High-temperature EMAT with double-coil configuration generates shear and longitudinal wave modes in paramagnetic steel

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ABSTRACT

The non-contact nature of electromagnetic acoustic transducers (EMATs) allows a continuous operation at high temperatures without physical coupling. The existing high-temperature EMATs are mainly shear-wave EMATs, and there are few reports on shear-longitudinal wave or longitudinal-wave EMATs due to the low intensity of the horizontal magnetic field. However, a desirable EMAT design characteristic is the possibility of selecting to generate different acoustic wave modes for various engineering applications. In this paper, a high-temperature EMAT with a double-coil configuration on waveform generation in paramagnetic steel was studied. By adjusting the configuration relationship between the electromagnetic coil and the EMAT eddy-current coil, the selective generation of shear-wave, longitudinal-wave, and shear-longitudinal wave modes was realized. According to quantitative analysis of shear and longitudinal waves generated by the double-coil EMAT, the amplitude ratio of shear and longitudinal waves was about 1 when the diameter of the EMAT eddy-current coil was equal to the inner diameter of the electromagnetic coil. Furthermore, shear-wave mode and shear-longitudinal wave mode high-temperature EMATs were designed and fabricated. The EMAT was placed in a high-temperature environment to continuously measure the paramagnetic steel SUS304. The amplitudes of the shear wave and longitudinal wave at 500 °C decreased by 10.2 times and 3.8 times, respectively, compared with that at 25 °C. The designed EMAT can selectively generate and receive different bulk acoustic wave modes at high temperatures.

1. Introduction

The high-temperature ultrasonic transducer is the key to industrial non-destructive testing (NDT) demands [1]. Pipelines, pressure vessels, tanks, and absorber tubes operate at high temperatures and suffer creep, thermomechanical fatigue, or hot corrosion [2]. Monitoring high-temperature metal structures via NDT techniques is essential to avoid defects and reduce maintenance costs [3,4]. Measurement of the instantaneous contact between the transducer and the high-temperature sample is common [5]. The transducer does not reach the temperature of the high-temperature test sample. However, the transducer sometimes requires long-term continuous monitoring on the high-temperature sample, resulting in the transducer being close to the temperature of the sample [6,7]. Therefore, the heat resistance of ultrasonic transducers should be improved in a high-temperature working environment.

Electromagnetic acoustic transducer (EMAT), a non-contact ultrasonic transducer [8], can be used for high-temperature measurement [9–14]. EMAT designs typically utilize SmCo or NdFeB magnets, whose working temperatures are limited by the Curie point (<300 °C) [15]. To overcome the limitation of permanent magnets, some researchers have adopted a water-cooled EMAT or pulsed electromagnet EMAT. A water-cooled EMAT is effective up to the Curie point (770 °C) of ferromagnetic steel based on instantaneous measurement [16]. Compared with the water-cooled EMAT, pulsed electromagnet EMAT has more advantages in heat resistance [15]. A pulsed electromagnetic EMAT can realize a short-time measurement of ferromagnetic steel at 600 °C within 1–2 min contact time between the transducer and the sample [17]. However, pulsed electromagnet EMAT should have the ability of long-term measurement in a high-temperature environment, even in the case of core demagnetization, rather than short-time measurement. Encouragingly, an air-cored pulsed electromagnet EMAT with a double-coil structure has been developed, which can withstand the environment temperature of 900 °C, and the maximum measurement temperature is 700 °C for ferromagnetic steel [18].

Many high-temperature EMATs have been developed and used for ferromagnetic steel or paramagnetic aluminum [15–18], but the high-temperature EMATs used for paramagnetic steel are very few because the conversion efficiency of EMAT based on the Lorentz force is...
much lower. Typically, the surface magnetic field of paramagnetic steel is about 1/2 times that of ferromagnetic steel [19]. Based on the Lorentz force mechanism, the conversion efficiency of permanent magnet EMAT for paramagnetic steel is about 1/4 times than that of ferromagnetic steel. Fig. 1 shows the received waveforms of ferromagnetic carbon steel and paramagnetic stainless steel based on pulsed electromagnet EMAT. The peak-to-peak voltages of the two samples are 2.129 V and 0.432 V, respectively. The experimental results of the pulsed electromagnet EMAT are consistent with those of the permanent magnet EMAT. In addition, the magnetостриктив mechanism of EMAT can enhance the conversion efficiency of high-temperature ferromagnetic materials [20, 21]. However, in paramagnetic materials, EMAT is only based on the Lorentz force mechanism. The amplitude of the received signal decreases with increasing temperature [20].

