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Longitudinal mode magnetostrictive patch transducer array employing a multi-splitting meander coil for pipe inspection

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Abstract

Recently, a magnetostrictive patch transducer (MPT) by means of the highly magnetostrictive (such as nickel or iron-cobalt alloy) patch attached on the specimen has been applied in nondestructive ultrasonic testing in waveguides. In the study, we proposed a new MPTs array employing a multi-splitting meander coil (MSMC) for generating and receiving longitudinal guided waves in pipes. In the suggested configuration, the directions of the static magnetic field produced by the permanent magnets and the dynamic magnetic field produced by the MSMC are in the axial direction of the pipe. Two finite element models were established to simulate the distribution of the static and dynamic magnetic fields in the patch, respectively. The proposed MSMC was made of flexible printed circuit (FPC), so it could be easily installed on pipe surface. The performance of the proposed MPTs array was experimentally studied. Firstly, it was experimentally verified that the axisymmetric longitudinal guided wave mode, $L(0,2)$, could be effectively generated and received in pipes with the developed MSMC-MPTs array. Secondly, the frequency response characteristics of the developed MSMC-MPTs array were related to D (the distance between adjacent belts of the MSMC). Thirdly, we demonstrated the ability of the developed MSMC-MPTs array for the identification and location of a crack defect in pipes. Finally, we compared the performances of the MSMC-MPTs array and conventional meander coil-MPTs and proved that the signals of the longitudinal guided wave mode could be enhanced by using the developed MSMC-MPTs array.

Keywords: Longitudinal mode, Pipe inspection, MPTs array, MSMC, Defect identification

1. Introduction

In recent years, the ultrasonic guided wave testing method has been widely applied in the inspection of pipe defect because of their major advantages, such as low attenuation, long distance propagation, and high detection efficiency [1-5]. Two techniques are commonly employed for exciting ultrasonic guided waves: the piezoelectric transducers and electromagnetic acoustic transducer (EMAT). With the proper penetration

depth and mechanical flexibility, the piezoelectric ultrasonic method is widely used for defect evaluation and material characterization [6-7]. However, the piezoelectric ultrasonic testing requires the good sonic contact with the test piece, thus affecting its inspection efficiency in some applications. The EMAT is able to generate and detect ultrasonic waves without contact due to the contactless electromagnetic coupling with the test object, rather than mechanical coupling adopted in standard piezoelectric transducers [8-10]. This feature makes EMAT suitable to inspect moving or high-temperature objects. Moreover, EMAT also has other features, such as flexibility, excellent repeatability, and durability.

In general, an EMAT consists of a permanent magnet (or electromagnet) to introduce a static field and a flat coil to induce a dynamic current in the surface of a sample. The electromagnetic energy can be converted into the mechanical energy via an air gap of few millimeters by non-contact coupling, thus realizing generation and detection of ultrasonic waves. EMAT can generate a wide range of ultrasonic wave modes through the careful design of the geometric configuration [11]. Moreover, EMAT is easier to motivate a pure mode and improve the identification and location of defects. The EMAT exploits mainly two transduction mechanisms: (i) the Lorentz-force mechanism caused by the interaction between eddy currents and the static magnetic flux density; (ii) the magnetostriction mechanism of the piezomagnetic effect [12]. Generally, the Lorentz-force mechanism arises in all conducting materials, while the magnetostriction mechanism appears only in ferromagnetic materials.

There are three ultrasonic guided wave modes in cylindrical waveguide structures: longitudinal, torsional, and flexural modes. The axisymmetric torsional and longitudinal guided wave modes are the most widely used for pipe inspection [13-14]. The longitudinal guided wave mode $L(0,2)$ is practically non-dispersive over typical frequency ranges, and the particle motion is roughly uniform throughout the pipe wall. The axial displacement of $L(0,2)$ mode within a certain frequency range is larger compared to its radial displacement, so the $L(0,2)$ mode shows the good attenuation performance [15]. $L(0,2)$ mode generated by magnetostrictive transducer is an effective choice for the long-range pipe inspection. Kwun et al. [16-17] proposed a longitudinal guided wave EMAT based on the magnetostriction mechanism. In the configuration of this EMAT, with the adopted simple single-belt coil, it was difficult to control the wave mode generated. To overcome this drawback, Huang S L et al. [18-19] proposed a new transducer configuration, in which a multi-belt coil was used to motivate pure $L(0,2)$ mode, and successfully identified the crack in the pipe. However, magnetostrictive EMAT directly applied on normal steel structure showed the comparatively poor performance [20]. In recent years, a type of EMAT based on magnetostriction, MPT (Magnetostrictive Patch Transducer) by means of a highly magnetostrictive (such as nickel or iron-cobalt alloy) patch attached on the

