This is a peer-reviewed, accepted author manuscript of the following conference paper: Martinelli, S, Reid, A, Domingo-Roca, R & Windmill, JFC 2023, Additive manufacturing of an insect bio-inspired hair acoustic sensor. in 2023 IEEE SENSORS Proceedings. Proceedings of IEEE Sensors, IEEE, Piscataway, NJ, IEEE Sensors 2023, Vienna, Austria, 29/10/23. https://doi.org/10.1109/SENSORS56945.2023.10324858

Additive Manufacturing of an Insect Bio-inspired Hair Acoustic Sensor

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Abstract— **Nature surrounds us with many bizarre and inspirational mechanisms. Insects are miniature organisms that can have exceptionally efficient and functional sensory receptors. Acoustic and air flow mechanoreceptors, commonly called trichoid sensilla or trichobothria, are used in different shapes and sizes by several insect species. The goal of this work is to develop hair-like sensor structures inspired by the *Barathra brassicae* caterpillar and adult *Buthus occitanus* scorpion. An early version of the sensor has been developed and realised using additive manufacturing. Mechanical analysis shows that the sensor design can be altered to move at different frequencies by changing its structure. Early development to convert mechanical displacement into an electric signal has begun and an electric response is recorded, albeit signal conditioning is required to be usable.**

Keywords— bioinspired, insect, sensor, additive manufacturing, trichoid sensilla

I. INTRODUCTION

Nature has been a significant inspiration for human technological development in past centuries. Countless sensing methodologies have been inspired by the way sensory mechanisms occur in nature. In the past century, thorough biological studies on insects allowed a better understanding of how their different acoustic sensory systems work [1]. Albeit much work still needs to be done, the way insect mechanoreceptors function has been described by several authors [2-9]. One of these fascinating structures, the hair shaped Trichoid Sensilla (TS), also known as trichobothria, allows insects to sense and react to airflow and low frequency, near field sound. Moreover, it is speculated that from this structure other sensing mechanisms are derived [10, 11]. From a change in the hair structure insects sense odors, temperature, acceleration, touch, and utilize gyroscope-like mechanisms [5, 10-12].

This paper describes the use of digital light processing (DLP) additive manufacturing (AM) to create a novel sensor inspired by the TS of adult *Buthus occitanus* scorpions [4], which have a flattened hair (instead of rod-like) structures and are not hinged at the basal area. The aim of this work is to develop a sensor that responds to different frequency bands based on the dimensions of the hair structure.

Similar sensors have been previously produced using silicon based microelectromechanical systems (MEMS) techniques by taking inspiration from the cerci of the crickets [13-19]. However, the use of AM for sensor production promises faster and less wasteful prototyping compared to conventional sensor fabrication techniques. Additionally, it also provides the opportunity to integrate arrays of sensors within a single structure and adapt it to different shapes and materials.

The future goal of the work is to use arrays of different iterations of the described sensor, where each iteration reacts to different frequencies. This would allow frequency content measurement without using digital processing techniques. This could make the system consume less power, have low latency, and low data overhead.

II. METHODOLOGY

The sensors were designed with the computer-aided design (CAD) software Shapr3D and 3D-printed via an ASIGA MAX X27 DLP 3D printer. Two different materials were used for the realisation of the sensor. The structure of the hair sensor is shown in Fig. 1a. The hair and body are 3D-printed using two materials to emulate the difference in stiffness shown by hair structures in nature: lower stiffness at the basal area and higher for the hair shaft [20, 21]. This maximizes mechanical energy transmission: the hair deflects the mechanical energy to the nervous tissue to generate a signal, instead of losing it while bending [21].

The hair structure was printed using Formlabs's Grey Resin (V4) and the rest of the structure is 3D-printed using a poly(ethylene glycol) diacrylate (PEGDA) based resin, with photoinitiator phenylbis (2,4,6-trimethylbenzoyl) phosphine oxide (Irgacure 819, 1% w/w) and photoblocker orange dye Sudan I (S1, 0.2% w/w). PEGDA, Irgacure 819 and S1 were purchased from SigmaAldrich, used as delivered. The solution was sonicated in an ultrasonic bath (Clifton SW3H) for 30 minutes prior to use. Once the sensors were 3D-printed, they were cleaned in isopropanol for 1 minute to remove resin residues. Before conducting the experiments, the sensors were left to rest for at least 2 days.

