A Self-Powered Magneto-Acoustic Tracking Transducer

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Abstract—Acoustic telemetry is widely used for many tracking applications. Objects or subjects are tracked by attaching an acoustic transmitter onto them or having them wear them. The acoustic signal is then detected by different microphones to determine the location of the tagged target. The size and the weight of the tag determine the size of the target that can be tracked. In the case of small-sized tags, about 80% of the volume is consumed by the battery and electronics, while less than 20% by the actual acoustic transducer. Here, we propose a self-powered acoustic tracking transducer that utilizes a magnetic frequency up-converter that directly converts the low-frequency motions of a target to a high-frequency acoustic signal. The intensity of the output signal is enhanced by realizing a bistable cantilever design by local crystallization of an amorphous metal transducer. A micro device has been realized with dimensions of $8 \times 13 \times 38 \text{ mm}^3$ and a weight of 1.3 g. The measurement results show that the transducer up-converts a low-frequency of 7 Hz to 15 kHz, directly and without the need for an external power source.

Keywords—frequency up-conversion, bistable cantilever, tracking, self-powered, resonator, magneto-acoustic

I. INTRODUCTION

The use of acoustic telemetry to track the location of the tagged objects has become increasingly popular nowadays. For example, acoustic telemetry is used to track the aquatic animals in the water to help the marine scientist to understand the migratory behaviors, the mortality rates, and the lifecycle of aquatic animals [1]. This is achieved by attaching an acoustic transmitter (tag) on the animal of interest, and placing stationary hydrophones under the water [1], [2], as shown in Figure 1. The location of the tagged animal is then determined by analyzing the acoustic signals received by the hydrophones. A similar concept can also be utilized for indoor tracking (*i.e.*, for tracking children or elderly people) or tracking land animals.

The configuration of the tag limits the type of species to be tracked. Currently, the acoustic tags are designed in many different shapes and sizes. The key features of an acoustic tag are: a) the size and the weight of the tag that determines the minimum size of the species to carry this tag; b) the operational lifetime of the tag; and c) the signal strength allowing for a greater coverage [3]. In general, it is challenging to have a tag that combines all of these features. For example, enhancing the operational lifetime is normally achieved by increasing the size of the battery. However, the size and the weight of the tag is increased [3], [4].

Fig. 1. Acoustic telemetry for tracking species

Vemco V4 is currently one of the smallest tags on the market. It has dimensions of $11 \times 3.6 \times 5.7 \text{ mm}^3$, and it weighs 420 mg in air. However, its operational lifetime is limited to 34 days (when operating in the Pulse Position Modulation mode with a nominal delay of 20 seconds) [5]. Another group introduced an injectable tag [4] that has a length of 15 mm, a diameter of 3.38 mm, weighs 217 mg in air and has a 100 days operational lifetime (when operating with 3 seconds delay mode). About 80% of the volume of this tag is consumed by the battery and the electronics, while less than 20% of the volume is consumed by the acoustic transducer. This same group enhanced the operational lifetime of their tag to one year by increasing the size of the battery [3]. However, this tag is more than 250% larger in volume and more than 230% heavier compared to the injectable tag. In [6], they replaced the battery with a long piezoelectric beam to harvests the mechanical motions of the aquatic animal and use it to power the electronics of the acoustic tag. However, the length of the proposed design is more than 77 mm and weighs about 1000 mg in air. Hence, the implementation of this tag is limited to the relatively large species. Furthermore, there is a need for the tag that combines the advantage of having a very long operational lifetime while still maintain the small size and the lightweight.

In this work, a self-powered magneto-acoustic frequency up-converter that directly converts the low-frequency motions to high-frequency acoustic signals is proposed. For the case of the aquatic animal tracking, the low-frequency motions are in the range of 0.15 Hz up to 100 Hz [7], [8]. Such a device eliminates the need of the battery and the electronics that consume up to 80% of the volume of the acoustic tag. The device is based on a recently introduced concept [9], which is here miniaturized and further enhanced by the implementation of a bistable design. The use of the bistable design significantly improves the intensity of the output acoustic signal of the converter, hence,

Fig. 2. Concept of the self-powered acoustic frequency up-conversion tag achieving a better acoustic signal to noise ratio that is ultimately translated to greater coverage.

II. MATERIALS AND METHODS

A. Concept

The self-powered frequency up-converter is shown in Figure 2 and has previously been developed in a macro version [9]. It consists of a permanent magnet attached to a low-frequency beam, and a high-frequency beam made of a soft magnetic material that is in range of the magnet's stray field. This stray field magnetizes the high-frequency beam, producing an attraction force. This force pushes/pulls the high-frequency beam upward or downward. Whenever the high-frequency beam flips from one side to the other, it vibrates at its resonant frequency. In other words, when the low-frequency beam oscillates (*i.e.*, due to the movement of the tagged target), the attraction force between the permanent magnet and the high-frequency beam flips the high-frequency beam, hence, the high-frequency beam generates a high-frequency acoustic signal. This design efficiently up-converts the low-frequency motions into high-frequency acoustic signals.

B. Buckled structure

The produced high-frequency acoustic signal can be enhanced significantly by introducing a buckled high-frequency beam, as shown in Figure 3a. The buckled beam has two stable states, namely, state 1 and state 2. The high-frequency beam changes state only when the external force is larger than the interwell threshold force [10]. As a consequence, the bistable design dramatically improves the output signal, as discussed in [10]-[12].