specimen, has been proposed to effectively generate high-power ultrasonic waves even in a non-ferromagnetic waveguide. Furthermore, the conversion efficiency and the SNR (Signal-to-Noise Ratio) of guided waves excited by MPT are significantly improved. Kwun et al. [21] proposed a method and apparatus employing the MPT for pipe inspection. The team of Kim [22-25] developed and optimized the configuration of several MPTs in pipes to increase the SNR and energy of the guided waves generated by MPT. In our previous study [26], we proposed a MPTs array employing a modified planar solenoid array (MPSA) coil for generating and receiving the torsional mode in pipes, which was suitable for the inspection of the pipe surface. Although, MPTs have been widely used in wave transduction in pipes, the generation of longitudinal guided wave mode in pipes by using MPT has not been reported.

In this paper, we proposed a symmetrically configured MPTs array for generating pure longitudinal guided wave mode in a pipe. It has the advantages of traditional longitudinal mode EMAT, such as compact structure and easy installation. The multi-splitting meander coil (MSMC) was used as the transmitting coil and receiving coil in the newly proposed MPTs array. With its characteristics of spatial periodicity, this coil structure can control the mode of the generated guided waves to make the interpretation of the inspected waveform easy. Finite element method was used in the simulation analysis of the distributions of the static and dynamic magnetic fields in the patch. In order to experimentally verify the performance of the developed MPTs array, the $L(0,2)$ mode was excited and received in an alloy steel pipe to inspect a typical artificial defect. Furthermore, the frequency response characteristics of the developed MSMC-MPTs array were studied. Finally, we compared the performances of the MSMC-MPTs array and conventional meander coil-MPTs.

2. Configuration and working principle of longitudinal mode MSMC-MPTs array

Figs. 1(a) and 1(b) show the configuration and working principle of the proposed longitudinal modes magnetostrictive patch transducers array employing MSMC (MSMC-MPTs array), respectively. It consists of three components: a 0.10-mm thick nickel patch, which is a magnetostrictive material and tightly bound around a pipe surface, a two-layer multi-splitting meander coil (MSMC), and permanent magnets with a sector cross-section. The principle that an EMAT generates longitudinal guided wave mode in a pipe is shown in Fig. 1(b). The permanent magnet and the MSMC will respectively induce the static bias magnetic field and dynamic magnetic field along the pipe axis. Under the action of the static bias magnetic field and dynamic magnetic field, the magnetostrictive force is generated to cause the time-variant mechanical deformation of the patch. Then, the patch deformation generates longitudinal guided wave mode in the pipe because the patch is tightly bonded on it. The magnetostrictive force under one belt of the coils can be

described as

$$F_{ms} = -\frac{1}{2}(3\tau + 2\mu)(1 - 2\nu) \frac{\partial \xi}{\partial M_0} \frac{\partial m_z}{\partial z}, \quad (1)$$

where τ and μ are Lamé constants; ν is Poisson's ratio; ξ is line magnetostriction; M_0 is the magnetization intensity of the static bias magnetic field; m_z is z -axis (the axis of pipe) component of the dynamic magnetic field magnetization intensity. According to Eq. (1), the direction of the magnetostrictive force is along the axis of pipe and the magnitude is controlled by the static magnetic field and dynamic magnetic field.

Moreover, in order to minimize the wave reflection at the patch edges, reduce the amount of trailing pulses, and alleviate the waveform distortion problem, the edges of the nickel strip are machined to guarantee the smooth thickness variation [27].

3. Design and development of longitudinal mode MSMC-MPTs array

3.1. Permanent magnet

In order to adapt the magnet to the pipe surface, the permanent magnet with a sector cross-section is proposed, as shown in Fig. 2. The inner diameter of the permanent magnet is equal to the outer diameter of the pipe for the better matching with the pipe wall. Eight identical permanent magnets were placed evenly on both sides of the patch to generate the static magnetic field along the axial direction of the pipe. Moreover, all the permanent magnets sintered from NdFeB material were adopted here to provide a strong static bias magnetic field. The geometric parameters of the permanent magnet are provided as follows: the inner radius r is 21 mm; the thick d is 5 mm; the height h is 10 mm; the center angle θ of the sector cross-section is 70° ; the polarization direction is the axial direction.

