# Impact of Magnetostriction Mechanism on Frequency Manipulation Ultrasonic Steering in EMAT

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In this paper, the impact of the magnetostriction mechanism is taken into consideration for the main idea. The axisymmetric FEM model of the spiral-coil EMAT is established to implement the simulation. With the help of the simulation, it is demonstrated that the directivity of ultrasonic wave can be manipulated by frequency. And it is found that the direction of Lorentz force that dominates in the rail varies with time, but the magnetostrictive force compels the ultrasonic wave mainly generated by the Lorentz force to the axis. This describes well that the power of two combined mechanisms is greater than that of only the Lorentz-force mechanism at low frequency.

*Introduction:* In electromagnetic acoustic transducers (EMAT) for rail inspection, the leakage of the reflected energy of the ultrasonic wave outside the receiving range will weaken the amplitude of ultrasonic echo [1-4] and then affect the ability to identify the defects, especially for the defect under the rail bottom [5]. As can be seen from Fig. 1, the ultrasonic wave is reflected at an angle in the interface, when the ultrasonic wave enters the solid at the angle. Because of the incident angle, the spiral-coil EMAT working in duplex mode cannot receive the reflected wave outside the receiving range, which is referred to as the leakage of the reflected energy here. Therefore, to reduce the impact on rail inspection, the incident angle should be decreased through manipulating ultrasonic steering.

Ultrasonic steering can be manipulated by the frequency of the excitation, as well [1,5]. The method is relatively easier than the phase delay to realize the ultrasonic steering manipulation. Because of the high permeability in a ferromagnetic material, the skin depth of rail is very thin. Under the circumstances, the ultrasonic source in the transducer area can be regarded as a point source, and the incident angle of the generated ultrasonic wave inside an aluminum plate is related to the frequency of the excitation, which has been discussed in [1]. In this publication, Hill and Dixon investigate that the shear horizontal wave (SH wave) can be steered by frequency in periodic permanent magnet EMAT (PPM EMAT) that is simplified as is shown in Fig. 1.

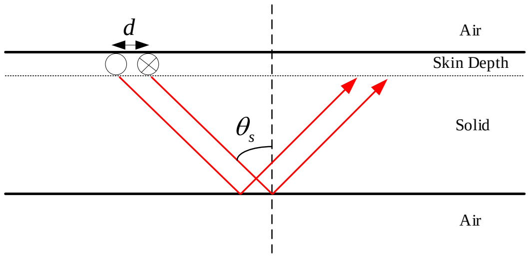


**Fig 1** *Ultrasound reflection in the interface between solid and air.*

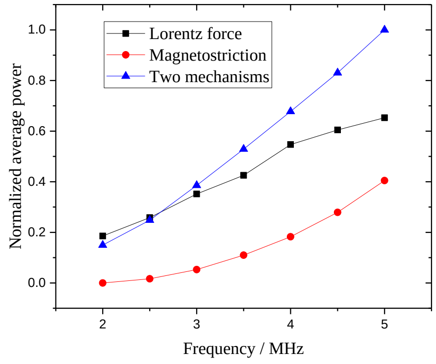


**Fig 2** *The normalized average power with frequency at three cases [5].*

Both the Lorentz-force mechanism and the magnetostriction mechanism works in rail. The Lorentz force is dominant, but the magnetostrictive force has an impact on the received echo, especially at low magnetic flux density. This case is discussed in the publication [5]. As is shown in Fig. 2, the echo signal under the Lorentz-force mechanism is stronger than that under the combined action of two mechanisms at low frequency. This indicates that the received signal is affected when the magnetostriction mechanism works. However, the impact of the magnetostriction mechanism on the ultrasonic steering is not considered in the previous publication. Accordingly, considering the magnetostrictive effect in rail, the frequency manipulation ultrasonic steering is studied through FEM simulation in this paper.

*The principle of spiral-coil EMAT:* The governing equation of wave is given [7]:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot \boldsymbol{\sigma} + \mathbf{F} \qquad (1)$$

Where $\mathbf{u}$, $\boldsymbol{\sigma}$, and $\mathbf{F}$ denote the displacement, the stress, and the outer force, respectively; $\rho$ is the density.

**Lorentz-force mechanism**. The configuration of the spiral-coil EMAT is shown in Fig. 3 of the publication [5] and consists of the spiral coil, a permanent magnet, and a rail. Based on the Maxwell equations, assuming that the alternating current with high power flows into the spiral coil, the dynamic magnetic field is generated in space and the eddy current is thus generated in the skin depth of the rail. Then, the eddy current interacts with the static magnetic field generated by the permanent magnet produce the Lorentz force $\mathbf{F}_L$:

$$\mathbf{F}_L = \mathbf{B}_0 \times \mathbf{J}_e \tag{2}$$

Where $\mathbf{B}_0$ is the static magnetic flux density; $\mathbf{J}_e$ is the eddy current.

