Research Article

Investigating the Influence of Design Frequency on the Ultrasonic Signal of PFSV-EMATs

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The point-focusing shear vertical wave electromagnetic acoustic transducer (PFSV-EMAT) with a concentric meander line (CML) coil has been developed to detect and size micro defection concealed within a certain depth of materials. It is proved to be sensitive to the design frequency, which is associated with the spacing of CML coil. In this work, the relationship between the design frequency and characteristic of PFSV-EMATs, such as the particle displacement and focal offset, is studied quantitatively. First, the configuration and working principle of PFSV-EMATs are introduced comprehensively. Then, a finite element model is established to simulate the incentive and propagation process of ultrasonic waves. In addition, the relationship between magnet-to-coil radius ratio and the signal amplitude generated by the PFSV-EMATs is explored to ensure the consistency of transducer parameters at different frequencies. Furthermore, under the optimal magnet-to-coil radius ratio, the influence of design frequency on the characteristic of PFSV-EMATs is studied. Finally, the experimental results show good agreement with the simulation results and indicate that the signal amplitude and point-focusing performance of PFSV-EMATs employing CML coils could be improved by carefully choosing the design frequency.

1. Introduction

Recently, various inspection techniques applicable for the nondestructive testing and evaluation (NDT&E) of key structural components have attracted much attention in many fields, especially in industry. The NDT&E methods include ultrasonic testing (UT), magnetic flux leaking (MFL), alternating current field measurement (ACMF), eddy current testing (ECT), etc. [1–5]. Among the NDT&E methods mentioned above, electromagnetic ultrasonic transducer (EMAT) as a nonconduct UT approach is widely used for thickness measurement and material characterization due to its ability to generate and receive ultrasonic waves without physical contact or coupling with the surface of the workpiece being inspected.

Also, since its inherent feature of no coupling and physical contact, EMATs are particularly used in automated inspection and harsh environments, such as hot, cold, and dry condition. For instance, EMATs with internal cooling allow them to work under high temperature environments

in excess of 500°C [6, 7]. More importantly, based on different combinations of permanent magnets/electromagnets and coils, EMAT can easily generate shear horizontal (SH) waves [8–10], shear vertical (SV) waves, Lamb waves [11, 12], Rayleigh waves, and all sorts of other guide wave modes in conductive and ferromagnetic materials [13].

However, the main drawback of EMATs is the weak energy conversion efficiency, hindering its further widespread application, especially in defect detection. In addition, the elastic waves launched by EMATs propagate in both directions with broad radiation patterns inside a solid, which is undesirable for flaw detection purpose. Moreover, the broad radiation patterns decrease the ultrasound waves to be concentrated on the target flaw.

Fortunately, many attempts were made to concentrate the ultrasound waves launched by EMATs towards a focal line or point with sharp directivity in the existing literature [14–22]. In [20], Takishita et al. presented a point focusing shear vertical electromagnetic ultrasonic transducer

FIGURE 1: (a) Configuration of the PFSV-EMAT with the CML coil and (b) side-view sketch of the Lorentz force distribution in a metallic plate.

(PFSV-EMAT), which is a specially designed array of the meander-line elements. Nakamura et al. reported the application of PFSV-EMAT to the stress corrosion cracking of welded stainless steel pipes, whose results demonstrated that the defect detectability and spatial resolution is sensitive to the deviation of the design frequency of PFSV-EMATs [22]. However, the cycles of the excitation burst signal are not guaranteed to be the same, indicating the design frequency being not the only variable. Summarily, PFSV-EMATs have the advantages of narrow radiation pattern and high signal-to-noise ratio but have the disadvantage of being susceptible to the excitation frequency.

