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A new longitudinal mode guided-wave EMAT with periodic pulsed electromagnets for non-ferromagnetic pipe

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ABSTRACT

L(0,2) Longitudinal mode guided wave shows great advantages for pipe inspection as it can be almost non-dispersive at certain frequency range and is sensitive to the circumferential defects. In this paper, a new plug-in longitudinal mode guided-wave EMAT with periodic pulsed electromagnets (PPEMs) is proposed for small non-ferromagnetic pipe inspection. The new guided-wave EMAT is designed with coil-only configuration, which consists of a periodic pulsed electromagnet and a periodic pulser/receiver coil. Both numerical simulation and experimental results validate it has good performance on generating and receiving L(0,2) mode guided wave in non-ferromagnetic pipes. Comparing with the GW EMAT with periodic permanent magnets (PPMs) in traditional design, the signal amplitude of the guided wave can be significantly enhanced with using the new GW EMAT with PPEMs.

1. Introduction

Non-ferromagnetic stainless steel pipes are widely used for fluid transportation and heat exchange in petroleum industries and power plants, such as steam generator pipes in nuclear power plant. These pipes experience various types of corrosion due to high temperature, high pressure, fluid flush and radiation effect during long-term services [1]. Integrity of the pipes must be carefully monitored and inspected regularly with nondestructive testing (NDT) techniques. Comparing with the other NDT methods, the ultrasonic guided wave testing method has the ability to inspect the whole-wall thickness and long distance in a short time. The major approaches to generate ultrasonic guided waves can be piezoelectric transducers (PZT) [2–4], magnetostrictive sensors [5,6] and electromagnetic acoustic transducers (EMATs) [7–9]. Compared with the first two contact transducers, the EMAT needs no physical contacts and can generate ultrasonic waves directly in the metallic specimens. Therefore, it can be directly used for the structures without surface preparation, even on the rusty, dirty surface, or surface with coatings. The mechanism of EMAT can be classified into Lorentz force and magnetostriction for non-ferromagnetic and ferromagnetic metallic specimen, respectively [10].

Although many magnetostriction based guided-wave (GW) electromagnetic acoustic transducers (EMATs) have been developed and used for ferromagnetic pipe or with using magnetostrictive patch for non-ferromagnetic pipe [11,12], the Lorentz force based GW EMATs used for non-ferromagnetic pipe are very few, because the conversion efficiency of EMAT based on Lorentz force is much lower. Nakamura et al. used an improved EMAT with periodic permanent magnets (PPM) to excite torsional guided waves in non-ferromagnetic pipes [13,14]. Thereafter Xinjun Wu et al. optimized the element number of the PPM GW EMAT array to enhance its excitation efficiency [7]. Yamasaki and Huang et al. used an electromagnet in place of permanent magnet to improve the performance of the magnetostriction based GW EMAT [15,16]. Steve Dixon et al. developed a new bulk wave EMAT with a pulsed electromagnet and demonstrated that signal amplitude can be enhanced approximately by a factor of three, compared to the conventional EMAT with permanent magnet [17].

In this work, a new GW EMAT based on Lorentz force mechanism with periodic pulsed electromagnets (PPEMs) is proposed for non-ferromagnetic pipe inspection. It is known that the conversion efficiency of Lorentz force based EMAT is proportional to the square of magnetic field intensity [8,9]. With much larger current amplitude, but less energy consumption, the pulsed electromagnet can provide much stronger magnetic field than conventional permanent magnet and DC electromagnet, and prevent overheating at the same time [18]. Therefore, comparing with the GW EMAT using