Moreover, a finite element simulation was conducted in commercial finite element software, COMSOL Multiphysics, to simulate the distribution of magnetic field in the patch. In the finite element model, the geometric parameters of the magnets were the same to the actual sizes mentioned above and the details of the standard modeling procedure is omitted. Fig. 3 shows the distribution of the static magnetic field in the patch. It is observed that the distribution of magnetic flux density is relatively uniform apart from the nearby position of the permanent magnets and the direction of magnetic field is almost the same along the axial direction of the pipe.

3.2. The design of MSMC

The proposed MSMC made of flexible printed circuit (FPC) can be bent optionally according to the curvature of pipe surface. Therefore, the proposed MSMC can easily be installed on the pipe surface. As shown in Fig. 4, the MSMC adopts the double-layer structure and the bottom layer coil is connected to the top layer in series by a hole. The current direction is always the same in the same location of the bottom and

top layers. In this way, the amplitude of the dynamic magnetic field will be improved. When alternating currents are introduced into the coils, the axial dynamic magnetic field in the patch can be generated by the vertical sections. However, the circumferential magnetic field can be generated by the horizontal sections of MSMC. Thus, some 0.04-mm thick iron-cobalt alloy foils, which have the higher magnetostrictive capability than nickel patch, are pasted on the bottom of horizontal sections of MSMC to suppress the circumferential magnetic field in the patch, as shows in Fig. 1. Furthermore, the current direction is opposite to the adjacent belts for inducing opposite dynamic magnetic field. The width of coils is 0.3 mm and the gap d between adjacent coils is 0.2 mm. It should be noted that the interval D (the distance between adjacent belts of the MSMC) illustrated is half of the wavelength, $\lambda/2$, at the theoretical center-frequency f_c of the developed MSMC-MPTs. It is designed according to the constructive interference phenomena of the meander coil to enhance the energy of the target guided wave mode [11, 28].

To study the distribution of dynamic magnetic field in the patch, a 2-dimensional finite element model was established in COMSOL Multiphysics. In this finite element model, the geometric parameters of the coils were the same to the actual sizes mentioned above. Fig. 5 shows the magnetic field distribution in the patch generated by the vertical sections of MSMC. As shown in Fig. 5, the distribution of magnetic flux density is almost uniform and varies periodically along the axial direction of the pipe. Due to the generation of the abundant axial magnetic flux density, the longitudinal guided wave modes can be generated and received effectively. Furthermore, another 2-dimensional finite element model was adopted to prove the effect of iron-cobalt alloy foils on suppressing the circumferential magnetic field in the patch. In the axis profile of the magnetic field distribution generated by a single horizontal section of MSMC (Fig. 6), the circumferential magnetic field is concentrated in the iron-cobalt alloy foils. Hence, the torsional modes cannot be generated in nickel strip.

4. Experimental investigation for the developed MSMC-MPTs array

To verify the performance of the proposed transducer array, we performed several experiments. Fig. 7 shows the experimental setup for the pipe inspection with a pair of the developed MSMC-MPTs array. It consists of a high power ultrasonic measurement system Ritec-RAM5000 with a high dB preamplifier, a personal computer (PC), an oscilloscope, a pair of impedance matching boxes, and a pair of developed MPTs array. The Ritec-RAM5000 controlled by a computer (PC) was used to generate high power tone burst voltages for the transmitter and amplify the received signal from the receiver. In order to enhance their conversion efficiency, a pair of impedance matching boxes were added into the transmitter and receiver, respectively. The transmitter and receiver were installed on a chosen alloy steel pipe (the length of 1970 mm,

inner diameter (ID) of 32 mm, and outer diameter (OD) of 42 mm). The transmitter was 500 mm away from the left end of the pipe and the distance between the transmitter and the receiver was 800 mm. An artificial axial crack with the dimensions (15 mm (Length)× 4 mm (Depth)× 2 mm (Width)) was 300 mm away from the left end of the pipe.

Fig. 8 shows theoretical dispersion curves of longitudinal guided wave modes for the tested alloy steel pipe. It is obvious that the group velocity dispersion curve is relatively flat from 200 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 4997-5210 m/s, which is faster than that of other modes, such as L(0,1) mode. Therefore, the defect echoes in the L(0,2) mode should be detected first, creating favorable conditions for signal processing and defect recognition. The center frequency chosen for the excitation signal used in these experiments was 270 kHz, and corresponding group velocity was 5061 m/s.

