Numerical investigation of unidirectional generation of circumferential SH waves applied to defect detection in pipe

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Abstract*— Circumferential Shear horizontal (CSH) ultrasonic guided waves are useful for non-destructive evaluation of pipes. SH waves can be efficiently generated using a periodic permanent magnet electromagnetic acoustic transducer (PPM EMAT). Those transducers generate waves that propagate in both clockwise and counterclockwise directions, which complicates the interpretation of the received signal since the scattered waves from a potential defect can mix with direct waves generated by the transmitter. We recently presented designs of dual-PPM EMATs that generate SH waves in a single direction. In this paper, we investigate through finite element simulations how unidirectional generation can ease the signal interpretation task for the higher-order CSH1 wave mode. Results show that, due to the mode conversion and dispersion, several wavefronts can be detected, under conventional bidirectional generation, rendering signal interpretation and defect echo identification complicated, for a range of defect positions. Unidirectional generation of CSH waves proves itself to be an important feature in pipeline inspection, providing more reliable signal interpretation.

***Keywords*—CSH waves, unidirectional generation, mode-conversion, pipe inspection**

I. Introduction

Shear horizontal (SH) ultrasonic waves are commonly used for plate and pipe inspection [1, 2]. In pipes, the propagation characteristics depend on the propagation direction, which most commonly is either longitudinal or circumferential, or even helical [3]. With circumferential shear horizontal (CSH) guided waves, a few transducers, typically one transmitter and one receiver, can be used to interrogate the whole circumference [4]. At a low frequency, a unique mode exists, namely, the fundamental SH mode, which is widely used [2, 5] since it is non-dispersive in flat plates, or low-dispersive in pipes [3]. Several works [6, 7, 8], however, investigate the application of high-order SH modes, due to their particular characteristics when interacting with defects [6], such as the existence of cut-off thickness [7]. In order to generate higher-order modes, one has to work at the high frequency-thickness regime, where, due to the interaction with a defect, mode conversion occurs [8]; which can make signal interpretation more complex, due to the existence of more than a single wavefront.

SH waves can be conveniently generated by periodic permanent magnet (PPM) electromagnetic acoustic transducers (EMATs) in metallic structures, which do not require contact with the material surface [9]. PPM EMATs generate SH waves that propagate in two main opposite directions, namely, forward and backward, or clockwise and counterclockwise, when propagating circumferentially in a pipe. In plates, bidirectional generation can introduce additional features in the received signal, since the wave generated in the unwanted direction can be reflected at the end of a finite-length plate and mix with the echo of interest, from a possible defect. Thus, positioning constraints must be considered in order to avoid those unwanted signals. In pipes, nevertheless, due to the closed circumferential propagation path, bidirectional generation inevitably produces additional signals at the receiver due to the wave generated in the unwanted direction, which can complicate signal interpretation [4].

We have recently presented dual-PPM EMATs that generate SH waves in a single direction [10, 11] with the adequate design of the excitation signal for unidirectional generation of either the fundamental [12] or high-order modes [13]. In [14], we showed that, for a non-dispersive wave mode, like the CSH0, as the angular position of the defect approaches 180^{o} from the transmitter, an echo from a defect, can be completely masked by the wave generated in the opposite direction with conventional bidirectional generation. Consequently, unidirectional generation plays an important role since it enables defect identification in such scenarios. In this paper, we extend this analysis for the dispersive first-order CSH1 wave mode, utilizing finite element simulations.

II. Unidirectional Generation of Circunferential SH Waves

A. *Circunferential SH waves*

Circumferential SH waves present a single-component displacement field, parallel to the longitudinal direction, z, of a pipe and propagate circumferentially around the pipe, in the θ-direction, adopting the cylindrical coordinate system of Fig. 1. CSH guided waves can propagate in distinct modes,

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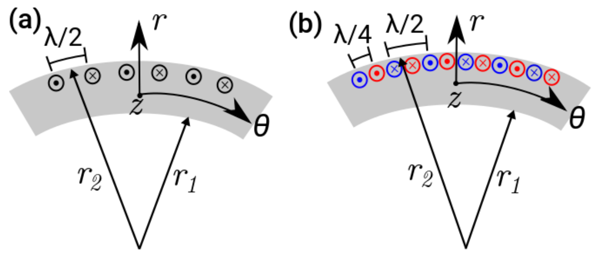

Fig. 1 Schematic representation of force pattern, in the z-direction (pointing inwards the page), to generate CSH waves. The symbols ⊗ and ⊙ mean, positive and negative, respectively forces. The separation between consecutive forces of alternate polarity defines half the nominal wavelength (λ) of the generated waves. Single-array source (a), that generates CSH waves in both directions of the θ axis, and dual-array sources, red and blue symbols, (b), separated by λ/4 that generates CSH in a single direction, when triggered by 90° phased pulses.