In addition, a numerical analysis was performed by means of orthogonal test methods, indicating that the design frequency of PFSV-EMATs, i.e., the closeness degree of coil spacing, has a significant influence on the signal amplitude of ultrasonic waves and point-focusing performance [23]. However, this analysis is not exhaustive and does not take into account the magnet size, which does have a strong effect on signal amplitude [23, 24]. For instance, in [24], the effect of varying a magnet-to-coil width ratio on the signal amplitude was analyzed, whose results indicated that a magnet width is about 20% larger than that of the coil yielded waves that is about 10% stronger and better collimated than a magnet whose width is equal to that of the coil. Another interesting phenomenon is that the amplitude of Rayleigh waves tends to reach its maximum value when the width of the magnet is narrower than the coil, which is inconsistent with the conventional case in the design process of EMATs [25]. In light of the background above, the impact of working frequency, i.e., the closeness degree of the coil spacing, on the performance of PFSV-EMATs has not yet been presented, which is the motivation of our work.

This work is aimed at investigating the influence of design frequency on signal amplitude of PFSV-EMATs with a constantly changing coil spacing and gives a suitable deviation of design frequency. The organization of this work is as follows. Section 2 introduces the configuration and basic

working principle of PFSV-EMATs under Lorentz force mechanism. Section 3 analyzes the influence of design frequency using the established finite element model of PFSV-EMATs designed with different operating frequency. Then, the experiment was carried out to verify the validation of the simulation in Section 4. Finally, the conclusions are drawn in Section 5.

2. The Configuration and Working Principle of PFSV-EMATs

2.1. Configuration of PFSV-EMATs. Figure 1 shows the configuration and working principle of the PFSV-EMAT, which consists of three components, i.e., a cylindrical permanent magnet, a concentric meander line (CML) coil, and a metallic specimen [20]. The permanent magnet with axial polarization adopted here is perpendicular to the surface of the specimen located on the CML coil, which is sintered from NdFeB (neodymium iron boron) material to provide a strong static magnetic field. As shown in Figure 1, the CML coil marked with a yellow solid line is a concentric meander-line coil with constantly changing spacing, enabling the ultrasound waves to focus on a point inside the specimen. In this work, an aluminum plate is used as the metallic specimen, a medium for the launching, and transmitting ultrasonic waves. For the convenience of analysis, a cylindrical coordinate system is established with the origin located at the center of the CML coil in Figure 1, where r , θ , and z , respectively, represent the radial, circumferential, and thickness direction of the aluminum specimen.

The arrangement of the CML coil is schematically presented in Figure 2, which illustrates the positional relationship between each line element and focal point. As shown in Figure 2, $(0, 0, z_F)$ is the location of the focal point. R_i is the radius of the i_{th} segment on the horizontal plane, and r_i is the radius of the concentric circle where the i_{th} line source is, i.e., the straight-line distance between the i_{th} line source and focal point. According to the principle of line-

FIGURE 2: Design of coil spacing for point-focused vertical shear wave EMATs.

focusing, the geometric relationship of two adjacent line sources should satisfy [14]:

$$r_i - r_{i+1} = \frac{c}{2f} = \frac{\lambda}{2}, \quad (1)$$

$$r_i = \sqrt{R_i^2 - z_F^2}, \quad (2)$$

where f is the design frequency of PFSV-EMAT and c and λ are the velocity and wavelength of shear vertical waves, respectively. Once the design frequency f and the velocity of SV waves c , the depth of focal point z_F is determined, and the position of each line source can be calculated. In addition, the position of each line source is guaranteed at the intersection of the surface and concentric circles, enabling the phase of the ultrasonic wave equal at the focal point.

2.2. Theoretical Considerations. It is well known that, in EMATs, ultrasonic waves are produced directly within the materials mainly due to Lorentz force mechanism for paramagnetic materials, magnetization, and magnetostrictive force mechanisms for ferromagnetic materials. In this work, the material used as the specimen is aluminum plate, which is a paramagnetic material. Therefore, the main focus of this paper, the Lorentz force mechanism, is assumed the dominant mechanism; this assumption is sound base on [2, 3, 16, 24]. Other mechanisms, such as magnetization and magnetostrictive force mechanisms, are ignored.

