ABSTRACT

This research aims to develop a whisker-like artificial fluid motion sensor capable of detecting both fluid direction and velocity for use in hydrodynamic wake detection and tracking. Our current design utilizes a cone-in-cone capacitive sensing mechanism attached to a 4 cm rigid whisker used to detect and transduce fluid motions. Numerical and finite element modeling of the design demonstrated the feasibility of such a mechanism and predicted capacitive changes of 1-2 pF for flows of up to 1.0 m/s. Experimental characterization of the fabricated whisker showed a significant performance improvement over the predicted behavior. In particular, the typical capacitor quadrant showed a resting signal nearly 6 pF higher than predicted and a range of up to 3 pF. In fact, one quadrant showed a resting capacitance nearly 7 pF higher than predicted and a range of up to 8 pF, owing to its slightly off-center position and thus smaller initial gap size. The experimental validation showed the sensor’s excellent discriminatory ability for both flow direction and magnitude under steady flow conditions.

INTRODUCTION

The ability to identify and track underwater wakes from fluid motion movements is useful for a number of enterprises, from military surveillance and tracking to aquatic bio-monitoring. Current technologies found in a single passive instrument lack or are limited in the combination of directional and velocity information necessary to enable such detection, especially at low fluid speeds.

This paper presents the current progress in our efforts to design, numerically model, fabricate, and experimentally characterize a novel, multi-directional fluid motion sensor utilizing capacitive measurements. The inspiration for our sensor comes from evolutionarily derived fluid motion sensors found in nature, in particular the harbor seal (Phoca vitulina). Using a 'go/no-go’ testing paradigm, Dehnhardt et al. showed that blind-folded and acoustically masked harbor seals are able to discriminate fluid velocities as low as 245 µm/s in the 10-100 Hz range using only their whiskers.3 In a follow-up study, Dehnhardt et al. then successfully trained a blind-folded harbor seal to identify and track the wake generated by a propeller-driven miniature submarine again using only its whiskers.4 The seal was able to successfully locate the submarine in 78.5% of the trials, even with search onset delays of up to 20 s.

Previous work in our lab by Barbier et al. demonstrated the feasibility of using parallel-plate capacitors as a mechanism for sensing deflections of an artificial whisker under exposure to a jet of air.5 For velocities at the nozzle tip of 22 m/s at a distance of 6.5 cm from the exposed whisker, Barbier was able to positively detect the motion and able to correlate the signal generated with the direction of the incoming flow. Building on these previous studies and the previous work accomplished in our lab, we aim to produce an artificial whisker sensor with a novel capacitive design and exhibiting improved performance characteristics.

METHODS

Investigations into the feasibility and performance of our artificial sensor took place in two phases: a preliminary design and numerical modeling of the expected drag forces, resultant whisker deflection, and generated capacitance changes, followed by an experimental characterization of the actual performance of the fabricated whisker. Outlined below are the equations and methods employed in both phases of the project.

A. Design

In designing our current sensor, we drew inspiration from the geometries and dimensions not only of harbor seal whiskers, but also from the fluid motion-sensing spider hairs known as trichobothria, which previous research has shown to be extremely sensitive to very small deviations in air flow and which have been extensively modeled mathematically.4,5 Considering the salient features of these models, in particular the length-to-diameter (L/d) ratios ranging from 20-100 and a characteristic length of seal whiskers ranging from 4-10 cm, we decided on an initial whisker length of 4 cm and diameter of 2 mm, yielding an L/d ratio of 20.

Additionally, given the previous work in our laboratory using capacitive-based sensors, we chose to use a similar, yet modified, sensing mechanism to capture and transduce the whisker deflections. In particular, our older designs utilized two circular flat plates attached at the base of the artificial whisker, which created a
delicate connection point and a limited surface area for generating capacitive signal.

For our new sensor, we modified the base structure so that the whisker now embeds firmly in a cone-in-cone design, in which the sides of the cones facing each other are metallically plated to create a parallel plate capacitor. The plates are divided into four quadrants in order to provide directional information for the flow, and an insulating silicone oil floods the gap to produce a dielectric constant of about 2.5. In order to provide an appropriate damping and restoring force, the cones are topped with a thin membrane of custom-fabricated polydimethylsiloxane (PDMS), approximately 200 µm in thickness. This design enables us to maximize the surface area of the capacitor plates to increase signal magnitude as well as provides for a more durable sensor construction (see Figure 1).

Unlike the flexible and intricately shaped seal whiskers and spider trichobothria, our sensor employs a smooth, rigid cylinder as the whisker in order to simplify the numerical modeling and reduce the amount of complexity to be accounted for in understanding the sensor performance. Future iterations may incorporate flexible, non-uniformly shaped whisker sections as our research into the characteristics of actual seal whiskers continues and can inform our design process.