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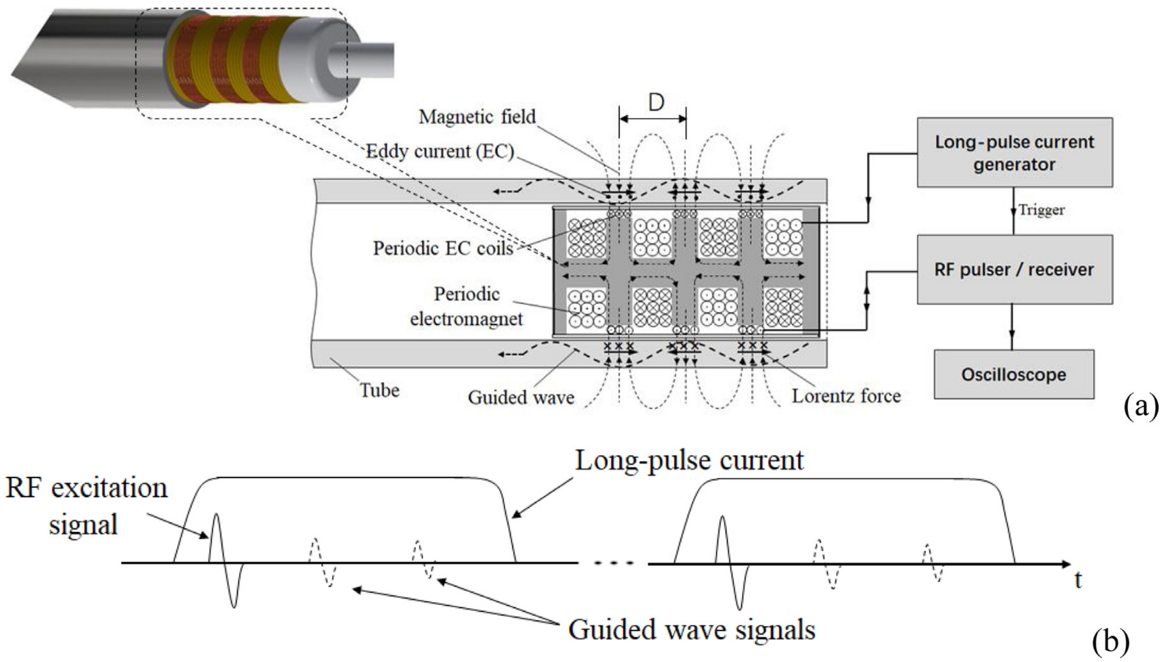


Fig. 1. Basic configuration and principle of the plug-in GW EMAT with pulsed electromagnet: (a) configuration of the EMAT, (b) driven currents and received GW signals.

permanent magnets or DC electromagnets in traditional design, the proposed GW EMAT with PPEMs can significantly enhance the conversion efficiency and signal amplitude of the guided wave.

2. Basic design and analysis of the PPEM GW EMAT

2.1. Basic design and principle

The basic configuration and principle of the new proposed plug-in GW EMAT using PPEMs is shown in Fig. 1. As shown in Fig. 1(a), the new periodic-pulsed-electromagnet (PPEM) GW EMAT is composed with a periodic electromagnet coil and a periodic eddy current (EC) coil attached to a cylindrical frame. The periodic electromagnet coil which made by winding wires is connected with a long rectangular-pulsed current generator to provide periodic and pulsed basis magnetic field. To generate a strong magnetic field perpendicular to the pipe wall, the adjacent coils of the PPEMs are in the opposite winding direction. The basis magnetic fields under the adjacent belts of periodic EC coil are in the opposite direction. The periodic EC coils, which can be made by winding wires or flexible printed circuit (FPC) technology, is connected with a radio frequency (RF) pulser and receiver to generate and receive eddy currents in the pipe wall with circumferential distribution. Therefore, longitudinal guided wave can be excited with the periodic Lorentz force in axial direction. It should be noted that the interval D (the distance between adjacent belts of the periodic EC coil) illustrated in the figure is half wavelength of the guided wave, $\lambda/2$, at the theoretical central frequency of the PPEM GW EMAT. As shown in Fig. 1(b), if the flat peak of the rectangular-pulsed current for bias-magnetic field is long enough (in the order of millisecond), and the current for EC coil is properly triggered, both ultrasonic guided wave generation and signal pickup can be realized in a similar way with the conventional GW EMATs using permanent magnets. It should also be noted that the pulse width of the long-pulse current should not be too long to prevent the electromagnet from overheating.

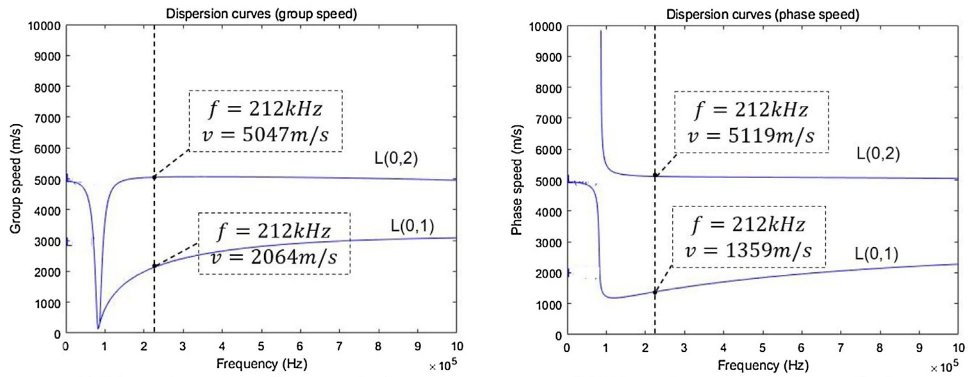
2.2. Longitudinal GW mode and frequency dispersion