4.1. L(0,2) mode generation and reception for defect localization

In this experiment, a 5-cycle 270-kHz sine burst modulated by a Hanning window was used as excitation signal. In order to improve the quality of original signal, the signal from the receiver was processed via wavelet denoising based on db10 mother wavelet. The signal-to-noise ratio of denoised signal is 40 dB, which is nearly 18 dB higher than the original signals. The received signals for denoised signals can be better visualized than that of original signals, as shown in Fig. 9. The wave packet a is the initial pulse applied to the transmitting coil which is electrically leaked to the receiving coil from the air at the velocity of light. The packet b occurring in approximately 162 μ s after the initial pulse is the direct arrival signal induced in the receiver. The wave packet d and e occurring in approximately 364 μ s and 438 μ s after the initial pulse are the left and right end-reflected signals, respectively. The packet c occurring in 248 μ s after the initial pulse is the crack reflection pulse.

In order to prove that the generated guided wave signal was the L(0,2) mode, the traveling distance of every wave packet to the initial pulse was estimated by multiplying the time difference Δt between the initial pulse and other packets by the group velocity of L(0,2) mode at the chosen frequency. Estimation results of crack and end locations by using the proposed transducers are shown in Table 1. In this table, Δd_1 and Δd_2 represent the experimentally measured and the exact distance difference among different wave packets, respectively. The experimentally measured distances are in good agreement with the actual ones (relative error within 5%), while the crack in the pipe is accurately detected with a relative error of 4.5%. This shows that the proposed MSMC-MPTs array can not only generate pure L(0,2) mode but also identify and locate

the crack in the pipe successfully.

Moreover, similar experiments were carried out under other frequencies (from 200 kHz to 340 kHz with the incremental step of 10 kHz) to further prove the correctness of the conclusion above. The group velocities v_{g-m} under different frequencies were measured and marked with the circles in Fig. 8(a). The measurements are in good agreement with the theoretical group velocity v_{g-L} for the L(0,2) mode under the corresponding frequencies.

4.2. Frequency response characteristics of the developed MSMC-MPTs

To investigate the frequency characteristics of the proposed MCSC-MPTs, several experiments were performed. As mentioned in Section 2, the interval D (the distance between adjacent belts of the proposed MSMC) is equal to half of the wavelength of the selected guided wave mode L(0,2). In the design parameters of the MCSC, D is 10 mm. Therefore, the corresponding theoretical center frequency f_c and phase velocity v_p of the developed MPSA coil-MPTs are respectively 267 kHz and 5336 m/s for the chosen alloy steel pipe. In the experiments, the excitation frequencies varied from 200 kHz to 340 kHz with an increment step of 10 kHz, while the maximum input current to the coil remained the same. The peak values obtained from the Hilbert envelop of the direct wave at different frequencies were extracted from the measured signals. The frequency response curve is shown in Fig. 10. The largest amplitude was obtained at the frequency of 270 kHz, which was highly consistent with the theoretical center frequency f_c , 267 kHz. Moreover, when the excitation frequencies deviated from the theoretical center frequency, L(0,1) mode, the other longitudinal guided wave mode, appeared. Fig. 11 shows the received signal at 220 kHz by using the developed MPTs array. It can be inferred that the group velocity of wave packet f is 3142 m/s based on the TOF (Time-of-Flight) method. In Fig. 8(a), the theoretical group velocity of L(0,1) mode is 3208 m/s at 220 kHz. Therefore, the relative error of the group velocity is 2%, indicating that the wave packet f is L(0,1) mode. These experimental results show good frequency response characteristics of the proposed MCSC-MPTs and validate the quantitative relationship between the center frequency and the interval D defined by the distance between adjacent belts of the proposed MSMC.

4.3. The performance of the developed MSMC transducer

In previous studies, the conventional meander coil shown in Fig. 12 was used as the sensitive core of a magnetostrictive transducer to generate a dynamic magnetic field [11, 29]. In the proposed MPTs array shown in Fig. 1, a multi-splitting meander coil was used to induce a stronger magnetic field to improve the performance. The performance comparison was made between the MPTs array employing conventional meander coils and the proposed MSMC-MPTs array in which bias static magnetic field was supplied by the

permanent magnets.

The experimental setup is the same as that in Section 4.1 except some alterations of the receiver and transmitter. There are several meander coils made of FPC (Flexible Printed Circuit). As shown in Fig. 12, the interval D_2 between meander lines of the double-layers FPC meander coil is 10 mm, which is equal to the interval D_1 of the developed MSMC. The received signals at the same excitation frequency of 270 kHz obtained from two different configurations of MPTs are shown in Fig. 13. In Fig. 13(a) and Fig. 13(b), the V_{p-p} value of the direct signal by the proposed MSMC-MPTs array is larger than that by the meander coil-MPTs. The results demonstrate that the proposed MSMC-MPTs array can effectively generate L(0,2) mode and enhance the signal of this mode to a certain extent.