The mechanical response of the sensors was investigated using a Polytec MSA-100 3D-Laser Doppler Vibrometer (LDV). A loudspeaker (Visaton WS 17 E) was held by a flexible articulating arm from a platform separated from the one where the LDV was situated. The speaker was positioned at ~13 cm from the sensor, producing a periodic chirp generated by the LDV internal function generator at 10 V, and amplified by a Onkyo A-9010 amplifier. A reference signal was acquired by using Brüel & Kjær 4138-A-015 microphone and Brüel & Kjær WH-3219 amplifier, positioned 13 cm from the speaker (Fig. 2). The LDV

This work is funded by the Defence Science and Technology Laboratory (DSTL), United Kingdom.

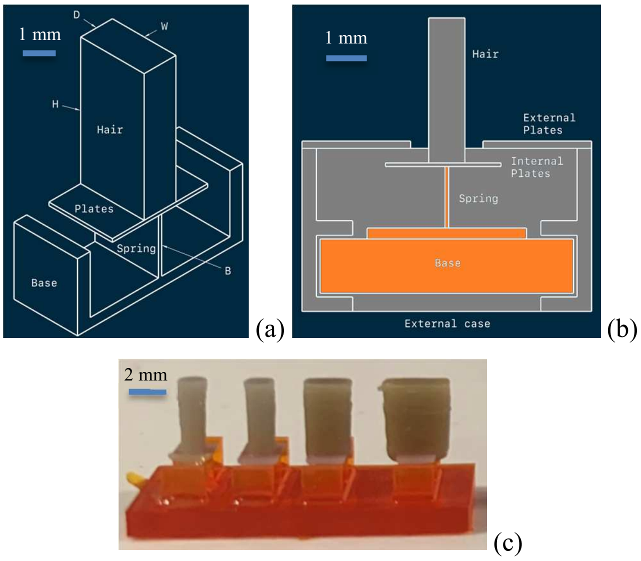

Fig. 1 : (a) Basic structure of the hair sensor used for mechanical testing. (b) Proposed final version of the hair in 2D, to allow for mechanical displacement to electric signal conversion. The external case with plates is printed separately and slid in around the sensor structure. (c) Structure used for shape comparison.

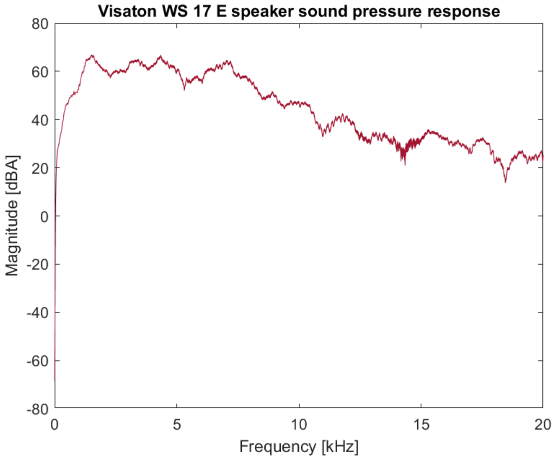

Fig. 2: Visaton WS17 E sound pressure response of the periodic chirp used to test the sensors acquired by a microphone.

acquisition is done in FFT mode with an averaging complex value of 5, 1600 FFT lines and a rectangular window. The multipoint scans were done using a point density of ~0.48 points/mm in both X and Y axes.

The sensor structures are named after their dimensions in millimeters; Height, ***H***, Width (squared hair), ***W***, Depth/Thickness (squared hair) or Diameter (cylindrical hair), ***D***, and Base/Spring Height, ***B***.

III. RESULTS

A. Mechanical Response

The following results represent the displacement obtained through the LDV by testing of the sensor's mechanical response to a periodic chirp from 50 Hz to 2 kHz. Three different experiments were made on the mechanical structure and for this, three different structures were produced inspired by different shapes found in nature. The first experiment, **Shape Comparison**, was made to understand the response of the sensor to different hair shapes (Fig. 3). On the same base four different sensors were 3D-printed, one cylindrical, ***H4D1***, and three squared, ***H4W1D1***, ***H4W2D1*** and ***H4W3D1***. A base height ***B1.7*** was used for all hairs. The cylindrical hair and its nearest squared version (***W1D1***) have a similar response, albeit they have slightly different resonant frequencies (360 Hz and 330 Hz, respectively). For the squared hairs the wider the hair the lower the resonant frequency and the higher the displacement. For smaller hairs, the displacement of the resonant frequency is equal to other structural noise; this might compromise the conversion of the mechanical displacement into an electrical signal.