As far as pipes are concerned, propagation of the longitudinal guided wave is dispersive. The general phase velocity and group velocity dispersion curves of longitudinal guided wave for a SUS304 stainless steel pipe with wall thickness of 1 mm are shown in Fig. 2. The young's modulus, Poisson's ratio and density of SUS304 stainless steel are 1.93×10^{11} N/m^2, 0.247 and 7930 kg/m^3, respectively. As shown in the figures, there are two modes. Since the GW EMAT typically operate up to a few hundred kHz frequency, only L(0,1) and L(0,2) modes waves are generally produced within this range. Meanwhile, as the velocity of the L(0,1) and L(0,2) modes is very different within this frequency range, each mode can be selectively generated by determining the dimensions of the EMAT coils. As shown in Fig. 2(a), It is obvious that the group velocity dispersion curve is relatively flat from 200 kHz to 300 kHz in the L(0,2) mode. Therefore, it was chosen as the excitation frequency region in the L(0,2) mode because of the relative low dispersive behavior in this region. In this frequency range, the group velocity in the L(0,2) mode is approximately 5040–5066 m/s, which is faster than that of other modes, such as L(0,1) mode(1994−2079 m/s). Therefore, the defect echoes in the L(0,2) mode should be detected first, creating favorable conditions for signal processing and defect recognition.

2.3. Theoretical and numerical analysis

The generation and reception of the elastic wave in non-ferromagnetic materials by EMATs are based on Lorentz mechanism. As for the proposed new PPEM GW EMAT, the electromagnet coil fed with a rectangular-pulsed current would generate a long-pulsed bias magnetic field, while the EC coil fed with a large alternating current would induce eddy currents within the skin depth of the pipe wall. Derived from the Ampere's and Faraday's laws, the field equation governing electromagnetic phenomena due to the electromagnet coil can be expressed as [19,20]:

$$\nabla \times \frac{1}{\mu} \times \mathbf{A_1} + \sigma_c \frac{\partial \mathbf{A_1}}{\partial t} = \mathbf{J_1} \tag{1}$$



(a) Dispersion curve of group velocity (b) Dispersion curve of phase velocity

Fig. 2. Dispersion curves of the longitudinal guided wave for the tested pipes.

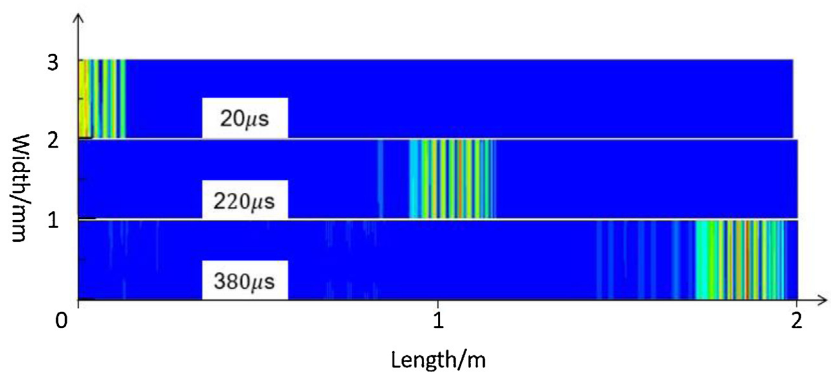


Fig. 3. Ultrasonic fields in the pipe wall at different time points.

where μ denotes the magnetic permeability, σ_c the electrical conductivity, J_1 the long rectangular-pulsed current fed in the PPEM coil, and $\mathbf{A}_1$ the induced magnetic vector potential. Since J_1 is a long pulse current with a flat peak, the time-dependent second term (related to the inducted EC) is much small while the first term related to the magnetic field is dominated in the time range of flat current peak. Therefore, the PPEM coil mainly transforms excitation current into magnetic field **B** which can be obtained by using:

$$\mathbf{B} = \nabla \times \mathbf{A_1} \tag{2}$$

With the same theory from Ampere's and Faraday's laws, the field equation governing eddy current field induced by the EC coil can also be expressed as:

$$\nabla \times \frac{1}{\mu} \times \mathbf{A_2} + \sigma_c \frac{\partial \mathbf{A_2}}{\partial t} = \mathbf{J_2} \tag{3}$$

where $\mathbf{J}_2$ denotes the RF pulse current fed in the EC coil. As J_2 is an alternating current with frequency exceed hundred kHz, and $\mathbf{A}_2$ the induced magnetic vector potential by the EC coil. The time-dependent second term related to the inducted EC is dominated in the left hand of Eq. (3). Therefore, the EC coil mainly transforms the excitation current into inducted eddy current J_e in the pipe. In the presence of the bias magnetic flux **B** and inducted eddy currents J_e, the transient Lorentz force $\mathbf{f}_L$ is produced as:

$$\mathbf{f_L} = \mathbf{J_e} \times \mathbf{B} = \sigma_c \frac{\partial \mathbf{A_2}}{\partial t} \times \mathbf{B} \tag{4}$$