In a paramagnetic materials, the excitation of acoustic waves by an EMAT is due to the Lorentz force acting on the eddy current in the present of a magnetic field, which is described below. An alternating current (AC) passing through an electric coil generates a reciprocal eddy current $\mathbf{J}_e$ in the electromagnetic skin of the material. Then, the eddy current $\mathbf{J}_e$ interacts with the bias magnetic field $\mathbf{B}_s$ to produce Lorentz forces $\mathbf{F}$ on the free electrons, which is perpendicular to both the bias magnetic field $\mathbf{B}_s$ and eddy current $\mathbf{J}_e$. This force field acts as a radiation force of SV waves, which is formed by the momentum exchange between the conduction electrons and lattice forms ultrasonic waves through mechanical collision [26, 27]. Afterwards, the SV waves are launched and propagate along the oblique path, then focus on a design focal point inside the metallic materials.

The Lorentz force due to the static and dynamic magnetic fields is governed by [2]:

$$\mathbf{F} = \mathbf{J}_e \times (\mathbf{B}_s + \mathbf{B}_D) + q\mathbf{E}, \quad (3)$$

in which $\mathbf{B}_s$ is the static magnetic field due to permanent magnets only. $\mathbf{B}_D$ is the dynamic magnetic field due to other contributions, e.g., eddy current. In general, the $\mathbf{B}_D$ term is smaller compared with the static one, so it is neglected in this work [28]. q is the charge per unit volume, and $\mathbf{E}$ is the electric field. The cross product of these two terms is not considered as there is no charge.

In a two-dimensional axisymmetric system, Lorentz forces F can be written as [16]:

$$f_z = -\mathbf{J}_e^{\text{phi}} \times \mathbf{B}_s^r, \quad (4)$$

$$f_r = \mathbf{J}_e^{\text{phi}} \times \mathbf{B}_s^z. \quad (5)$$

For homogenous and isotropic media satisfied the assumption of linear elasticity and continuity, the motion equations of the tested sample experienced elastic deformation under the effect of Lorentz force are [16]:

$$\begin{aligned} \nabla \cdot \mathbf{T} + \mathbf{F} &= \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}, \\ \mathbf{T} &= \mathbf{c} : \nabla_s \mathbf{u}, \end{aligned} \quad (6)$$

where $\mathbf{T}$ is the stress tensor, ρ is the volume density of metallic materials, $\mathbf{u}$ is the displacement vector, $\mathbf{c}$ is the stiffness tensor and denotes the double dot product, and $\nabla_s \mathbf{u}$ is the symmetric part of the gradient of the vector $\mathbf{u}$. In view of the relationship between $\mathbf{T}$ and $\mathbf{u}$, Equation (6) can be expressed as:

$$\lambda \nabla^2 \mathbf{u} + (\lambda + \mu) \nabla (\nabla \cdot \mathbf{u}) + \mathbf{F} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2}, \quad (7)$$

in which λ and μ are Lamé constants, respectively. ∇^2 is the Laplace operator.

3. Finite Element Simulation of PFSV-EMATs

3.1. Finite Element Model Using COMSOL Multiphysics. A finite element model (FEM) is established to study the effect of design frequency on signal amplitude and point focusing performance generated by PFSV-EMATs, through the commercial software COMSOL Multiphysics 5.2 (COMSOL Inc., Massachusetts, USA) capable of multiphysical field coupling simulation. For the PFSV-EMATs, the FEM numerical simulation is performed by time-transient analysis in magnetic fields, magnetic fields without currents and mechanical structure modules. The three physical fields are coupled to each other to produce ultrasonic waves with a metallic conductor. Note that the magnetic field module is used to calculate the eddy current excited by CML coils on the surface of the specimen; magnetic fields without current module are used to calculate the static magnetic field generated by the

FIGURE 3: (a) The finite element model and (b) geometrical parameters of PFSV-EMAT.

permanent magnet; mechanical structure module is performed to simulate the generation and propagation of the ultrasound waves launched by Lorentz forces.

