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Investigation of Beam Features of Unidirectional Rayleigh Waves Electromagnetic Acoustic Transducers (EMATs) by a Wholly Analytical Solution

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Abstract. Electromagnetic acoustic transducers (EMATs) are widely used in industries due to its non-contact nature. This paper investigates the beam features of unidirectional Rayleigh waves EMATs, especially the effect of the wire length on beam directivity. A wholly analytical model is developed to calculate the Lorentz force distribution and ultrasound displacement distribution. The modelling results indicate that, compared to the coil consists of shorter wires, the coil consists of longer wires results in a narrower bandwidth of main lobe of unidirectional Rayleigh waves, which means the ultrasound are more concentrated. This study can be used for unidirectional Rayleigh waves EMATs design and optimization.

Keywords. Unidirectional Rayleigh waves, EMATs, analytical solutions, beam features

1. Introduction

In industries, such as petrochemical industry and nuclear power area, non-destructive testing (NDT) techniques are commonly used for structural integrity monitoring, and thus NDT is the guarantee for long-term and safe operation [1-3]. Frequently used NDT methods include eddy current testing, ultrasonic testing, magnetic leakage testing, and acoustic emission testing, etc [4-7]. Such technologies can be used for corrosion detection, defect locating and sizing, and material characterization [4-7].

Ultrasonic testing can be implemented via piezoelectric transducers (PZTs) or electromagnetic acoustic transducers (EMATs) based on different ultrasound generation mechanisms [8, 9]. PZTs have the benefits of mechanical flexibility, insensitive to electromagnetic interference, and good penetration depth, but suffer from the need of contact between transducers and samples, which limits them in applications such as detection under high temperature [10]. EMATs, on the other hand, are advantageous due to their non-contact nature and the fact of a variety of waves modes can be generated

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[11]. There are two working principles of EMATs, magnetostriction and Lorentz force mechanism, applied for different materials detection [12].

Unidirectional Rayleigh waves EMATs are firstly proposed in [12], from which the beam features of Rayleigh waves are investigated via experiments, and then were optimized based on FEM modelling. This paper focuses on using a wholly analytical solution to analyze unidirectional Rayleigh waves generated by EMATs working on Lorentz force mechanism, especially to analyze the beam features of the Rayleigh waves and investigate the wire length effect on Rayleigh waves' beam directivity. The working principle of unidirectional Rayleigh waves and its analytical model are introduced in Section 2. The beam features analysis and the wire length effect are investigated in Section 3, followed by conclusions and discussions in Section 4.

2. Analytical solutions for Unidirectional Rayleigh waves EMATs

2.1. Working principle of Unidirectional Rayleigh waves EMATs

The EMATs used to generate unidirectional Rayleigh waves consists of a permanent magnet and a double-meander-line (DML) coil. The DML coil, as shown in Figure 1(a), is formed by two separate meander line coils Tx 1 and Tx 2. The DML coil is designed to manufacture via a 4-layer flexible printed circuit board (FPCB), from which Tx 1 occupies the first and second layers while Tx 2 occupies the third and the fourth layers of FPCB. *'L'* denotes the length of the DML coil, *'W'* denotes the center-to-center distance between adjacent wires of each meander line coil, and *'S'* means the spacing between two meander-line coils.

Each meander line coil has a *'W'* equaling to one half of the Rayleigh waves' wavelength to generate Rayleigh waves. *'S'* is set to one quarter of Rayleigh waves' wavelength, and the excitation signals for these two meander line coils have a phase delay of 90^0, so that the generated Rayleigh waves only propagate in one direction based on the wave superposition. In this work, *'L'* is 50mm (the vertical length), *'W'* is 3.033mm, *'S'* is 1.5165mm and the excitation frequency is 483 kHz for aluminum plate detection. The excitation signals used are gaussian modulated sine wave signals as shown in Figure 2(a), and the waves superposition progress is presented in Figure 2(b); the working principle of unidirectional Rayleigh waves EMATs have been illustrated in [13] and are not introduced here.

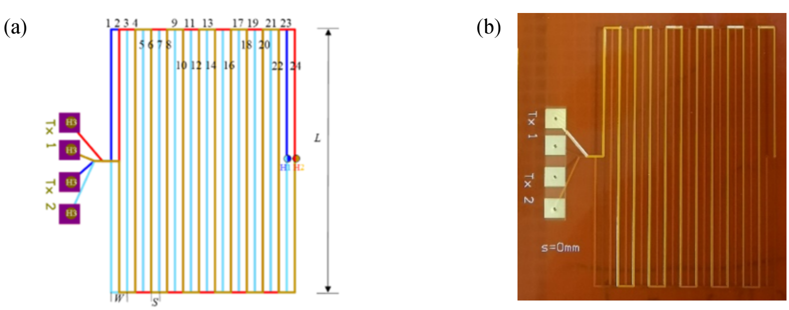

Figure 1. DML coil. (a), the schematic diagram, (b), the manufactured FPCB.