In order to generate a large attractive force, the high-frequency beam should have a high saturation magnetization in combination with high permeability. Therefore, it is implemented by an amorphous-metal [13]-[17]. Locally heating the amorphous-metal results in a buckled and bistable high-frequency beam, as shown in Figure 3(b). The annealing process transforms the amorphous structures into a crystalline one. Since the crystalline state is up to 3% denser compared to the amorphous one [18], locally annealing the amorphous-metal results in locally shortening the length of the high-frequency beam. As a consequence, the free-end of the high-frequency beam is

Fig. 3. (a) Stable states of the buckled high-frequency beam, and (b) photograph of buckled high-frequency beam achieved by local annealing a piece of amorphous-metal

buckled with a bistable behavior. The relation between the density variation and the length variation is explained by

$$\Delta\rho = -\frac{3W\Delta L_f(t)/L_0}{L_0^3[1+3\Delta L_f(t)/L_0]}, \quad (1)$$

where $\Delta\rho$ is the variation in the density, W is the sample weight, L_0 is the initial length, and ΔL_f is the change in the length [18]. In this way, the high-frequency beam has double-well restoring force, and it vibrates at its resonant frequency as soon as the exciting force is higher than the interwell threshold force of the buckled structure.

C. Fabrication

The low-frequency beam is made of a 250 μm thick polystyrene sheet, the high-frequency beam is made of a 27 μm

Fig. 4. Photographs of the acoustic frequency up-converter in different sizes

Fig. 5. Photographs of the states (a) 1 and (b) 2 of the high-frequency beam in the absence of the permanent magnet. (c) X-ray diffraction results showing the partial crystallization of the amorphous metal after local annealing.

thick amorphous-metal (Metglas 2605SA1), and the permanent magnet is made of neodymium-iron-boron (NdFeB).

The buckled high-frequency beam is realized by laser cutting the amorphous metal using a 50 W ytterbium fiber laser with a $1.06 \mu\text{m}$ wavelength. The low-frequency beam is achieved by laser cutting polystyrene using a 75 W carbon dioxide (CO_2) laser with a $10.6 \mu\text{m}$ wavelength. After that, the permanent magnet is glued to the low-frequency beam, and then both of the low- and the high- frequency beams are glued to the bulk material using a clear epoxy adhesive (ALTECO F-05). The bulk material is made of Poly(methyl methacrylate) (PMMA). Figure 4 shows photographs of the magneto-acoustic transducer.

III. MEASUREMENT RESULTS

Figure 5a, b shows the stable states of the high-frequency beam. Note, these images are taken in the absence of the permanent magnet. Figure 5c shows the X-ray diffraction (XRD, Bruker D2 PHASER) results for a piece of the Metglas 2605SA1 after the laser cutting (*i.e.*, after the local annealing). The peak around 45° is evidence for the presence of the partial crystallization of the material.

Figure 6a shows the measurement setup of the magneto-acoustic transducer. The transducer is placed on an electromagnetic shaker (TIRA TV- 50018) that is oscillating at 7 Hz. The output acoustic signal is then detected by a 1/2" free-field microphone (4189 Brüel & Kjaer) that is placed about 10 cm away from the tag. The recorded signal is then amplified using a preamplifier (Brüel & Kjaer 2695) followed by a high-gain amplifier (Brüel & Kjaer 1704). The data is then plotted on an oscilloscope (Tektronix TDS5054B) and further processed in MATLAB.

Figure 6b shows the frequency domain of the recorded acoustic signal generated by the transducer. The recorded signal has a resonant frequency at 15 kHz with a peak amplitude of 580 mV. By de-embedding the gain and the losses of the measurement setup, the sound pressure level at the surface of the microphone (SPL Mic.) is calculated by

$$P(\text{dB SPL Mic.}) = 20\text{Log}\left(\frac{V_{\text{Osc.}} \times \text{Microphone sensitivity}}{\text{gain} \times 20 \mu\text{Pa}}\right), \quad (2)$$

where $V_{\text{Osc.}}$ is the average voltage at the oscilloscope for a one-pulse duration, and *gain* is the total voltage gain of the measurement setup. Note that, the SPL Mic. is in decibel and

Fig. 6. (a) Measurement setup of the self-powered magneto-acoustic transducer, and (b) the measured signal in the frequency domain.

normalized to the $20 \mu\text{Pa}$ SPL. The measurement results indicate that the sound pressure is 75 dB SPL at the surface of the microphone, which is equivalent to 55 dB SPL at 1 m of distance. In the case of using a device with the same dimensions but without the buckled structure, the output acoustic signal is indistinguishable from the background noise.

IV. CONCLUSION

This work presents a self-powered magneto-acoustic transducer that can directly convert low-frequency motions into a high-frequency acoustic signal. The device utilizes the movement of a permanent magnet to trigger the oscillation at the resonant frequency of a high-frequency beam made of a soft-magnetic amorphous metal. To boost the output signal, a bistable high-frequency beam is realized by locally annealing the high-frequency beam at the edges, resulting in a buckled structure with a bistable behavior. The measurement results show that the proposed tag is able to up-convert a 7 Hz low-frequency motions to a 15 kHz acoustic signal with a 55 dB SPL intensity.

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