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Measurement of Elastic Constants Using Halbach-Array Enhanced EMAT

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Abstract—**Elastic constants of metal can be extracted by measuring the ultrasound longitudinal and shear wave velocities. The Electromagnetic Acoustic Transducer (EMAT) technique provides a non-coupling approach to generate ultrasound. Aiming at the rapid determination of elastic constants, we propose an EMAT that can simultaneously excite and receive longitudinal and shear waves. In one aspect, the pole directions of permanent magnets in this array are arranged so that it obtains both horizontal and vertical magnetic fields. These two magnetic fields are required to generate longitudinal wave and shear wave. In another aspect, this magnetic array enhances the magnetic flux density. A planer array is fabricated with permanent magnets with an initial magnetic flux density of 444mT, the resulting magnetic flux density of the magnetic array is as high as 918mT. A square spiral coil is placed under the enhanced magnetic field to excite both shear and longitudinal waves. By measuring the time of flight (TOF) of longitudinal and shear echoes within a single receiving signal, ultrasonic velocities of shear wave and longitudinal wave are calculated with the knowledge of plate thickness. Elastic constants of the 7075 aluminum alloy and TA2 titanium plates are extracted subsequently. The comparison of the measured elastic constants and the previous researches' result implies the feasibility of the approach.**

Keywords—EMAT, planar magnet array, magnetic field enhancement, elastic constants

I. Introduction

Elastic constants of solid are the basis for evaluating its elasticity. Especially for the polycrystalline metallic materials, which are generally considered to be isotropic, two elastic constants are required to determine their elastic property. These two elastic constants are Lamé constants (λ, μ) or Young's modulus and Poisson's ratio (E, ν). In practice, it is non-destructive and convenient to measure elastic constants with ultrasound by measuring the plane wave velocities [1-3].

It is efficient to measure the velocities of longitudinal and shear wave simultaneously to determine these two elastic constants of isotropic material because both of them are related to the longitudinal and shear wave velocities [4-5]. At present, some investigations have focused on the design of the ultrasonic transducer that can generate both shear and longitudinal waves.

Mak [5] took advantage of wave mode conversion in the tested material to measure ultrasonic velocities of both wave modes. However, these PZT transducers require coupling mediums. Especially for shear waves, coupling medium with large viscosity is strongly required to couple the shear stress at the interface, which will result in various contact condition during measurement [6].

The Electromagnetic Acoustic Transducer (EMAT) technique requires no coupling medium and even no contact due to its ultrasound generation and detection mechanism [7]. An EMAT is composed of a bias magnetic field, a coil, and the tested material with good electrical conductivity [8]. According to the Lorentz's law of force, when the direction of the magnetic field is perpendicular to a metal plate surface (vertical magnetic field), the Lorentz force is along the surface and excites shear waves [9]. When the direction of the magnetic field is along the metal surface (horizontal magnetic field), the Lorentz force is perpendicular to the metal surface and excites longitudinal waves [10]. In addition, compared with shear wave EMATs, the longitudinal wave EMATs are less efficient. The less efficiency of longitudinal EMAT is due to (1) large coil-size air-gap, which reduced magnetic field strength; and high "non-active" coil, which increases the EMATs' impedance [10]. Hence, to design the EMAT that generates and receives both wave modes efficiently, it requires vertical and horizontal magnetic fields with high magnetic flux density and a low "non-active" excitation coil.

In this research, to measure the elastic constants with ultrasound efficiently, a novel EMAT is proposed to generate longitudinal wave and shear wave simultaneously. This EMAT is enhanced by a planar magnet array, which provides both vertical magnetic field and horizontal magnetic field and increases the magnetic flux density.

In the following of this paper, the details of the design of planar array are presented in section II, and three different magnetic arrays are compared in this section. The EMAT that can excite and receive both wave modes are verified in section III. Subsequently, Young's modulus and Poisson's ratio are measured by the designed EMAT in section IV.

II. Magnetic Field Enhancement by a Planar Magnet Array

According to the mechanism of longitudinal wave and shear wave EMAT, both horizontal and vertical bias magnetic fields are required to excite both longitudinal and shear waves. In addition, the efficient generation of both wave modes requires an enhanced magnetic field, and its direction is required to be designed so that all of the induced currents can contribute to the

Lorentz force. Hence, three different planar configurations are designed to obtain this magnetic field. Fig.1 shows the three magnet array configurations. For the eight cubes parts surrounding the central magnet in Fig.1(b), four parts are permanent magnets and points to the center, the other four are soft iron. In addition, the magnetic pole direction of edge permanent magnets is opposite to that of the center magnet, as shown in Fig.1(c). In the proposed planar array, as shown in Fig.1(d), horizontal magnets replace vertical magnets on the edge of the array to guide the magnetic line from the corner to concentrate on the central region.

