# Piezoresistive Chopped Carbon Fiber Rubber Silicone Sensors for Shedding Frequency Detection in Alternating Vortex Streets

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***Abstract*—In nature, fish use sensory input to feel and adapt to flow conditions. Creating solutions that mimic these capabilities need flexible and sensitive sensor solutions. In this paper we use readily available carbon fibers as a conductive filler in a rubber silicone matrix to create a piezoresistive material, capable of sensitively gathering frequency information of small, repeatedly, applied forces. The material is easily cast into a flexible hydrofoil and suspended in two alternating vortex streets flowing at 0.04m/s and 0.1m/s. The gathered data is used to examine the shedding frequency of the vortex streets where the sensors are able to detect frequencies in proximity to the expected frequencies of the flow conditions.**

***Keywords—Piezoresistive composite pressure sensor; Soft Sensor; Flow Sensing; Carbon Fiber;***

## I. Introduction

Kármán gating is the effect where fish in flows are able to stay semi stationary behind objects which shed vortices in an alternating pattern with minimal muscular input [1], [2]. While even inanimate fish bodies are able to generate propulsive efficiencies greater than 100% when suspended in alternating Kármán vortex streets corresponding to their size in lab conditions [3], in nature, fish feel water flow and vortices along their bodies through hair cells along their lateral lines [4] and are able to dynamically adapt to the flow conditions they are in through muscular output. Naturally, understanding and recreating this effect in engineered solutions becomes a challenge in terms of both sensory input [5]–[7], data analysis [8], [9], and actuation [10]–[12], where the latter two cannot come without the first. The most fundamental sensory inputs needed is arguably the shedding frequency of the vortex street, detecting the presence of an alternating vortex street, and detecting the body's position in the sequence of flow changes. Most of these can be approximated by measuring pressure changes along the fish body [8].

Fish-like propulsion systems share many of the same challenges as those found in wearable technologies, soft robotics, and e-skins, in that solutions need to be able to sense small external stimuli as well as flex and move. Typically, the solutions often involve conductive polymer composites (CPCs), as they can be designed to hold a multitude of electromechanical properties as well as material properties to fit different purposes. While flexible pressure sensors can be either capacitive, piezoelectric, or piezoresistive, piezoresistive properties of CPCs are frequently investigated for sensing of external stimuli. Arguably due to their simple fabrication and structure, low energy consumption, easy read-out, and broad detection range [13]. These piezoresistive composites typically consist of a dielectric flexible matrix with some conductive filler dispersed into them, and in recent years carbon based fillers such as Carbon Nano Tubes (CNT) [14], [15], Carbon black (CB) [16], [17] and graphene [18], [19] have shown impressive properties in terms of sensitivity, gauge factors, and ease to cast to desired shapes and flexibilities. While the composites can also achieve extreme gauge factors [16], [20] cost of materials and need of careful handling might make them less desirable for implementation in low budget and rapid prototyping projects. Combating this, it has been shown that introducing chopped carbon fibers (CCF) along with CNT in sensor materials might yield similar sensor properties while greatly reducing production cost [21]. Similar to CNT, CB, and graphene, carbon fibers show piezoresistive properties that can be used to create sensors on their own [22]–[24]. Despite low purchase price, high availability, and easy handling CCF still seems like a less popular filler choice for soft sensor production. This might be due to their high non-linearity in resistance change [25]. In this paper we will look at the characteristics of a CCF rubber silicone composite and how it might be used for data acquisition for an adaptive hydrofoil in a Kármán street.

## II. Carbon Fibre Silicone Composites.

The mechanical structure of CCF fillers in dielectric rubber silicone forms conductive paths where one filament meets another. Deformation of the material leads to reconfiguration of conductive paths within the composite [25] and changes in resistance for sufficient deformations. As carbon fibers themselves show a variation of piezoresistive properties with both positive and negative gauge factors [22], tuning resulting sensor properties of CCF rubber silicone composites is not necessarily straight forward. In this paper we have chosen to retrospectively confirm that the sensors meet our needs, rather than pre-designing the desired properties of the sensors.

In a master's project an adaptive hydrofoil was made, meant to adapt and utilize vortices in a Kármán street. The flexible body and skin of the foil created a need for flexible wiring and sensor solutions. In order to make conductive silicone for use in the foil, 4wt.% TC35 3K (Tairyfil, Formosa Plastics) cut with shears to rough lengths of 5-10mm were mixed and cast in an

Ecoflex 00-30 (Smooth-On, Inc.) rubber silicone matrix. Upon investigation it was found that the resulting material's resistance would greatly fluctuate when sudden, but small, external forces were applied (e.g. vibrations from road work outside the lab). To further investigate the effect, the material was cut to a 6x15x15mm block for testing. The material sample was placed in a Hounsfield Tensiometer stretch bench suspended vertically and with an additional electronic 1kg load cell and an amplifier (HX711) to read it. The sample was connected to a 2200Ohm voltage divider through needles acting as electrodes inserted through the sample 10mm apart, perpendicular to the direction of applied deformation. The needles were inserted all the way through the material to ensure good connection with the conductive fibers. The electrodes were connected to the voltage divider through 10µm thin copper insulated wires to minimize movement of the electrodes during testing. A cyclic deformation of half revolutions at the drive wheel of the tensiometer, translating to 0.042mm deformation of the sample was applied by hand to minimize mechanical vibrations. The resulting changes in resistance can be seen in Fig. 1.

