Development of Tb-Dy-Fe Detection Transducer

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Abstract. The erbium-dysprosium-iron magnetostrictive alloy is used as the acoustic generator of ultrasonic detection transducer. According to the characteristics of the magnetostrictive alloy, the alternating magnetic field is generated by the altering current of the coil around the magnetostrictive rod the circuit system. As the magnetic field changes, the magnetostrictive rod will produce stretching deformation along the axial direction, which drive the radiation plate vibrate and generate ultrasonic wave. The Tb-Dy-Fe detection transducer has the advantages of simple structure, fast response and large output power so that can be used in various field of industrial detection.

1. Introduction
The common nondestructive testing method includes: ray testing, ultrasonic testing, magnetic particle testing, penetration testing, eddy current testing, etc. With the advantages of strong penetration, good direction, fast and accurate of pulse ultrasonic signal, ultrasonic flaw detector is more widely used in online testing and diagnosis [1,2]. The ultrasonic transducer is a key component which is used to exchange the electrical and acoustic signals of the ultrasonic frequency range of in ultrasonic detection equipment. By the material and signal conversion mechanism, the ultrasonic transducers can be divided into piezoelectric transducer, electrostatic transducer, magnetostrictive transducer, etc. Magnetostrictive transducer is based on magnetostrictive effect of ferromagnetic materials or ceramics. General magnetostrictive materials include nickel alloy, aluminum-iron alloy, iron-cobalt-vanadium alloy, etc. However, the electromechanical conversion of traditional magnetostrictive transducers are so inefficiency that the excitation circuit is more complex and limit its application.

With the development of material science and technology, and the successful development of rare earth-iron giant magnetostrictive material, researchers pay more attention to magnetostrictive transducer and its application.

2. Ultrasonic transducer design
Ultrasonic transducer is an energy converter, and the parameters of its performance description and evaluation includes resonance frequency, electromechanical coupling coefficient, electroacoustic efficiency, sensitivity, etc. The requirements for transducer performance are depend on the type and application. In the nondestructive testing of bridge cable, transmitting ultrasonic transducer should be selected and requires higher output power and energy conversion efficiency.

In application of ultrasonic testing, the acoustic energy usually generated by three methods, hydrodynamic, piezoelectric effect and magnetostrictive effect [3]. The output power of terbium-dysprosium ferro-magnetostrictive materials can reach 6-25kw, so the magnetostrictive effect transducer is used in cable nondestructive testing.
Magnetostrictive transducer is mainly composed of giant magnetostrictive rod, permanent magnet, alternating coil and metal sheet, shown in Fig. 1.

![Figure 1. Structure of magnetostrictive transducer](image)

The magnetostrictive rod is placed in the magnetic field generated by the alternating coil and permanent magnet. When the alternating current is applied to the coil, the alternating magnetic field will be generated around the giant magnetostrictive rod, and stretching deformation along the rod axial direction will be produced, acoustic wave will be generated by the vibration of metal sheet, and finally transited to high-power ultrasonic signal [4].

3. Tb-Dy-Fe magnetostrictive material
A giant magnetostrictive material of TbDyFe alloy is used in transducer, and its magnetostrictive coefficient is greater any other material at room temperature. The advantages of TbDyFe alloy includes: (1) large strain, the magnetostrictive strain is 50 times larger than pure Ni, and 5~25 times larger than PZT material; (2) great thrust, the thrust produced by the magnetostrictive strain is great, and a 10mm diameter TbDyFe rod could produce 200kg thrust. (3) high energy density, its energy density is 400~800 times larger than Ni alloy, and 14~30 times larger than PZT material. (4) high energy conversion efficiency, its electromechanical coupling coefficient is nearly 70%, while only 16% of Ni alloy and 40~60% of PZT material. Therefore, Tb-Dy-Fe magnetostrictive alloys can efficiently convert electrical energy into mechanical energy, and the convert time is short to $10^{-5}$~$10^{-6}$s, the response almost no delay matching the static and dynamic characteristics of magnetic field accurately and steadily. Its stable response and fast speed significantly reduce the reaction delay time of the mechanical system with TbDy-Fe alloy driving element, so the rapid expansion strain response in alternating magnetic field. Tb-Dy-Fe alloy is more widely used as actuator, control element, sensitive element, etc. [5,6]

4. Transducer system design
Transducer system design mainly include hardware circuit and electromagnetic design.

4.1. Hardware circuit design
The hardware circuit is mainly consist of pulse signal generator, power amplifier and matching circuit, shown in Fig. 2.