In a homogenous and isotropic media, the ultrasonic wave field excited by the Lorentz force can be described as following wave equation [21]:

$$\mu \nabla^2 \mathbf{u} + (\lambda + \gamma)\nabla(\nabla \cdot \mathbf{u}) + \mathbf{f_L} = \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} \tag{5}$$

where **u** denotes the particle displacement of ultrasonic motion, λ and γ the Lame parameters and ρ the density.

In order to investigate the feasibility of the proposed PPEM GW EMAT design, a two-dimensional axisymmetric finite element numerical model of pipe is built since the longitudinal mode guided wave is axisymmetric. The details of the numerical method have been given in the previous paper [19]. In the numerical model, the proposed EMAT is inserted at one end of a SUS stainless steel pipe with length of 2000 mm, an inner diameter of 20 mm and a wall thickness of 1 mm. The lift-off distance between the EMAT and the pipe is set as 1.0 mm. The current J_1 inputted in the PPEM coil is a rectangular-pulsed current with amplitude of 100 A and duration of 1.5 ms, while the current J_2 inputted in the EC coil is a three-cycle tone burst current with amplitude of 1 kA at a center frequency of 210 kHz.

Fig. 3 shows the simulated ultrasonic fields in the pipe wall at the given time from 20 μs to 380 μs. It can be seen that ultrasonic wave energy is mainly in one wave mode. Fig. 4 shows the simulated testing signal of the guided wave, a strong end reflection signal can be observed at the time of 0.79 ms in the waveform. It can be calculated that the corresponding group velocity of the guided wave is about 5063.2 m/s. According to the dispersion curve of the guided waves, the guided wave generated and received by the proposed GW EMAT is L(0,2) mode.

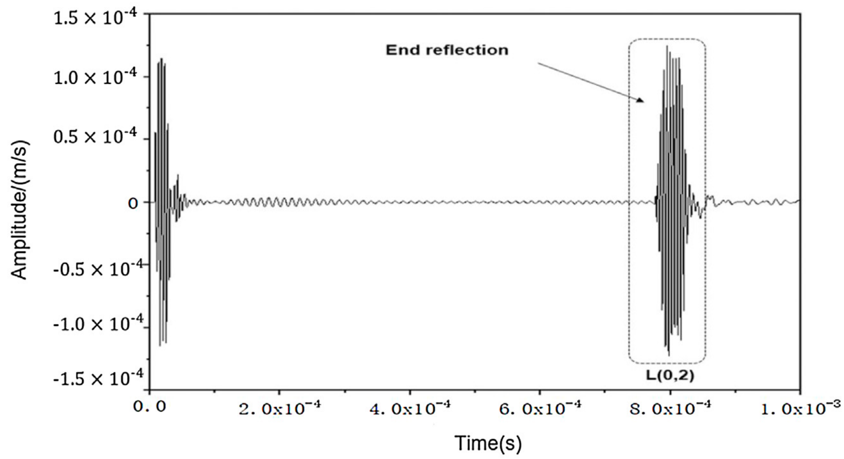


Fig. 4. Simulated guided wave signal in time domain.

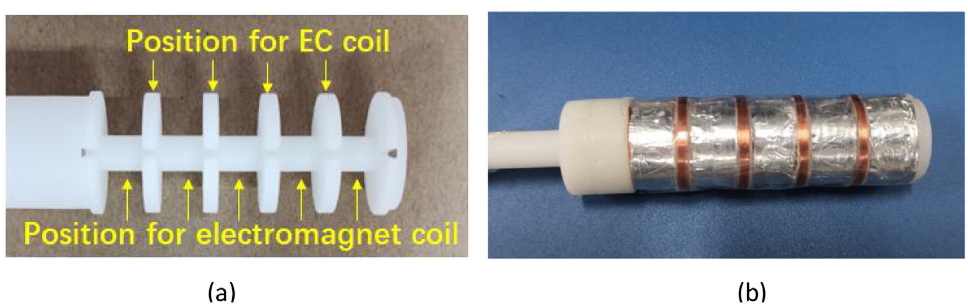


Fig. 5. The plug-in GW EMAT with pulsed electromagnet: (a) the resin frame of the transducer, (b) the finished transducer.