The second experiment, **Spring/Base Height Comparison**, was conducted to determine the effect of different spring heights on the sensor's response. The same hair (***H4W3D1***) was 3D-printed on bases with five different heights, ***B1.7***, ***B1.5***, ***B1.3***, ***B1.0*** and ***B0.5***. The results (Fig. 4) indicate that for a lower spring height there is a lower displacement at the tip and a higher resonant frequency. Moreover, for higher springs, the band of frequencies at which the hair produces cantilever-like movements is narrower. The cantilever-like movement of the ***B0.5*** sensor is the region comprehended from 580 Hz to 1250 Hz, while for the ***B1.7*** sensor it was recorded from 150 Hz to 200 Hz.

The third experiment, **Hair Size Comparison**, investigated the sensor's response when changing sensor height and depth/thickness, while having the same width and spring height (***W3B1.7***). Six different sensors were tested, a combination of three different heights ***H5***, ***H4*** and ***H3***, and two different thicknesses ***D1*** and ***D0.5***. The results (Fig. 5) showed that the higher the hair the higher the displacement and the lower the resonant frequency. An interesting observation is the fact that by halving the thickness of the hair, the frequency response resembled the one of the next 1 mm shorter hair with 1 mm thickness, but with higher displacement (see ***H5D0.5*** compared to ***H4D1*** and ***H4D0.5*** compared to ***H3D1***).

Fig. 6 shows the ***H4W3D1B1.7*** sensor response from the previous experiments in one plot to investigate the reproducibility of the sensor. The resonant frequency and displacement are comparable, but with small differences. These discrepancies may depend on some or a combination of the following factors. **Time of experiment after printing**, the polymerization reaction continues after printing, changing its material properties [22]. Further study is needed to understand the time taken by the sensor to settle its response. **Cross-contamination** between the two different materials when changing the trays while printing, this can be improved by cleaning the tray and support between tray changes. **Time of immersion in isopropanol**, in our past experiments it was ascertained that longer immersion times made the sensor brittle. Timing consistency between each print is fundamental to decrease inconsistency. **Misalignment of the tray**, when changing tray in our early work it was noticed that, in some instances, the plate and the hair were not properly aligned to the spring as per design. More attention from the operator when inserting the resin trays can reduce this issue. **Slight variation in light intensity in DLP** might occur while

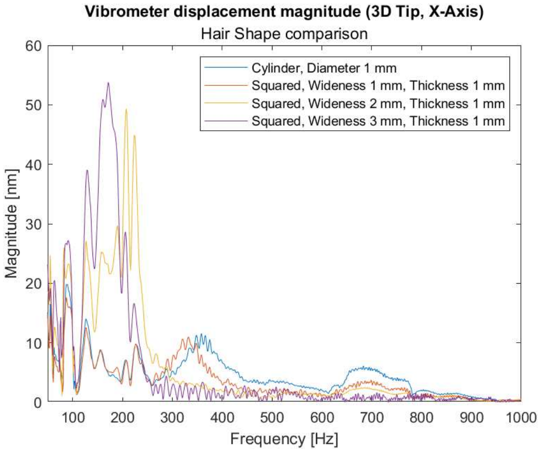

Fig. 3: Displacement magnitude collected by the 3D LDV at the tip of the hair. Only X-axis displacement shown (parallel to the speaker). Results for same spring height (1.7 mm) and different hair shapes.

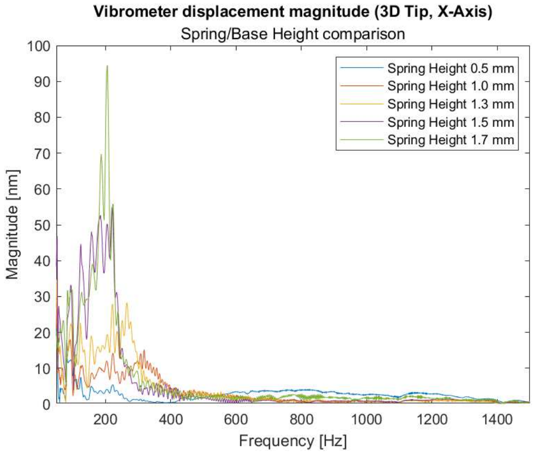

Fig. 4: Displacement magnitude collected by the 3D LDV at the tip of the hair. Only X-axis displacement shown (parallel to the speaker). Results for same hair structure (Height 4 mm, Width 3 mm, Thickness 1 mm) and different spring/base heights.