The magnetic fields are calculated by the finite element method to obtain the magnetic flux density distributions of different magnetic arrays. Within these finite element models, the magnet array is composed of permanent magnets with dimensions of 5mm×5mm×5mm. The material of the permanent magnet was NdFe35 with a magnetic coactivity of 890000A/m.

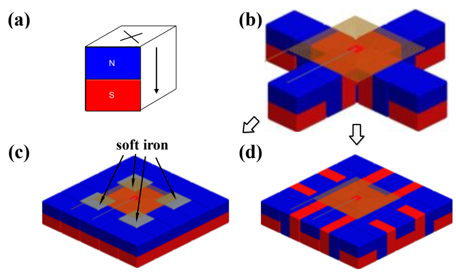


Fig.1. (a) The orientation of a single permanent magnet, (b) cross magnet array, (c) planar magnet array with soft iron, (d) the proposed planar magnet array.

The magnetic flux density on the surface 0.4mm above these arrays is plotted in Fig.2 to compare the magnetic flux density quantitatively. The sharp peaks in this figure are corresponding to the magnetic flux density on the edge of a single permanent magnet. In these edge regions, the magnetic flux density is significantly higher than that in their neighboring region. In addition, the cross magnet array obtained a higher magnetic flux density than the planar magnet array with iron. The magnetic flux density of the proposed planar magnet array is much higher than that of other configurations in the center region.

The magnetic field is required to be enhanced to excite the longitudinal and shear waves, and vertical and horizontal magnetic fields are also required. Fig.3(a) and Fig.3(b) plot the horizontal and vertical magnetic flux density distributions, respectively.

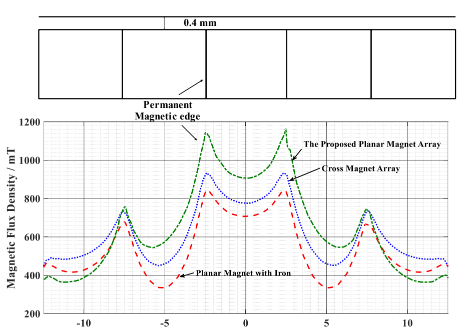


Fig.2. The magnetic flux density of different configurations of the magnet arrays.

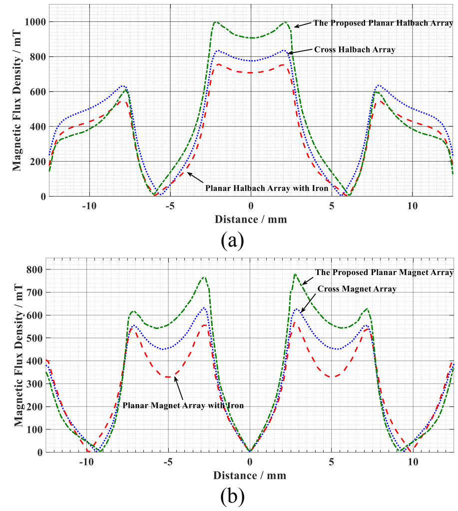


Fig.3. (a) The vertical magnetic flux density of different configurations. (b) The horizontal magnetic flux density of different configurations.

As Fig.3 indicated, apart from some distinct regions, the magnetic field is not strictly horizontal or vertical. These arrays obtained a high vertical magnetic flux density in the central region, whereas a high horizontal magnetic flux density in its neighboring region. Although the horizontal magnetic flux density is zero in the center, it increased dramatically from the center to the neighboring region and reached its maximum near the edge of the central permanent magnet. As for the vertical magnetic flux density, it is almost even in the center region. However, it reduces significantly in the neighboring area. Among these array configurations, the proposed planar magnet array obtained the highest horizontal and vertical magnetic flux density. Hence, it seems that the proposed magnet array provides the most promising performance.

A planar magnetic array is fabricated to verify the enhancement of the magnetic field with the proposed planar magnet array, as shown in Fig.4. This array consists of 25 cubic N52 NdFeB permanent magnets, and the dimensions of a single permanent magnet are 4.7mm×4.7mm×4.7mm. The magnetic flux density is measured with the Gauss meter, and the magnetic flux density on the strong side center is 939.6mT. For a single permanent magnet, its magnetic flux density is 444.4mT.

Fig.4. (a) The fabricated planar magnet array. (b) A single permanent magnet.

III. Design and Verification of the Proposed EMAT

According to the generation mechanism of the longitudinal and shear waves with EMAT, in order to generate longitudinal and shear waves simultaneously, the square spiral coil is required to cover both the central region and its neighboring area. Three different coils were designed in this study. A vertical coil covered only the central region, a square ring coil covered only the horizontal region, and general square coil covered both regions, as shown in Fig.5.