The conversion efficiency of the EMAT based on Lorentz force is proportional to the square of magnetic field intensity [22]. Pulsed electromagnetic EMAT can provide a stronger magnetic field than permanent magnet EMAT by controlling the input current of the electromagnetic coil [23,24]. A pulsed electromagnet EMAT can provide 818 mT magnetic field intensity, and its received signal amplitude is about three times higher than that of permanent magnet EMAT [15]. In addition, the maximum input current of double-coil EMAT is 2 kA, and the maximum magnetic field measured by the experiment was 870 mT [18]. For developing a kA-level pulsed current generator, electromagnetic forming (EMF) technology can be a good reference [25,26]. Dirk Ruetter and Tino Morgenstern proposed a high power and coil-only EMAT [27]. The input current of the coil-only EMAT is 10 kA, and the magnetic field intensity is about 10 T. This is quite challenging, even if a 2 T magnetic field, the currently conventional magnet materials are impossible [28]. Therefore, using the pulsed electromagnet instead of the permanent magnet to improve the magnetic field intensity of EMAT is very promising.

The existing high-temperature EMATs are mainly shear-wave EMATs [15–18]; there are few reports on shear-longitudinal wave or longitudinal-wave EMATs due to the low intensity of horizontal magnetic field [29,30]. However, a desirable EMAT design characteristic is the possibility of selecting to generate different acoustic wave modes for various engineering applications [31–34]. For example, acoustoeelastic stress measurement requires the transducer to generate and receive longitudinal-wave and shear-wave at the same location and under identical measurement conditions [35]. To effectively generate the longitudinal-wave and shear-longitudinal waves at high temperatures, the pulsed electromagnet EMAT is a good choice due to its strong magnetic field supply ability. Recently, a new longitudinal mode guided-wave EMAT with periodic pulsed electromagnets for the non-ferromagnetic pipe has been reported [36].

In this paper, a high-temperature EMAT with double-coil configuration generates shear and longitudinal wave modes in paramagnetic steel was studied. The structure of this paper is as follows: basic design and analysis of double-coil EMAT is presented in Section 2, and finite element model is simulated in Section 3. An experimental platform for double-coil EMAT is developed and experiment results are documented in Section 4, followed by the conclusion in Section 5. According to the simulation and experimental results of double-coil EMAT, by adjusting the configuration relationship between the EMAT eddy-current coil and electromagnetic coil, the mode of generating shear-wave, longitudinal-wave, or shear-longitudinal wave can be selected. In addition, high-temperature double-coil EMATs with shear-wave and shear-longitudinal wave modes are designed and fabricated. The proposed EMAT measured paramagnetic steel in a closed high-temperature environment continuously, and realized the generation and reception of shear-wave and shear-longitudinal wave modes.

2. Basic design and analysis of double-coil EMAT

2.1. Structure and working principle

There are three mechanisms to generate waves through the interaction of magnetic fields in EMAT transduction. In paramagnetic metals, the electromagnetic force generated by the interaction of magnetic fields includes only the Lorentz force. In ferromagnetic metals, the electromagnetic force generated by the interaction of magnetic fields includes the Lorentz force, magnetization force, and magnetostriective force. This paper focuses on the waveform generation in paramagnetic steel based on double-coil EMAT. Therefore, the Lorentz force mechanism is the dominant factor in generating and receiving ultrasonic waves.

The double-coil EMAT consists of an electromagnetic coil and an EMAT eddy-current coil, as shown in Fig. 2(a). The electromagnetic coil and the eddy-current coil are coaxial spiral coils. The time-domain sequences of the excitation pulse and signal pickup are shown in Fig. 2(b). The low-frequency long-pulsed current, a 100 Hz level semi-sinusoidal wave was used to generate the magnetic field. The received waveforms of ferromagnetic carbon steel and paramagnetic stainless steel based on pulsed electromagnet EMAT.

![Fig. 1. Received waveforms of ferromagnetic carbon steel and paramagnetic stainless steel based on pulsed electromagnet EMAT.](image)

![Fig. 2. Schematic diagram of double-coil EMAT: (a) configuration of double-coil EMAT, (b) time-domain sequences of the excitation pulse and signal pickup.](image)
pulsed current fed to the electromagnetic coil, can generate a quasi-static bias magnetic field. Similarly, the radio-frequency (RF) pulsed current, a MHz level sinusoidal pulsed current fed to the eddy-current coil, can induce alternating eddy-current within the skin-depth of the sample surface. The duration of the long-pulsed current is much longer than that of the RF pulsed current, showing that the bias-magnetic field provided by the long-pulsed current is stable in RF pulsed signal triggering and ultrasonic back-wall echo signal receiving.