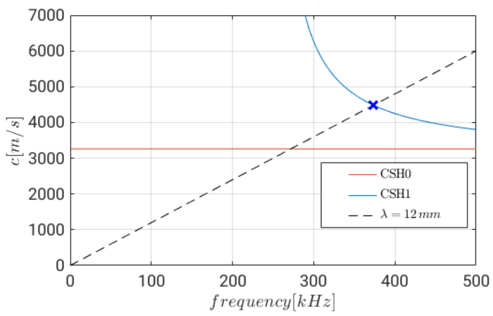

Fig. 2 Dispersion curves for the CSH0 and CSH1 modes in 324 mm outer diameter 6.25 mm wall thickness steel pipe. The dashed line is the locus for 12 mm wavelength.

whose phase speeds are determined by the roots of its characteristic equation [3]. Fig. 2 shows the dispersion curves for a 324 mm outer diameter, 6.25 mm wall thickness mild steel pipe, with bulk shear wave $c_T = 3200$m/s.

B. Generation of SH waves in a single direction

Periodic permanent magnet electromagnetic acoustic transducers are commonly used to generate and receive SH waves [9]. It consists of an array of alternate polarity magnets with a racetrack coil underneath. The coil and magnet array are positioned on the surface of a conductive medium. Due to magnet and coil arrangement, PPM EMATs impose a force distribution on the specimen surface that matches the SH shear stress profile, hence, being able to generate it efficiently. Fig. 1(a) illustrates the approximate force distribution on the pipe surface that can be generated by a 3-cycle PPM EMAT. The magnet array spatial period defines the nominal, or dominant, wavelength, λ, of the generated waves [4, 12].

The frequency of the current signal injected into the coil must match the transducer's nominal wavelength in order to efficiently generate an SH wave mode of interest. Fig. 2 shows, superposed to the dispersion curves, a straight line that defines the locus of constant wavelength. The adequate frequency to generate each wave mode is determined by the crossing point between the constant wavelength straight line and the dispersion curve of the wave mode of interest [4, 12]. In the example shown in Fig. 2, the transducer wavelength is $\lambda = 12$ mm wavelength, thus one should set the frequency of the excitation signal at 370 kHz, in order to generate the CHS1 mode, as indicated by the blue cross.

Conventional PPM EMATs generate SH waves that propagate in two main opposite directions, namely, clockwise and counterclockwise directions when propagating

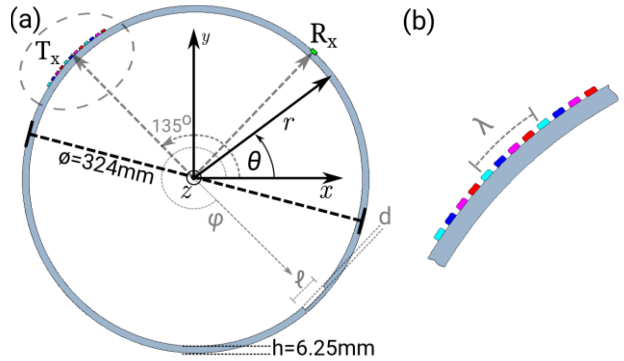

Fig. 3 Modelled pipe with an inner defect (a); and detail of the generation section (b), which is the dashed ellipse in (a).

circumferentially around a pipe. Bidirectional generation can complicate signal interpretation because two wavefronts are simultaneously generated and both arrive at the receiver due to the closed loop propagation path. For instance, a direct wave generated to one side can be mistaken for a defect echo from the other side, or completely mask a real defect echo [14].

