Unidirectional shear horizontal wave generation with side-shifted periodic permanent magnets electromagnetic acoustic transducer

Alan C. Kubrusly, Lei Kang and Steve Dixon

***Abstract*—Periodic permanent magnet (PPM) array electromagnetic acoustic transducers (EMATs) can efficiently generate and receive shear horizontal (SH) ultrasonic waves. Conventional PPM EMATs typically generate waves which simultaneously propagate both forwards and backwards. This can complicate the received signals and make it difficult to locate the position of scatterers. Unidirectional generation of ultrasounds can be achieved if two ultrasonic sources are separated by a predefined distance and are excited with the proper delay. Relying on this principle, EMATs have been previously designed aiming to generate other modes of ultrasonic waves. The main challenge when extending this conception to an SH-wave EMAT is how to restrict each coil to its specific magnet array. We present the concept of a unidirectional SH EMAT consisting of two racetrack coils and two interlaced PPM arrays, that are slightly shifted sideways, in such a way that the generated wavefronts still properly interfere. The design was fabricated and experimentally evaluated in an aluminum plate generating the SH0 guided wave mode. The forward to backward generated wave ratio is above 20 dB and well agrees with finite element simulations.**

***Index Terms*— Electromagnetic acoustic transducers; unidirectional generation; shear horizontal waves; guided waves**

I. Introduction

SHEAR horizontal (SH) ultrasonic waves present a single, non-zero displacement component, perpendicular to the propagation direction and parallel to the sample's surface. SH waves are useful to non-destructive evaluation [1], [2], [3] and have relatively simple dispersion relations when guided in thin structures [4]. SH guided waves can be generated with piezoelectric transducers but require bonding and attaching to the sample surface with high pressure. They, however, are efficiently generated and detected using periodic permanent magnet (PPM) electromagnet acoustic transducers (EMATs) in metallic media.

A PPM EMAT typically consists of a periodic permanent magnet array and a racetrack coil, which is shown in Fig. 1. The coil is placed underneath the magnet array, and ultrasonic waves can be generated in a conductive medium through the Lorentz principle [5]. The induced Lorentz forces in the material are given by the cross product $\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B}$, where $\boldsymbol{B}$ is the static magnetic field from the permanent magnet, and $\boldsymbol{J}$ is the electric current density induced in the sample, which is often schematically shown as a current close to the surface, in the opposite direction to the current flowing in the coil (I). In reality, the magnitude and phase of the eddy current vary with depth, but for the purpose of keeping descriptions simple and because the ultrasonic wavelength is always much larger than the electromagnetic skin depth, the effect of averaging the eddy currents is equivalent to the eddy current being just under the surface of the sample [6]. In PPM EMATs the magnet array and coil are positioned in such a way that the alternating induced forces are parallel to the surface of the sample and perpendicular to the propagating direction [7]. The spatial period of the magnet array and the operating frequency of the current flowing through the coil can be used to selectively control the modes of the SH waves [3], [8], [9]. In Fig. 1, the conventional PPM EMAT generates Lorentz forces in the z direction and the ultrasonic waves propagate in both the positive and the negative directions of the x-axis. The SH wave that propagates backwards is eventually reflected at the end of a finite medium and can complicate the received signals and hinder the interpretation of the signal of interest. Unidirectional generation of SH ultrasonic waves generated by EMATs can, therefore, provide a clearer and easier signal interpretation.

There has been some effort in designing unidirectional point-focused SH wave [10], [11], [12]. Huang et al. [10] proposed a curved interlaced array for unilateral focusing and Song and Qiu [11] used two rows of PPM that were rotated in the horizontal plane for unilateral focusing. Sun et al. [12] used obliquely biased magnets in the vertical plane together with curved periodic magnets for unilateral focusing. A focused EMAT provides a strong ultrasonic field at a predetermined distance, but its intensity decreases as one moves away from the focal position. In some applications where one wants to inspect a wider area or longer region of a sample, focusing may be

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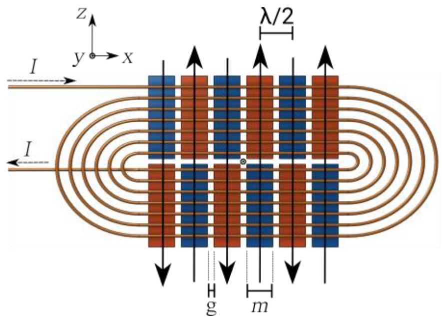

