A Magnetostrictive Underwater Transducer Directly Driven by Iron-Gallium Alloy (Galfenol) without Bias Magnetic Field*

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***Abstract*—This paper developed a Janus underwater transducer driven by slotted Galfenol rods and the transducer has no permanent magnet bias and is driven by current of half the mechanical resonant frequency. The mechanical resonant frequency of the prototype is about 4.8 kHz. The performances such as transmitting current response, sound level, the impedance and the phase between the driving voltage and the current are measured in anechoic tank. The frequency of the underwater sound is twice as that of the driving voltage or current in the frequency range around the resonant frequency. The maximum of the tested sound level is about 189dB (0dB=1µPa/A@1m) with a driving current 7.4 A_{rms} at the resonant frequency 4.8 kHz.**

Keywords—Galfenol; transducer; magnetostrictive; without bias magnetic field

I. INTRODUCTION

Iron-Gallium alloy (Galfenol) as a new magnetostrictive functional material has shown great properties such as moderate magnetostriction of ~200ppm under low applied magnetic field, a Young's modulus of ~70 GPa, a relative permeability of 60~200 and good machinability [1-2]. Because of these advantages, Galfenol offers promising applications in magnetostrictive vibrators and transducers [3-8]. Zhang etc. [3] proposed a self-propelling mechanism integrated with a Galfenol magnetostrictive vibrator which consists of a U-shaped core (Galfenol), driving coils and a yoke. The vibrator was driven by sawtooth waveform current applied to the coils and the sawtooth waveform of current is either slow rise and rapid drop or rapid rise and slow drop so as to implement slow expansion and rapid contraction or rapid expansion and slow contraction. It is noted that the vibrator does not contain a bias magnet field and each rise or drop of the sawtooth waveform of current induces a expansion or contraction of the vibrator. Magnetostrictive transducer is one of the common electroacoustic transducers in underwater sound sources. S.P.Porter [4] developed a Galfenol tonpilz transducer and the resonant frequency in the transmitting current response is 10.4 kHz. In order to mitigate the eddy current loss, the Galfenol rods are laminated into very thin sheets. And this Galfenol tonpilz transducer is biased with permanent magnets.

Besides, there have been developed other Galfenol underwater transducers such as low frequency slotted cylinder transducer [9] and so on [7-8].

This paper developed a Janus underwater transducer driven by slotted Galfenol rods and the transducer has no permanent magnet bias and is driven by current of half the mechanical resonant frequency. The performances such as transmitting current response (TCR), sound level (SL), the impedance and the phase between the driving voltage and the current are measured in anechoic tank. The transducer has a mechanical resonant frequency about 4.8 kHz.

II. CONSIDERATION AND CONFIGURATION

A. Consideration

As mentioned in Section 1, Galfenol magnetostrictive materials can work with or without a biased magnetic field. Fig.1 illustrates the differences between the two cases. In the biased case, when the alternating *H*-field is applied around a magnetic bias H_0, the magnetostriction operates in an approximately linear region yielding large strains. And in the unbiased case, a frequency doubling will occur with low strain output if an oscillating *H*-field is applied around the origin for the quadratic relationship between magnetic field and strain.

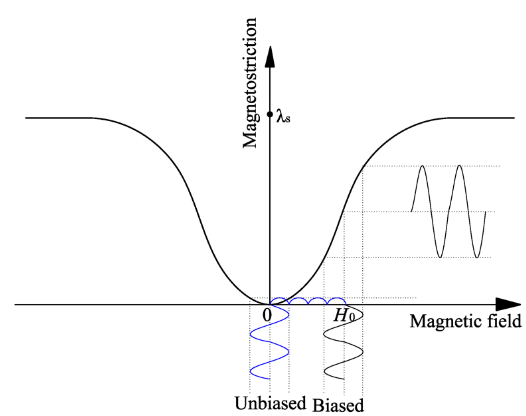

Fig. 1. Typical strain versus magnetic field plot, showing application of unbiased and biased magnetic fields with resultant strains.