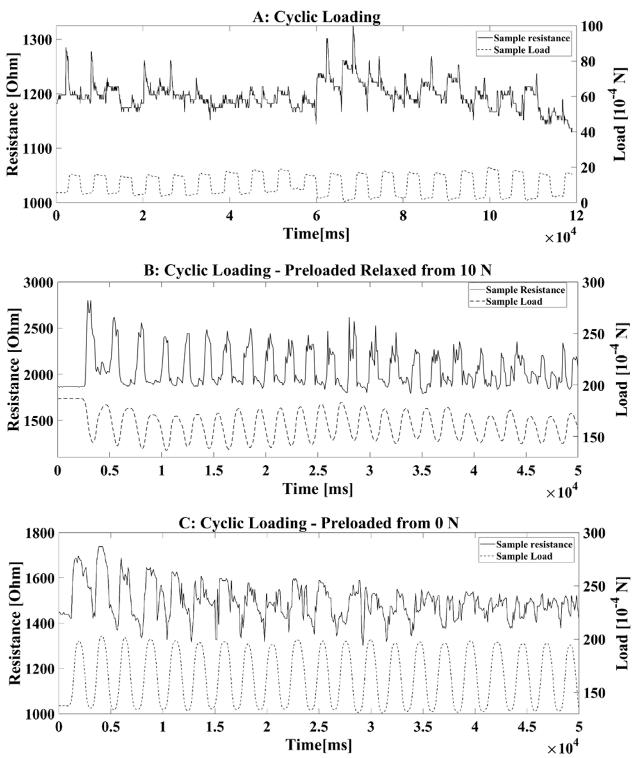


Fig. 1. Resistance change as cyclic deformations of 42µm are applied to test sample. **A:** Stretch bench is run until load cell register it as touching the sample with 0.005N of force. The sample is compressed over one second, rested for two, relaxed over one and then rested for two repeatedly. **B:** The sample is brought deformed under a higher load of 10N before being relaxed to 0.15N after settling for two minutes the sample is relaxed and compressed 42µm in two second intervals. **C:** The sample is brought from a non-compressed state to a preload of 0.14N and compressed and relaxed 42µm in two second intervals.

When no preload was applied to the sample in Fig. 1. A, deforming the sample resulted in fluctuating changes in the resistance with high noise to signal ratio, applying some preload as in Fig. 1. C resulted in more stable changes to the resistance, perhaps due to forming a more even contact surface between the flexible sensor material and load applying surface when pre-deformed against each other, that closely follow the load of the sample with a positive gauge factor (distance between electrodes is elongated as sample is compressed due to orientation). When preloading the sample to a higher load as in fig. 1. B and relaxing it to the same preload as in fig.1 C we get a similar change in resistance that follows the load, but with a negative gauge factor. Both resistance change tendencies for B and C seem to decrease as the sample is repeatedly deformed, which previous research hypothesize to be caused by either microcracking, rearrangement of conductive paths or bending of the fibers causing piezoelectric effects [26]. It is clear from the plots that the piezoresistive behavior of the material is not linear, and while some of this, such as additional peaks of increased resistance as the material is being unloaded, might be correlated to Poisson's effect [27] or tunneling [28], making a model for correlating the sensor readings to actual pressure is not novel. We do however see a good response to sudden changes in pressure. We performed a simple drop of a weight on the table below which the stretch bench is suspended to indicatively illustrate this effect. The stretch bench was not in direct contact with the table but suspended from an additional table on top of the first one as to loosely decouple and dampen it from the surroundings. A small weight of 33g was repeatedly dropped from a height of 50mm at a distance of 1m from the sample every 4 seconds. The resulting resistance changes can be seen in Fig. 2.

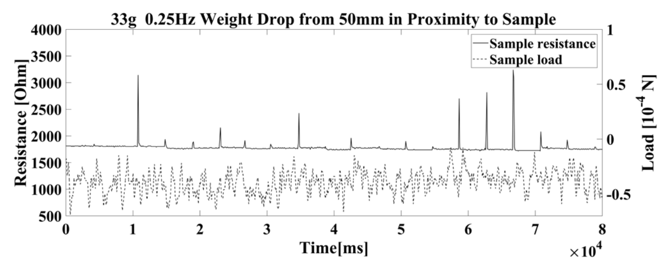


Fig. 2. Peaks of increasing resitance as a weight is dropped on a wooden table top in proximity to the sample every four seconds. The non-uniform weight shape might explain the differeces in resistance change as the weight disperses its energy differently depending on its orientation upon impact.

For the drop test we see clearly visible peaks of increased resistance when the sudden forces were applied, and the frequency of the drops can be easily deduced from the data. A similar use in an adaptive hydrofoil in a Kármán street might enable a simple way to include sensing of shedding frequencies, as well as orienting the foil in the vortex street.