Unidirectional generation can be achieved by resorting to the interference mechanism of two wave sources [12]. Fig.1(b) illustrates two interlaced sets of forces separated by a quarter wavelength. If the second source set is excited with a 90° phase shift, relative to the first set, then the waves generated by both sources are in-phase in one direction and out-of-phase in the opposite direction, therefore producing overall unidirectional generation. We recently presented designs of non-conventional dual-PPM EMATs that can impose this force pattern and consequently unidirectionally generate SH waves [10, 11].

III. Finite Element Simulation

A commercial finite element solver was used to model a 324 mm outer diameter, 6.25 mm wall thickness steel pipe, with $c_T = 3200$m/s. Either a model without defect or with a half-thickness deep, 27 mm long, defect were simulated, as illustrated in Fig. 3(a). For the latter, the angular position of the defect centre was varied.

In order to generate the SH waves, a set of constant force densities were applied along the z-direction at predefined regions on the surface of the model that corresponds to the areas under each magnet and coil element, where forces are induced, following the simulation procedure validated previously elsewhere [10]. Fig. 3(b) shows the sector of the FE mesh where generation takes place at the outer surface of the pipe. The coloured rectangles are the areas where forces are applied. The red and blue rectangles correspond, respectively, to positive and negative forces of the first array; whereas magenta and cyan rectangles are positive and negative forces, respectively, for the second array. Each array has three spatial cycles, following the design presented in [10], with a nominal wavelength of λ = 12 mm. Thus, according to the dispersion curves in Fig.2, the CSH1 mode is generated with an excitation signal centred at 370 kHz. The green rectangle represents a single-element receiver, distant 90° in the clockwise direction from the transmitter.

The direction in which the waves propagate is ruled by the relative phase of the excitation signals applied to both arrays. If the pulse applied to the first (resp. second) array is delayed by 90° relative to the second (resp. first), then waves are generated in the clockwise (resp. counterclockwise)

