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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.

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 reputability, 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.

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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 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

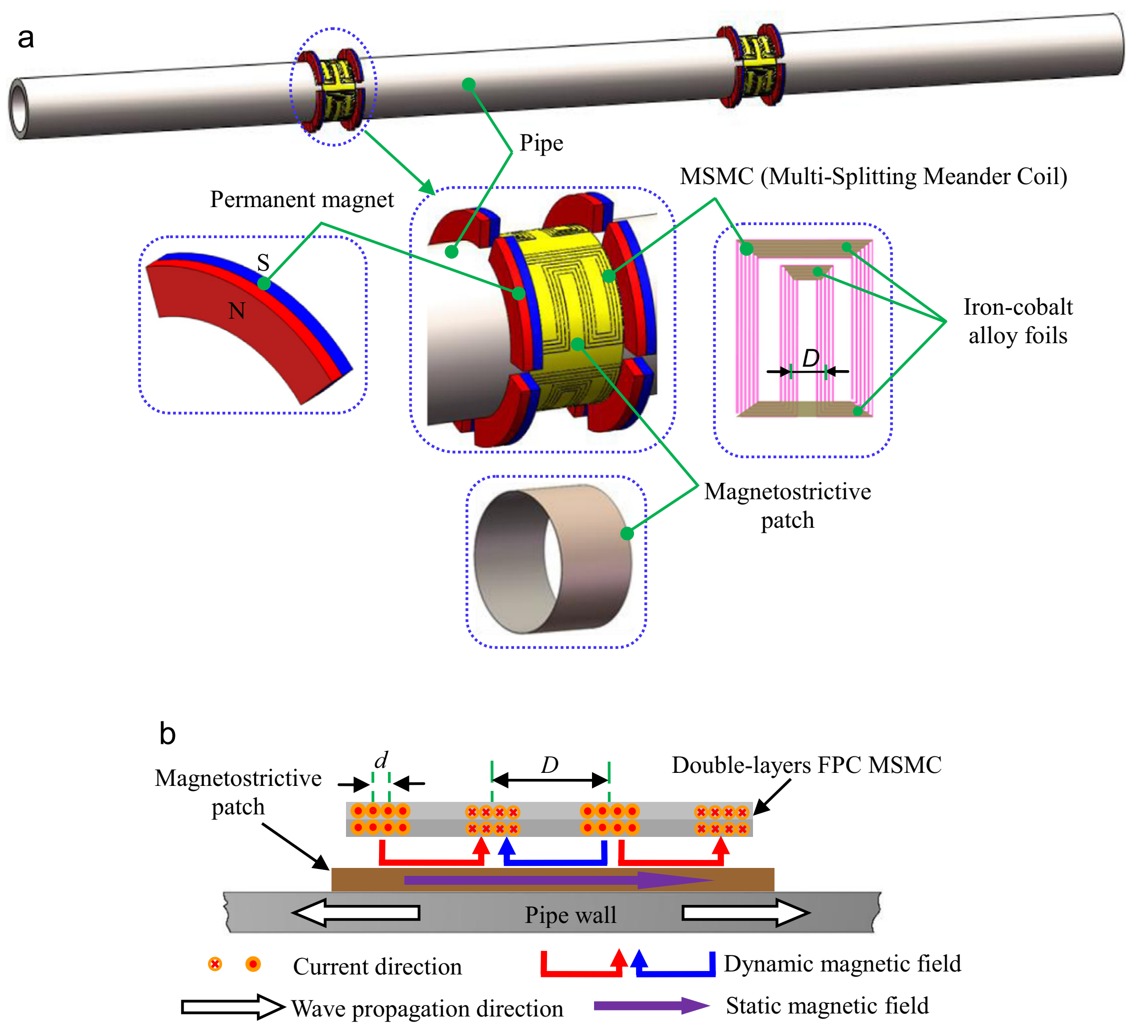

Fig. 1. Configuration and working principle of the proposed longitudinal modes magnetostrictive patch transducers array employing MSMC (a) three-dimensional view and (b) cross-sectional view.