2.2. Theoretical analysis

For the double-coil EMAT, the field equation of the electromagnetic coil can be expressed by the Ampere law and Faraday law [37].

\[ \nabla \times \frac{1}{\mu} \times A_1 + \sigma \frac{\partial A_1}{\partial t} = J_1 \]  

(1)

where \( \mu \) is the magnetic permeability, \( \sigma \) is the electrical conductivity, \( A_1 \) is the induced magnetic vector potential of the electromagnetic coil, and \( J_1 \) is a long-pulsed current fed in the electromagnetic coil. Since \( J_1 \) is the long-pulsed current of a few 100 Hz, the second time-related item is much smaller, and the primary item related to the magnetic field is dominant in Eq. (1). Therefore, the electromagnetic coil generates a quasi-static bias-magnetic field \( B \) in the sample.

\[ B = \nabla \times A_1 \]  

(2)

Similarly, the field equation of the eddy-current coil can also be expressed by the Ampere law and Faraday law.

\[ \nabla \times \frac{1}{\mu} \times A_2 + \sigma \frac{\partial A_2}{\partial t} = J_2 \]  

(3)

where \( A_2 \) is the induced magnetic vector potential by the eddy-current coil, and \( J_2 \) is a short alternating pulsed current fed in the eddy-current coil. Since \( J_2 \) is a short alternating pulsed current of a few MHz, the second time-related item is dominant in Eq. (3). Therefore, the eddy-current coil induces an alternating eddy-current \( J_e \) at the skin-depth of the sample surface.

The Lorentz force \( f_l \) is produced by the interaction of the bias-magnetic field \( B \) and the eddy-current \( J_e \), as shown below:

\[ f_l = J_e \times B \]  

(4)

The Lorentz force excites an ultrasonic wave on the sample surface, which can be described by the following wave equation:

\[ \gamma \nabla \times (\nabla \times u) - (\kappa + 2\gamma) \nabla (\nabla \cdot u) + \rho \frac{\partial^2 u}{\partial t^2} = f_l \]  

(5)

where \( \gamma \) and \( \kappa \) are the Lamé parameters, \( u \) is the particle displacement of ultrasonic motion, and \( \rho \) is the mass density.

EMAT receiving ultrasonic wave is the inverse process of its transmitting. The current \( J \) at the skin-depth of the sample surface is produced by the interaction between the bias-magnetic field and vibrated particles, as shown in the following:

\[ J = \sigma \frac{\partial u}{\partial t} \times B \]  

(6)

The current \( J \) induces the electromotive force in the eddy-current coil and is produced when the signal is received.

3. Finite element simulation

3.1. Modeling of double-coil EMAT

Since the double-coil EMAT is an axisymmetric model, the simulation model can be simplified to a two-dimensional model, as shown in Fig. 3. The magnetic field distribution and ultrasound propagation of double-coil EMAT are solved using the COMSOL Multiphysics. The magnetic field module is used to solve the magnetic field and the eddy-current in the sample excited by the electromagnetic coil and the eddy-current coil. The solid mechanics module is then used to model the ultrasound generated in the sample with respect to the Lorentz force. The absorbing boundary is used to avoid ultrasonic reflections from the sample side edge. The sample is paramagnetic steel SUS304 in the software library.

A partially enlarged view of the finite element model is shown in Fig. 4. The maximum element size in the sample is \( \lambda/10 \), where \( \lambda \) is the wavelength. The maximum element size in the air domain and the electromagnetic coil is \( \lambda/4 \) and \( \lambda/2 \), respectively. This model can save significant computing resources without loss of accuracy. To improve the model’s accuracy, the maximum element size in the eddy-current coil is set as \( \lambda/32 \), and the region around the eddy-current coil is further subdivided into more elements. The refinement of the model improves its accuracy, while the time consumption of the solution increases significantly. In practice, the degree of refinement is determined by continuously comparing the models’ calculation results at different extents of refinement - when the result hardly varies with the refinement, further refinement is unnecessary [22].

3.2. Magnetic field distribution

When the input current amplitude of the electromagnetic coil is 1 kA, the magnetic field distribution of the double coil EMAT is shown in Fig. 5. Fig. 5(a) shows the two-dimensional magnetic flux density distribution, and Fig. 5(b) shows the magnetic flux density distribution on the sample surface. \( B_x \), \( B_y \), and NormB are horizontal magnetic flux density, vertical magnetic flux density, and magnetic flux density modulus, respectively. The mark pointed on the curve are used to calculate the amplitude ratio of vertical and horizontal magnetic flux densities. The amplitude ratios of \( B_x \) and \( B_y \) at \(-20 \text{ mm}, -15 \text{ mm}, -10 \text{ mm}, -5 \text{ mm}, \) and \( 0 \text{ mm} \) are \(-0.31, 0.23, 0.88, 3.09, +\infty \), respectively. The main magnetic flux density under the electromagnetic coil is \( B_x \) and under the electromagnetic coil’s inner hole is \( B_y \). The maximum
amplitudes of $B_y$ and $B_y$ are 1.76 T and 1.77 T, respectively. It is shown that the double-coil EMAT can provide both horizontal and vertical magnetic fields of similar intensity.