**Magnetostriction mechanism**. In a ferromagnetic material, the constitutive equation is given [7]:

$$\varepsilon_I = S_{IJ}^H \sigma_J + d_{I\lambda}^{MS} H_\lambda \tag{3}$$

Where $\varepsilon_I$, $\sigma_J$, and $H_\lambda$ are the strain, the stress, and the magnetic field, respectively; $S_{IJ}^H$ and $d_{I\lambda}^{MS}$ are the compliance matrix and the piezomagnetic coupling matrix, respectively; $I, J = 1,2,\cdots,6$ ; . The magnetostrictive force in rail is originated from the magnetostrictive strain. That is to say, the magnetostrictive force can be obtained by the displacement of the particle [8]:

$$\mathbf{F}_M = -\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \tag{4}$$

Then, according to the relationship between the strain and the displacement of the particle, the magnetostrictive force can be obtained [8]:

$$F_{Mx} = -\rho\omega^2 \int_z^{-\infty} \varepsilon_5 dz \, , F_{My} = -\rho\omega^2 \int_z^{-\infty} \varepsilon_3 dz \tag{5}$$

*FEM simulation and result:* To further study the impact of the magnetostrictive effect in rail, a FEM model of the spiral-coil EMAT is established here. According to the structural features of the spiral-coil EMAT, the axisymmetric model is given as shown in Fig. 3. It is noted that the center of a semicircle, i.e., the conductor in Fig. 3, is the origin of the coordinate system.

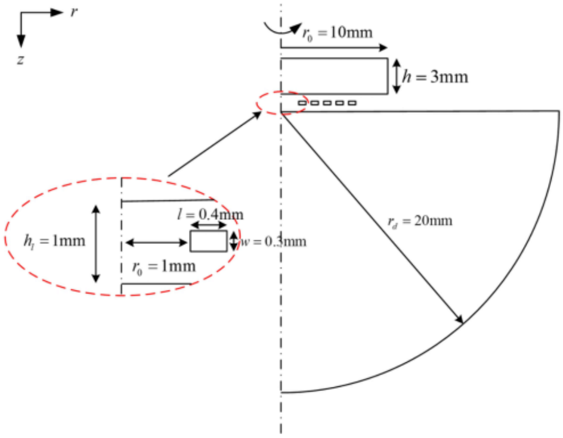


**Fig 3** *The axisymmetric model of a spiral-coil EMAT.*

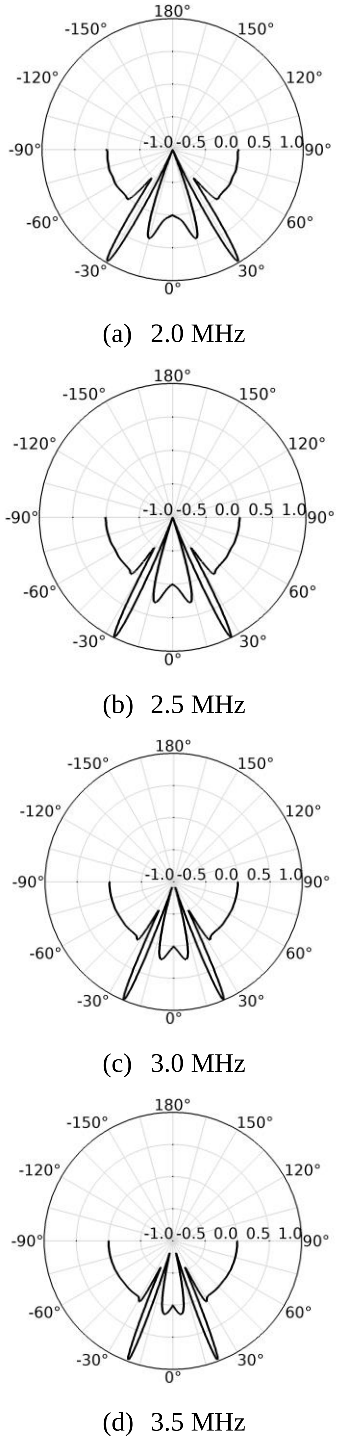


**Fig 4** *The directivity of ultrasonic displacement wave.*

Fig. 4 shows the directivity of ultrasonic displacement wave at various frequencies. It results are obtained by the displacement of the ultrasonic wave along the curvature of the semicircle of Fig. 3. It can be found that the maximum incline angle is 30 degrees at 2 MHz. The directivity of the ultrasonic wave varies with the frequency increasing, and the incline angle is also reduced as the frequency. Therefore, the directivity of ultrasonic wave can be steered by the excitation frequency.