The two-dimensional FEM of PFSV-EMAT includes a CML coil, a cylindrical magnet, and a metallic specimen and air domain, as shown in Figure 3(a). It should be noted that the CML coil is simplified to an axisymmetric structure consisted of multiple annular coils, since the coil is an asymmetric structure with nonannular parts, but the nonannular parts are small. In order to reduce calculation amount and memory space, the two-dimensional axial symmetry model is established instead of the three-dimensional one. The rectangular air domain is established around the PFSV-EMAT, because it requires a certain solution domain to calculate the electromagnetic field. One side of the rectangular model is set to the axisymmetric axis, whereas the other sides are set to absorption boundaries, as described in the literature [16, 28]. This is to avoid back reflections from the sides of the aluminum block. In addition, the absorption boundaries of the aluminum block, i.e., the top and bottom boundaries, are set to be free boundaries without loads and constraints. The FEM of PFSV-EMAT is meshed, among which the aluminum plate and remaining regions use the quadrilateral and triangle elements with the maximum element size of 0.135 mm (roughly 1/10 of the SV wavelength in aluminum at 2 MHz), respectively.

The transmitting coils are carrying a 6-cycle sinusoidal signal with the frequency of 2 MHz and the amplitude value of 150 A. It is worth mentioning that the transmitting currents in adjacent conductors are I_0 and $-I_0$, respectively, due to the opposite current direction in them. Hence, the current signal period corresponding to this design frequency is $0.5 \mu\text{s}$. In the simulation, the depth of focus point z_F is 20 mm, and the thickness of aluminum plate is 30 mm, which is slightly greater than the depth of focus point in order to reduce the impact of the ultrasonic echo from the bottom of the aluminum plate and facilitate the analysis of the point-focusing characteristics of SV waves. The wave speed is set to be 3100 m/s; then, the wavelength, i.e., the diameter difference $2(r_i - r_{i+1})$ of the adjacent concentric circles, can be calculated to be 1.55 mm according to the geometric relationship and Equations (1) and (2).

3.2. Analysis of the Effect of Magnet Dimension. In this section, to show how the magnet dimension effect the signal

amplitude and point-focusing performance, we define ρ as the ratio of magnet radius R_m to coil radius r_c , that is

$$\rho = \frac{R_m}{r_c}. \quad (8)$$

Therefore, the FE model with different values is established, as illustrated in Figure 3(b). F denotes the position of the design focal point. The magnet-to-coil radius ratio ρ is from 0.6 to 1.6 with a step of 0.1.

3.2.1. Analysis of Eddy Current. Figure 4 shows the induced eddy current density transient distribution generated by the PFSV-EMATs, which is represented by a colour scale in Ampere per square. Note that the induced eddy current density is captured at $6 \mu\text{s}$.

Obviously, the adjacent regions of eddy current under successive wires in the FEM are in antiphase with each other. Moreover, induced eddy current is concentrated below the coil. The magnitude of the induced eddy current varies with the excitation current, and the maximum value is $4.59 \times 10^6 \text{ A/m}^2$.

3.2.2. Analysis of Lorentz Force. The local Lorentz force density transient distribution of the PFSV-EMATs with different magnet-to-coil radius ratios ρ represented by a colour scale in Newton per stere is shown in Figure 5, in which the size and direction of red arrows represent the magnitude and direction of Lorentz force, respectively. Due to limited space, the Lorentz force distribution with a magnet-to-coil radius ratios ρ of 0.8, 1.0, and 1.2 is given only in Figure 5.

As expected, the maximum Lorentz force density appears below the coil. At the vicinity of the edge of the permanent magnet, the Lorentz force density is very small due to the effect of the uneven distribution static magnetic field. However, near the center of the permanent magnet, the amplitude of Lorentz force is larger. In addition, at the edge of the permanent magnet, the magnetic flux density perpendicular to the direction of the aluminum plate is greater than that at the center of the permanent magnet; the direction of Lorentz force is horizontal near the center of the magnet. As the radius of the magnet increases, the magnitude of Lorentz force increases, and the direction of Lorentz force tends to be more horizontal. It should be noted that the adjacent regions of eddy current under successive wires in the FEM are in

FIGURE 4: Transient distribution of induced eddy current density for PFSV-EMATs with magnet-to-coil radius ratios R_m/r_c of 0.8 in the aluminum plate.