The distribution of $B_x$ and $B_y$ on the sample surface at different inner diameters of the electromagnetic coil is shown in Fig. 6. Fig. 6(a) shows that the $B_x$ under the electromagnetic coil’s inner hole is relatively stable. Besides, the electromagnetic coil with a smaller inner diameter can obtain a larger $B_y$. As shown in Fig. 6(b), the $B_y$’s peak value gradually moves away from the center axis as the inner diameter of the electromagnetic coil increases. When the inner diameters of the electromagnetic coil is 10 mm, 15 mm, 20 mm, 25 mm, and 30 mm, the peak value of the $B_x$ is $-1.722$ T, $-1.768$ T, $-1.796$ T, $-1.814$ T, and $-1.826$ T, respectively. It is shown that the peak value of the $B_x$ is less affected by the inner diameter of the electromagnetic coil.

At the midpoint of the sample surface, the relationship between the vertical magnetic flux density ($B_y$) and the lift-off distance at different inner diameters of the electromagnetic coil is shown in Fig. 7. As the lift-off distance increases, $B_y$ gradually decreases. When the lift-off distance is 0.5 mm, the $B_y$ of the electromagnetic coil with inner diameters of 10 mm and 30 mm is $-2.01$ T and $-1.2$ T, respectively. When the lift-off distance is 8 mm, the $B_y$ of the electromagnetic coil with inner diameters of 10 mm and 30 mm is $-1.04$ T and $-0.9$ T, respectively. It is indicated that the $B_y$ of the electromagnetic coil with a smaller inner diameter is stronger than that of the larger one and is more sensitive to the lift-off distance.

### 3.3. Displacement field distribution

The structural diagram of the configuration relationship between the EMAT eddy-current coil and the electromagnetic coil is shown in Fig. 8. The EMAT eddy-current coils in Fig. 8(a) ~ (c) and Fig. 8(d) are spiral coil and annular coil, respectively. $D_1$ and $D_2$ represent the inner and outer diameters of the electromagnetic coil, and $d_1$ and $d_2$ represent the inner and outer diameters of the EMAT eddy-current coil. According to Fig. 8(a), the outer diameter of the spiral coil is smaller than the inner diameter of the electromagnetic coil. According to Fig. 8(b), the outer diameter of the spiral coil is equal to the inner diameter of the electromagnetic coil. As shown in Fig. 8(c), the outer diameter of the spiral coil is larger than the inner diameter of the electromagnetic coil. As shown in Fig. 8(d), the annular coil is placed under the electromagnetic coil.

Fig. 9 shows the displacement distribution of acoustic waves in different configurations of double-coil EMAT. The current inputted in the eddy-current coil is a 3-cycle sinusoidal pulsed current with an amplitude of 20 A at a center frequency of 4 MHz. Fig. 9(a) ~ (c) corresponds to Fig. 8(a) ~ (c); Fig. 9(d) ~ (f) corresponds to Fig. 8(d). According to Fig. 9(a) ~ (c), the ratios of the inner diameter of the electromagnetic coil to the outer diameter of the eddy-current coil are 1.5, 1, and 0.5, respectively; the corresponding amplitude ratios of shear waves to longitudinal waves are 3.65, 3.04, and 1.68 respectively. In addition, the amplitude ratios of shear and longitudinal waves corresponding to Fig. 9(d) ~ (f) are 1.16, 0.51, and 0.49. Compared with the spiral coil, the annular coil is more helpful in generating longitudinal waves.

A desirable EMAT design characteristic is the possibility of selecting to generate different acoustic wave modes for various engineering applications. For the shear-wave EMAT, it is usually necessary to reduce the interferences of the longitudinal wave and mode-converted wave on the received signal. As shown in Fig. 9, the spiral coil configurations used in Fig. 9(a) and (b) are suitable for designing the shear-wave EMAT. Similarly, the annular coil configurations used in Fig. 9(e) and (f) are...
suitable for designing the longitudinal-wave EMAT. To generate and
receive shear waves and longitudinal waves simultaneously under
identical measurement conditions, engineering constants such as
Young’s modulus and Poisson’s ratio are required to measure both shear
and longitudinal waves [35]. For this reason, the corresponding
double-coil EMAT configurations in Fig. 9(c) and (d) are suitable for
designing the shear-longitudinal wave EMAT.