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Although magnetostrictive underwater transducers are usually designed to operate in linear region with a biased *H*-field for higher efficiency, there still are some advantages in the unbiased case. One important advantage is that it can decrease eddy current loss. It is known that eddy currents exist in magnetostrictive materials such as Terfenol-D and Galfenol. The power loss due to eddy currents, Q_{ec}, is given by

$$Q_{ec} = \pi^2 \sigma f^2 t^2 B^2/6 \quad (1)$$

where σ is the electrical conductivity of the conductor, f is the frequency of the magnetic field, t is the lamination thickness and B is the peak magnetic induction [4]. From (1) it can be seen that, neglecting σ and B, the power loss is proportional to the square of the product of f and t. In order to mitigate the eddy current loss, the drivers of magnetostrictive transducers are usually made of laminated stacks or slotted rods [4]. In addition, it is more suitable for magnetostrictive materials to work at lower frequency especially under the condition of high power and long duration. It is known that if the Galfenol magnetostrictive transducer works under an unbiased condition, the frequency of strain is twice that of the driving voltage and current. If the frequency of strain is f_0, the frequency of driving voltage or current in unbiased case is $0.5f_0$, while the frequency of driving voltage or current in biased case is f_0. And the power loss Q_{ec} due to eddy currents in unbiased case is only a quarter of that in biased case.

There are some other advantages of Galfenol working in an unbiased case. Terfenol-D or Galfenol Magnetostrictive transducers are often biased by permanent magnets, and the permanent magnets are removed under unbiased condition. So there is no need to worry about demagnetization of the magnets when the high temperature caused by eddy currents is above the Currie point. The relative permeability of permanent magnet is very low and the dynamic magnetic impedance can be decreased without permanent magnet bias. Because the frequency of the underwater sound is twice as that of the driving voltage or current, the electromagnetic interference can be easily shielded from the receiving system. Besides, the transducer without permanent magnet bias can also be biased by DC current.

In this work, a prototype of Galfenol transducer without permanent magnets is developed and driven by current with frequency range around half the mechanical resonant frequency. It is noted in Fig.1 that the waveform of the strain in unbiased case is not a sine wave, which raises a question that what is the waveform of the underwater sound yielded by the unbiased Galfenol transducer.

B. Configuration

Fig.2 shows the structure of the Galfenol Janus transducer. It consists of four pairs of Galfenol rods with each pair comprised of two shorter rods, four driving coils, two end pistons, two iron plates to complete the magnetic path, a prestressed bolt and a cylindrical housing. Besides, a rubber boot is covered on each end of the pistons to isolate water.

Each Galfenol rod is 80 mm long with a diameter 30 mm and is slotted along the axis direction into segments. The titanium bolt with a diameter 20 mm pre-stresses the Galfenol rods between the pistons. The titanium pistons are circular conical frustums with the base and top diameters 110mm and 140mm respectively; and the heights of the top and the bottom frustums are 23 mm and 27 mm respectively. The iron plates is used to complete the magnetic loop with the thickness 5 mm and they are slotted to reduce the eddy currents. There are four driving coils each with 1120 rounds. And there are two magnetic paths and each path contains two coils. The two coils in each path are connected electrically in series. And then the two coils connected electrically in series in one path are connected electrically in parallel to those of the other path. A prototype was developed with overall size (including the cover boot) about Φ183 × 270 mm and weight 26 kg in air (showing in Fig.3).

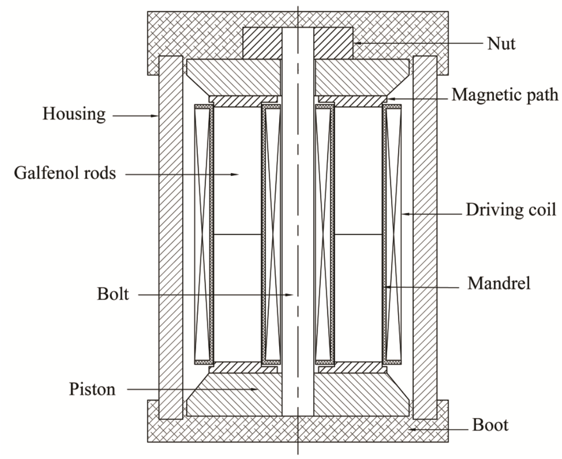

Fig. 2. Vertical section of the Galfenol Janus transducer.


