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Torsional mode magnetostrictive patch transducer array employing a modified planar solenoid array coil for pipe inspection

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ABSTRACT

In recent investigations, the application of the transducers used in plates has been extended to pipe inspection with circumferential arrays because of the similar particle displacement patterns of some modes between plate and pipe, such as SH and torsional modes. Motivated by the configuration of magnetostrictive patch transducer (MPT), in which a planar solenoid array (PSA) coil was adopted to generate SH waves in plates, we proposed a MPTs array employing a modified planar solenoid array (MPSA) coil, i.e. MPSA coil-MPTs array, for generating and receiving the torsional mode in pipes. The configuration of the MPSA coil modified from PSA coil is suitable to be arranged on the pipe surface and can generate high-power waves. In the suggested configuration of MPT, because the direction of the actuating dynamic magnetic field produced by the MPSA coil is orthogonal to the direction of the static magnetic field produced by the permanent magnets in the magnetostrictive patch, the shear deformation induced by the magnetostriction in the patch will be delivered to the pipe, thus generating the torsional mode. First, it was experimentally verified that the fundamental torsional mode, T(0,1), could be effectively generated and received in pipes with the developed MPSA coil-MPTs array. Then, we studied the relationship between the frequency response characteristic of the developed MPSA coil-MPTs array and the interval defined by the distance of adjacent solenoids in the MPSA coil. Simultaneously, the circumferential crack defects in pipe were successfully identified. Finally, the performance of the MPSA coil-MPTs array was compared with that of previous meander coil-MPTs array. The comparison results demonstrated that the developed MPSA coil-MPTs array could enhance the power of the torsional mode.

1. Introduction

Ultrasonic guided waves are widely applied in the inspection of pipe defects because of their several advantages, such as low attenuation, long distance propagation, and the high detection efficiency [1–3]. Due to the characteristics of the dispersion and multi-mode, the selection of appropriate mode and driving frequency of ultrasonic guided waves affects the detection performance. Several wave modes, such as longitudinal, torsional, and flexural modes, can be applied in the inspection of pipe defects. The torsional mode is preferred in the nondestructive evaluation of pipes because the fundamental torsional mode, T(0,1), is totally non-dispersive and hence travels a long distance without any signal distortion. The torsional mode, T(0,1), shows great potential and advantages in pipe inspection [4–9].

Currently, there are two major approaches to generate the torsional mode in pipes: piezoelectric transducers [4–6] and EMATs (Electromagnetic acoustic transducers) [7–9]. Due to the positive and negative piezoelectric effects of piezoelectric materials, piezoelectric transducers can generate and receive the ultrasonic guided waves. Piezoelectric-based guided waves transducers are widely used in the industry due to their low signal-to-noise ratios. The EMATs are receiving the growing attention in the application as an alternative to piezoelectric transducers in some cases for their particular features. The generation and reception of ultrasonic waves with EMATs are chiefly based on two different electromagnetic coupling mechanisms: Lorentz force and magnetostriction [10]. As for the Lorentz force mechanism, when the eddy in the metal induced by the coil of EMATs carrying the alternating current is exposed to a static bias magnetic field, the alternating Lorentz force will be generated in the metallic structures, which can excite the guided waves without contact or couplant. In the magnetostriction mechanism, the coil of EMATs flowing into an alternating current can generate a dynamic magnetic field which changes the volume of the ferromagnetic materials as a result of the deformation of magnetic domains in the material. The static magnetic field applied on the ferromagnetic material makes the directions of the magnetic domains

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orderly, so that the deformation can well spread around the pipe in the form of desired waves. Compared with piezoelectric transducers, EMATs usually have the non-contact and couplant-free characteristics [11].

Since EMATs are mainly made up of magnet and coil, a huge design space for the versatile assembly can be obtained by adopting different winding ways of coil, magnetic geometries and polarization directions. The versatile assembly is exactly another attractive feature of EMATs compared with piezoelectric transducer. In this way, many ultrasonic guided waves can be effectively generated by exploiting different combinations of coil and magnet, especially for SH (shear horizontal) and torsional modes which are not easily excited via traditional piezoelectric transducers [12]. Moreover, they are easier to motivate a pure mode and improve the identification and location of defects. Generally, the energy conversion efficiency of EMATs based on magnetostriction is lower than that of EMATs based on Lorentz force. However, with regard to the inspection of ferromagnetic materials with high magnetostriction coefficients (such as nickel and iron-cobalt alloy), EMATs based on magnetostriction possess the higher conversion efficiency. For the inspection specimen made of the less ferromagnetic or non-ferromagnetic material, a type of EMATs based on magnetostriction, MPT (Magnetostrictive Patch Transducer) has been put forward to improve the conversion efficiency and the SNR (Signal-to-Noise Ratio) by means of the highly magnetostrictive patch attached on the specimen. Thin magnetostrictive patch is fixed tightly or bonded on the surface of specimen and serves as a medium, so that the deformation of the magnetostrictive patch can be delivered to the specimen. In this way, at the cost of the noncontact nature of EMATs, the wave energy is greatly enhanced and the non-ferromagnetic materials can be effectively inspected by utilizing MPT-type EMATs [12].