To analyze the effects of the configuration relationship between
EMAT eddy-current coil and electromagnetic coil on waveform gener-
ation in detail, single-turn eddy-current coils with different diameters
are used. The induced current density on the cross-section of the eddy-
current coil is calculated during the reception, so the received signals
needed to be multiplied by the corresponding diameters of the eddy-
current coil. Induced current density waveforms are obtained in the
receiving process of single-turn eddy-current coils at different diameters,
as shown in Fig. 10. The inner and outer diameters of the electromag-
etic coils corresponding to Fig. 10(a) and (b) are (15 mm, 45 mm) and
(25 mm, 55 mm), respectively. The red dotted frames indicate longitudi-
dinal waves, and the blue dotted frames indicate shear waves. In the
dotted frames, the top waveform corresponds to the eddy-current coil
diameter of 5 mm, and the bottom waveform corresponds to the eddy-
current coil diameter of 35 mm. Between adjacent waveforms, the cor-
responding eddy-current coil diameter difference is 2 mm.

Fig. 11 shows the first echo amplitudes of shear and longitudinal
waves extracted from Fig. 10. In Fig. 11(a), the eddy-current coil’s di-
ameters corresponding to the maximum amplitude of the shear waves
and longitudinal waves are 13 mm and 29 mm, respectively. In Fig. 11
(b), the eddy-current coil’s diameters corresponding to the maximum
amplitude of the shear waves and longitudinal waves are 23 mm and 33

(a)

(b)

(c)

(d)

Fig. 8. Structural diagram of the configuration relationship between the EMAT
eddy-current coil and the electromagnetic coil.

Fig. 9. Displacement distribution of acoustic waves in different configurations
of double-coil EMAT. (a) $D_1/d_2 = 1.5$; (b) $D_1/d_2 = 1$; (c) $D_1/d_2 = 0.5$; (d) $D_1 =
d_1$, $D_2 > d_2$; (e) $D_1 < d_1$, $D_2 > d_2$; (f) $D_1 < d_1$, $D_2 = d_2$.

Fig. 10. Induced current density waveforms obtained in the receiving process
of single-turn eddy-current coils at different diameters. (a) $D_1 = 15$ mm, $D_2 =
45$ mm; (b) $D_1 = 25$ mm, $D_2 = 55$ mm.
Fig. 11. Induced current density amplitudes of single-turn eddy-current coils at different diameters. (a) $D_1 = 15$ mm, $D_2 = 45$ mm; and (b) $D_1 = 25$ mm, $D_2 = 55$ mm, respectively. It is shown that the diameter of eddy-current coil corresponding to the maximum amplitude of the shear waves and longitudinal waves is smaller than the inner and outer diameters of electromagnetic coil, respectively.

As the eddy-current coil diameter increases, the amplitude ratio of shear waves and longitudinal waves gradually decreases. The amplitude ratio of shear waves to longitudinal waves ($S/L$) is 1. The corresponding inner diameter of the electromagnetic coil ($D_1$) and the diameter of the eddy-current coil ($d$) are: (a) $D_1 = 15$ mm, $d = 15.9$ mm; (b) $D_1 = 25$ mm, $d = 24.3$ mm. Based on the characteristics that the amplitude ratio of shear waves and longitudinal waves is about 1 when the eddy-current coil diameter is equal to the inner diameter of the electromagnetic coil, the following suggestions for designing the double-coil EMAT with different bulk acoustic wave modes are put forward:

(a) Shear-wave mode requires the inner diameter of the electromagnetic coil to be as large as possible than the eddy-current coil diameter of the current coil;
(b) Longitudinal-wave mode requires the diameter of the eddy-current coil to be larger than the inner diameter of the electromagnetic coil and is appropriately smaller than its outer diameter;
(c) Shear-longitudinal wave mode requires an overlapping area of the electromagnetic coil and the eddy-current coil.

4. Experiment

4.1. Experimental platform

The structure diagram of an experimental platform used for the double-coil EMAT is shown in Fig. 12. In double-coil EMAT, EM and EC represents the electromagnetic coil and eddy-current coil, respectively. The experimental platform includes an FPGA-controlled transmitting circuit, receiving circuit, double-coil EMAT, and sample. The transmitting circuit is divided into electromagnetic coil excitation and eddy-current coil excitation. The electromagnetic coil excitation process is as follows: the long-pulsed signal was input into the isolated driving circuit to control the conduction of the thyristor connected to the high voltage capacitor. After the thyristor was turned on, the bulk capacitor rapidly discharged to the electromagnetic coil. In this paper, the output current acting on the electromagnetic coil was 3 kA.

The excitation process of the eddy-current coil is as follows: RF signal was input into the isolated driving circuit to control the on-off of the H-bridge circuit connected to the high voltage capacitor. H-bridge circuit output high voltage pulse, which improved the output power through an impedance matching circuit, and finally acted on the EMAT eddy-current coil. In this paper, the RF signal frequency acting on the eddy-current coil was 4 MHz. The receiving process of the eddy-current coil is as follows: the ultrasonic signal received by the eddy-current coil was first improved by the impedance matching circuit, then amplified and filtered, and finally transmitted to the oscilloscope. The maximum gain of the amplifier was 100 dB, and the bandwidth of the band-pass filter was 1–5 MHz.