B. Numerical Modeling

The starting point for our numerical analysis was to determine the expected range of fluid velocities to which we planned to expose our artificial whisker. Though harbor seals are able to swim up to 5 m/s while tracking prey, our experimental characterization of the sensor is ultimately limited by the maximum speed of our laboratory’s water tunnel, approximately 1 m/s. Due to this limitation we confined the range of our investigation to fluid velocities between 0.1–1.0 m/s; however, we expect the sensor’s performance to be readily scalable to larger velocities for future prototypes.

In order to calculate the drag force experienced by the sensor’s exposed artificial whisker section, we utilized the standard drag equation

$$F_d = \frac{1}{2} \rho v^2 A C_d$$  \hspace{1cm} (1)

where $\rho$ is the fluid density (approximately 995.6 kg/m$^3$ for water at 30°C), $v$ is the fluid velocity, $A$ is the exposed whisker area (80 mm$^2$ in our design), and $C_d$ is the coefficient of drag (1.15 for a typical cylinder). Having determined the total drag force for the length of the whisker, this sum was approximated as a point force at the whisker tip using a balance of torque approach. This assisted in simplifying further numerical modeling and for force testing during the experimental validation phase. For the initial modeling and testing, we considered only steady flows past the whisker, leaving investigations into dynamic, oscillatory flows to be completed once the steady flow condition had been well characterized.

Once the expected range of forces had been calculated, these values enabled us to perform a finite element analysis (FEA) of the entire structure using the designed geometries and calculated forces as appropriate boundary conditions. Using commercially available FEA software from ANSYS Inc., the structural response of the sensor was modeled for three flow regimes: 0.1 m/s, 0.5 m/s, and 1.0 m/s. In each condition, the resulting angular deflection of the whisker and the change in gap size between the two plates of the capacitor were calculated. The changes in gap size of the capacitor produce a corresponding change in the capacitive output signal, which can be modeled using the standard equation for capacitance

$$C = \epsilon \kappa \frac{A}{d}$$  \hspace{1cm} (2)

where $\epsilon$ is the permittivity of free space ($8.85 \times 10^{-12}$ F/m), $\kappa$ is the dielectric constant of the silicone oil (approximately 2.5), $A$ is the exposed plate area ($1.93 \times 10^{-4}$ m$^2$), and $d$ is the gap distance (initially at 1.5 mm).

Combining the FEA modeling results with the capacitance results, we are able to map the given steady flow field to an expected capacitance value, and when combined with the information from each of the four
quadrants, this should provide us with enough data to determine the flow velocity and direction from a single sensor.

C. Experimental Validation

Upon completion of the design process and the numerical modeling of the sensor response to steady flows, we submitted our design to our manufacturing partner Mikro Systems Inc. of Charlottesville, VA, who completed the fabrication of the first generation prototype. Mikro Systems’ proprietary photolithography techniques and precision manufacturing capabilities enabled us to build a sensor with much greater exactness than would have been possible in our laboratory. Figure 2 provides photographs of the finished sensor.

Experimental characterization of the sensor utilized a custom built force rig that enabled us to apply sub-millinewton forces over prescribed distances with micron-level resolution. The rig has a linear actuator (Zaber Technologies, model T-NA08A25) attached to a translation stage (Zaber Technologies, model TSB28-M) on which the sensor is mounted. The tip of the sensor’s whisker is positioned to align with the tip of a force gauge (Mark-10, model BG012), and the capacitive read out from the sensor is measured by a capacitance meter (BK Precision, model 890B) attached to the sensor’s leads (see Figure 3).

In order to simulate steady flows past the whisker, the linear actuator was systematically driven by steps of approximately 240 microns. After each step, the resulting force on the whisker tip as displayed on the force gauge and the capacitance as displayed on the capacitance meter were recorded. In this manner, we were able to characterize a range of forces up to the expected maximum of 0.02N by determining the associated displacement and capacitance output at each step. These experimental results were then compared to the numerical results to determine the accuracy of our modeling and the performance of the sensor.

RESULTS

From the numerical modeling phase of our project, we were able to determine the expected drag forces on the whisker tip, the whisker angular deflection with its associated gap change, and the capacitive output for a range of fluid velocities up to 1.0 m/s. In addition to a baseline condition of no flow, three flow velocities (0.1 m/s, 0.5 m/s, and 1.0 m/s) and their resulting impact on the sensor were calculated. These results are summarized in Table I.

