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DESIGN AND CALCULATION OF THE SHEAR HORIZONTAL WAVE MAGNETOSTRCITIVE PATCH TRANSDUCER BASED ON WIEDEMANN EFFECT

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ABSTRACT

The lowest-order shear horizontal model SH0 wave shows a great advantage in nondestructive testing (NDT) and structural health monitoring (SHM), due to the low-attenuation and non-disperse properties. In order to excite SH0 waves in non-ferromagnetic plate, this paper presents a modified design of the magnetostrictive patch transducer (MPT) based on Wiedemann Effect, which consists of an annular magnetostrictive patch, an electric toroidal coil and a permanent magnet. The cylinder permanent magnet is wider than the magnetostrictive patch to ensure the uniform distribution of the static magnetic field on directivity and amplitude. After presenting the configuration and its working principle, the governing equation of Wiedemann Effect are derived based on the theory of Joule Effect through coordinate transformation, which represents the relationship between the deformation behavior and the magnetic field. It is found that only shear stress and strain vary with additional static longitude and dynamic tangential magnetic field. The principle of the modified model is investigated by finite element simulation, which shows the optimization methods of the new model and verifies the validity of the derived equation.

Keywords: magnetostriction, Wiedemann Effect, shear horizontal wave, governing equation, coordinate transformation

NOMENCLATURE

λ	the wave length of excited ultrasonic waves
r_i	the inner radius of the magnetostrictive patch
r_o	the outer radius of the magnetostrictive patch
h	the thickness of magnetostrictive patch
μ_r	the relative permeability of nickel
E^*	Young's modulus of nickel patch
λ_m	the magnetostriction constant of nickel

1. INTRODUCTION

In recent years, the exploiting of ultrasonic guided waves in nondestructive testing (NDT) and structural health monitoring (SHM) has been widely investigated due to the long propagation capability with low attenuation and excellent sensitivity to multiple defects. Compared with Lamb waves, shear horizontal waves, especially the lowest order model SH0 waves, show more simple dispersion characteristics and less mode-conversion in the propagation behavior, which leads to easier signal interpretation and more reliable NDT methods. As a result, several types of SH wave transducers have been developed and employed in the inspection of plate and pipe-like structure. The magnetostrictive patch transducer (MPT), a type of new transducer based on the magnetostriction effect, has been proposed and developed recently. MPTs have some critical advantages over other transducers such as good sensitivity, durability, no direct wiring to a transducer or a test specimen itself, long-range inspection, easy implementation, and cost-effectiveness.

In general, a MPT consists of a magnetostrictive patch, an electric coil and a permanent magnet. The coils and magnets induce dynamic and static magnet field, respectively. As the key element of a MPT, the magnetostrictive patch is glued or fixed on the surface of specimens to excite and receive ultrasonic waves through magnetostrictive transduction. Magnetostriction is a coupling phenomenon of dimension or shape change caused by the magnetization in ferromagnetic materials such as iron, nickel and some rare earth alloy. Joule Effect, which refers to the change in length or size, is widely applied in the design of MPTs. Wiedemann Effect refers the shearing deformation in a ferromagnetic material generated by a static and a dynamic magnetic field perpendicular to each other.

This paper proposes a modified design of a shear horizontal wave magnetostrictive patch transducer based on Wiedemann Effect (WE-MPT). The new type of transducer applies a wider

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permanent magnet than the magnetostrictive patch to ensure the uniform distribution of static magnetic field on directivity and amplitude. After analyzing the working principle, we derive the governing equation of Wiedemann Effect based on that of one-dimensional Joule Effect, which characterizes the relationship between the strain and the magnetic field and proves that the torsional deformation of Wiedemann Effect is a special manifestation of the elongation deformation of Joule Effect. Finite element simulation is applied to optimize magnet and coil parameters and verify the validity of the derived equation.

2. CONFIGURATION AND CALCULATION

In this section, the detailed configuration of the modified design of WE-MPT will be given and the derivation process of the governing equation will be proposed.

2.1 Configuration of the MPT

The schematic diagram of the modified design of WE-MPT is shown in Figure 1. The new type of transducer consists of an annular magnetostrictive patch, an electric toroidal coil and cylinder permanent magnet. To avoid the non-axisymmetric problem of the torsional deformation, we choose a magnetic isotropic materials of nickel as the magnetostrictive material. The annular nickel patch is glued onto the surface of aluminum plate. The geometric parameters of the magnetostrictive patch are provided as follow: the inner radius $r_i=\lambda/4$, the outer radius $r_o=3\lambda/4$, the height $h=0.5mm$, and λ is the wave length of the target SH0 mode wave at an excited frequency. This configuration resulting $r_o-r_i=\lambda/2$ ensures that the largest circumferential displacements occur on the inner and outer circumferences of the annular patch, respectively. The cylinder permanent magnet is wider than the nickel patch to ensure the uniform distribution of the provided static longitudinal magnetic field on directivity and amplitude. The specific parameters setting will be optimized in the simulation. The electric toroidal coil twined around the thin patch provides dynamic magnetic field controlled by electric signals.