FIGURE 5: Transient distribution of Lorentz force density for PFSV-EMATs with magnet-to-coil radius ratios R_m/r_c of (a) 0.8, (b) 1.0, and (c) 1.2 in the aluminum plate.

(a)

(b)

FIGURE 6: (a) Signal amplitude and (b) normalized signal amplitude for the PFSV-EMAT modelling with various magnet-to-coil radius ratios obtained from finite element simulation.

antiphase with each other, leading to the direction of the corresponding Lorentz force launched by the interaction between the eddy current and magnetic field in the opposite direction accordingly.

3.2.3. Analysis of Signal Amplitude. Figure 6(a) shows the signal waveform obtained from finite element simulation when the ratios ρ is 0.9, 1.0, and 1.1. The normalized amplitude for the PFSV-EMAT modelling with various magnet-

to-coil radius ratios ρ is shown in Figure 6(b), in which black points and blue line represent the simulation values and its fitting curve, respectively. It is interesting to note that, unlike the Rayleigh wave EMAT, where the magnet is a little narrower than the coil [25], the normalized amplitude of the excited SV waves has a single peak between the signal amplitude and magnet-to-coil radius ratios ρ when the magnet is wider than that of the coil. As shown in the fitting curve, the signal amplitude increases drastically from almost 0.28 at an

FIGURE 7: Schematics of the sparsity of coil spacing at 2 MHz.

ρ of 0.6 to 0.96 at an ρ of 1.1. Then, it grows slightly between 1.1 and 1.2, reaching a peak with a critical ρ of 1.2 for this particular PFSV-EMAT transmitter designed with aluminum as the test specimen. Furthermore, the signal amplitude could not be increased but decreased slowly, by further increase in magnet-to-coil radius ratios ρ beyond this point.

This phenomenon indicates that the signal amplitude is more sensitive to smaller magnet-to-coil ratio. This can be explained on the premise that a small magnet will reduce the effective working area of the transducer or at least reduce the contribution of the edges of CML coil to ultrasonic waves.

3.3. Analysis of the Effect of Design Frequency

3.3.1. Analysis the Simulation Model of PFSV-EMATS. In the above section, the influence of design parameters on signal amplitude was analyzed at a certain frequency of 2 MHz, indicating that the closeness degree of coil spacing for the PFSV-EMAT with various magnet-to-coil radius ratios ρ is consistent. To investigate the influence of design frequency, i.e., the closeness degree of coil spacing, the PFSV-EMAT is designed and modeled with different design frequencies from 0.5 MHz to 3.5 MHz at 0.5 MHz intervals. Due to limited space, only the schematic diagrams of the closeness degree of coil spacing at 2 MHz are plotted, as shown in Figure 7. They are comprised of eight line sources and 4.06 mm from the z -axis to the coil closest to the center.

It should be noted that the number of line sources is constant; thus, the outer radius of CML coil increases as the design frequency decreases, which is due to the fact that the design frequency is inversely proportional to the wavelength. Based on the previous subsection alone, the optimum radius of a PFSV-EMAT magnet should be about 1.2 times greater than the outer radius of the CML coil. Therefore, a magnet-to-coil radius ratio ρ of 1.2 is adopted for PFSV-EMAT models with different design frequency.

3.3.2. Analysis of Design Frequency. Figure 8 illustrates the normalized amplitude for the PFSV-EMAT modelling with various design frequency, in which black points and purple solid line represent the simulation results and its fitting curve, respectively. As shown in the fitting curve, the normalized amplitude increases drastically during 0.5 MHz to 1.5 MHz, reaching a peak with the design frequency of 2.2 MHz. Then, after plummeting from 2.5 MHz, the normalized amplitude shows a sharply reduction. This change indicates that the design frequency has a significant effect on the signal amplitude, and the design frequency near 2.0 MHz is more sensitive to the signal amplitude. For

FIGURE 8: Normalized amplitude for the PFSV-EMAT modelling with various design frequency obtained from finite element simulation.

instance, the PFSV-EMAT with design frequency of 1.5 MHz has a larger signal amplitude (more than 23.92%) than the one with design frequency of 1.0 MHz. The reason for this phenomenon is directly related to the design frequency (wavelength). When the frequency is lower, the wavelength of the ultrasonic wave is larger, which is not conducive to the point focusing of the ultrasonic wave due to the principle of constructive interference. When the frequency is higher, the wavelength is smaller, and the distance between adjacent coils is smaller, which is not conducive to the wave transmission on the propagation path. Therefore, a reasonable selection of design frequency can improve the point-focusing performance of PFSV-EMATS.

