Advances on the side-shifted dual periodic permanent magnet electromagnetic acoustic transducers design for unidirectional generation of shear horizontal ultrasonic guided wave

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***Abstract*—Shear horizontal (SH) ultrasonic guided waves can be generated by periodic permanent magnet (PPM) electromagnetic acoustic transducers (EMATs) and are attractive for non-destructive evaluation. Conventional PPM EMATs generate SH waves in two main, opposite, directions, which can hinder signal interpretation. One can generate waves in a single direction through the interference mechanism of two spatially separated wave sources. This principle cannot be applied to a conventional PPM EMAT due to the coil and magnets' arrangement. A variation of PPM EMAT, namely, side-shifted dual PPM EMAT, overcame this limitation and generated SH waves in a single direction. The original design presented unwanted backward propagating side lobes and required fine alignment in its fabrication procedure to appropriately work. This paper reviews the advances in the side-shifted dual PPM EMAT design and in signal processing techniques that yielded improvements to its unidirectional radiation pattern and unidirectionality.**

***Index Terms*—SH waves, unidirectional generation, dual EMAT, side-shifted PPM EMAT.**

I. Introduction

Ultrasonic guided waves are widely used in the field of non-destructive evaluation, since they present high sensitivity to defects, propagate long distances and can inspect large areas [1]. Shear horizontal (SH) ultrasonic guided waves are advantageous since there is no leakage to non-viscous liquid in contact with the propagating medium and the fundamental SH0 mode is non-dispersive [2].

SH waves can be conveniently generated with periodic permanent magnet (PPM) electromagnetic acoustic transducers (EMAT) [3], which do not require contact with the medium. PPM EMATs generate SH waves that mainly propagate in two opposite directions, which can complicate signal interpretation because the backwards-generated wave can reflect at the medium boundaries or propagates around a closed-loop path and ultimately arrives at the receiver simultaneously with the echo from a defect, hindering signal interpretation on even completely masking the presence of defects [4].

One can generate waves in a single direction resorting to the interference mechanism when two spatially separated wave sources are driven with adequate time-delayed excitation pulses [5]–[9]. This principle however cannot be readily applied to conventional PPM EMATs due to the coil and magnet's array arrangement, unlike meander-line EMATs which generate Lamb waves [9]–[11]. This was overcome with the side-shifted dual-PPM EMAT [12].

This design, however, presented backward side lobes in its radiation pattern, which can complicate signal processing. Therefore, we moved on in order to enhance its unidirectionality by decreasing the generated side lobes with more rows of magnets and reduced lateral separation between them [13], [14]. Besides, the proposed design requires precise alignment between magnets and coil, so we adopted an assembling procedure that ensures alignment [15]. From the signal processing side, unidirectionality can be optimised by adopting excitation signals that yield ideal destructive interference for waves generated in the unwanted direction [16]. Moreover, this procedure can be extended to generate higher-order wave modes, through the use of synthetically propagated excitation signals [17]. This paper reviews the main advances in the side-shift dual periodic permanent magnet electromagnetic acoustic transducer design and on its capacities.

II. Unidirectional generation of SH guided waves in plates

Shear horizontal (SH) waves are defined as having a displacement polarization parallel to the medium's surface and perpendicular to the propagation direction [2]. SH waves can be generated by PPM EMATs which consist of an array of alternate polarity magnets and a racetrack coil [3]. Fig. 1(a) illustrates a conventional PPM EMAT. The current, I, injected into the coils induces alternating eddy currents, $\mathbf{J}$, that, due to the skin-depth effect and low separation between the coil and the surface, can be considered as acting uniformly at

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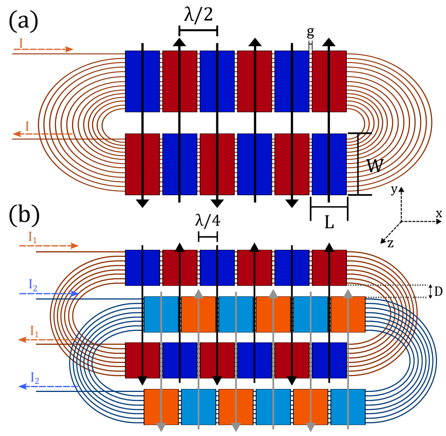

Fig. 1. Schematic representation of a conventional (a) and a side-shifted dual-PPM EMAT (b). Coloured blocks are the magnets of the PPM array, with red and orange blocks representing the north pole and blue and cyan representing the south pole. I_1 and I_2 are the currents injected into the racetrack coils, represented by the copper- and blue-coloured lines. The Lorentz forces are represented by the upward and downward black and grey arrows. The transducer construction parameters are defined by the magnets' length, L, width W and their longitudinal separation g. At the side-shifted dual-PPM EMAT, the lateral separation is defined by D.