No matter what the Lorentz force or the magnetostrictive force, the shear force is the main contribution to generate the ultrasonic wave. Hence, the normal force is not considered here. Fig. 5 shows the comparison of the shear force of both mechanisms in the time domain. It can be known from Fig. 4 that there is a phase difference between both forces. Therefore, the function of both forces is different at the same time. For example, the direction of both forces is the same at 1 us, but different at 1.5 us. It is indicated that the Lorentz-force mechanism and the magnetostriction mechanism reinforce each other at one moment and weaken each other at other moments, which is reflected in Fig. 5.

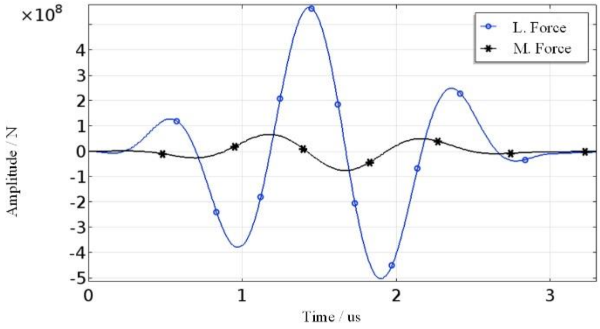


**Fig 5** *The shear force of two mechanisms at a point (2.5mm, -0.01mm) with time. Noted: L. force and M. force denote the Lorentz force and magnetostrictive force.*

(a) 1 us

(b) 1.2 us

(c) 1.5us

(d) 1.6us

**Fig. 6** *Changes in the direction of two mechanisms at z = -0.01 mm. Red line: magnetostrictive force; Blue line: Lorentz force. The arrow denotes the direction.*

As is mentioned above, the interaction of both forces is different in time scale, and it still exists in spatial scale. As is shown in Fig. 6, the direction of Lorentz force changes with time along the straight line, and thus the interaction of both forces not only reinforces but also weakens. According to the analysis, the Lorentz force does not have a force in the normal direction when it is close to the central axis of the magnet, but it gradually increases when it is close to the edge of the outer surface of the permanent magnet. Although the normal-direction Lorentz force in the normal direction is smaller than the radial-direction one, it can affect the direction of the resultant force. For example, it can be known that the resultant force is completely parallel to the surface of the magnet, while at the outer edge of the magnet it will point to the upper right corner or the lower right corner. Currently, the Lorentz force compels ultrasonic wave to propagate at an incline angle, causing a part of energy out of the received coil. However, the magnetostrictive force only exists in the radial direction. At a certain moment, it will strengthen or weaken each other with the Lorentz force, but it will always enhance the Lorentz force to the axis. That is to say, the magnetostriction mechanism can reduce the incline angle. This is why the power of the two mechanisms is greater than that of the Lorentz-force mechanism in Fig. 3.

*Conclusion:* In this paper, a FEM model of the spiral-coil EMAT in rail is established. It can be known from the simulation that the maximum incline angle is 30 degrees at 2 MHz, and the incline angle is decreased as the frequency. Therefore, the directivity of ultrasonic wave can be steered by the excitation frequency. In addition, the fact is that the Lorentz-force mechanism is dominant in rail, and the magnetostriction mechanism has an inconspicuous effect. However, considering the magnetostriction mechanism, the magnetostrictive force can compel the ultrasonic wave to propagate to the axis.

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## References

1. Hill S, Dixon S: Frequency dependent directivity of periodic permanent magnet electromagnetic acoustic transducers, NDT & E International, 62 (2014), 137–143.
2. Dixon S, Hill S, Fan Y, et al. The wave-field from an array of periodic emitters driven simultaneously by a broadband pulse. Journal of the Acoustical Society of America, 133 (2013), 6, 3692.
3. Xie Y, Liu Z, Yin L, et al. Directivity analysis of meander-line-coil EMATs with a wholly analytical method. Ultrasonics, 73 (2017), 262-270.
4. Ogi H, Goda E, Hirao M. Increase of efficiency of magnetostriction SH-wave electromagnetic acoustic transducer by angled bias field: piezomagnetic theory and measurement. Japanese Journal of Applied Physics, 42 (2003), 3020-3024.
5. Li Y, Liu Z, Miao Y, et al. Study of a spiral-coil EMAT for rail subsurface inspection. Ultrasonics, 108 (2020),106169.
6. Su R, Chen X, Yin J, et al. Unidirectional line-focusing electromagnetic acoustic transducer. Journal of Beijing Institute of Technology (English Edition), 22 (2013), 139-142.
7. Hirao M, Ogi H. EMATs for science and industry: noncontacting ultrasonic measurements. Springer Berlin, 2014.
8. Li Y, Liu Z, Yuan W, et al. Analytical model and analysis of spiral-coil EMAT above a ferromagnetic plate. IEEE Transactions on Magnetics, 56 (2020), 9, 6200710.