Fig. 3. Components of the transducer.

III. Results

The performance of the transducer is measured in anechoic water tank and the measurement setup is shown in Fig.4. The

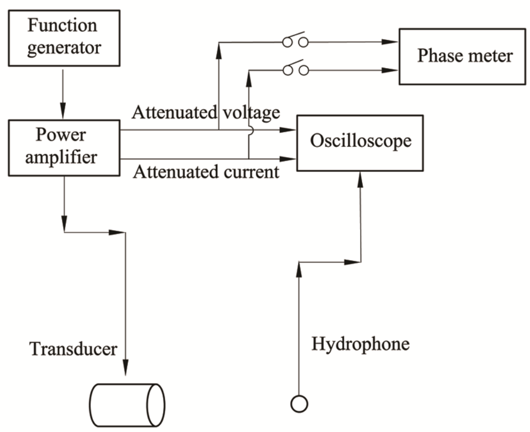

Fig. 4. Experimental setup for the measurement of the transducer.

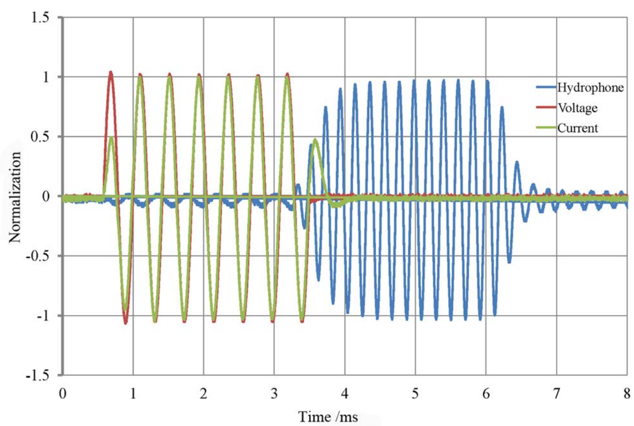

Fig. 5. Normalized signals of the driving voltage, the current and the hydrophone. The frequency of the driving voltage is 2.4 kHz.

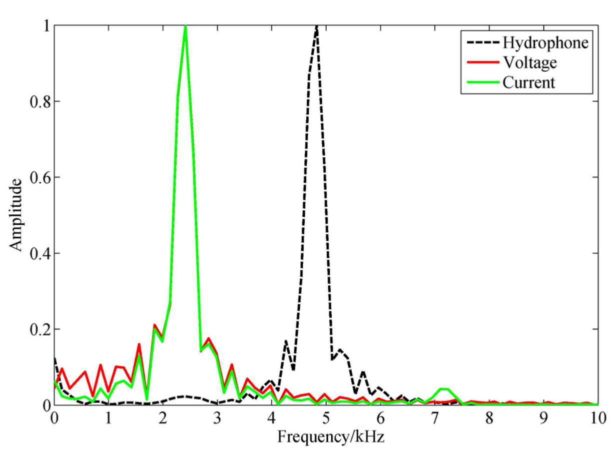

Fig. 6. Fast Fourier Transform (FFT) results of the normalized signals of the sampling voltage, the sampling current and the hydrophone showed in Fig.5.

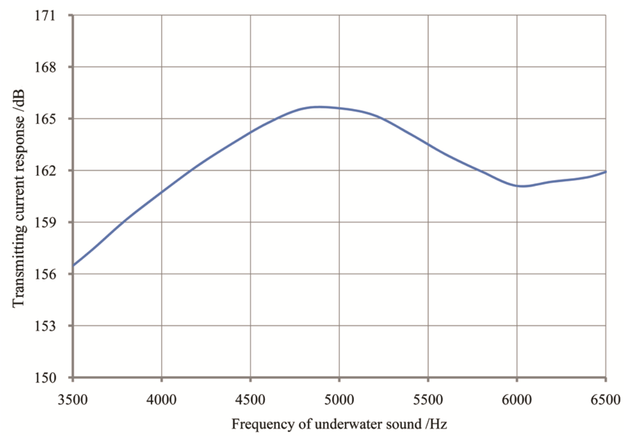

Fig. 7. Tested transmitting current response of the transducer. The *x*-axis is the nominal frequency which is twice of that of the driving voltage.