3. Experimental validation

3.1. The new PPEM GW EMAT and corresponding experimental setup

As shown in Fig. 5, the new PPEM GW EMAT was composed with a periodic electromagnet coil and a periodic EC coil attached on a resin cylindrical frame made by 3D printing. The periodic electromagnet coil was made up of enamel coated, fine copper wire (with diameter of 0.4 mm) wrapped around the resin frame. The inner and outer diameter of the electromagnet coil is about 4 mm and 17.5 mm, respectively. The lateral width of each element of the electromagnet coil is 9 mm. The EC coil was made up of enamel coated, fine copper wire (with diameter of 0.1 mm) wrapped around in between two electromagnet coil segments. The diameter of the EC coil is about 17.6 mm. The lateral width of each element of the EC coil is 3 mm. The interval distance D of the periodic EC coil is 12 mm. Therefore, the corresponding theoretical center frequency f_c of the developed PPEM GW EMAT is about 212 kHz for the steel pipe with wall thickness of 1 mm. The silver part of the transducer in Fig. 5 is tin foil, which mainly plays the role of electrical shield on the electromagnetic coil.

To verify the performances of the proposed transducer, several experiments needed to be performed. The experimental setup for the new plug-in PPEM GW EMAT is shown in Fig. 6. A long-pulse current generator ① with voltage amplitude up to 350 V and pulse width less than 10 ms was used to energize the pulsed electromagnet. The EC coil was connected with a RF pulser/receiver system (RAM-5000, RITEC Inc.) ② that consists of a large pulsed alternating current unit (with voltage amplitude up to 1500 V and central frequency from 50 kHz to 20 MHz) and a built-in pre-amplifier. A TTL trigger signal is generated by a signal generator ③ for the RF pulser/receiver system to drive the EC coil with a certain delay after the pulsed electromagnet is energized. A frequency band-pass filter ④ was used to filter the noise of the guided wave signals received by the RF pulser/receiver. A digital oscilloscope ⑤ with signal averaging (32×) was used to record the filtered signals for further improved signal-to-noise ratios (SNRs). The repetition rate of the whole system is controlled at less than 10 Hz to prevent the pulsed electromagnet coil from overheating. A software ⑥ was used to control the RF pulser and receiver. A duplexer ⑦ is used to isolate the high-voltage transmitted signal to the signal receiving circuit. The GW EMAT was inserted at the left end of the pipe ⑧ with length of 2000 mm, inner diameter of 18 mm and wall thickness of 1 mm. An artificial circumferential crack with the dimensions (15 mm (Length)×0.5 mm (Width) ×0.5 mm (Depth)) was 1800 mm away from the left end of the pipe.

3.2. Performance investigation of the new GW EMAT

Fig. 7 shows experimentally measured signals with the new GW EMAT in a SUS304 stainless steel pipe without defect and with defect, respectively. In the experiment, a 5-cycle 210-kHz sine burst modulated by a Hanning window was used as excitation signal. In Fig. 7(a), the wave packet occurring at approximately 0.79 ms is the end reflection signal of the guided wave from the right end of the pipe, and the corresponding group velocity of the guided wave is about 5063.2 m/s based on the time-of-flight method. This is consistent with the numerical simulation result in Fig. 4. In Fig. 7(b), the wave packet occurring at approximately 0.7 ms before the end reflection is the defect reflection signal in L(0,2) mode.

In order to investigate the frequency response characteristics of the proposed transducer, a series of experiments of different frequencies were performed. At the same voltage of the electromagnet, we have carried out 15 groups of experiments with

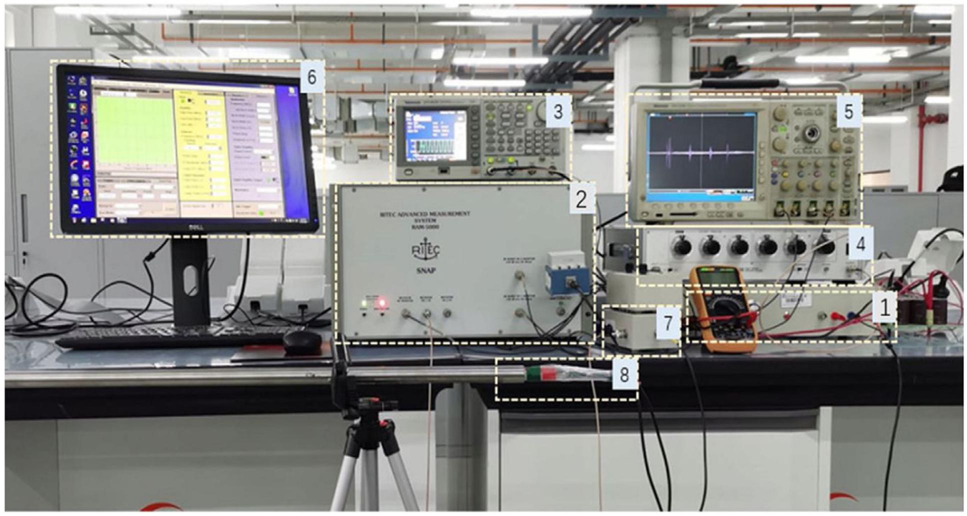


Fig. 6. Experiment setup for pipe inspection with the plug-in PPEM GW EMAT.

