First results of a Soft, 3D-Printed, Resistive Cantilever Flow Sensor

Alexander Dijkshoorn, Jiahao Cui, Stefano Stramigioli, Gijs Krijnen
Robotics and Mechatronics Group, University of Twente, Enschede, the Netherlands
a.p.dijkshoorn@utwente.nl

Abstract—This paper introduces the fabrication and characterization of a soft, 3D-printed, resistive cantilever flow sensor, inspired by nature. The sensor has a wider end, to increase drag, and a thin bending section with differential resistive strain gauges. Wind tunnel tests show the operation of the sensor. The relation between tip displacement and resistance change is experimentally determined, as well as the dynamic properties. Finally the sensor is demonstrated in a feedback-loop to control the flow of a propeller. The sensor shows potential for future use, e.g. in micro aerial vehicles (MAV’s). However, first non-linearities and underdamping of the sensor have to be addressed.

Index Terms—3D-printing, Fused Deposition Modeling, cantilever, flow sensing, soft

I. INTRODUCTION

Cantilever-shaped mechanosensors are ubiquitous in nature, where they have multiple sensing purposes, such as flow and tactile sensing [1], [2]. These natural sensory organs have their qualities distributed in both geometry and material properties, allowing for a wide range of functions [3]. They are also a source of inspiration [4] for improving sensitivity, noise level and frequency response of bio-inspired sensing [1], [2].

One area which can greatly benefit from advancements in bio-inspired flow sensing is the field of micro aerial vehicles (MAV), where distributed flow sensor arrays could provide flow information to benefit the operation of the MAV’s [5], [6]. Especially for the complex field of flapping wing robotics, the authors expect that flow sensing is essential for improved flight performance [7].

Multi-material 3D-printing is a technique that holds potential for the fabrication of embedded sensors [8]. Therefore, in this research the authors want to investigate the possibility to 3D-print cantilever sensors for flow sensing, with the potential to be embedded in wing structures, reducing cost and assembly time while at the same time easily reducing packaging constraints.

Several examples of 3D-printed flow sensors and cantilever-based sensors can already be found in literature, where most 3D-printed flow sensors use a resistive transducer. A soft, fully 3D-printed flow sensor is presented by Al-Rubaiai et al. using resistive sensing with flexible materials [9]. Their design is difficult to use in MAV’s due to the doubly-clamped geometry. 3D-printed moulds are also used for fabrication of flow sensors, showing good results for flow sensing, however adding more complex and costly fabrication steps [10], [11]. Noteworthy examples of fully 3D-printed whisker-inspired cantilever-sensors are sensors for vortex detection in water [12], tactile sensing [13] and arrays tuned to measure specific frequencies [14], all using resistive sensing. No accounts of a fully 3D-printed, cantilever-shaped flow-sensor have been found by the authors.

This work presents the fabrication and characterization of the first fully 3D-printed cantilever flow sensor. The principles of its operation are presented, followed by an explanation of the used fabrication methods and experimental methods. Finally the experimental results are presented and discussed.

II. SENSING PRINCIPLE

The sensor uses a strain-based sensing principle analogous to nature, where the drag force induced by the flow deforms the cantilever, causing an electrical impulse at the base as described in [5], [10]. In this research the strain at the base is measured through the change of the electrical resistance of embedded strain sensors.

![Sensor Concept](image)

**Fig. 1.** A. The cantilever flow sensor concept showing a thin, flexible part with embedded strain sensor for bending under drag force and a stiff, wide plate, sticking out of the boundary layer, for increased drag. B. The dimensions of the different sections are: rigid plate (24 x 16 x 2 mm); flexible beam (10 x 10 x 0.9 mm); bottom part for clamping and contacting (22 x 7 x 0.9 mm).

In both nature and engineering the sensitivity of cantilever-shaped sensors is sometimes improved by increasing the cross-sectional area of the cantilever, because this increases the drag force exerted on the cantilever [1], [4]. In this research the end of the cantilever consists of a wider, stiffer section, sticking out of the boundary layer for increased drag, figure 1A.

For small drag-induced deformations this type of sensor can achieve an approximately linear relation between resistance change and strain (apart from material non-linearities) [15]. The drag force is given by equation 1, where \( \rho_{\infty} \) represents...
the free stream air density, \( C_D \) the drag coefficient, \( A \) the cross-sectional area and \( V_\infty \) the free stream velocity [16]:

\[
F_{\text{drag}} = \frac{1}{2} \rho_\infty C_D AV_\infty^2
\]

Therefore, a quadratic relation \( \Delta R/R \propto V^2_\infty \) is expected between the resistance change and the flow velocity.

### III. Methodology

#### A. Sensor Design

The sensor design is shown in figure 1B. The sensor consists of a thick, large plate of \( 24 \times 16 \times 1.2 \) mm; a thin, flexible beam of \( 10 \times 10 \times 0.9 \) mm; and a clamping section with contact pads of \( 22 \times 7 \times 0.9 \) mm.

A soft material (Young’s modulus of \( 10 \times 10^3 \) Pa to \( 10 \times 10^9 \) Pa [17]) is required for obtaining soft, flexible sensors. It is shown by Al-Rubaiai et al. that a combination of thermoplastic polyurethane with and without electrically conductive filler can be used for printing of soft, flexible flow sensors with strain gauges. These materials do suffer from a non-linear response [18]: viscoelasticity, hysteresis and creep [19]. Therefore, differential sensing with strain gauges on both sides is applied to obtain a more linear response and to remove common disturbances like temperature-dependence [15]. A Wheatstone half-bridge is used for this to measure the differential voltage.