In the process of designing the transducer, the fluctuation of the designed frequency, that is, deviation from the optimal frequency, will result in the reduction of signal amplitude and reduce the detection accuracy and sensitivity. Therefore, a tolerable deviation of the design frequency probably needs to be determined. By assuming that a -2 dB decrease of signal amplitude is probably accepted in practical applications, a tolerable deviation of design frequency is obtained based on simulation results. As shown in Figure 9, a -2 dB decrease of signal amplitude corresponds to about 1.31 MHz deviation of design frequency (i.e., from 1.59 MHz to 2.9 MHz).

The signal amplitude dependences on design frequency at the focal point, for magnet-to-coil radius ratios ρ ranging from 0.5 to 3.5, are shown in Figure 9, which illustrates that the design frequency has an important influence on the signal amplitude. However, it is interesting that the degree of influence is governed by magnet-to-coil radius ratios ρ . To facilitate the observation and comparison, the curves of ρ ranging from 0.6 to 1.0 are drawn in Figure 9(a), while those of ρ ranging from 1.0 to 1.6 are drawn in Figure 9(b). When $\rho \leq 1$, the signal amplitude monotonically increases with the increase of design frequency, as shown in Figure 9(a). In addition, at the same design frequency, the larger the ρ , the larger the signal amplitude when the design frequency is greater than or equal to 1.5 MHz. When $\rho > 1$, as the

FIGURE 9: Design frequency dependence on the signal amplitude at the focal point z_F , for magnet-to-coil radius ratios ρ ranging from (a) 0.6 to 1.0 and (b) 1.1 to 1.6.

FIGURE 10: Design frequency dependence on the focal offset in radical direction for magnet-to-coil radius ratios ρ ranging from (a) 0.6 to 1.0 and (b) 1.1 to 1.6.

FIGURE 11: Schematic diagram of experimental setup.

frequency increases, the single-peak value appears in the fitting curve between 2 and 2.5 MHz, as shown in Figure 9(b).

The focal offset in radial direction (the distance between the designed focus point and the actual one) dependence on design frequency, for magnet-to-coil radius ratios ρ ranging from 0.6 to 1.6, is shown in Figure 10. To facilitate the observation and comparison, the curves of ρ ranging from 0.6 to 1.0 are provided in Figure 10(a), while those of ρ ranging from 1.0 to 1.6 are in Figure 10(b). It illustrates that the design frequency has a certain influence on the focal offset in radial direction. When $\rho \leq 1$, the design frequency has a great influence on the focal offset in radial direction, as shown in Figure 10(a), while when $\rho > 1$, the impact is very small, as shown in Figure 10(b). Furthermore, at the same design frequency, the larger the ρ , the smaller the focal offset in radial direction. Furthermore, beyond this point ($\rho > 1.2$), only marginal further reductions of focal offset in radial direction are generated. Therefore, in the process of designing a transducer, a magnet-to-coil radius ratios ρ

FIGURE 12: Signals received by PFSV-EMATs designed with the frequencies of (a) 1.5 MHz, (b) 2 MHz, and (c) 2.5 MHz.

should be selected prudently according to the designed frequency to achieve a desired deviation and point-focusing performance of PFSV-EMATs.

It should be noted that, despite the PFSV-EMATs designed at 0.5, 1.0, and 1.5 MHz launches a larger signal amplitude and better point focusing characteristic, but their wavelength is wider, indicating that lower spatial resolution of PFSV-EMATs designed at 0.5, 1.0, and 1.5 MHz than others in the direction of ultrasonic propagation. Nevertheless, as the design frequency is higher, such as 3.0 and 3.5 MHz, the stress field, especially around edges and defects, becomes complicated due to the intricate ultrasonic waves scattering and interferences at a tip or opening. In conclusion, the PFSV-EMAT designed at medium frequency, such as 2 and 2.5 MHz, possesses a strong signal amplitude, appropriate point-focusing, and spatial resolution. In this work, a frequency of 2 MHz is considered to be the optimum frequency for PFSV-EMATs.