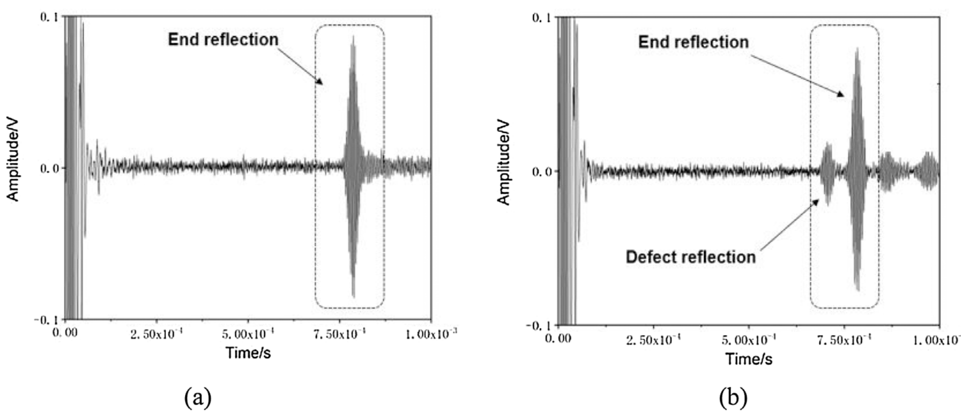


Fig. 7. Measured guide wave signal with the new EMAT: (a) in pipe without defect, (b) in pipe with defect.

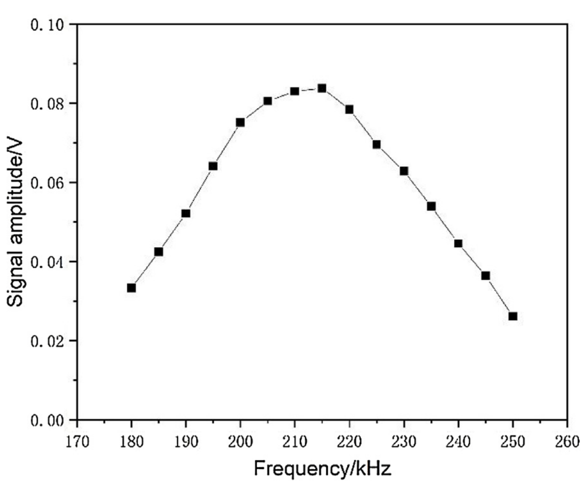


Fig. 8. Signal amplitudes of the guided wave at different exciting frequencies.

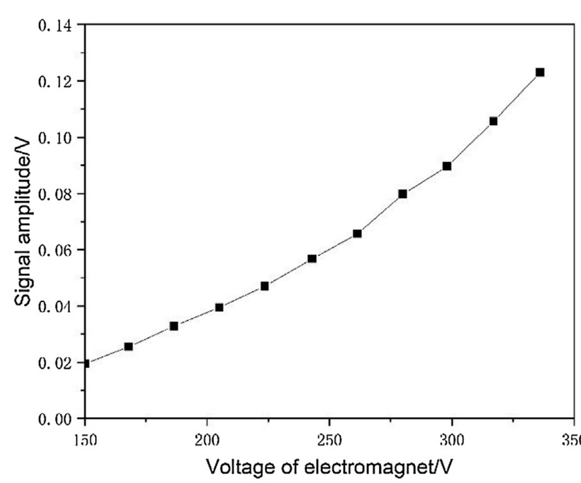


Fig. 9. Signal amplitudes of the guided wave under different voltages of the PPEMs.

bandwidth from 180 kHz to 250 kHz. Fig. 8 shows the amplitude change of the guided wave (end reflection signal) between the frequency of 180 kHz and 250 kHz. The frequency corresponding to the maximum amplitude was obtained at the frequency 215 kHz, which was highly consistent with the theoretical center frequency f_c, 212 kHz.

