (2):

$$R_{Air}(\alpha) = \frac{\rho_{air} * \sin(\alpha - .5)(b-a)}{2\pi * \sin(\alpha) * (b-a)} \quad (2)$$

where ρ_{air} is the resistivity of air.

We use the complete circuit model, shown in Fig. 4, to calculate the gain. The gain is the ratio of the output peak-peak voltage across a load resistor to the peak-peak input voltage applied to the sensor. The transfer function is as follows (3):

$$H(s) = \frac{[(\frac{R_{gap}}{sR_{gap}C_{gap}+1}+R_{wire}+\frac{R_{load}}{sC_{wire}R_{load}+1})^{-1}+sC_{wire})]^{-1}}{R_{wire}+(\frac{R_{gap}}{sR_{gap}C_{gap}+1}+R_{wire}+\frac{R_{load}}{sC_{wire}R_{load}+1})^{-1}+sC_{wire})^{-1}} * \frac{\frac{R_{load}}{sC_{wire}R_{load}+1}}{\frac{R_{gap}}{sR_{gap}C_{gap}+1}+R_{wire}+\frac{R_{load}}{sC_{wire}R_{load}+1}} \quad (3)$$

$$s = j2\pi f \quad (4)$$

where C_{wire} is the wire capacitance, R_{wire} is the wire resistance, C_{cone} is the parasitic cone capacitance from the seal, R_{gap} is the resistance of the medium, C_{gap} is the gap capacitance due to deflection, C_{base} the parasitic capacitance from the base, R_{load} is the load resistance, and f is the frequency. R_{wire} and C_{wire} are added to the model due to the effects of the higher frequency sinusoid.

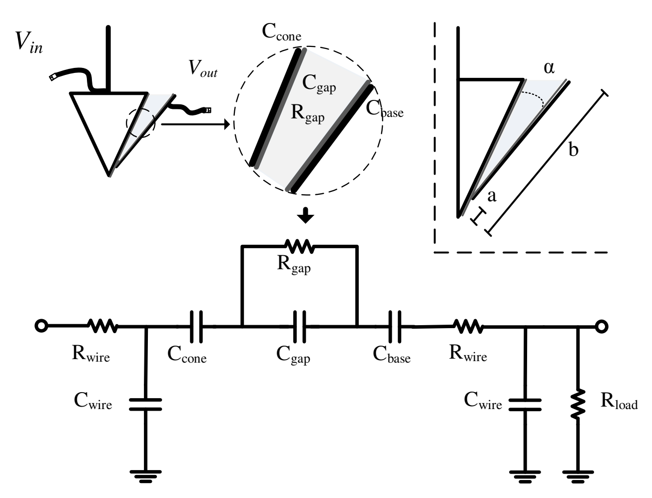

Figure 4. Schematic of the circuit model used to estimate sensor performance.

By computing the gain of the sensor, it becomes possible to predict the range of the sensor output voltage for a given frequency and input signal as the whisker deflects. We chose to use gain for analysis because the input sine wave amplitude changes during testing. The load of the sensor changes as the whisker deflects (changing the gap capacitance and resistance) affecting the amplitude of the input sine wave.

The sensor improvements including the new waterproofing layer, modified cone, and measurement modality improved the sensor resolution and allow for the whisker-like sensor to work in a variety of environments. The coaxial cables limit the noise due to electromagnetic interference. Overall, the new sensor has a resolution improvement of 300X, which is discussed in the next section.

IV. Results

The measured voltage gain range of the prior art sensor and the improved sensor across a frequency range of 10 kHz to 20 MHz is shown in Fig. 5. The gap was filled with silicone oil for each test. The silver epoxy, thinner waterproofing layer, and shielded wires attributed to the significant increase in signal quality and resolution.

The circuit model for the new sensor is in good agreement with the measurements. Results for the gain range with a load resistor of 4.62 kΩ and air in the gap are shown in Fig. 6. The theoretical model is with 25% of the measured values and illustrates matching trends as a function of frequency. The overestimate of the theory may be attributed to some signal loss through the wire connections, electromagnetic interference, and mismatch in values for specific parameters. Similar matching results and trends are observed with silicone oil and distilled water on the sensor gap.

Input frequency and the dielectric constant of the liquid in the gap both affect the gain range. As in Stocking et al. [4], the whisker exhibits properties of a high pass filter. While a higher frequency initially yields a larger gain, it quickly reaches a maximum value. Also, a fluid with a larger dielectric constant in the gap yields a larger capacitance and therefore a higher output gain. However, the gain range of the signal actually has a peak at a much lower dielectric material. The gain range of the improved sensor is illustrated in Fig. 7 for air

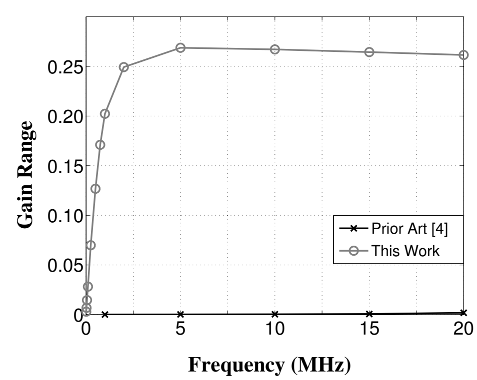

Figure 5. Comparison of the gain range between the prior art sensor and the improved model as a function of frequency with silicone oil in the gap.