The transmitting circuit schematic of the eddy-current coil is shown in Fig. 13. The numbers marked in Fig. 13 respectively represent: (1) Flyback boost circuit, used for high voltage charging of capacitor; (2) Isolated driving circuit, used to drive the on-off of power MOSFET and isolate high-voltage MOSFET and front-end circuit; (3) H-bridge circuit, consists of four power MOSFETs, used to output MHz level high frequency and 1 kV high voltage pulse signals; (4) Impedance matching circuit, used to reduce eddy-current coil inductance impedance and increase output current amplitude.

In the transmitting circuit of the eddy-current coil, the design of an isolated driving circuit and H-bridge circuit is critical. In this paper, the isolated driving chip is UCC21220 (Texas Instruments). The designed driving circuit has a driving frequency of 8 MHz, a maximum transmission delay of 60 ns, with under-voltage protection and dead-time adjustment functions. The power MOSFET in the H-bridge circuit requires high voltage tolerance and large output current characteristics. In this paper, the power MOSFET is NTHL080N120SC1 (ON Semiconductor). The main parameters include the drain-to-source voltage of 1200 V, continuous drain current of 31 A, turn-on delay time of 13 ns, and turn-off delay time of 22 ns. In the design of the H-bridge circuit, the influence of PCB line inductance on the on-off delay and overshoot of MOSFET should be considered; the PCB line length between the MOSFET and the isolation drive circuit should be minimized to avoid overheating or high voltage breakdown of MOSFET in high frequency and high voltage modes.

The transmitting circuit schematic of the electromagnetic coil is shown in Fig. 14. The numbers marked in Fig. 14 represent: the capacitor charging circuit and pulsed current generating circuit, respectively. The capacitor charging circuit comprises a boost control circuit, voltage detection circuit, transformer (T1), switch tube (D1), and capacitor (C). The boost control circuit and voltage detection circuit constitute a closed-loop circuit. When the capacitor voltage is detected to be less than the preset voltage, the boost control circuit starts to work and charges the capacitor. When the capacitor voltage is detected to reach the preset voltage, the boost control circuit stops working.

The pulsed current generating circuit comprises capacitors (C1/C2/C3), a thyristor (SCR), and an electromagnetic coil. Turning on the thyristor, the energy in the capacitor is quickly released into the
The electromagnetic coil. The electromagnetic coil establishes a strong pulsed magnetic field through a large current. The magnitude of the electromagnetic coil through the current mainly depends on the capacitor charging voltage, line resistance, and the choice of key components. The capacitor is an aluminum electrolytic capacitor. The main parameters include a rated voltage of 250 V, a capacitance of 33 mF, and equivalent series resistance (ESR) of 10 mΩ. The main parameters of the thyristor include a rated voltage of 1200 V, a rated current of 14 kA, a gate-controlled delay time of 4 μs, and a slope resistance of 0.27 mΩ. In addition, the connection resistance in the circuit is restricted. The
connection wires between the capacitors, thyristor, and electromagnetic coil are multi-core copper wires with 20 mm$^2$ diameters.

The input current and the vertical magnetic flux density of the electromagnetic coil were measured using Tektronix TCPA300 AC/DC current probe and CH-3600 digital gauss meter. The measured time-domain waveforms of the input current and the vertical magnetic flux density are shown in Fig. 15(a). The input current and vertical magnetic flux density of the double-coil EMAT are 3.02 kA and 2.83 T, respectively. The intensity of the received signal is proportional to the square of the bias magnetic field, indicating that the double-coil EMAT can significantly improve the energy conversion efficiency, compared with the vertical magnetic flux density of magnet (about 0.76 T [19]). Fig. 15(b) shows the simulation and experimental results of the vertical magnetic flux density measurement at the inner hole of the electromagnetic coil. The simulation results are consistent with the measured data, although there are some differences. The main reason for the differences may be that the manual measurement causes a certain tilt of the Gaussian probe.

### 4.2. Experiment validation

In the experiments, the effect of double-coil EMAT configuration on waveform generation in paramagnetic steel was studied. It should be noted that if there is an overlap area between the electromagnetic coil and the eddy-current coil, the induced current will generate ultrasonic waves on the sample and the electromagnetic coil. To shield the interference from ultrasonic waves in the electromagnetic coil on the received signal in the eddy-current coil, a 0.1 mm thick copper foil was placed between the electromagnetic coil and the eddy-current coil. Fig. 16 shows the experimental results with and without copper foil placed, in the case of overlap between the electromagnetic coil and eddy-current coil.

#### Fig. 16. Experimental results with and without copper foil placed, in the case of overlap between the electromagnetic coil and eddy-current coil.