It is known that the conversion efficiency of Lorentz force based EMAT is proportional to the square of magnetic field intensity, the bias magnetic field in the most important factors that influences the performance of the transducer. As the bias magnetic field of the proposed PPEM GW EMAT is induced by the PPEMs, the bias magnetic field intensity can be changed by changing the output voltage of the long-pulse current generator connected to the PPEMs. Fig. 9

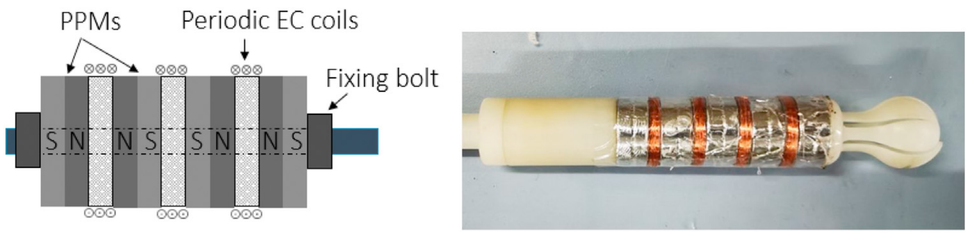


Fig. 10. PPM GW EMAT for comparison: (a) configuration of the transducer, (b) the finished transducer.

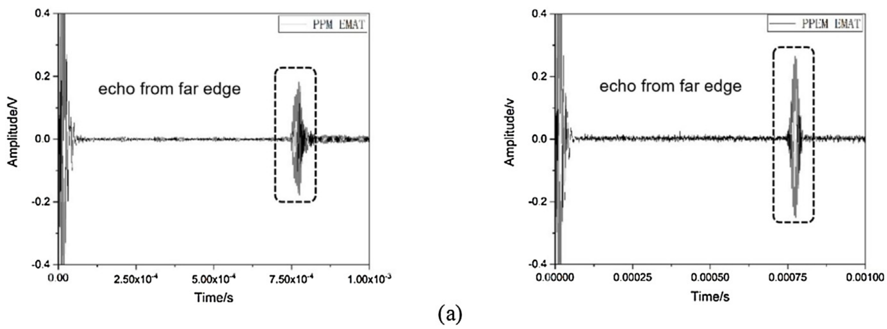


Fig. 11. Comparison of measured signals in an aluminum pipe with using: (a) traditional PPM GW EMAT, (b) new PPEM GW EMAT.

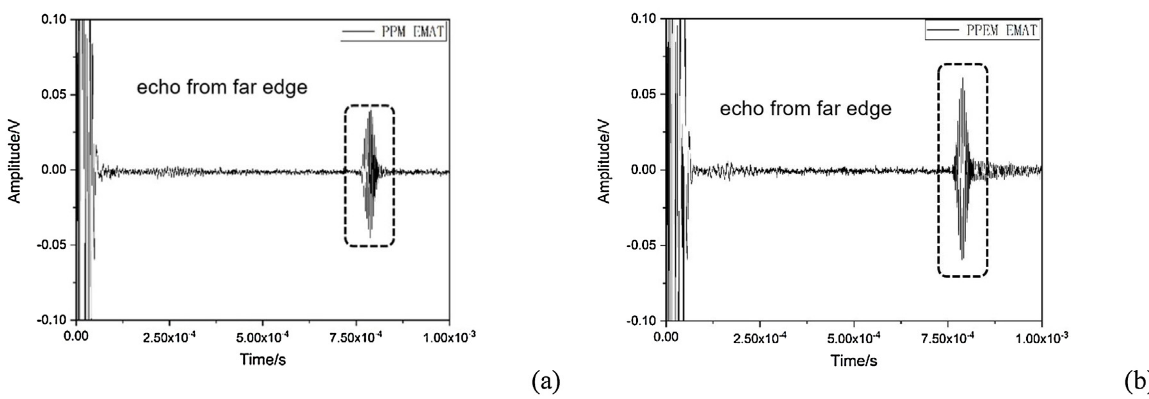


Fig. 12. Comparison of measured signals in an SUS304 stainless steel pipe with using: (a) traditional PPM GW EMAT, (b) new PPEM GW EMAT.

gives the amplitudes of the guided waves when the output voltage of the long-pulse current generator connected to the PPEMs increased from 150 V to 340 V. We can find that the amplitudes of the guided waves increase faster and faster as the voltages of the PPEMs increase. This is consistent with the theory of that the conversion efficiency of Lorentz force based EMAT is proportional to the square of magnetic field intensity. Therefore, it is a very promising way to increase the conversion efficiency of the EMAT with using PPEMs, instead of using permanent magnets.