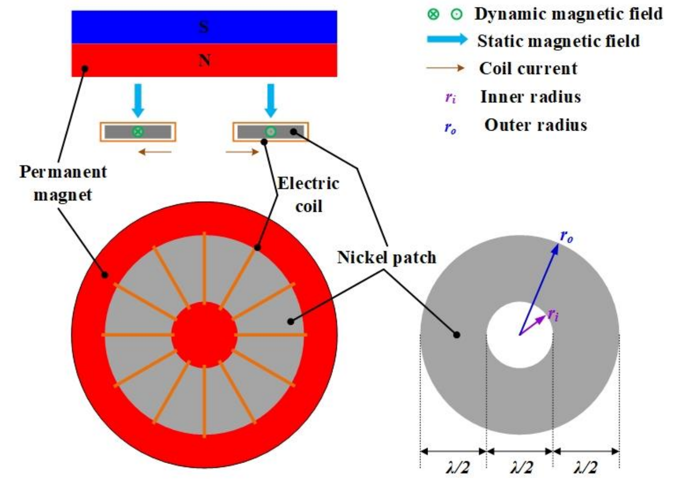

FIGURE 1: THE SCHEMATIC DIAGRAM OF THE MODIFIED DESIGN OF WE-MPT WITH INDICATIONS OF THE MAGNETIC FIELD DIRECTIONS IN THE PATCH PROVIDED BY THE COIL AND MAGNET.

2.2 Calculation of the Wiedemann Effect

The basic equation of one-dimensional Joule Effect has been proposed, shown as

$$H = \frac{1}{\mu_r} B - 4\pi\lambda \frac{\partial u}{\partial z} \tag{1}$$

$$\sigma = E * \frac{\partial u}{\partial z} - \lambda B \tag{2}$$

Taking a micro surface element as calculated object, the magnetic field and strain is analyzed and calculated through coordinate transformation, shown as Equation (3), (4) and (5). The results prove that Wiedemann Effect is a special manifestation of the elongation deformation of Joule Effect and show only torsional deformation occurs in the patch with the variation of dynamic torsional magnetic field.

$$\begin{bmatrix} H_x \\ H_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H_z \\ H_\theta \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \varepsilon_z \\ \varepsilon_\theta \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} \Delta\varepsilon_z \\ \Delta\varepsilon_\theta \end{bmatrix} = \begin{bmatrix} \Delta\varepsilon_x \\ \Delta\varepsilon_y \end{bmatrix} \begin{bmatrix} 0 & 0 \\ 0 & \tan\alpha\sin\alpha + \cos\alpha \end{bmatrix} \tag{5}$$

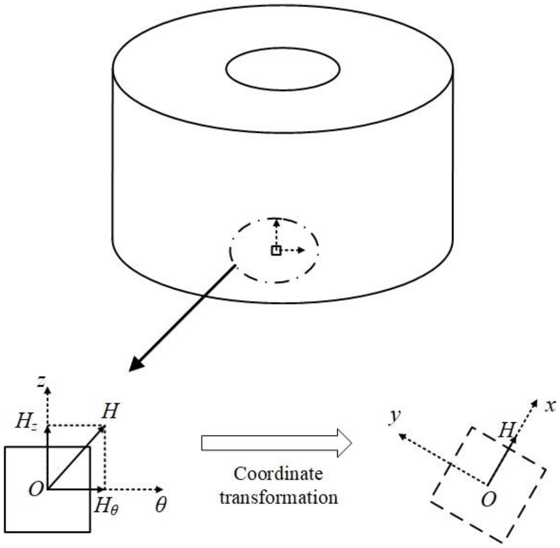

FIGURE 2: THE COORDINATE TRANSFORMATION OF A MICRO ELEMENT FROM THE CURVE SURFACE OF THE MAGNETOSTRICTIVE PATCH

The governing equation of Wiedemann Effect could be derived with the combination of the stress analyzation and the polar moment of inertia formula of the annular patch, shown as Equation (6), (7) and (8). The Equation (8) represents the relationship between torsional deformation and magnetic field.

$$I_p = \frac{1}{2}\pi(r_o^{\,4} - r_i^4) = \frac{\pi D^4}{32}(1-\alpha^4) \tag{7}$$

$$J = \frac{1}{2}m(r_o^{\,2} + r_i^2) \tag{8}$$

$$\frac{\partial^2 \varphi}{\partial z^2} - a^2 \frac{\partial^2 \varphi}{\partial t^2} = f(z,t) \tag{9}$$

Here, a is a parameter related to the relative permeability, Young’s modulus and the shear wave velocity of the nickel patch.

3. RESULTS AND DISCUSSION

To optimize the parameters of the coil and patch, three-dimensional finite element simulation is carried out with the simplified model shown as Figure 3. Then the excitation process of ultrasonic wave is simulated to verify the validity of the derived equation of Wiedemann Effect and the feasibility to excite shear horizontal wave with WE-MPT.

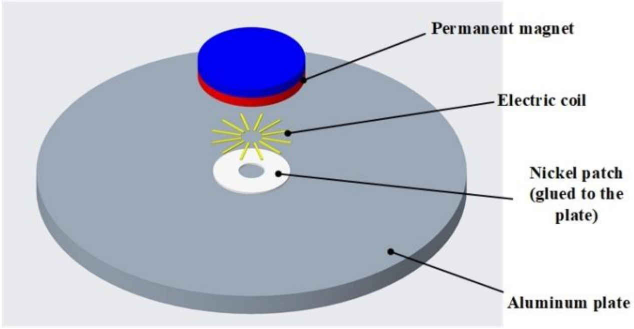

FIGURE 3: SCHEMATIC DIAGRAM OF THE MODIFIED DESIGN OF WE-MPT WITH INDICATIONS OF THE MAGNETIC FIELD DIRECTIONS IN THE PATCH PROVIDED BY THE COIL AND MAGNET.

4. CONCLUSION

Based on Wiedemann Effect, a modified design of MPT is proposed. After presenting the working principles, governing equation of two-dimensional Wiedemann Effect is derived based on the theory of one-dimensional Joule Effect. Finite element simulation is carried out to optimize parameters and verify the validity of the derived equation.

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