4. Experiments

In order to establish the validity of the analytical predictions regarding with the effect of design frequency on the performance of PF-EMATs and the validation of simulation, experimental measurements on an aluminum plate are carried out. Figure 11 illustrates the configuration of the experimental setup used on an aluminum plate with the thickness of 20 mm, a width of 80 mm, and a length of 150 mm. The PFSV-EMAT includes a CML coil and a cylindrical permanent magnet with a height of 30 mm and a radius of

25 mm; the size and dimension of which are the same as described in the modeling section. Note that the magnet adopted here is sintered from Nd-Fe-B (neodymium iron boron) material to provide a strong static bias magnetic field perpendicular to the surface of a specimen. The CML coil is fabricated by PCB (printed circuit board) technique according to Equations (1) and (2) at design frequency of 1.5 MHz (EMAT_1), 2 MHz (EMAT_2), and 2.5 MHz (EMAT_3), and the thickness of the copper sheet is 35 μm.

The excitation current loaded on the CML coil is a 6-cycle tone burst signal with a center frequency of 1.5 MHz. The output signal from the EMAT was being amplified using a RITEC RPR4000 gated amplifier (Ritec Inc., Warwick, RI, USA) and then recorded on a digital oscilloscope. In addition, the external computer is used to further process the received signal. In the case of EMAT measurements, impedance matching networks are used for matching the relatively low impedance of the EMAT to the relatively high impedance of the amplifier. It should be noted that all the measurements presented here were obtained in a pulse-echo configuration; that is, the PFSV-EMAT operates as a transceiver, transmitting SV waves and receiving SV wave echoes reflected from the underside of aluminum plate.

Figure 12 displays the received signals of the three PFSV-EMATs, from which we can see that the signal amplitude of EMAT_2 has a maximum value, which is 93.55% larger than that of EMAT_1 and 27.66% larger than that of EMAT_3. Figure 13 depicts the simulation and experimental results. For a fair comparison, the results are normalized to 1 with

FIGURE 13: Experiment and simulation of the normalized amplitude for the PFSV-EMAT modelling with various design frequency.

respect to the peak amplitude in the frequency range of interest. At the frequency of 2.5 MHz, the simulation fitting curve has the maximum amplitude, while the maximum amplitude occurs at the frequency of 2 MHz in the experiment results.

5. Conclusions

In this work, the relationship between the design frequency and characteristics of PFSV-EMATs is analyzed quantitatively by numerical simulations and experiments. A finite element model is established so that the transducer characteristics, such as Lorentz force and particle displacement, can be calculated, allowing for investigation into the influence of design frequency. It shows that the signal amplitude tends to be the maximum when the magnet-to-coil radius ratio ρ is 1.2 approximately, beyond which the amplitude could not be increased. In addition, a single peak value in the design frequency versus signal amplitude generated by PFSV-EMAT, with the optimal magnet-to-coil radius ratio ρ of 1.2, is observed, indicating that the deviation of the design frequency may lead to the changes of signal amplitude and focal offset and further reduce the spatial resolution of the ultrasonic signal. To maintain high resolution and signal strength, a tolerable deviation of 1.31 MHz (i.e., from 1.59 MHz to 2.9 MHz here) of the design frequency is determined. The experimental results verify the validation of optimization and demonstrate that a reasonable choose of design frequency can improve the signal amplitude and characteristic of PFSV-EMAT. Therefore, the conclusion of this paper could provide reliable reference and evidence probably for the parameter design of PFSV-EMATs, especially the design frequency.

Not considered in this work is the influence of design frequency on defect detection capabilities. This is a meaningful opening problem, thus worthy of further research in the future. Moreover, in the further work, more number of coils will be manufactured and tested experimentally.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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