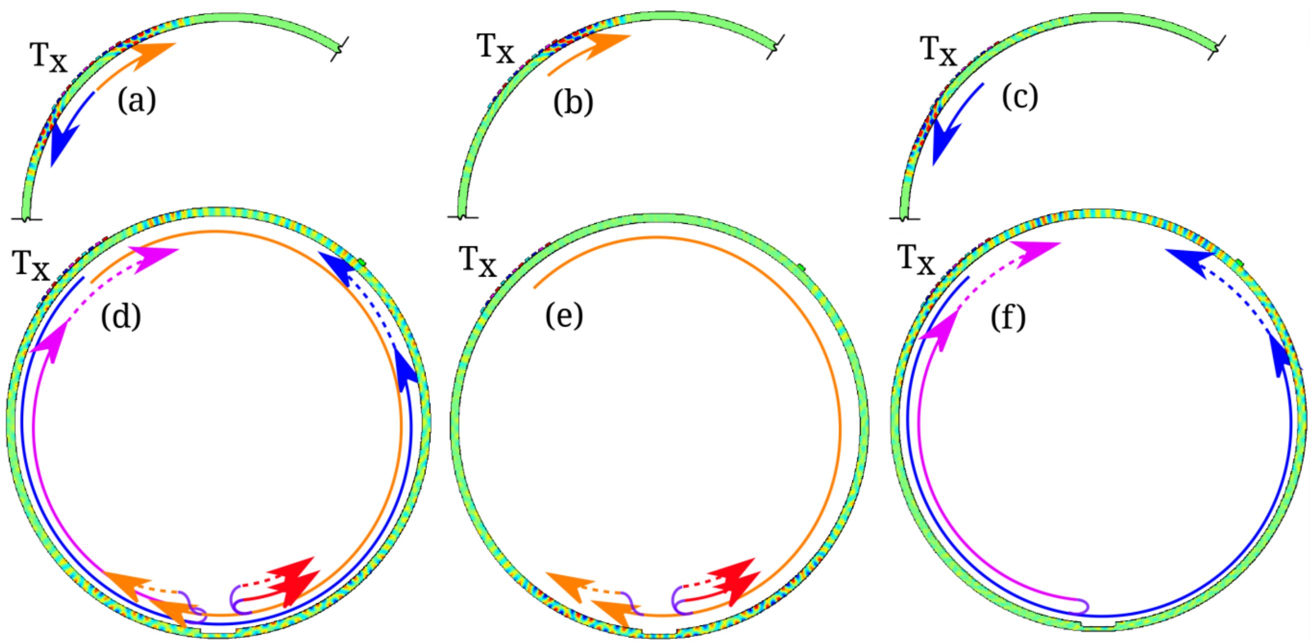

Fig. 4 Snapshots of the generation of the CSH1 wave mode in the pipe at 25μs (a) - (c) and its interaction with a half-thickness deep wall-thinning defect positioned at the angular position of 270° at 300 μs (d) - (f). Bidirectional generation (a) and (d), unidirectional generation in the clockwise direction (b) and (e) and in the counterclockwise direction, (c) and (f). Tx means the transmitter. The orange and blue arrows represent the direct wave in the clockwise and counterclockwise propagation directions, respectively. The red and magenta arrows represent the reflected wave from the clockwise and counterclockwise generation, respectively. Dashed arrows represent mode-converted CSH0 mode due to the interaction of the CHS1 with the defect.

direction. If no delay is applied, then the dual array act as a single array, and waves are generated bidirectionally.

IV. Results and discussion

Fig. 4 shows the displacement field in the z-direction for the generation, at 25 μs [Fig.4(a)-(c)] of the CSH1 mode in the modelled pipe, and its interaction with a defect centred at the angular position of 270°, at 300 μs [Fig.4(d)-(f)]. Tx indicates the position of the dual-array transmitter. Orange and blue arrows represent the generated waves in the clockwise and counterclockwise directions, respectively; red and magenta arrows represent the reflected wave from the defect due to clockwise and counterclockwise generation, respectively; dashed lines represent the mode-converted CHS0 wave after the interaction of the incident CHS1 mode with the defect, either as reflection or transmission through the defect.

Either bidirectional generation [Fig.4(a) and (d)], unidirectional generation in the clockwise direction [Fig.4(b) and (e)] or unidirectional generation in the counterclockwise direction [Fig.4(c) and (f)] were evaluated. As can be seen in Fig.4(a)-(c), the dual-array with adequate delay is effective in generating the desired CSH1 mode in the desired direction. Regarding the interaction with the defect, bidirectional generation creates, for a single propagation loop, eight wavefronts after the first interaction with the defect, as shown in Fig.4(d), namely, two reflected CSH1 modes, two reflected CHS0 modes, due to mode conversion when the incident mode interacts with the defect [4, 8], two through-transmitted CSH1 modes and, finally, two mode-converted transmitted CSH0 mode. On the other hand, with unidirectional generation, as shown in Fig. 4(e) and (f), there is only one reflected and one transmitted wavefront for each wave mode. In Fig. 4(e), reflection and transmission have just occurred for the time instant portrayed in the wavefield snapshot, and both CSH1 and mode-converted CSH0 modes are mixed. In Fig. 4(f), the wave modes have propagated further, after interacting with the defect, and hence are separated. One can clearly distinguish, at the tip of the arrows, the antisymmetric and symmetric wave profiles for the CSH1 and CSH0 modes, respectively. This illustrates how unidirectional generation can reduce the number of received wavefronts, and consequently, simplify the interpretation of the received signal.

Fig. 5 shows the received signal at the angular position of 45° (90° from the transmitter in the clockwise direction, as shown by Rx in Fig. 3), either under bidirectional generation (upper row) or unidirectional generation in the clockwise direction (lower row). Three angular positions for the defect are shown, namely, at 270° (left-hand size column), at 292.5° (middle column), and at 315° (right-hand size column), which corresponds to the defect diametrically opposed to the transmitter. The receiver signal in the absence of a defect is shown by the black line, for the sake of comparison. The direct wave travelling in the clockwise direction arrives at approximately 100 μs and, after a whole loop around at approximately 550 μs; the direct wave travelling in the counterclockwise direction arrives approximately at 300μs, as indicated by the arrows in Fig. 5.