Fig. 1. Conventional PPM EMAT, bottom view. Red and blue blocks represent the magnets' poles and the racetracks coil is represented by copper-color wires. The magnets' magnetic field $\boldsymbol{B}$ is in the y direction and its sign depends on the polarity of the magnets. The dashed lines represent the current injected into the coil. Generated forces given by the Lorentz principle are represented by vertical black arrows. The magnets' length is m and the gap between magnets is g. The distance between opposite forces equal half-wavelength, that is, $\lambda/2 = m + g$.

inappropriate, but unidirectionality may still be desired to achieve a high-efficiency inspection. This requires a design of a PPM-like EMAT that effectively generates non-focused SH wave in a single direction.

II. Unidirectional PPM EMAT design

Efficient unidirectional generation can be achieved if two ultrasonic sources are separated by a quarter-wavelength and are excited with a delay of 90º in order to ensure that the ultrasonic waves of the two sources constructively interfere in one direction and destructively interfere in the opposite direction. This setup was used previously to generate unidirectional Rayleigh and SV waves with a double meander-line coil EMAT [13], [14], [15]. Here, we have designed a unidirectional SH EMAT following this principle by introducing a second PPM array as shown in Fig. 2(a). In order to accomplish this, the arrays are slightly shifted sideways relative to each other (in the z-direction) and then two coils are positioned underneath their respective arrays. Since the arrays are longitudinally separated by quarter-wavelength in the x direction, induced forces lying in the z direction are also properly shifted by the same amount and when exciting the second coil delayed by 90º, one generates, ideally, waves that propagate uniquely towards the positive x direction. Note, however, that the wavefronts produced by each array are shifted in the width coordinate, z. Thus, unidirectional wave generation relies on the principle that the separation of both arrays in the width direction is small so that the wavefronts still interfere with each other as the waves from each EMAT coil diffract with beam spread as they propagate away from the coil, interfering constructively in one direction and destructively in the opposite direction as shown schematically in Fig. 2(a).

III. Results

A. Finite Element Simulation

In order to assess the performance of the proposed unidirectional SH-wave generation principle on a plate-like sample, a three-dimension finite element simulation was performed. Forces along the z direction are applied at predefined regions on the surface of the model, that correlate with the areas under each magnet where the Lorentz forces are generated. This follows the design shown in Fig. 2(a), with magnet width and length, $m = w = 5$ mm, and a gap between magnets in the same linear array, $g = 1\,mm$, creating a nominal wavelength of 12 mm on each EMAT, which are themselves shifted relative to each other with a side shift $d = 8\,mm$. The direction of forces along the z-axis in the model is alternating, in order to mimic the Lorentz force pattern produced by each array. This approach facilitates the generation of SH guided waves without the need for including the EMAT coupling mechanism in the simulation model, as validated previously elsewhere [2], [3], [7], [8]. It is worth highlighting that this approach assumes that the Lorentz force is uniformly distributed within each region that corresponds to the magnets, which approximately holds when the lift-offs are kept small. A $1.5\,mm$ thick aluminum plate was modeled, with the transverse material wave speed set to $c_T = 3111\,m/s$. The EMAT experiment is designed to generate the non-dispersive SH0 guided wave mode, whose phase speed equals the material bulk shear wave speed [4], with the forces being modulated by an 8-cycle, sinusoidal tone-burst of $260\,kHz$, and the forces corresponding to the second PPM array are delayed by 90º, relative to the first, in order to simulate the delayed driving current on the second PPM array. Fig. 3 shows a snapshot of the generated wavefield at 50 μs. The wavefront on the positive side (to the right of the generation location in the center of the plot) is much more intense than on the negative side. Along the