The pulse signal generator is composed of FPGA and DDS [7], The output of signal of DDS is high frequency square wave and its crystal frequency is 125MHz. The major function of DDS is to divide the frequency of FPGA crystal frequency signal into low frequency selective signal, shown in Fig. 3. The frequency control of current signal is realized by controlling the output signal frequency of DDS and the broadband control signal of low frequency, shown in Fig. 4.
The power amplifier is composed of prefix drive and boost circuit. The prefix drive circuit adopts push-pull structure to provide driving current for secondary boost chip. The boost circuit is H bridge amplifier circuit and when the excitation signal pulse arrives temporarily, the MOS transistor is turned on. During the interruption time, the power signal pass through to form the pulse signal.

In order to improve the output power and get an ideal signal, it’s necessary to design the impedance matching circuit. The formula of capacitance $C$ is:

$$C = \frac{L_{eq} + L_{t}}{R_{eq} + [\omega_{0} (L_{eq} + L_{t})]^{2}} - C_{d} \quad (1)$$

Where $L_{eq}$ is equivalent inductance, $L_{t}$ is secondary equivalent inductance of transformer, $R_{eq}$ is equivalent resistance of alternating coil, $\omega_{0}$ is angular frequency of alternating signal, $C_{d}$ is distributed capacitance.
When the high frequency alternating signal is put in, the alternating coil will produce inductance and there is distributed capacitance between the coils. The resonant condition of the alternating coil is satisfied, the output power can reach the maximum.

4.2. Electromagnetic coil

The variable magnetic field is generated by alternating current in the electromagnetic coil which is the focus of the transducer design. The geometric size of electromagnetic is a major factor affecting the conversion rate. And the formula of the influence of the electromagnetic coil on the magnetic field is as follows:

\[ H_c = G_c \times \sqrt{\frac{R_c \times I \times F}{\sigma \times a_i}} \]  \hspace{1cm} (2)

where \( H_c \) is magnetic field intensity produced by coil, \( G_c \) is geometric shape parameter of coil, \( R_c \) is resistance of coil, \( I \) is exciting current intensity, \( F \) is coil conductor coefficient (value of circle is \( \pi/4 \)), \( \sigma \) is conductor resistivity, \( a_i \) is the radius of inner circle.

And the geometric parameter formula is:

\[ G_c = \frac{1}{a_i} \left[ \frac{2 \pi \beta}{2} \right]^{1/2} \ln \left[ \frac{a_i + (a_i^2 + \beta^2)^{1/2}}{1 + (1 + \beta^2)^{1/2}} \right] \]  \hspace{1cm} (3)

where \( \alpha \) is the ratio of outer radius to inner radius, \( \beta \) is equal to \( 1/2a_i \).

When wall thickness of electromagnetic coil equal to inner radius the geometric figure is the best, where \( \alpha \) is 2 and \( \beta \) is 3, and \( G_c \) is 0.179. When the length of coil is twice the inner diameter, the magnetic energy consumption of the electromagnetic coil is the lowest and the electromagnetic conversion rate is the highest, so the magnetic field intensity is relatively maximum.

4.3. Test result

The intensity of ultrasonic waves produced by PZT and TbDyFe transducer are compared. With the same input signal, the output signals of PZT and TbDyFe transducer are shown in Fig.5. And the test result of 5 times is shown in Tab. 1. The signal and result comparison show that the power produced by TbDyFe transducer is about 25 times to PZT transducer. And the TbDyFe alloy transducer can improve the conversion power of electromechanical system.

| Table 1. Test result of PZT and TbDyFe transducer |
|-----------------|-----|-----|-----|-----|-----|
| Peak value      | 1   | 2   | 3   | 4   | 5   |
| PZT             | 0.55| 0.48| 0.51| 0.49| 0.47|
| TbDyFe          | 13.8| 12.1| 11.5| 11.1| 10.9|

(a) PZT  
(b) TbDyFe  

Figure 5. Output signal of transducer
5. Conclusion
TbDyFe is used to replace magnetostrictive alloy is traditional ultrasonic transducer, which greatly improves the conversion efficiency of the electromechanical system. The developed TbDyFe transducer has the characteristics of high transmitting power, high sensitivity and strong environmental adaptability and can be used in other industrial testing.

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