

Detection of the Oscillation of a Magnetic Artificial Cilium using an Electromagnetic Pickup

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Summary:

Inspired by biological cilia used for nutrient transport, locomotion or sensing, researchers fabricated artificial counterparts that are supposed to perform equivalent tasks. Previous studies have primarily focused on the ability of an artificial cilium regarding fluid transport. In contrast, our study focuses on the sensing ability, and in a first step, the oscillation modes and the associated resonance properties were investigated. Magnetizable artificial cilia were devised and fabricated using poly(dimethylsiloxane) enriched with Iron(II,III) oxide nanoparticles. The resulting composite material simultaneously features elasticity and magnetic properties and thus, the movement of the cilium can be evaluated using an electromagnetic pickup. Experiments show a decreasing oscillation frequency with increasing distance between pickup and cilium which converges towards 5 Hz at large distances. By using digital image processing, the natural frequency of the cilium without interaction with a magnetic field was evaluated to be 5.29 Hz and matches the data obtained by simulation and calculation.

Keywords: Magnetic artificial cilia, PDMS mould technology, Composite material, Electromagnetic pickup, bioinspired

Introduction

Thin, hair-like structures (cilia), found in a variety of biological organisms, are used for nutrient transport, locomotion, or sensing [1]. Inspired by these structures, researchers fabricated artificial cilia that mimic the behaviour of the biological counterparts. In previous studies, active motion [2], [3] and sensing ability [4] of these bioinspired structures have been investigated in isolation, with focus on motile artificial cilia. Motile as well as passive cilia rely on the change in motion based on fluidic parameters or changes regarding the actuation [5]. The characterization of the motion of cilia is crucial for further processing regarding the aforementioned applications. Active cilia, which are typically actuated using an external magnetic field as well as electric forces, light or pneumatics [1], optical approaches like digital image processing [3] are used, while passive cilia can consist of an integrated structure resembling a resistive strain gauge [4]. For the fabrication of artificial cilia, lithography processes [2], [3], template-based processes [4] and template-free processes [6] are of greater interest. This work focuses on the sensing ability of a magnetizable artificial cilium and, in a first step, the characterization of its movement and resonance properties. The artificial cilium is fabricated using a mould-based process and evaluated using an electromagnetic pickup device, similar to the pickup of an electric guitar.

Fabrication Process

In a mould-based process, the cilia are made out of poly(dimethylsiloxane) (PDMS – SYLGARD™ 184 Silicon Elastomer Kit) enriched with Iron(II,III) oxide (Fe_3O_4) nanoparticles (50 nm) from Sigma Aldrich in a mass concentration of 10:1. The combined use simultaneously enables elasticity and introduces magnetic properties. The nanoparticles and PDMS base are mixed for 5 min after which the curing agent is added followed by another 5 min mixing period. After degassing the mixture in vacuum, it is filled into an aluminium mould. An additional degassing step ensures air bubble free fabrication after curing at 100°C for 2 h and cooling down to room temperature.



Fig. 1 Cilium ($d = 1$ mm, $l = 35$ mm) fabricated in a mould-based approach.

Experimental Setup

The sensing setup combines the use of an electromagnetic pickup, consisting of a custom-wound coil with 1500 turns utilizing a neodymium (NdFeB) magnet as a core, and a camera to

track mechanical displacement via digital image processing. The cilium ($d = 1$ mm, $l = 35$ mm, see Fig. 1) is attached to an XYZ-stage (THORLABS components), which is primarily used to vary the distance between the tip of the cilium and the pickup's pole piece and adjust slight XY-mismatches. The electromagnetic pickup is used to measure the oscillation of the cilium based on electromagnetic induction inside the coil. The induced voltage is amplified by about 94 dB and monitored using an oscilloscope. To actuate the cilium, compressed air directed at its tip is used, ensuring mechanical displacement followed by an oscillation until the cilium is back in the initial position. The resulting measurement setup is depicted in Fig. 2.

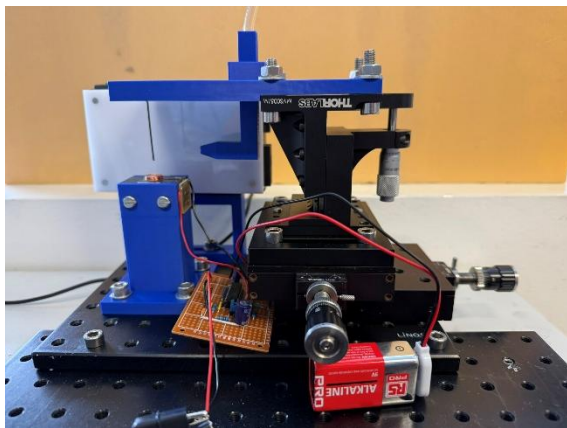


Fig. 2 Setup to measure the movement of the magnetic artificial cilium using a guitar pickup.

Results and Discussion

The oscillation of the artificial cilium for different distances between the tip of the cilium and the surface of the pickup's pole piece was measured where the determined oscillation frequencies are depicted in Fig. 3. With increasing distance between cilium tip and pickup, the resonance frequency decreases approaching 5 Hz. Observations show that the pickup affects the mode shapes of the oscillation. When considering the cilium as a Euler-Bernoulli beam, the cilium approximately operates in a clamped-clamped configuration for distances below $z = 4.5$ mm, where the attraction force of the pickup is high, while for larger distances, the cilium's configuration resembles that of a clamped-free beam. Besides the determination of the oscillation frequency from the pickup's signal, the natural frequency of the cilium without interaction with the pickup is obtained using digital image processing and is given by $f_r = 5.29 \pm 0.12$ Hz. This value approximately corresponds to the calculated first natural frequency of an Euler-Bernoulli beam in a clamped-free configuration [7].

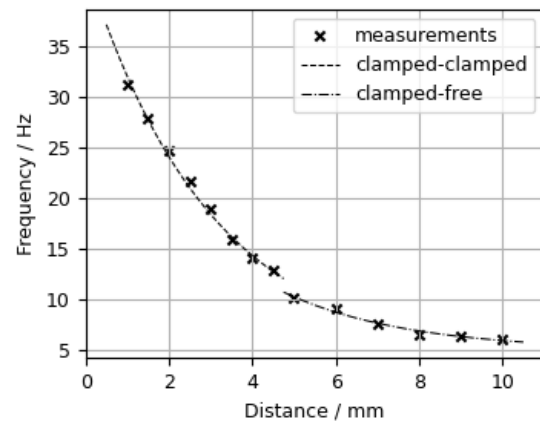


Fig. 3 Oscillation frequency of the cilium versus distance between the tip of the cilium and the pickup's pole piece.

Outlook

The work shows that the detection of the oscillation of a magnetic artificial cilium using an electromagnetic pickup is possible even for large distances of $z = 10$ mm, with the oscillation frequency being off resonance. In a next step, the size of the magnetic artificial cilium will be reduced and the concentration of the nanoparticles inside the PDMS material will be varied. Stimulation of the cilium by using a varying external magnetic field to evaluate its active sensing properties is planned.

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