As mentioned in Section 3, the MSMC adopts double-layer structure to improve the performance of MPTs. Hence, a contrast experiment was conducted between the single-layer MSMC-MPTs array and the double-layer MSMC-MPTs array. Fig. 14 shows three signals measured at 270 kHz employing different pairs of transducer and receiver. When the receiver and transmitter are both single-layer MSMC-MPTs array, the signals shown in Fig. 14(a) are obtained. When the transmitter is the single-layer MSMC-MPTs array and the receiver is the double-layer MSMC-MPTs array, the result shown in Fig. 14(b) is obtained. When the receiver and transmitter are both double-layer MSMC-MPTs array, the results illustrated in Fig. 14(c) can be obtained. It is obvious that the V_{p-p} value of the received direct signal increases with the increase of the number of coil layers. This confirms that the inspection performance of steel pipes can be significantly improved by employing a double-layer arrangement for coils of the MPTs array.

4. Conclusions

The magnetostrictive patch transducer is a good choice of generating and receiving longitudinal guided waves for pipe axial inspection. In this paper, we proposed a longitudinal mode magnetostrictive patch transducer array with a new MSMC to generate longitudinal modes in pipes effectively. Several customized permanent magnets were adopted to supply an axial static magnetic field for the nickel strip installed on the pipe surface. Meanwhile, the proposed MSMC carrying an alternating current also provides a dynamic magnetic field along the axis in the nickel strip. The mechanical deformation of nickel strip is formed and then transferred to the pipe, thus contributing to the generation of the longitudinal modes in the pipe. The distributions of static and dynamic magnetic fields in the patch were simulated, respectively. Furthermore, experimental results in this study indicated that the developed MPTs array could generate pure L(0,2) mode, and had the potential to detect defects in pipes accurately. Then, the frequency response of the developed MPTs array was characterized to provide beneficial insight into the design optimization of the transducers.

Furthermore, the experiments demonstrated that the MSMC-MPTs array had a better performance than previous the meander coil-MPTs array. Subsequently, it was proved that the double-layer MSMC-MPTs had the better performance than the single-layer MSMC-MPTs array. In the future, further experiments will be conducted with the developed MSMC-MPTs array to achieve two-dimensional imaging of the defects in pipes based on a phased array system.

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- The proposed two-layer MSMC made of FPC can generate high-power waves.
- The proposed MPTs array can generate and receive the longitudinal mode, $L(0,2)$, in pipes.
- Pipe defect detection and localization were realized with the proposed MPTs array.
- The center frequency of MPTs array is related to the distance between adjacent belts of the MSMC.

Fig. 1. Configuration and working principle of the proposed longitudinal modes magnetostrictive patch transducers array employing MSMC

Fig. 2. Schematic diagram of the permanent magnet

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Fig. 3. The magnetic field distribution in the nickel strip

Fig. 4. Schematic diagram of the MSMC

Fig. 5. The dynamic magnetic field distribution in the nickel strip

Fig. 6. The dynamic magnetic field distribution in the iron-cobalt alloy foils

Fig. 7. Experimental setup for the pipe inspection by using a pair of the developed transducers

Fig. 8. Theoretical dispersion curves of longitudinal guided wave modes for the tested alloy steel pipe

(a) Group velocity (b) Phase velocity

Fig.9. The original and de-noised signals at 270 kHz by using the developed transducers

Fig. 10. Frequency response curve of the proposed transducer

Fig.11. The original and de-noised signals at 220 kHz by using the developed transducers

Fig. 12. Schematic diagram of the MSMC

Fig.13. The signals measured at 270 kHz respectively employing (a) a pair of conventional meander coil-MPTs (b) a pair of MSMC MPTs

Fig. 14. Three signals measured at 270 kHz respectively employing (a) a pair of single-layer MSMC-MPTs (b) a single-layer MSMC-MPTs as the transmitter and a double-layer MSMC-MPTs as the receiver (c) a pair of double-layer MSMC-MPTs

Table 1 Estimation of crack and ends location by the proposed transducer

Pulse	b	c	d	e
Δt (μ s)	162	248	364	438
Δd_1 (mm)	820	1255	1842	2216
Δd_2 (mm)	800	1200	1800	2140
Relative error (%)	2.5	4.5	2.3	3.6

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