Observing the waveforms under the presence of the defect (blue dashed line) due to the clockwise generation, Fig. 5(d)-(f), one can see that the reflection from the defect, composed of dispersed (CSH1) and mode-converted (CSH0) waveforms, arrives between 300 μs and 500 μs, depending on the position of the defect. However, under bidirectional generation, those reflection echoes and through-transmitted waves, due to the generation in the counterclockwise direction, arrive simultaneously and interfere, which hinders signal interpretation since the defect echo can be mistaken by the direct wave in the opposite direction. In [14], we showed that, for the generation of the CSH0 at the low-frequency regime, when the defect position is at 180° from the transmitter, like in Fig.5. (c), the defect echo was completely masked by the direct wave in the opposite direction with a bidirectional generation. In the present case, due to dispersion and mode conversion, there is some degree of

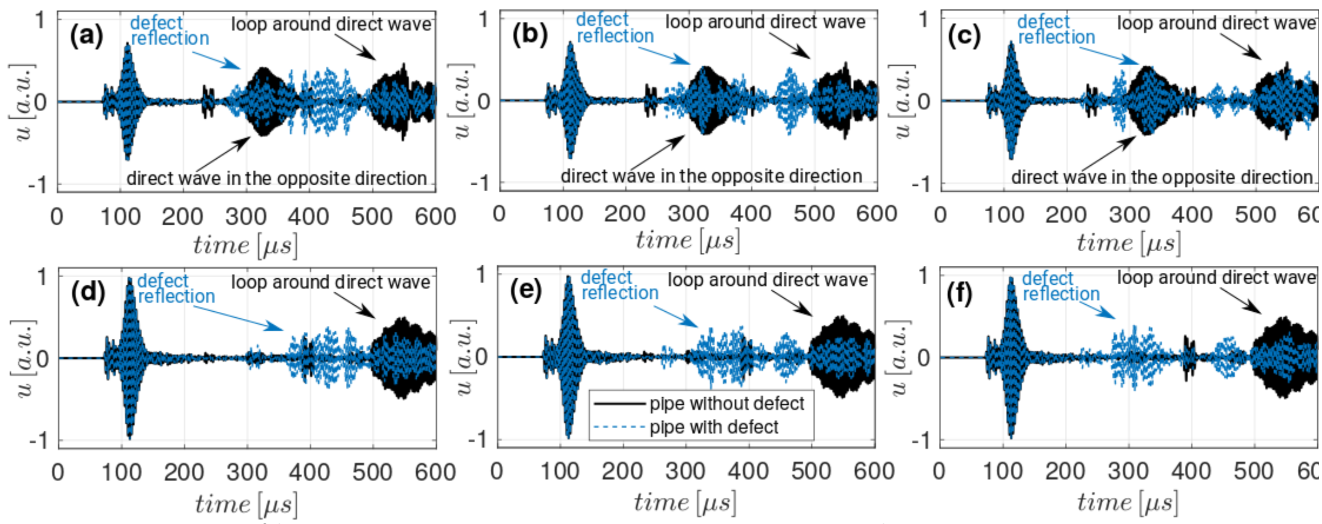

Fig. 5 Received signals, at 90º from the transmitter in the clockwise direction, due to the generation of the CSH1 mode in a 324 mm outer diameter, 6.25 mm thick steel pipe without any defect (black line) and with a 27 mm long, half-thickness deep wall-thinning defect (blue dashed line) positioned at the angular position of 270º (a) and (d), 292.5º (b) and (e), and 315º (which means diametrically opposite to the transmitter) (c) and (f). Conventional bidirectional generation (a) - (c), unidirectional generation to the clockwise direction (d) – (f).

wave mixing, between reflected and transmitted waves for a range of defect positions, making signal interpretation more susceptible to misinterpretation.

V. Conclusion

Circumferential shear-horizontal guided waves are useful for pipeline inspection, either generating the fundamental CSH0 or higher-order CSH1 mode. SH wave can be generated with PPM EMAT, which generates waves in both clockwise and counterclockwise directions. Non-conventional dual-PPM EMAT can generate SH waves in a single direction with only two, 90º phased, excitation pulses. Here, we exploited finite element simulations to case study the interaction of the CSH1 mode in a steel pipe with a corrosion-like defect. Either bidirectional generation or unidirectional generation, in both possible directions, were analysed. It was shown that, under bidirectional generation, the reflected waves from the defect and the transmitted waves throughout the defect, due to the generation in opposite direction, are mixed in the received signal for a range of defect positions; unlike the generation of the fundamental CSH0 mode, where this phenomenon occurred mainly when the defect was positioned diametrically opposed to the transmitter. Unidirectional generation of SH waves proves itself to be an important feature in pipeline inspection, providing more reliable signal interpretation.

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