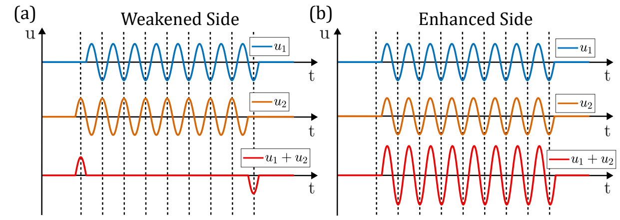

Fig. 2. Interference mechanism for the unidirectional generation. At the weakened side (a), u_1 and u_2 arrive out-of-phase due to the combination of the proper longitudinal separation and time delay, therefore destructively interfering with each other. At the enhanced side (b), the wavefronts arrive in phase, creating a constructive interference.

the projection of each coil wire on the medium's surface [3]. By interacting with the static magnetic field, **B**, produced by the array of magnets, a set of alternating Lorentz forces is generated, given by:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \quad . \tag{1}$$

Lorentz forces of a PPM EMAT are polarized in the y-direction [Fig.1(a)], therefore effectively generating SH waves in plates which propagate in both directions of the x-axis, due to the symmetrical nature of the transducer.

Bidirectional generation can complicate signal interpretation [18]. Effective unidirectional wave generation can be achieved with two spatially separated wave sources driven by time-delayed signals [9]. Consider a set of two independent wave sources, namely sources 1 and 2, positioned at the same transversal position (y-axis in Fig.1), but longitudinally separated (in the x-axis) by Δx, which are excited by a time-delayed, Δt, signals. That is, the waves generated from both sources are given by:

$$u_1^{\pm} = e^{j(\omega t \mp \kappa x)} \quad , \tag{2}$$

$$u_2^{\pm} = e^{j(\omega (t+\Delta t) \mp \kappa (x+\Delta x)} \quad , \tag{3}$$

where the symbol $\mp$ stands for the wave propagating to the right $(+)$ and to the left $(-)$ directions of the x-axis, κ is the wavenumber and ω is the angular frequency. If the sources are separated by a quarter-wavelength ($\Delta x = \lambda/4 = \pi/2\kappa$), and the time shift equals a quarter period ($\Delta t = \pi/2\omega$), then the total wavefield at the right- and left-hand sides, u^+ and u^-, respectively, are given by:

$$u^+ = u_1^+ + u_2^+ = 2e^{j(\omega t - \kappa x)} \quad , \tag{4}$$

$$u^- = u_1^- + u_2^- = 0 \quad . \tag{5}$$

Therefore, in this situation, one obtains destructive interference on one side (left) and constructive interference on the other (right), namely, the weakened and enhanced sides, respectively. In practical applications, finite-length pulses are used, and the overall mechanism still holds, as depicted in Fig. 2.

This principle, however, cannot be straightforwardly applied to PPM EMATs since PPM arrays would need to be stacked on top of each other and the second racetrack coil would generate unwanted Lorentz forces due to sharing the same coil [12]. The side-shifted dual-PPM EMAT [12] overcame this limitation by positioning the second PPM array at a slight lateral separation, D, from the first one and imposing a longitudinal separation of a quarter-wavelength, as schematically shown in Fig. 1(b). Due to the diffraction of the wavefield generated by each coil, it effectively generates unidirectional SH waves,

This transducer was initially fabricated with $D = 3$ mm, and generated waves in a single direction with more than 20 dB of unidirectionality [12]. Due to its side shift, a relative misalignment between the wavefronts from each individual PPM array is introduced. Therefore, it only ensures ideal constructive or destructive interference along its centre line (x-axis), which consequently generates waves sideways in the backward semi-plane, i.e., it produces inherently backward side-lobes as shown in Fig. 4(a). These backward side-lobes may cause similar complications as a conventional backward wave generation from PPM EMATs, therefore side-lobe reduction is of interest.