3.3. A comparison to the traditional PPM GW EMAT

In order to verify the advantages of the proposed GW EMAT using PPEMs, a longitudinal mode GW EMAT using periodic permanent magnets (PPMs) in traditional design is also developed here and the performance of the two transducers is comparatively studied by experiment. The GW EMAT using PPMs in traditional design is shown in Fig. 10. The periodic-permanent-magnet (PPM) EMAT has a series of permanent magnets with periodically alternation north and south (N/S) poles facing with each other to generate periodic magnetic field perpendicular to the pipe wall. The permanent magnets are a ring NdFeB magnets with thickness of 4 mm, inner diameter of 4 mm and outer diameter of 17.5 mm. The interval distance D of the periodic EC coil is 12 mm. Therefore, the corresponding theoretical center frequency f_c of the developed PPM GW EMAT is about 215 kHz for the steel pipe with wall thickness of 1 mm. A gauss meter with a transverse probe was applied to measure the magnetic field strength of the two EMAT. The measured results show that the maximum magnetic field strength of the PPM EMAT and PPEM EMAT were about 0.33 T and 0.4 T, respectively. It should be noted that the magnetic field strength of the PPEM EMAT can be further increased by increasing the supply voltage of the electromagnet.

Fig. 11 gives the comparison of measured signals in an aluminum pipe (with the same dimension with the previous stainless steel pipe) with using the traditional PPM GW EMAT and the new PPEM GW EMAT, respectively. In the contrast experiment, the two of the EMATs were excited at the same frequency (215 kHz), and the current parameters supplied to the EC coils are the same. It can be seen that there is a same waveform distribution in the two signals of the two EMATs. The end reflection wave packet of the L(0,2) guided waves present at the same time can be observed in the two signals. However, the signal amplitude of the guided wave of the new PPEM GW EMAT is larger (about 1.44 times) than that of the traditional PPM GW EMAT. Fig. 12 gives the comparison of measured signals in the stainless steel pipe with using the traditional PPM GW EMAT and the new PPEM GW EMAT, respectively. The signal amplitude of the guided wave of the new PPEM GW EMAT is larger (about 1.41 times) than that of the traditional PPM GW EMAT. And with the increase of the voltage applied on the electromagnetic coil, the proposed PPEMs can get larger amplitude. It can be seen from Figs. 11 and 12 that the signal measured in aluminum pipes is much larger than that in stainless steel pipes. This is because the stainless steel has much lower conductivity and higher mass density than that of aluminum (about 3.4×10^7 S/m for aluminum and 0.14 3.4×10^7 S/m for SUS 304, respectively), so the conversion efficiency of the Lorentz force based EMAT in the stainless steel is much lower than that in the aluminum. Therefore, it is further verified that the conversion efficiency and signal strength of the guided wave are significantly enhanced with using the proposed PPEM GW EMAT.

4. Conclusion

In this paper, a new longitudinal mode GW EMAT with using PPEMs was proposed and developed for non-ferromagnetic pipe inspection with high conversion efficiency and signal strength. Instead of using permanent magnets to provide bias magnetic field, the new PPEMs driven with a large pulsed current generator was used to generate strong pulsed bias magnetic field for the guided wave generation and detection. To investigate its feasibility, the ultrasound fields generated by the PPEM GW EMAT in Lorentz force mechanism and the measured signals in a stainless steel pipe were simulated. The simulation results indicated that the new EMAT is suitable to generating L(0,2) mode guided wave in the non-ferromagnetic pipe, which was verified by the corresponding experiment. The experiment results also show that it can be used to measure the defect in the stainless steel pipe. Then, the frequency response of the new PPEM GW EMAT was characterized to provide beneficial insight into the design optimization of the transducer. Furthermore, it was verified that the bias magnetic field has very important influence on the amplitude of the guided wave signal. The amplitudes of the guided waves increase faster and faster as the voltages of the PPEMs increase. This is consistent with the theory of that the conversion efficiency of Lorentz force based EMAT is proportional to the square of magnetic field intensity. Therefore, as the pulsed electromagnets can induce much stronger magnetic field than conventional permanent magnet and DC electromagnet, it is a very promising way to increase the conversion efficiency of the EMAT with using PPEMs. Finally, to further verify the advantage of the proposed PPEM GW EMAT, a traditional PPM GW EMAT was also developed and used for comparison. The comparative experiments show that the L(0,2) guided wave signal amplitude of the new PPEM GW EMAT is larger than that of the traditional PPM GW EMAT in both aluminum pipe and stainless steel pipes. Therefore, it is further verified that the conversion efficiency and signal strength of the guided wave are significantly enhanced with using the proposed PPEM GW EMAT.

Author statement

Cuixiang Pei have made substantial contributions to the conception or design of the work; AND the author have revised it critically for important intellectual content. The author agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, "A Longitudinal Mode Guided-wave EMAT with Periodic Pulsed Electromagnets for Non-ferromagnetic Pipe".

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