Though the drag forces varied significantly with the different flow conditions, we see that the FEA analysis shows a minimal change in gap size and angular deflection, resulting in rather small changes in capacitance from the sensor. This limitation is due to the error in estimating the stiffness of the PDMS membrane that covered the cones. The analysis was
Fluid flow (m/s) | Drag force (mN) | Gap size (mm) | Angular Deflect. (°) | Capacitance (pF)
--- | --- | --- | --- | ---
0.0 | 0.00 | 1.500 | 0.0 | 2.848
0.1 | 0.12 | 1.498 | 0.009 | 2.852
0.5 | 2.85 | 1.462 | 0.243 | 2.922
1.0 | 22.9 | 1.193 | 1.956 | 3.581

Table I. Summary of numerical modeling results for expected flow regimes. Drag force and capacitance values are calculated from equations 1 and 2, respectively, and the change in gap size and angular deflection are calculated via ANSYS finite element analysis software.

performed using the manufacturer’s standards for Young’s modulus, but our membrane was modified to reduce its stiffness significantly. Currently tensile testing is underway to obtain a more accurate measure of the membrane stiffness, which will improve the accuracy of the modeling, but these preliminary results still provide a good indication of the picofarad (pF) level of capacitive output that we expect.

Upon fabrication of the sensor, we proceeded to characterize the capacitive output for each of the four quadrants under both compression and separation for a range of forces up to 0.0229 N. To achieve a range of forces on the whisker tip, the actuator was driven stepwise in 240 micron increments until the force gauge registered a load of 0.0229 N. At each step, the force and capacitance were recorded, and these results are presented in Figure 4.

The graphs indicate that quadrants 1, 2, and 4 all exhibited very similar behavior—starting with a resting capacitance of between 7-8 pF and rising to a peak of 9.5-10.5 pF under maximum loading conditions. Quadrant 3 showed a significantly larger range of capacitive signal for the same loads, which was a result of the inner cone being positioned slightly off-center. This resulted in quadrant 3 starting with a much smaller initial gap size (thus explaining the slightly higher 8.5 pF resting capacitance) and decreasing in size more quickly. This result helps to inform our suggestions for future revisions to the sensor design.

Figure 5 illustrates the results of separation testing for three of the four quadrants. Quadrants 2, 3, and 4 exhibit similar responses, but quadrants 2 and 4 show a smaller range of roughly 0.5-1.0 pF. Quadrant 3 again shows a higher resting signal due to its smaller initial gap size and thus a greater range of almost 2.0 pF.

![Capacitance as a function of applied force for quadrant 1 during compression](image1)

![Capacitance as a function of applied force for quadrant 2 during compression](image2)

![Capacitance as a function of applied force for quadrant 3 during compression](image3)

![Capacitance as a function of applied force for quadrant 4 during compression](image4)

Figure 4. Results of capacitive output for each of the four capacitor quadrants under compression. Note the scale change on the y-axis of quadrant 3, which exhibited a much greater range of response for the same loads. This was due to the inner cone being seated slightly off-center and starting at a closer position to the outer cone than the other quadrants.
Figure 5. Results of capacitive output for three of the four capacitor quadrants under separation. Note again the higher resting capacitance for quadrant 3 and the greater range in response. Quadrant 1 testing is still in progress.

The smaller range during separation versus compression is likely due to the capacitor plates reaching a point of separation that essentially mimics the plates being entirely separated. The residual capacitance is generated by the individual plates and the bulky leads. Presently, testing is underway to finish the characterization of quadrant 1, as well as to characterize all four quadrants during compression at 45° off-center to generate more information about directional flow.

DISCUSSION AND CONCLUSIONS

The artificial whisker-like sensor that we designed, numerically modeled, and experimentally characterized for steady flow conditions performed remarkably well for a first-generation prototype. Considerable work remains to be done in fully characterizing this sensor, in particular off-angle loading conditions need to be completed, followed by testing of the sensor in our lab’s water tunnel in order to compare its performance in air to its intended hydrodynamic performance.

The current design shows very good performance in discriminating different loading conditions, especially given the small magnitude of the forces being applied—an accomplishment that presented challenges to previously developed sensors. Unfortunately the range of capacitive output is still very small, on the order of a few picofarads, which leaves the sensor vulnerable to significant interference from noise. However, future iterations of the sensor will be modified to include a higher dielectric material in the capacitor gap and a smaller initial gap size, which should allow us to generate a much larger capacitance signal and a much larger range of signals for the same small forces.

Additionally, current research in our lab into the mechanical characteristics of a variety of seal whiskers will enable us to alter the design of the exposed whisker section of the sensor, potentially to include a flexible, non-uniformly shaped design that is better suited to detect eddy shedding and more sensitive in transmitting fluid motion to the capacitive sensor at the base. And finally, numerical and experimental characterizations of dynamic, oscillatory flows, which include a virtual mass component due to changes in acceleration, need to be completed. These flow regimes more closely resemble the types of conditions found in nature, and being able to successfully detect and identify these fluid motions will be invaluable to the sensor’s ultimate performance and utility.

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