III. Enhancements of the side-shifted PPM EMAT design

In order to reduce the backward side-lobe level of the side-shifted dual-PPM EMAT design, the effect of its construction parameters was analysed in [13]; namely, the lateral separation between the magnet rows in the array, given by the parameter D in Fig. 1(b) and the number of rows of magnets per PPM array, which is defined as the parameter Q. In order to accommodate more than two rows of magnets per magnet array, a new type of racetrack coil was devised, namely, a multi-lap racetrack coil. A side-shifted dual-PPM EMAT with $Q = 3$ and its new coil is schematically displayed in Fig. 3.

By increasing the number of rows of magnets or decreasing the side-shift between them, the backward side-lobe level

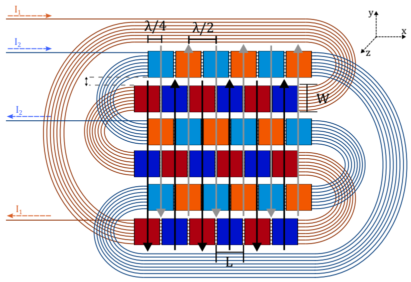

Fig. 3. Schematic representation of a multi-lap racetrack coil (copper- and blue-coloured lines) and a $Q = 3$ PPM array positioned on the top of it.

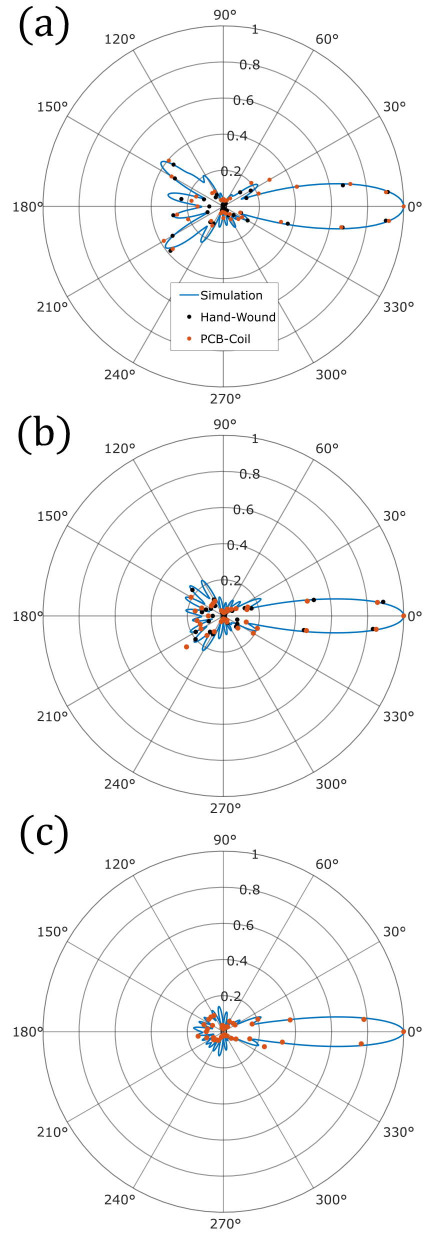

Fig. 4. Radiation pattern of the side-shifted dual-PPM EMAT for three different configurations: $Q = 2$ and $D = 3$ mm (a), $Q = 3$ and $D = 2$ mm (b) and $Q = 4$ and $D = 1$ mm (c). Solid blue lines are analytical model calculations while black and orange dots represent the experimental results from the hand-wound and PCB coils, respectively.

reduces because the relative misalignment between the wavefronts generated by each individual PPM array decreases. This mechanism was thoroughly discussed in [13] and its results are summarized in Fig. 4(a) and (b), where continuous blue lines refer to calculations with an analytical model [19] and dots to experiments in a 1.5 mm-thick aluminium plate. As can be seen, the backward side-lobe level was effectively reduced with the increase of Q and reduction of D from approximately -7.5 dB with $Q = 2$ and $D = 3$ mm, to approximately -12 dB with $Q = 3$ and $D = 2$ mm.