The received waveforms of the eddy-current coil at different diameters are shown in Fig. 17. The inner diameters of the electromagnetic coil in Fig. 17(a) and (b) are 25 mm and 15 mm, respectively. The eddy-current coil is a spiral coil structure with a diameter of 10 mm, 15 mm, 20 mm and 25 mm, respectively. L and S represent the longitudinal wave and the shear wave, respectively. As shown in Fig. 17, whether the inner diameter of the electromagnetic coil is 15 mm or 25 mm, multiple bottom echoes of the shear wave from $S_1$ to $S_3$ are obtained. When the electromagnetic coil’s inner diameter is larger than the eddy-current coil’s outer diameter, the longitudinal wave is very weak, making it difficult to distinguish from the ambient noise, as shown in Fig. 17(a). When the electromagnetic coil’s inner diameter is smaller than the eddy-current coil’s outer diameter, both shear wave and longitudinal wave
are obtained, as shown in Fig. 17(b). The results are consistent with the simulation.

When the inner diameter of the electromagnetic coil is 15 mm, the received waveforms obtained by the eddy-current coil with an annular structure are shown in Fig. 18. The inner and outer diameters of the annular coil are: (1) \( d_1 = 10 \) mm, \( d_2 = 20 \) mm; (2) \( d_1 = 15 \) mm, \( d_2 = 25 \) mm; (3) \( d_1 = 20 \) mm, \( d_2 = 30 \) mm. These annular coils have overlapping areas with the electromagnetic coil. As the size of the annular coil increases, the overlap areas with the electromagnetic coil gradually increase. As shown in Fig. 18, the first echo amplitude of the longitudinal wave and shear wave are: (1) \( L_1 = 0.5 \) V, \( S_1 = 1.26 \) V; (2) \( L_1 = 0.65 \) V, \( S_1 = 0.94 \) V; (3) \( L_1 = 0.74 \) V, \( S_1 = 0.39 \) V. It can be seen that as the overlap areas of the annular coil and the electromagnetic coil increase, the longitudinal wave amplitude increases and the shear wave amplitude decreases. Therefore, the amplitude of the shear wave and longitudinal wave can be adjusted by changing the overlap areas between the annular coil and the electromagnetic coil.

4.3. High-temperature experiment

The electrical conductivity of the eddy-current coil and the sample is changed at high temperatures, which leads to changes in the electrical parameters (AC resistance and inductance) of the eddy-current coil. For this reason, HIOKI 3532-50 LCR meter and Tektronix TCPA300 AC/DC Current Probe were used to measure the electrical parameter and input current waveform of the eddy-current coil at high temperatures. The eddy-current coil was a pure silver wire with an inner diameter of 3 mm, an outer diameter of 18 mm, a wire diameter of 0.1 mm, and turns of 30 in total. The eddy-current coil was separated from the paramagnetic steel by a 0.25 mm thick ceramic plate and heated in a high-temperature furnace.

The relationship between the AC resistance and the inductance of the eddy-current coil with temperature are shown in Fig. 19(a). The AC resistance and inductance of the eddy-current coil increase with temperature. At 25 °C and 500 °C, the changes of the AC resistance and inductance of the eddy-current coil are 25.11% and 8.82%, respectively. The input current waveforms of the eddy-current coil are shown in Fig. 19(b). At 25 °C and 500 °C, the peak-to-peak current values of the eddy-current coil are 14.87 A and 13.66 A, respectively. The output current is reduced by 8.86%. Since the change of the output current is close to the change of the coil inductance, the output current should be mainly affected by the inductance of the eddy-current coil.

To verify the ability of the double-coil EMAT to generate different bulk acoustic wave modes in paramagnetic steel at high temperatures, an experimental platform was built, as shown in Fig. 20. The experimental platform mainly includes: hardware circuit, high-temperature double-coil EMAT, high-temperature furnace, and oscilloscope. The diameter and height of the fabricated high-temperature dual-coil EMAT are 45 mm and 20 mm, respectively. The electromagnetic coil was a silver-coated copper wire with a wire diameter of 1.2 mm and turns of 25 (5 turns and 5 layers) in total. 0.1 mm thick copper foil was placed between the electromagnetic coil and the eddy-current coil. Both the electromagnetic coil and the eddy-current coil were insulated and sealed at high temperatures using ceramic adhesives.

In the experiment, double-coil EMAT and sample were heated in a high-temperature furnace. The temperature of the furnace rises by 50 °C, keep it warm for half an hour and perform the test. The experiment lasted for about 6 h, and the door of the high-temperature furnace was kept closed during the test. The received waveforms of double-coil EMAT in shear-wave mode at different temperatures are shown in Fig. 21. The eddy-current coil is a spiral coil with a diameter of 18 mm, and the inner diameter of the electromagnetic coil is 25 mm. The sample is paramagnetic steel SUS304 with a diameter of 40 mm and a thickness of 10 mm. As shown in Fig. 21, the arrival time of the shear wave gradually increases with temperature mainly because the material’s
elastic modulus, Poisson’s ratio, and density change at high temperatures [7].

