Magneto-Acoustic Resonator for Aquatic Animal Tracking

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Over the past three decades, passive acoustic telemetry has significantly helped marine scientist to study and understand the spatial ecology, migratory behaviors, and mortality rates of aquatic animals. A popular telemetry system consists of two components: an acoustic transmitter tag attached to an aquatic animal and powered by a small battery; and a stationary station that receives the acoustic signals from the tagged animal and determines its location. The added weight and increased size of the tag introduced by the battery limits the implementation of this system to relatively large animals. Moreover, these tags have a limited operational time determined by the lifetime of the battery in combination with the measurement frequency and data’s resolution and transfer rate. In this work, a self-powered magneto-acoustic resonator for animal tracking is proposed. It is achieved by utilizing the low-frequency motions of the animals to excite high-frequency acoustic pulses. The measurement results show that the device is capable of producing an average acoustic sound of 55 dB SPL at 1 meter of distance with a resonant frequency of 15 kHz.

Index Terms— resonator, frequency up-conversion, bistable cantilever, MEMS, animal tracking, self-powered, amorphous ribbon, acoustic, magnetic

I. INTRODUCTION

Since the 1970s, marine scientists used acoustic telemetry to study and understand the spatial ecology, migratory behaviors, and mortality rates of aquatic animals [1]. At the early stage, active tracking was used, where the target animal was equipped with an acoustic tag and followed in real-time by using a directional hydrophone attached to a boat [1], [2]. This approach was challenging and required extensive labor [1]. In the late 1980s, passive acoustic telemetry progressed that utilized stationary hydrophone stations placed under water and powered by batteries, as shown in Figure 1. The data were then extracted from the stationary stations and processed to determine the behaviors of the tagged animals [1], [3].

Acoustic telemetry systems are implemented to date [4]-[6], with the focus on improving the functionality of the acoustic transmitter (tag). The key features of an acoustic tag are: 1) the weight and size of the tag, as smaller and lighter tags allow the tracking of smaller aquatic animals; 2) the operational lifetime of the tag, allowing for long-term monitoring of the aquatic animal; and 3) the signal strength allowing for greater detection range [7].

In general, it is challenging to have a small and lightweight tag with a supreme operational lifetime. Vemco Ltd. is a leading company for passive acoustic telemeter systems. The type V4 is currently their smallest tag, the dimensions of which are 11 mm × 3.6 mm × 5.7 mm, and it weights 420 mg in air. However, the operational lifetime is limited to 34 days, when operating in the Pulse Position Modulation (PPM) mode with a nominal delay of 20 seconds [8]. Another tag introduced in [9] has a length of 15 mm, a diameter of 3.38 mm, weights 217 mg in air, and offers about 100 days operational lifetime with 3 seconds delay. By inspecting the components of the tag, we can see that the acoustic transmitter occupies about 20% of the volume while about 80% of the tag is occupied by the battery and the electronics [9]. To extend the operational lifetime of the tag, [4] proposed a long-life acoustic tag that has a 1-year lifetime, when operating with 15 seconds time interval. The extended operational lifetime came on the expense of the size and weight of the tag, with a 24.4 mm length, 5 mm in diameter and weights 720 mg in air. Again, by inspecting the components of the tag, one can see that the battery by itself occupies about 67% of the volume of the tag, while the acoustic transducer occupies about 12% of

![Fig. 1. Passive acoustic telemetry system for tracking aquatic animal](image-url)
the tag. To reduce the burden of the operational lifetime, in another approach, the battery was replaced with a long flexible beam that harvests the motion of the tagged fish to power the electronics of the tag [10]. However, this tag has a length of 77 mm and weights about 1 g in air. As a consequence, the implementation of this tag is, again, limited to relatively large aquatic animals. Existing acoustic tags, in general, suffer from relatively large sizes and/or limited operational lifetime. Therefore, there is a need for small and lightweight tags that are capable of operating for a very long period [7].

In this work, we introduce a self-powered magneto-acoustic tag that directly upconverts the low-frequency motions (that ranges from 0.15 Hz up to 100 Hz [11], [12]) of animals into high-frequency acoustic signals. This approach has the potential to significantly reduce the weight and the size of the acoustic tag by eliminating the need for both the battery and electronics that occupies the majority of the volume in existing tags, while at the same time increase the tag’s lifetime.

II. MATERIALS AND METHODS

A. Concept

In order to convert the low-frequency motions of the animals to high-frequency acoustic signals, an efficient frequency up-conversion concept is needed, as shown in Figure 2(a). The proposed magneto-acoustic design (Figure 2(b)) consists of a low-frequency membrane, a high-frequency membrane made of a soft-magnetic material, and a permanent magnet attached to the low-frequency membrane. The membranes are realized as cantilever beams, whose resonant frequencies are given by

$$f_0 = \frac{t}{4\pi L^2} \sqrt{\frac{E}{\rho}},$$

(1)

where $f_0$ is the fundamental frequency, $t$ is the thickness of the membrane, $L$ is the length of the membrane, $E$ is the Young’s modulus, and $\rho$ is the density of the material [13].

The stray field of the magnet magnetizes the soft-magnetic material, producing an attractive force between the high-frequency membrane and the poles of the magnet, which is given by

$$F = \frac{\mu q_1 q_2}{4\pi r^2},$$

(2)

where $F$ is the attraction force, $q$ is the magnitude of the magnetic pole, $\mu$ is the permeability and $r$ is the distance between the two magnets. In this bistable system, the high-frequency membrane will always bend toward one of the two poles.