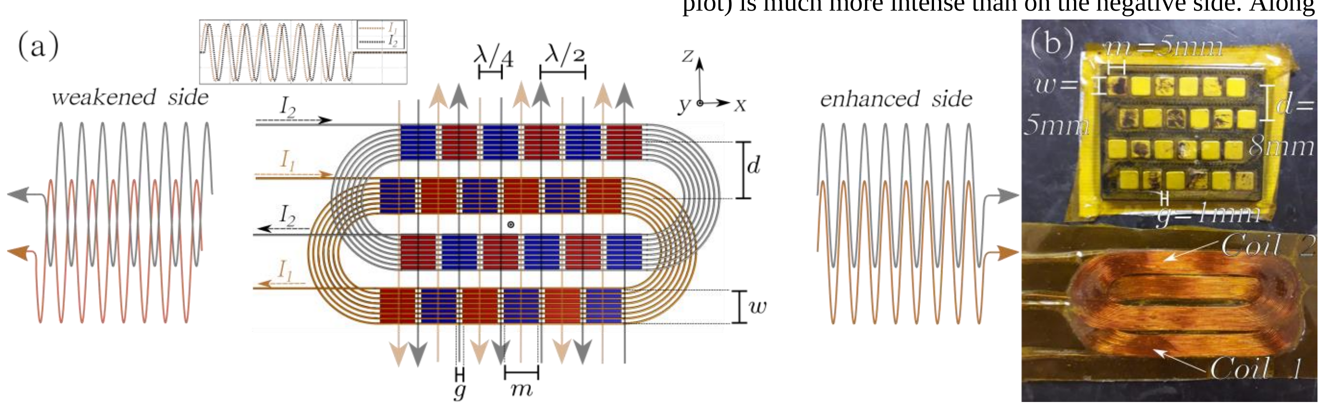

Fig. 2. Design and principle of operation of unidirectional dual PPM EMAT, bottom view (a). Red and blue blocks represent the magnets' poles and the two racetracks coils are represented by grey and copper-color wires. The dashed lines represent the currents I_1 and I_2 injected into coils 1 and 2, respectively. I_2 is 90º delayed respect to I_1, as represented by the dotted-line signals in the top inner plot. Array and coil sets are side-shifted by a distance d and longitudinally shifted by quarter-wavelength. Forces generated by the first array and coil are represented by vertical copper-color arrows, whereas the ones related to the second array with grey vertical arrows. The copper-color and grey continuous wavy lines at the right and left-hand sides represent the generated waves by arrays 1 and 2, respectively. The generated waves at the right-hand side interfere constructively, whilst destructively at the left-hand side even though their wavefronts are slightly side-shifted. Photograph of fabricated unidirectional SH EMAT with dimensions (b). Interlaced PPM array (top) and double coil (bottom).

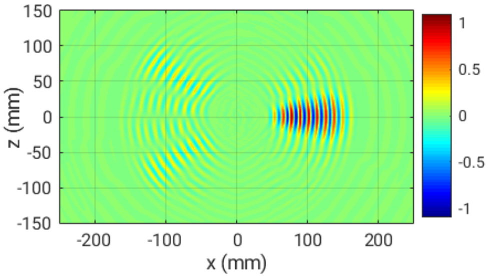

Fig. 3 Snapshot of normalized wavefield at 50 μs at the top surface of the plate.

centerline of the array, the x-axis, the amplitude of the wave travelling to the left of the central generation location is relatively very low.

B. *Experimental Evaluation*

The proposed design was fabricated with the same dimension as the numerical simulation, with two twenty-turn coils, as shown in Fig. 2(b). A two-channel signal generator was used to synthesize two 8-cycles tone-bursts at 260 kHz with 90º phase shift which were power amplified prior to connecting to each coil of the unidirectional transducer. The transmitter's coils were positioned right on plate's surface and the magnets array right on the top of the coils, thus providing a minimal lift-off either for the coils (virtually zero) or for the magnets, equal to the diameter of the coils' wire (about 0.3mm). A conventional 3 cycles 10 mm nominal wavelength PPM EMAT from Sonemat Ltd was used as a receiver. The received waveforms on the centerline, 250 mm away from the center of the transmitter, to the right and left sides of the generation location are shown in Fig.4 (a) and (b), respectively, along with numerically simulated signals, which correspond to the in-plane particle velocity component perpendicular to the propagation direction at the surface of the plate. To provide a fairer comparison with the experimental signals, including the receiver effects, the numerical signals were further processed by spatially convolving the velocity field with the receiver profile, which was approximated by a spatial tone-burst with the same number of cycles and nominal wavelength as the receiver used in the experiment; a procedure validated previously elsewhere [2], [3]. As can be seen in Fig.4, the wave that propagated to the right is much stronger than the one that propagated to the left. In the latter, one can see that the signal is composed of weak waves from each end of the transducer, which are not completely suppressed. The ratio of the peak-to-