## III. SHEDDING FREQUENCY DETECTION

To test the applicability of CCF Rubber silicone composite material for detection of shedding frequencies, a foil was cast with 8 by 8 10x10x6mm sensors and can be seen in Fig. 3. The sensors were connected with conductive threads which were sewn into the foil with spirals to enable flexing in the longitudinal direction. Copper tape was used as electrodes in the non-flexing direction. Two 16-channel multiplexers (CD74HC4067) enabled reading of the sensors to a single analog pin on an Arduino UNO but limited the reading speed to 10 Hz. The foil was placed in a purpose built water tunnel [29] and calibrated over a 5 minute period with no turbulence generating obstacles in a 0.04m/s flow. The resulting maximum and minimum values for each sensor were saved and used to normalize the sensor readings during further sampling. A vortex generating D-shaped cylinder with a diameter of 30mm was introduced to generate a Kármán street in the water tunnel. Data was sampled in 200 second intervals at 10Hz for two flow speeds of 0.04m/s and 0.1m/s. The shedding frequencies were observed by generating a hydrogen bubble sheet and were found to be 0.58Hz and 1.5Hz respectively.

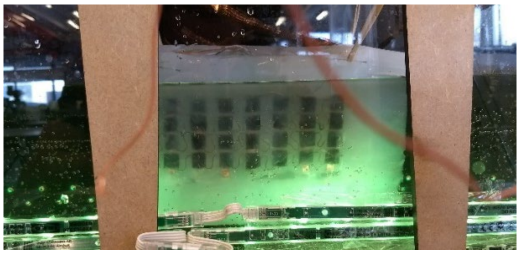

Fig. 3. Wing with integrated sensors in water tunel.

## IV. Results

To interpret the gathered data, we performed a power spectral density (PSD) analysis (FFT and Welch method) of the data from a single sensor located at the third column from the leading edge and third row down on the port side of the foil. The resulting plot can be seen in Fig. 4.

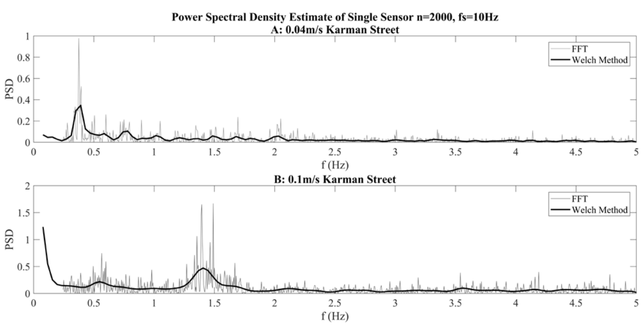


Fig. 4. Power spectral density analysis of single sensor. The shedding frequency for A was observed to be 0.58Hz, while the shedding frequency for B was observed to be 1.5Hz. Peaks in both plots are in proximity to their expected shedding frequency.

## V. Discussion

Most PSD analysis for sensors along the first three columns from the leading edge revealed similar plots as the one in Fig. 4. with frequency peaks at around 0.4Hz and 1.4Hz. While both flow scenarios show clear peaks in the proximity of the true shedding frequencies, the sensed frequency of alternating pressure on the sensor is slightly lower in both cases. Sensors further back on the foil showed little correlation to shedding frequencies, as the flows were altered due to high cross-sectional reduction and turbulence generated along the foil body in the narrow water tunnel. The reduced frequencies might also be due to similar effects as the ones above, or issues with sampling frequencies, as the mean sampling frequency over the period was used rather than time stamped data, we might also be seeing the shift towards lower frequencies due to the effect previously mentioned where during unloading of the material, and decrease in resistance, an additional peak of increased resistance is observed where for linear behavior one would expect it to keep decreasing.

While there are still issues in using CCF rubber silicone composites for reliable pressure sensing, we have seen that it is possible to use these types of sensors for integrating frequency detection of repeated low force impacts. The CCFs comes at a negligible cost as compared to that of the flexible polymer matrix and can quickly be prototyped and integrated for testing in projects where polymer casting is already involved.

Although there might be piezoresistive material solutions that offer far better sensor performance in terms of gauge factor, noise, overshooting, linearity, and so forth, the use of readily available materials might make this a low threshold entry point into piezoresistive flexible sensor technology. In further research, we wish to investigate how we can further tune these sensors through varying material properties, external and internal structure, and composition, to gather more reliable data that can be used for dynamic adaption of hydrofoils in the flow as well investigating the applicability of such materials in other fields.

## VI. Conclusion

A piezoresistive composite consisting of CCF and rubber silicone was developed and some data of the piezoresistive behavior of the material under deformation has been presented. Embedding the material into an adaptive hydrofoil is shown to enable sensing of shedding frequencies along the foil body when suspended in an alternating vortex street. The piezoresistive material enabled a low threshold solution for detecting frequency of repeatedly applied impacts of low magnitude and might be applicable in similar sensor cases were precise pressure read-outs are not needed.

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