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Low-frequency active noise control of an underwater large-scale structure with distributed giant magnetostrictive actuators

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ABSTRACT

A light and thin underwater large-plate active acoustic structure is developed that satisfies the particular requirements of high pressure resilience, low frequency and high efficiency encountered in underwater work environments. A low-frequency miniaturized active control unit, with a thickness of less than 50 mm, is designed using giant magnetostrictive material (GMM). The noise reduction performance is measured with an active control system based on a multi-channel adaptive filter. The active control system is developed within a LabVIEW environment and can achieve significant levels of noise reduction within time intervals of less than one second achieving absorption coefficients far exceeding 0.8 even under high pressures. The new active-control system incorporates hardware and software components and represents a novel technology for low-frequency underwater noise reduction.

1. Introduction

Since the emergence of silent submarines, navies in the developed countries have primarily focused on noise detection frequencies substantially below 2 kHz. In recent years active detection sonars with substantially low frequencies have been used regularly. Low-frequency detection sound waves can not only achieve over the horizon (OTH) detection, but also lead to shell resonance, increase the target intensity, and overcome acoustic stealth. Thus, low frequency detection can leave the target fully exposed to the enemy in the monitoring system. It is of crucial importance for large scale targets to resolve this safety hazard at low frequency.

Traditional passive acoustic structures are unable of response to incoming low-frequency sound waves. This is due to sound reflection being governed by the material properties and the overall structure of the target. Active noise control techniques, however, offer an effective means to achieve low frequency noise reduction. Nevertheless, compared with the significant progress in the aerodynamic field, active noise control is hardly used in underwater acoustics due to its harsh application requirements such as high pressure, light weight and high efficiency. Low-frequency active control of a large-scale underwater target is rarely reported because of its special military background.

Structures for active noise control employing piezoelectric ceramics [1] and accelerometers for underwater targets are referred to as "Smart Tiles", this terminology was introduced by the Naval Civil Engineering Laboratory in 1996 [2–4]. Multifunctional active noise reduction structures can have many concurrent functions such as active sound absorption, active sound insulation and active sound radiation control [5]. Related research based on PVDF thin films and Sonopanel composite structures, resulted in the development of active acoustic structures for underwater targets. Two layers of PVDF thin films are used as signal separator to separate the incident wave and the reflected wave by means of a delay algorithm. The most efficient active noise- reduction effect can be achieved with these signals by active methods as described by Howarth et al. [6–8].

The most important component of signal separation and secondary sound source in active noise control are low-frequency acoustic transducers. Giant Magnetostrictive Materials (GMM) can be designed for piston-type underwater acoustic transducers. This low frequency active sonar can transmit signals of 200 Hz whose sound intensity is 200 dB [9,10]. Macro Fiber Composites are another new smart material for shell active noise control [11,12].

Frequently used materials are piezoelectric materials [13–16] (such as piezoelectric ceramics PZT, piezoelectric film PVDF) and magnetostrictive materials (such as rare earth material, giant magnetostrictive material). Nevertheless, the most common materials are piezoelectric ceramics. However, the disadvantages of ceramics are the required high driving voltage, small actuating amplitude, and the fragility of the material which limits its scope for underwa-

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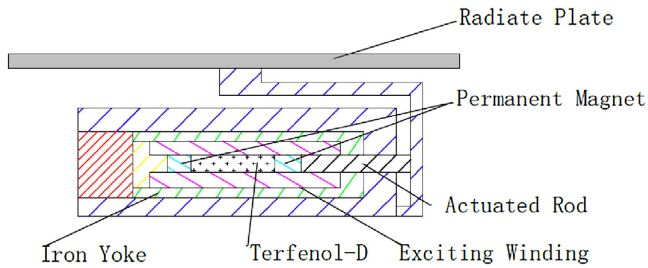

Fig. 1. GMA structure.

ter applications. Meanwhile, giant magnetostrictive material used in land high-frequency or ultra-high frequency transducer fields and GMM has problems associated with heat transfer and cooling [17–20]. Although GMM do not need to cooling in water, it is difficult to use them at low frequencies especially when the structural size of the Giant Magnetostrictive Actuator (GMA) is less than 50 mm.

In this paper, an active-control technology of an underwater large-scale target based on giant magnetostrictive materials is studied in the low-frequency range. A GMA was designed step by step to meet these requirements. The multi-channel control software was developed within a LabVIEW environment and achieves transient acoustic noise reduction. A limited area composed of active control units was used as the secondary sound source in a high pressure anechoic tank. The performance characteristics of the active noise control were evaluated by means of monitoring the reflection coefficients.