As for the MPT (a kind of the EMATs based on magnetostriction), Kwun et al. [13] proposed a method and apparatus employing the MPT for pipe inspection. In the configuration of Kwun's MPT, a magnetized magnetostrictive patch was pressed circumferentially against the pipe for generating the torsional mode in pipes. In order to achieve the better control over the mode selection and increase the amplitude of the torsional mode generated by MPT, the team of Kim [14–17] optimized the configuration of the MPT in pipes proposed by Kwun et al. [13]. By changing the geometric shape, direction, and material of magnetostrictive patch, the performance of the MPT in pipes was greatly enhanced. Moreover, an excitation coil providing direct current was used to generate a static magnetic field to avoid tedious pre-magnetization for the magnetostrictive patch.

As demonstrated in an earlier investigation [18], the particle displacement pattern of the torsional mode in pipes resembles that of SH waves in plates. Based on the Lorentz force mechanism, Vasile et al. [19] used the PPM (Periodic Permanent Magnet) EMAT to excite SH waves in an aluminum plate. Nurmalia et al. [7] adopted the PPM EMAT as a unit to form a circular array on the pipe surface. The torsional mode was effectively excited in pipes and the conversion phenomenon of the torsional mode was also studied. Based on magnetostrictive effect, Thompson [20] used meander coils to generate SH waves in ferromagnetic material. The team of Kim [21–24] successfully excited the SH and torsional modes in pipes via circumferentially laying out the meander coils on the pipe surface. Furthermore, the two-dimensional imaging of surface defects in pipes was attempted with the circumferential phased array [24]. Lee et al. [25] integrated the characteristics of figure-of-eight coil MPT [26] and the meander coil MsS [20] and proposed a PSA (Planar Solenoid Array) coil MPT which could produce a high-intensity dynamic magnetic field and generate the

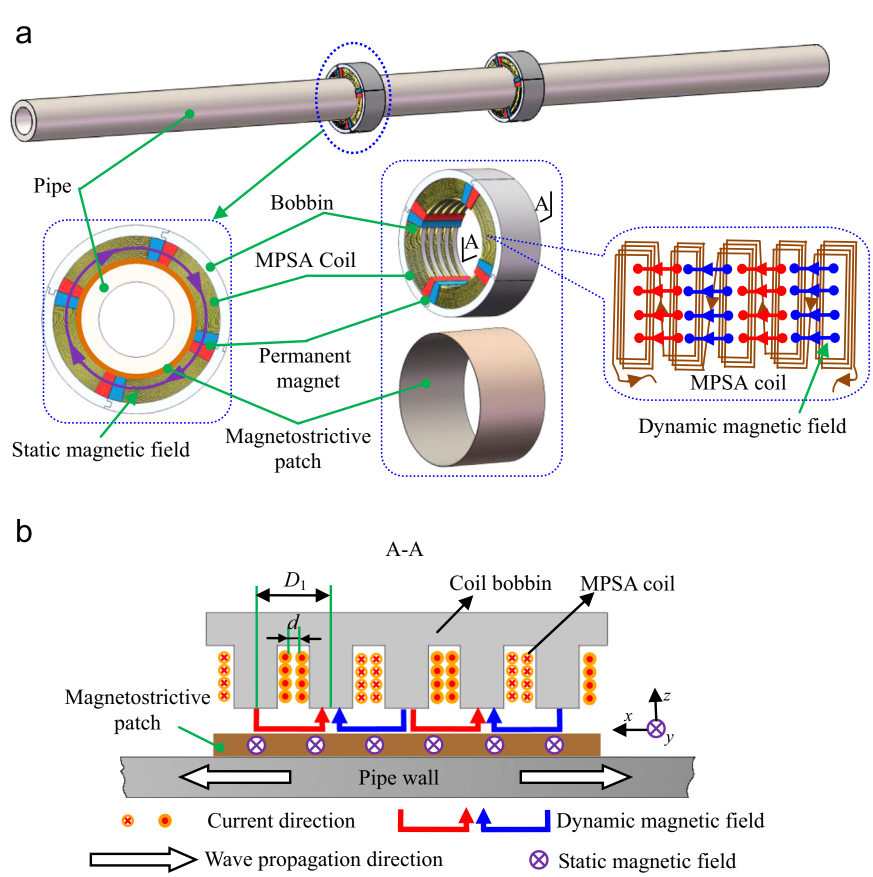

Fig. 1. Configuration and working principle of proposed torsional mode MPSA coil-MPTs array.