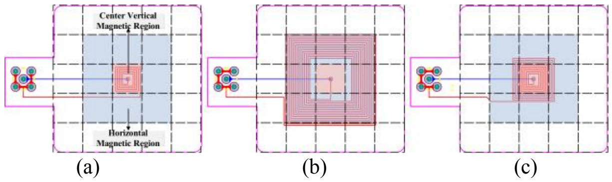


Fig.5. (a) The square coil covers the vertical magnetic field region. (b) Ring square coil covers the horizontal magnetic field region. (c) The square coil covers both the horizontal and the vertical magnetic field region.

The proposed EMAT consisted of a PCB board with the coil, an MMCX connector, a planar magnet array, and the outer covering, as shown in Fig.6. Pulse-echo approach was applied. After the EMAT excited ultrasound, the ultrasound wave propagated through the thickness and reflected from the bottom side of the plate. The same EMAT will receive a sequence of echoes.

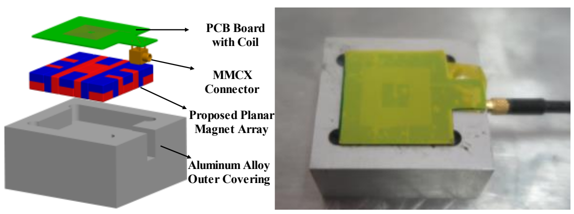
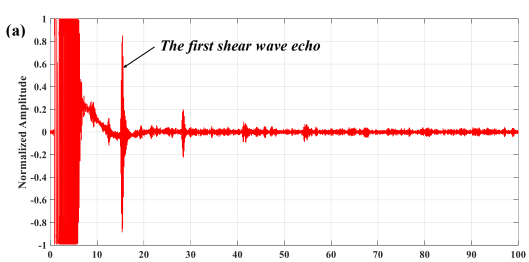


Fig.6. The design of the EMAT assembly. (a) Components of the EMAT, and (b) the fabrication of the EAMT.

Aluminum alloy plate with a thickness of 20.32mm was tested to verify the feasibility of ultrasound. The transmitting and receiving signals for different coil were shown in Fig.7. As shown in Fig.7(a), the time of flight (TOF) between two adjacent echoes was 13.26μs, and the calculated velocity is 3063.6m/s. This velocity magnitude was corresponding to the shear wave velocity in aluminum alloy. As for these echoes in Fig.7(b), the TOF between two adjacent echoes was 6.47μs, and the calculated velocity was 6278.4m/s. This velocity magnitude was corresponding to the longitudinal wave velocity in aluminum alloy.

However, the receiving waveforms of the coil that covered both magnetic regions were quite complex, as shown in Fig.7(c). The first longitudinal echo was in the dead zone of the waveform. Because the longitudinal wave velocity in the aluminum alloy was almost twice of the shear wave velocity, the second echo of the waveform was the overlap of the first shear wave echo and the second longitudinal wave echo. In addition, the amplitude of two adjacent shear wave echoes was higher than that of the longitudinal wave. This confirmed that when the coil covered both the horizontal and vertical magnetic region of the proposed planar magnet array, the EMAT was able to excite and receive both longitudinal and shear waves.



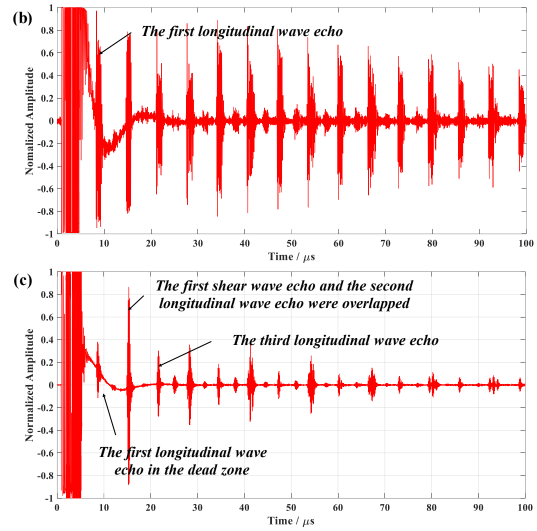


Fig.7. Receiving waveforms of three different coil: (a) square coil that covered the vertical magnetic field region, (b) square coil covered the horizontal magnetic field region, (c) square coil covered both regions.