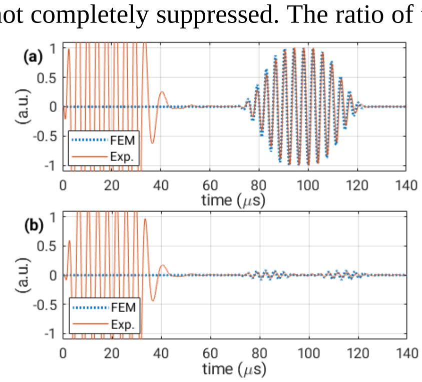

Fig. 4 Numerical, dotted line, and experimental, continuous line, received signals at x=+250 mm (a) and x= -250 mm (b). Amplitude is normalized per the maximum value of the received wave signal at x=+250 mm. The strong signal for times less than 40μs is the electrical interference of emitting signal, present only at experimentally received signals.

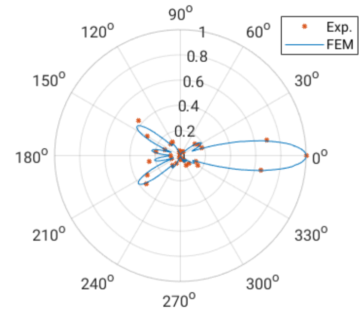

Fig. 5 Numerical, solid line, and experimental, red dots, directivity diagram for unidirectional SH EMAT.

peak amplitude of the received waves at the right to the left-hand sides was 18.8 which is 25.5 dB unidirectionality, higher than reported elsewhere for Rayleigh wave [13], [15]. Further analysis was carried out by assessing the directivity of the unidirectional transducer, which was measured by the peak-to-peak amplitude of the received wave as a function of the angle from the center of the transmitter, shown in Fig. 5. Directivity was calculated both numerically (shown as solid lines), and experimentally in 10º steps (shown as red dots). Generally, experimental and numerical results show good agreement.

IV. Discussion

It is worth highlighting the challenges in extending the concepts of unidirectional generation to SH waves generated by PPM EMATs. This approach has previously been employed by other authors to meander-line EMATs for generation of Rayleigh and SV waves, due to forces induced in the x or y directions [13], [14], [15]. Those EMATs have just one magnet that lies above the whole coil, and imposes a series of forces whose direction and position are determined by each coil turn underneath the magnet. Therefore, in order to produce unidirectional waves, a second quarter-wavelength spaced meander-line coil can be straightforwardly introduced. For PPM EMATs, on the other hand, the direction and position of forces are governed by the polarity of the magnets, as shown in Fig. 1, instead of the coil's wire turn position. If another array of magnets were simply introduced between the original one, it would lie above the same racetrack coil as the first one. Thus, for employing the aforementioned unidirectional generating principle to PPM EMATs, a second racetrack coil has to be somehow restricted to its respective array. This was accomplished here by insightfully waiving the restriction that the individual waves generated by each coil shall be aligned, exploiting the diffraction from each coil, that is, by side-shifting the second array and thus a racetrack coil is readily positioned. Also, this type of interleaved EMAT coil design lends itself to being deployed circumferentially around a pipe or rod, providing a convenient approach to generate guided unidirectional torsional waves in pipes [16], which will be covered in detail in a future paper.

V. Conclusion

Line sources separated by a quarter-wavelength with a phase shift of 90º is effective for generating unidirectional SH waves, similar to other kinds of waves. However, the construction of an SH EMAT with these characteristics is non-trivial because the direction of the forces generated by a PPM EMAT is determined by the orientation of the magnets. Here, we have devised a simple and easy design that comprises two side-shifted interlaced arrays of magnets that are shifted by a quarter wavelength in the longitudinal direction with two racetrack coils. Since the side-shifted distance is short, the wavefronts still properly interfere, generating waves that propagate nominally in a single direction. Experiment and numerical simulation confirmed that the proposed solution is effective in generating unidirectional SH waves with more than 20 dB unidirectionality, which can significantly simplify the received ultrasonic signals, beneficial for the applications of SH waves in the fields of nondestructive testing and evaluation.

Acknowledgment

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