2. Active unit design method

The active unit used a giant magnetostrictive actuator which is based on the magnetostrictive effect. The basic parameters proposed in accordance with task requirements must be determined prior to the design of the magnetostrictive actuator. This section describes the design of an actuator which can improve on the weakness of piezoelectric ceramics such as fragility, low efficiency and high drive voltage.

2.1. Structure parameters of the active unit

Based on the design principle of an alternating current electromagnetic circuit, the giant magnetostrictive actuator under 2 kHz is designed with a Terfenol-D rod, as illustrated in Fig. 1, which can be applied to special requirements such as low frequency, high power and miniaturization.

Depending on the working conditions such as high pressure and current density, the diameter of the bare wire can be chosen from standard sizes. The diameter of the bare wire can be obtained from the current density. The magnetic circuit will be working repeatedly within short time intervals.

The coil thickness is:

$$e = \frac{H}{4\pi n_1 n_2 I} \tag{1}$$

where, H is the magnetic field intensity. n_1 and n_2 are the number of turns per unit length and the unit thickness of layers respectively. I is the current.

The outer radius of the coil is:

$$r_2 = r_1 + e + e_j(N_2 - 1) \tag{2}$$

where, r_1 and r_2 are the outer radius of the Terfenol-D rod and the outer radius of the coil respectively. e_j is the thickness of each layer of the insulation materials (e_j = 0.05 mm) and N_2 is the number of coil layers ($N_2 = e{\cdot}n_2$).

The total number of turns is:

$$N = (n_1 L_c)(n_2 e) \tag{3}$$

where, L_c is the length of the coil.

Set one end of the coil as the coordinate origin, the axis of the distribution of the magnetic field (approximation for multilayer coil) is:

$$H_x = 2\pi n_1 n_2 I\{(x+l)\ln \frac{r_2 + \left[r_2^2 + (x+l)^2\right]^{1/2}}{r_1 + \left[r_1^2 + (x+l)^2\right]^{1/2}} + (l-x)\ln \frac{r_2 + \left[r_2^2 + (x+l)^2\right]^{1/2}}{r_1 + \left[r_1^2 + (x+l)^2\right]^{1/2}} \tag{4}$$

where, H_x is the magnetic field at position x.

Due to the alternating current (AC) in the coil, the total impedance coil consists of two parts, that is the resistance and the inductance.

$$R = \rho_T \pi (r_1 + r_2) N / S_d \tag{5}$$

$$S_d = \frac{\pi}{4} d_n^2 \tag{6}$$

where, R is resistance. S_d is the effective cross-sectional area of the wire and d_n is the diameter of the bare wire. The resistance coefficient of the conductor is ρ_T = 0.01191.

The calculation to determine the self-induction coefficient is, in general, complex. However, for the particular case of a simple straight solenoid coil, as considered in this paper, the Biot-Savart law can be used to obtain an approximation of its value. Nevertheless, this approximation is larger than the actual value. This is so because the magnetic field of the coil is assumed to be uniform whereas the actual magnetic field is non-uniform and the discrepancy is particularly pronounced for short coils. Due to the existing edge effects the field strength near the ends of the coil is only half its center value.

The self-induction coefficient is:

$$L = \mu_0 N^2 V_c / L_c \tag{7}$$

where, μ_0 is the permeability of air, N is the total number of turns on the coil. V_c is the volume of the coil.

When the frequency of the alternating current within the coil is f, the impedance is

$$X_L = 2\pi f L \tag{8}$$

The total impedance of the coil is

$$Z = \sqrt{R^2 + X_L^2} \tag{9}$$

The required voltage and consumption power of the coil is:

$$U_m = IZ; \quad P_m = I^2 R \tag{10}$$

The bias magnetic field of permanent magnets is used to eliminate Second Harmonic Generation (SHG) of a Terfenol-D rod and provide mechanical movement of the Terfenol-D rod in a linear range. The calculations associated with the bias magnetic field are also very complex and the results obtained are generally not very accurate. For engineering application it is therefore a common procedure to use an estimate in the first instance and, thereafter, the actual measurement provides a reference for improvements. The estimate is obtained from the λ-H curve. If this estimate does not satisfy the requirements then the shape of the permanent magnet should be improved until the performance is satisfactory.

The design requirements and the steps outlined above define the geometric dimensions of the actuator. The diameter of radiation plate located in the end of the actuator drive rod is 150 mm and its