IV. MEASUREMENT OF ELASTIC CONSTANTS

Polycrystalline metal is generally regarded as linear isotropic material. Two elastic constants are required to describe its elastic property. These two elastic constants are in pairs, and they are Lamé constants (λ, μ) or Young's modulus and Poisson's ratio (E, ν). Additionally, for the case of longitudinal wave and shear wave propagation in the metal plate, their velocities are intrinsically related to elasticity or two elastic constants of the metal. The longitudinal wave velocity c_l and shear wave velocity c_s are:

$$c_l = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{E(1-\nu)}{(1-2\nu)(1+\nu)}} \tag{1}$$

$$c_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2(1+\nu)\rho}} \tag{2}$$

Two different metal plates are measured: a 7075 aluminum alloy plate and a TA2 titanium plate. The dimension and mass density of these two metal plate samples are shown in TABLE I. The first dimension of the plates is the thickness of the sample.

TABLE I DETAILS OF THE METAL PLATE SAMPLE

Material	Dimensions (mm)	Mass (g)	Density (kg/m^3)
7075 Aluminum Alloy	20.32×100.78×201.03	1151.4	2796.84
TA2 titanium	30.12×83.42×123.25	1398.1	4514.67

where ρ is the mass density of the metal.

The receiving waveforms of the proposed EMAT are shown in Fig.8 and Fig.9. However, the longitudinal echo and the shear echo are overlapped. Hence, the TOF of longitudinal echo is decided by the first and third longitudinal wave echoes, because these two longitudinal wave echoes are not contaminated by shear waves.

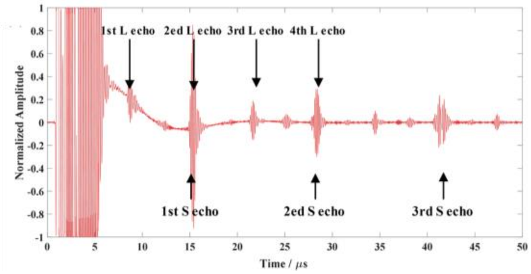


Fig.8. Receiving waveforms when measuring the 7075 aluminum alloy plate.

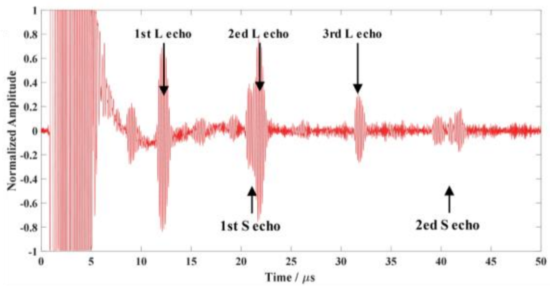


Fig.9. Receiving waveforms when measuring TA2 titanium plate.

For the shear wave echo, its amplitude is much higher than that of the longitudinal wave echo. The TOF of shear waves is calculated directly by the first shear wave echo. After the TOFs of longitudinal wave echo and shear wave echo are calculated, the ultrasonic velocities of these two wave modes are calculated with the knowledge of the plate thickness, and their elastic constants of these two metal plate can also be drawn, as shown in TABLE II. The measured Young's modulus was comparable to previous research [11] and tested data, which verified the feasibility of the measurement approach.

TABLE II THE CALCULATED RESULTS

Material	7075 Aluminum Alloy	TA2 Titanium
LTOF (μs)	6.4730	9.8338
STOF (μs)	13.2653	19.0088
c_l (m/s)	6278.39	6125.81
c_s (m/s)	3063.62	3169.06
Young's Modulus (GPa)	70.55	119.45
Poisson's Ratio	0.34	0.32

LTOF stood for TOF of longitudinal wave echo, STOF stood for TOF of shear wave echo.

V. THE CONCLUSION

A novel EMAT that can excite and receive longitudinal and the shear waves is proposed. This EMAT is applied to measure elastic constants of aluminum alloy plate and a titanium plate. The main conclusions are as:

(1)The proposed planar magnet array generates both horizontal and vertical magnetic field on the strong side. In addition, this array also enhances the magnetic flux density to 939mT on the strong side, which is about twice of the magnetic flux density of a single permanent magnet.

(2)By using the proposed planar magnet array, different ultrasonic modes can be excited. When the square spiral coil that covers both horizontal and vertical magnetic regions is employed, longitudinal and shear ultrasound can be excited and received.

(3)When using the EMAT that can excite and receive the longitudinal and shear waves, the shear wave echos will be overlapped by the longitudinal wave echos in the receiving waveform. This is due to the longitudinal wave velocity is about twice of the shear wave velocity. As the amplitude of the shear wave echo single is much larger than that of longitudinal wave echo, its TOF can be calculated by the first shear echo. As for the longitudinal wave echo, the TOF is calculated by the 1st and 3rd longitudinal wave echoes. The elastic constants can be calculated with the longitudinal and shear wave velocities, and they fit well with previous researches.

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