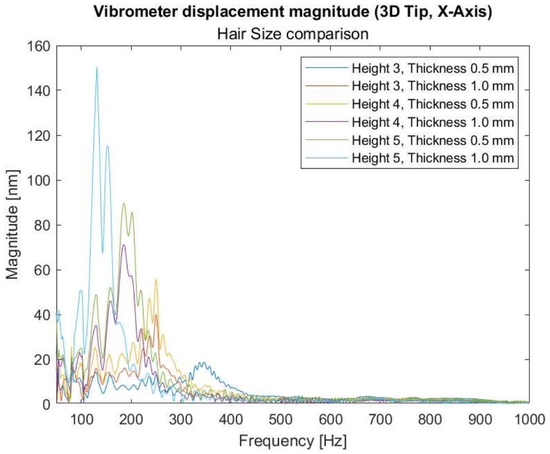

Fig. 5: Displacement magnitude collected by the 3D LDV at the tip of the hair. Only X-axis displacement shown (parallel to the speaker). Results for same hair width (3 mm) and spring height (1.7 mm) and different hair height and thickness.

printing, this can slightly affect the sample's properties and it is outside user control. **Dimensional variations** might occur during the printing process, these might be mitigated by a better selection of the print parameters.

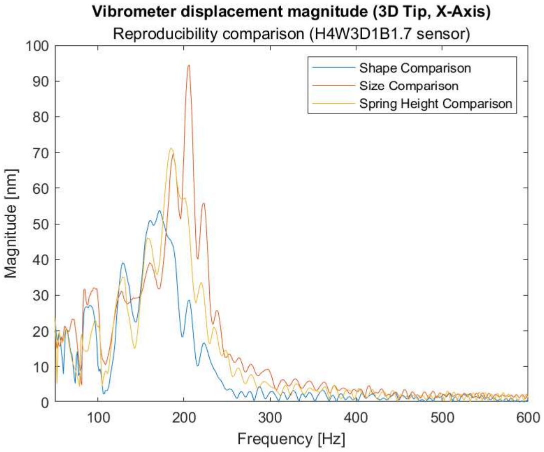

Fig. 6: Displacement magnitude collected by the 3D LDV at the tip of the hair (X-axis) for the ***H4W3D1B1.7*** (Height 4 mm, Width 3 mm, Thickness 1 mm, Spring Height 1.7 mm) sensor from the comparison experiments.

B. *Electrical Signal*

To make the sensor conductive, the upper side of the internal plate and the bottom side of the external ones (Fig. 1b) were hand painted with Agar Scientific's Quick Drying Silver Paint (G302). The purpose is to turn the two sides into capacitive plates. To improve precision, future iterations will instead use a deposition system, similarly to [23]. In a similar setting to the one used for the LDV experiments an electric signal was acquired through an oscilloscope. Nevertheless, conditioning is required for it to be usable.

C. *Design Optimization*

Numerical models based on insects' hair have been developed and they could be used for development of artificial hair sensors [6, 24-26]. Nevertheless, they require an accurate measurement of the torsional stiffness to work. Finite element analysis (FEA) can be useful for this task, but appropriate settings for the simulation are needed. Once a numerical method has been developed optimization techniques can be included to optimize displacement and help designing higher frequency operation [27, 28].

IV. CONCLUSIONS

The aim of this work was to develop a bio-inspired hair-like acoustic sensor fabricated via AM that can react to different frequency bands. This objective was achieved on the mechanical side as shown in Fig. 3-Fig. 6, albeit with room for improvement. Fabrication of the sensor using two different materials to mimic insect hair-like structures was successful and provided a satisfactory response. Meanwhile, appropriate structural changes provide designs with different frequency responses, from 170 Hz to 1.2 kHz. The next step was to convert the mechanical displacement of the hair to an electric signal. In the early experiments, an electric response was recorded but conditioning is required to properly acquire it. Improvements in manufacturing have been stated. Further work will include the development of a tool to aid in the design of the sensor and conversion of the mechanical displacement into an electric signal. Once this is accomplished the sensor structures can be tailored to specific applications providing low-power, low-latency, and low-data overhead system capabilities.

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