A further enhancement was obtained by using flexible printed circuit board coils (PCBs) which allowed a standardized coil fabrication procedure enabling the lateral separation to be reduced down to $D = 1$ mm, which was not achieved with hand-wound coil due to the required level of fabrication precision [14]. The aforementioned advances reduced the side-lobe levels by 8.6 dB, with $Q = 4$ and $D = 1$ mm [Fig. 4(c)], in comparison with the original side-shifted dual-PPM EMAT configuration [Fig. 4(a)].

Unidirectional generation relies on producing identical stimuli by both sets of active elements of a dual-PPM EMAT. If there is a slight difference between the generated forces of one array with respect to the other, then unidirectionality is compromised. In practice, such differences may arise from slight experimental imprecision in positioning the magnet array on top of the coil. That is, unlike conventional single-element or single-array transducers, for the side-shift dual-PPM EMAT design, any slight misalignment between coils and magnets is a crucial factor that influences the quality of unidirectional generation. Therefore, in order to ensure alignment, an enclosed-case misalignment-free side-shifted dual-PPM EMAT was fabricated [15]. It consisted of a fine mold for both the racetrack coil and the dual-PPM array with guide holes in order to ensure precise alignment of coil and magnet. Equivalent results to the previously developed side-shifted dual-PPM EMAT when carefully hand-aligned were obtained, without requiring fine manual positioning.

IV. Optimal unidirectional generation

The transducer's spatial distribution and the excitation signal applied to it dictate the wave generated in both directions. In [16] it was shown that, when a pair of time-delayed excitation signals are used, destructive interference at the weakened side only occurs at the centre frequency of the excitation pulse, resulting in a signal shape as in Fig.1(a). However, by using time-delayed and inverted (TDI) excitation signals, there is theoretically no generation to the weakened side for the whole frequency range of interest, i.e., one obtains optimal unidirectional generation to the enhanced size. Experimentally, the SH0 wave mode was generated with approximately 40 dB unidirectionality using TDI [16].

A similar principle was applied to the higher-order SH1 wave modes [17] resorting to synthetic propagated excitation methods in which the excitation signal is computed in the frequency domain through the theoretical wavemode dispersion curve. Using the so-called synthetic propagated and inverse (SPI) method one obtained approximately 30 dB unidirectionality of the dispersive SH1 wavemode. Next, by superposing optimal excitation signals given by the TDI or SPI methods, simultaneous unidirectional generation of the SH0 and SH1 wave modes to predefined directions was obtained [20]. This is of practical relevance since distinct wave modes can be employed for specific inspection goals in different sectors of a structure.

Finally, optimal unidirectional generation was used to measure plate thickness [21]. The principle consists of utilizing the SPI excitation method and sweeping its central frequency, which theoretically depends on the plate thickness. Hence, the plate thickness value is experimentally obtained when the maximum unidirectionality is reached. Due to the high selectivity of the SPI method, the plate thickness was measured with high accuracy, allowing less than 0.8% error when measuring aluminium plates of several thicknesses..

V. Conclusion

PPM EMATs are efficient in generating SH waves in conductive media without the need for contact. A conventional PPM EMAT generates SH waves in two principal opposite directions, which can complicate signal interpretation. By resorting to the interference mechanism of two independent spatially separated wave sources, one can effectively generate ultrasonic waves in a single direction. This principle, however, cannot be applied to conventional PPM EMAT due to the coil and magnet arrangement. The side-shifted dual-PPM EMAT overcame this limitation, by introducing a lateral shift between arrays which allows two independent SH wave sources to be accommodated. The original design presents inherent side lobes due to the side shift. It was then enhanced by increasing the number of rows and reducing the lateral gap, both of which reduced the backward side-lobes, and therefore allowed reduction of up to 8.6 dB on the backward side-lobe level. Next, the enclosed case produced a standard ready-to-use single-piece device that does not require manual alignment. From the signal processing side, optimal synthetic propagated excitation signals designed on the frequency-wavenumber domain produced optimal excitation signals that allowed up to approximately 40 dB unidirectionally for the non-dispersive SH0 wave mode and 30 dB for the dispersive SH1 mode. Since its first version, enhancements on the side-shifted dual PPM EMAT allowed its evolution to a ready-to-use unidirectional transducer that is beneficial for non-destructive evaluation and allows for several industrial applications, such as thickness measurement.

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