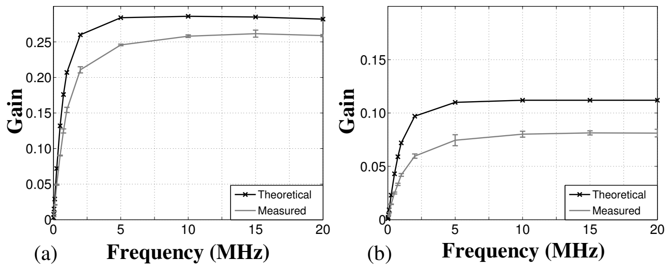

Figure 6. Comparison of gain between the improved sensor and circuit model for a) Compression b) Separation

(dielectric 1), silicone oil (dielectric 2.5), and distilled water (dielectric 80) in the gap. Although distilled water has the highest dielectric (generating the largest gains) the gain range as the sensor deflects is lower than the other two fluids with much lower dielectric constants. Examining the theoretical gain range as a function of dielectric constant for a given frequency and resistivity, shows a peak at a low dielectric constant (Fig. 8). By examining the gain range it becomes apparent that maximizing the capacitance of the sensor will not provide the best resolution.

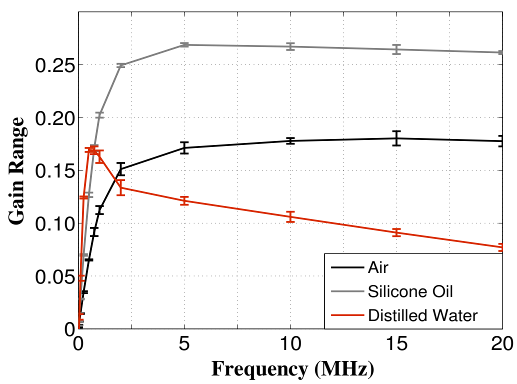

Figure 7. Measured gain range of the improved sensor comparing different fluids in the gap with error bars (5 tests).

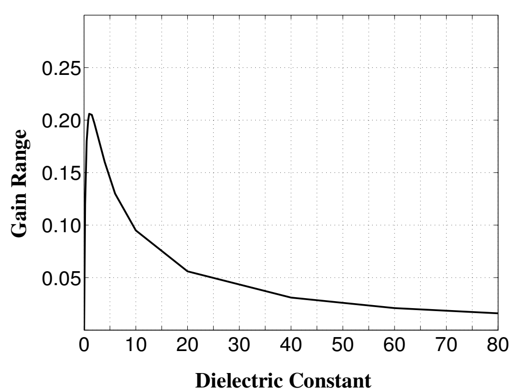

Figure 8. Theoretical gain range of the improved sensor with silicone oil in the gap at 1 MHz as a function of the dielectric constant of the fluid in the sensor

V. Discussion

The improved sensor and measurement modality allow the bio-inspired artificial whisker to be functional in a variety of fluids. The improved design shows a 300X improvement in the gain range as the whisker deflects.

While a higher frequency generates larger gains, the range of the gain actually decreases. This indicates an advantage to using lower frequencies (from 200 kHz to 1 MHz) to conserve power, allow data collection at lower sampling rates, and improve resolution. Although the gain range is smaller in fluids of higher dielectric constants, it still peaks at a low frequency and is easily measurable, which is not possible with prior art.

The circuit model demonstrates reduced output signals in fluids of very low resistivity. In a fluid, such as salt water (0.2 Ω*m), the gain range is severely limited for all frequencies (trend similar to prior art sensor in Fig. 5). The PDMS membrane examined in [4] may provide a solution to low resistivity environments by allowing a separate fluid providing a better gain range to be encapsulated in the sensor gap.

Future improvements to the sensor include creating the capacitor plates with gold to prevent corrosion limiting the signal. This also allows for the removal of the waterproofing layers on the plates. This will remove the unwanted parasitic capacitors and will improve the sensor resolution. The remaining electromagnetic noise will be reduced with the incorporation of SMA connectors for all the capacitor plates. SMA connectors will improve the sensor life and provide easy transition between test loads.

The signal gain and resolution may further be improved by using a load that matches the impedance of the sensor. A load that includes a capacitor may provide increased signal range than a simple resistor load at lower frequencies. The sensor currently behaves as a high pass filter. Transitioning the load to before the artificial whisker may create a low pass filter allowing for a lower frequency input signal further reducing power consumption and data collection.

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