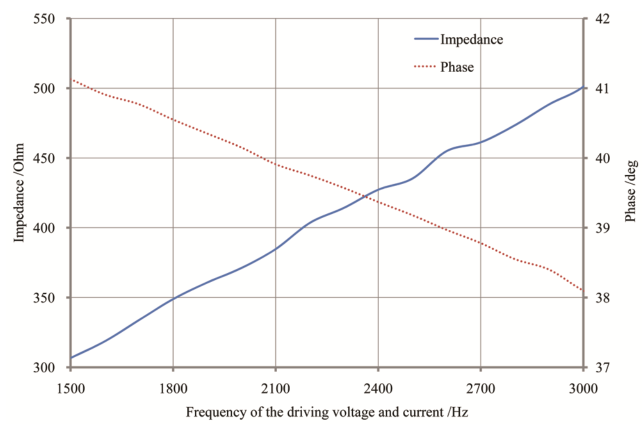

Fig. 8. Tested impedance and phase between the voltage and current of the transducer. The *x*-axis is the frequency of the driving voltage and current.

transducer has no biased magnetic field, so the relationship between strain and *H*-field is quadratic. Fig.5 shows the normalized signals of the driving voltage, the current and the underwater sound in time domain, and the frequency of the driving voltage is 2.4 kHz (The mechanical resonant frequency is about 4.8 kHz, which is shown in Fig.7.). The driving voltage is a sine wave pulse with 7 cycles in one pulse (red line), the yellow line represents the current through the transducer, and the blue one represents the underwater sound received by the hydrophone. Fig.6 shows the FFT results of the signals showed in Fig.5. The frequencies of the peaks is 2.41 kHz, 2.41 kHz and 4.83 kHz corresponding to the signals of voltage, current and hydrophone, respectively. The frequency of the underwater sound is basically doubled compared to that of the driving voltage and current.

The transmitting current response(TCR), the impedance and the phases are measured in the frequency range around the mechanically resonant frequency 4.8 kHz. Fig.7 and Fig.8 are the measured TCR and phases between the driving voltage and current, respectively. The driving voltage is basically a constant of $810V_{rms}$ during the testing process. The *x*-axis of Fig.7 is the nominal frequency which is twice of that of the driving voltage and is regarded as the frequency of underwater sound; and the *x*-axis of Fig.8 is the frequency of the driving voltage and current. It can be seen from Fig.7 that there is resonance at 4.8 kHz with the maximum TCR 165.6 dB (0 dB=1 μPa/A @ 1 m) and the current is about 1.9 A_{rms} with 810 V_{rms} driving voltage at 2.4 kHz.

Besides, when the transducer is applied with 3 A_{rms} current, the sound level is 178.8 dB; and when applied with 7.4 A_{rms} current, the sound level is 189 dB. The TCR differs with current at the same frequency. This apparently shows that the sound level or the TCR is not linear with the current because of the quadratic relationship between the strain and *H*-field.

IV. SUMMARY

A Janus underwater transducer driven by Galfenol rods without bias magnetic field is developed, and the performances such as TCR, SL, impedance and phase between the driving voltage and the current are measured around the mechanical resonant frequency about 4.8 kHz. The frequency of the underwater sound is twice as that of the driving voltage or current for the quadratic relationship between the strain and *H*-field. The maximum of the tested sound level is about 189 dB with a driving current 7.4 A_{rms} at the mechanical resonant frequency 4.8 kHz.

It is applicable for Galfenol or Terfenol-D transducers work without permanent magnet bias. This kind of transducers may be used in high temperature environment and can be directly driven by half-frequency current or biased by a DC current.

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