Since the magnet is attached to the low-frequency membrane, the magnet will oscillate in the presence of any motion. As a consequence, the high-frequency membrane gets alternatingly attracted to the opposite poles, thereby oscillating at its resonant frequency, which is designed to generate high-frequency pulses. This way, the proposed design up-converts the low-frequency motions to high-frequency acoustic pulses.

In order to maximize the force between the permanent magnet and the high-frequency membrane, a material with very soft magnetic properties is required (2). Amorphous metals are ideal candidate materials, since they are mechanically durable and highly soft magnetic, due to the lack of crystalline anisotropy. Hence, they have been heavily utilized for various resonant sensor systems [14], [15] and monitoring applications [16]-[19].

B. Fabrication

The design of the magneto-acoustic tag is depicted in Figure 3(a). The low-frequency membrane is made of 40 mm × 9 mm × 0.25 mm polystyrene membrane. The high-frequency membrane is made of 4 mm × 4 mm × 25 μm amorphous-metal (Metglas 2605SA1), and it is designed to have a 15 kHz resonant frequency. The permanent magnet is made of neodymium (NdFeB) and it has a cylindrical shape with a diameter of 4 mm and a length of 8 mm. The bulk is made of Poly(methyl methacrylate) (PMMA), and its main role is to support the structure of the magneto-acoustic tag.

Cutting the amorphous-metal is achieved using a 30 W ytterbium fiber laser (Universal laser systems, PLS6MW) with a 1.06 μm wavelength. Using the laser to cut the amorphous-metal locally induces strains that result in a stiffening of the beam structure [20]. By optimizing the power, speed and the frequency it is possible to cut the amorphous-metal membrane with a minimum impact [21]. Cutting the polystyrene and the PMMA is achieved using a 75W carbon dioxide (CO₂) laser (Universal laser systems, PLS6.75) with a 10.6 μm wavelength. After that,
assembling the components was achieved using clear epoxy adhesive (ALTECO F-05). Figure 3(b) shows a photograph of the fabricated magneto-acoustic tag.

III. RESULTS AND DISCUSSION

A. Amorphous-metal characterization

Figure 4 shows the magnetization curve of a 2.5 × 2.5 mm sample of the amorphous-metal. The measurement results are obtained using a Vibrating Sample Magnetometer (VSM). The sample is secured into a sample-holder using a silicon grease, and the sample-holder is set to oscillate at 83 Hz with a 1 mm amplitude, then the magnetic field is swept between -100 and +100 mT. The measurement results indicate a typical performance for a soft magnet amorphous-metal that has a high slope at the origin, and very low remanent magnetization and coercive fields. In fact, from the slope we can extract the permeability of the material that is $\mu_r = 84334$. According to (2), this high permeability results in a very large force between the soft magnet (high-frequency membrane) and the permanent magnet (low-frequency membrane).

B. Magneto-acoustic tag characterization

Figure 5 shows the measurement setup for the magneto-acoustic tag, which consists of: a shaker (TIRA TV-50018), a 1/2" free-field microphone (4189 Brüel & Kjaer), a 1/2" CCLD preamplifier (Brüel & Kjaer 2695), a 100 V/V gain amplifier with a built-in 20 Hz – 20 kHz bandpass filter (Brüel & Kjaer 1704), and an oscilloscope (Tektronix TDS5054B). The tag was placed on the shaker with 7 Hz oscillation frequency (which is within the range of the locomotion frequency of the aquatic animal [12]) and 0.4g acceleration. The microphone was leveled, facing the high-frequency membrane and placed 10 cm away from it. The microphone was connected to the
preamplifier and the high-gain amplifier, and the output was connected to the oscilloscope. The data was stored and processed using MATLAB.

Figure 6(a) shows the measured voltage at the oscilloscope, when the magneto-acoustic tag is in oscillatory motion, induced by the shaker. The measurement results show a peak voltage of 1.4 V and a pulse duration of about 1.2 ms. Figure 6(b) shows the frequency domain for the duration of one pulse that shows a resonant frequency of 15 kHz with an average amplitude of 0.58 V. The equivalent pressure at the surface of the microphone is determined by de-embedding the gain and the losses of the measurement system

\[ P(\text{dB SPL}) = 20 \log \left( \frac{V_{\text{rms, gain}}}{20 \mu Pa} \frac{\text{Microphone sensitivity}}{\text{Sound Pressure Level (SPL)}} \right) \]  

where \( P(\text{dB SPL}) \) is the acoustic pressure at the surface of the microphone in decibel and normalized to the Sound Pressure Level (SPL), \( V_{\text{rms, gain}} \) is the average voltage at the oscilloscope for a one-pulse duration, and \( \text{gain} \) is the total voltage gain of the measurement setup. The results show a 75 dB SPL at the surface of the microphone (10 cm away from the tag), or equivalently, 55 dB SPL at 1 meter of distance.

IV. Conclusion

This work proposes a self-powered frequency-upconverter magneto-acoustic tag that directly converts the low-frequency motions into high-frequency acoustic signal. The direct conversion for the frequency eliminates the need of the electronics and battery found in conventional acoustic tags. Once the tag is in motion, it is capable of generating a resonant frequency of 15 kHz with an average acoustic signal of 55 dB SPL at 1 m of distance. The concept consists of simple, passive components that enable considerable reduction in size and further optimization, potentially creating a long-lasting miniaturized tracking tag.

REFERENCES