According to Fig. 21, the maximum measurement temperature of double-coil EMAT is 500 °C. Based on the attenuation characteristic of the received signal, the ultrasonic echo signal should still be obtained at higher temperatures. However, the echo signal cannot be received at higher temperatures due to the material selection of the eddy-current coil. In this paper, the eddy-current coil material used pure silver wire to prevent the coil’s oxidation at high temperatures. However, when the temperature is above 500 °C, the pure silver wire will be soften, resulting in a decrease mechanical strength. Since the mechanical force generated by the electromagnetic coil acts on the sample and the eddy-current coil, the silver wire used in the eddy-current coil will break after softening.

Fig. 22 shows the amplitudes of the echo signal extracted from the first to the fourth time in Fig. 21. As the temperature increases, the amplitudes of the echo signal show a downward trend. The main factors causing this phenomenon include the followings: (1) Thermal phonon–phonon interactions increase as temperature increases, leading to more significant scattering [38]; (2) The internal resistance of the electromagnetic coil increases as temperature increases, resulting in a decrease of the long-pulsed current amplitude [18]; (3) The inductance of the eddy-current coil increases as temperature increases, resulting in a decrease of the RF pulsed current amplitude.

The received waveforms of double-coil EMAT in shear-longitudinal wave mode at different temperatures are shown in Fig. 23. The eddy-current coil is an annular coil with an inner diameter of 20 mm and an outer diameter of 30 mm. The inner diameter of the electromagnetic coil is 15 mm. The sample is paramagnetic steel SUS316 with a diameter of 50 mm and a thickness of 12.5 mm. As shown in Fig. 23, the second shear wave (S2), located between the third and fourth longitudinal waves, has no apparent interference. However, the interference between the first shear wave (S1) and the second longitudinal (L2) wave is enhanced gradually with the increase of temperature. It is indicated that the velocity changes in shear wave and longitudinal wave are not the same at different temperatures. Experiments show that the designed double-coil EMAT can generate and receive both shear and longitudinal wave modes in high-temperature environment.

Fig. 24 shows the amplitudes of the echo signal extracted from the first to the second time in Fig. 23. The amplitudes of the shear wave and longitudinal wave decrease monotonically with increasing temperature. At 25 °C, the amplitudes of S1, S2, L1, and L2 are 493 mV, 330 mV, 577 mV, and 515 mV, respectively. At 500 °C, the amplitudes of S1, S2, L1, and L2 are 48 mV, 20 mV, 152 mV, and 118 mV, respectively. The first echo amplitudes of the shear wave and longitudinal wave at 500 °C decreased by 10.2 times and 3.8 times, respectively, compared with that at 25 °C. Thus, the longitudinal wave with less attenuation in the sample has an advantage in high-temperature measurement.

5. Conclusions

The existing high-temperature EMATs are mainly shear-wave EMATs. There are few reports on shear-longitudinal wave or
longitudinal-wave EMATs. To overcome this shortage, a high-temperature EMAT with double-coil configuration generates shear and longitudinal wave modes in paramagnetic steel is studied. The conclusions are as follows:

1. An experimental platform for double-coil EMAT was developed. The input current of the electromagnetic coil was 3.02 kA, and the corresponding output magnetic field was 2.83 T. The proposed EMAT significantly improved the energy conversion efficiency, compared with the permanent magnet EMATs.

2. The proposed EMAT can provide both horizontal and vertical magnetic fields with similar strength. By adjusting the configuration relationship between the electromagnetic coil and the eddy-current coil, the selective generation of shear-wave, longitudinal-wave, and shear-longitudinal wave modes was realized.

3. High-temperature double-coil EMATs of the shear-wave and shear-longitudinal wave modes were designed and fabricated. The proposed EMAT can generate and receive both shear and longitudinal wave modes in high-temperature environment.

CRediT authorship contribution statement

Guofu Zhai: Conceptualization, design of study, Writing – review &amp; editing, critically for important intellectual content, Approval of the version of the manuscript to be published. Bao Liang: Conceptualization, and design of study, acquisition of data, Writing – original draft, Writing – review &amp; editing, critically for important intellectual content, Approval of the version of the manuscript to be published. Xi Li: Formal analysis, interpretation of data, Writing – original draft, Approval of the version of the manuscript to be published. Yuhang Ge: Acquisition of data, Writing – original draft, Approval of the version of the manuscript to be published. Shujuan Wang: Conceptualization, and design of study, Writing – review &amp; editing, critically for important intellectual content, Approval of the version of the manuscript to be published.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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