#### B. Fabrication

The sensors are fabricated with Fused Deposition Modeling (FDM) for its low-cost and multi-material capabilities [20]. The sensor is printed with the Diabase H-series multi-material 3D-printer, printing with a layer thickness of \( 150 \) \( \mu \)m with repeatable results. It consists of two layers for each strain gauge and the dielectric. The plate has eight layers. As conductive material TPU filament filled with carbon black, called PI-ETPU 85-700+ from Palmiga Innovation, is used [21] and as dielectric Ninjaflex TPU filament from Ninjatek [22]. Silver paint (Electrolube SCP26G) is applied on the contact pads to improve electrical connection. The final sensor can be seen on the right in figure 1B. The resistances of the strain gauges are approximately \( 13 \) k\( \Omega \) (top side) and \( 18 \) k\( \Omega \) (bottom side), where the difference occurs since the first printed layer has different properties than the succeeding layers [19].

#### C. Measurement Set-ups

Several measurement set-ups are used to characterize the sensor properties:

- **Displacement-resistance relation:** The sensor tip is displaced with a linear actuator (SMAC LCA25-050-15F) while the resistance change is measured with a digital oscilloscope (Picoscope 5443B) (the used set-up is similar to that of Kosmas et al. [19]).
- **Dynamic measurement:** The sensor is excited with an electromagnetic shaker (MB Dynamics PM50A Shaker) sweeping over a frequency range of 1 Hz to 200 Hz, while the resistance is measured. The Q-factor can be determined from \( Q = \frac{f_r}{\Delta f} \), with \( f_r \) the resonance frequency and \( \Delta f \) the peak width at half maximum.

- **Measurements with a constant flow and a step-wise increase and decrease of flow from \( 0 \) m/s to 10 m/s are performed in a wind tunnel (Aerolab EWT [23]).**

### D. Control Demonstration & Simulations

As a first step towards an application in MAV’s, the sensor is demonstrated in a feedback-loop with a drone propeller to control a constant flow velocity. A schematic of the set-up is shown in figure 2. The resistance is measured with two half-bridges with a microcontroller (Arduino Uno) with an additional ADC (DFRobot ADS1115), connected to Simulink real-time. The sensor signal is filtered with a low-pass filter with 32 rad s\(^{-1}\) cut-off frequency. A drone motor (MK3638 Mikrokopter) and propeller (13 inch diameter) are controlled through a motor controller linked to Simulink.

![Fig. 2. The set-up used for the control demonstration with the sensor.](image)

The control set-up is simulated using the same Simulink control code, describing the sensor with a fit from the wind tunnel measurement and the resonance frequency and Q-factor from the dynamical measurement data. A relation between input and flow velocity from the propeller is measured with an anemometer (Techno Line EA-3010) at the sensor position. Furthermore the sampling of the microcontroller is included and a simplified delay between motor and sensor of 0.2 s for a flow setpoint of 5 m/s\(^{-1}\) with the sensor at 0.1 m distance.

### IV. Results

Results from the tip displacement measurement show non-linear behaviour with both an upward shift of the signal over time, due to creep, as well as hysteresis, Figure 3. However, as an approximation for later use, a linear fit can be made.

Figure 4 shows the results from the dynamic measurement. From this data a resonance frequency of 21.3 Hz and a Q-factor of 4.4 are determined, which can be used to describe the sensor as a second order system.

Figure 5 shows the wind tunnel measurement for constant flow (top graph), indeed showing a relation close to \( \Delta R/R \propto V^2_\infty \). For large flow velocities, the sensor started oscillating, which likely indicates fluid-structure interaction [24].
first increasing and then decreasing the flow velocity (bottom graph), hysteresis can be observed in the measurement. Figure 5 indicates 3% resistance change at 10 m s^{-1}, which is 1.5 times higher than for the 3D-printed sensors in [9], but around 15 times lower than for the moulded sensors in [11].

In figure 6 the experimental and simulation results from the control demonstration are presented on the top. The average flow velocity quickly arrives at the set-point but then oscillates around it due to the combination of the delay from the setup and the underdamping of the sensor, the simulations show the same behaviour. To solve the oscillations, the sensor signal is filtered with a low-pass filter cut-off of 0.5 Hz to take out the sensor dynamics, giving a more stable but slower result for both the experiment and simulation in 6 at the bottom.

V. DISCUSSION AND CONCLUSIONS

In conclusion, for the first time a soft, cantilever flow sensor has been 3D-printed and characterized. The sensor is mechanically tested, showing hysteresis and creep as well as a large Q-factor of 4.4. Wind tunnel experiments demonstrate its functionality and approximately show an expected proportionality between resistance and squared flow velocity. In a control demonstration the underdamping of the sensor in combination with a delay in the system causes oscillations around the setpoint. This was solved by filtering out the sensor dynamics from the sensor signal. All-in-all 3D-printing of soft, cantilever flow sensors shows potential for flow sensing. However, first the non-linearities and underdamping of the sensor have to be addressed.

In future research the sensor will be designed with a lower Q-factor to improve the flow-control. The fluid-structure interaction will be considered in the redesign. Furthermore we will investigate benefits of linearisation for the hysteresis [19] and the improved sensor will be tested in an MAV application.

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