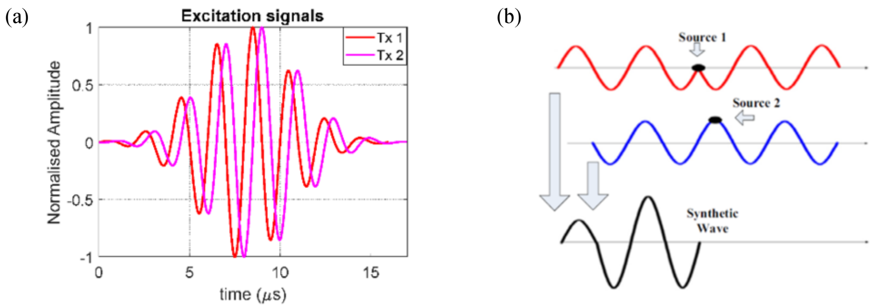

Figure 2. (a), The excitation signals for coil Tx 1 and Tx 2; (b), wave superposition between the source 1 and source 2.

2.2. Analytical solutions to Unidirectional Rayleigh waves EMATs

Since EMATs involve two physical phenomena- electromagnetic (EM) induction and ultrasound (US) propagation, the analytical model for unidirectional Rayleigh waves EMATs can be divided into two parts, EM model and US model. The test piece used was an aluminum plate. For EM model, the classic analytical solution, Dodd and Deeds solution, is employed and adapted to calculate the magnetic vector for the straight wire, and in turn to calculate Lorentz force distribution. Such adaption has been detailed in our previous work [13-14]. The computed Lorentz force from EM model are used as the vibration sources of the US model to excite ultrasound waves; in other words, the calculated Lorentz forces are the link between the EM model and the US model. The combination between the EM model and the US model is shown in Figure 3.

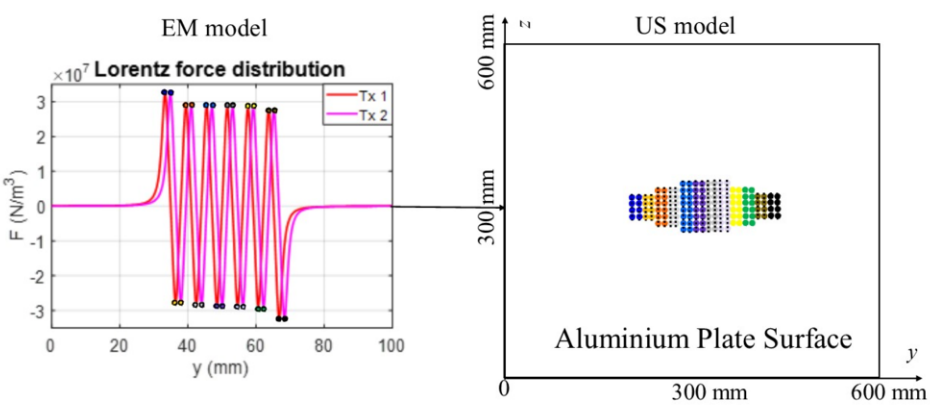

Figure 3. The link between the EM model and the US model.

The analytical solutions for Rayleigh waves radiation have been introduced detailed in our previous work [14]. The modelling parameters are showing in Table 1. Field spatial step means the distance between two adjacent field points on the surface of the aluminum plate; the dimension of the surface of the aluminum plate is $600\times600\times20$ mm^3 and the field spatial step used is 1 mm, so there are totally 601×601 field points on the surface of the aluminum plate. Source spatial step for each wire means the distance between two adjacent source points on each wire; the length of the wire is 30 mm and the source spatial step used is 0.2 mm, so there are 151 source points on each wire. The reason we choose dense source points is that lots of source points guarantee the wave interference' integrity.

Table 1. The parameters used for modelling.

Description	Symbol	Value
Length of the sample	Y	600 mm
Width of the sample	Z	600 mm
Field spatial step	Δx_f	1 mm
Length of the meander-line-coil	L	50 mm
Source spatial step for each wire	Δx_s	0.2 mm
Density of the Aluminum plate	ρ	2700 kg/m^3
Frequency	f	483 kHz
Longitudinal waves' velocity	C_L	6.375 mm/μs
Shear waves' velocity	C_s	3.14 mm/μs
Rayleigh waves' velocity	C_R	2.93 mm/μs

The calculated Radiation pattern of the unidirectional Rayleigh waves is shown in Figure 4. From this figure, the Rayleigh waves mainly propagate along one direction with a main lobe and several side lobes. The part circled in the red ellipse should not have a larger intensity compared to that of main / side lobe, which is due to the approximation of the proposed analytical solutions. However, the part included in the red ellipse is not the focus of this work and hence is ignored. The beam features to analyze are the beam directivity of the unidirectional Rayleigh waves, in other words, the displacement field distribution of the main lobe and side lobes.

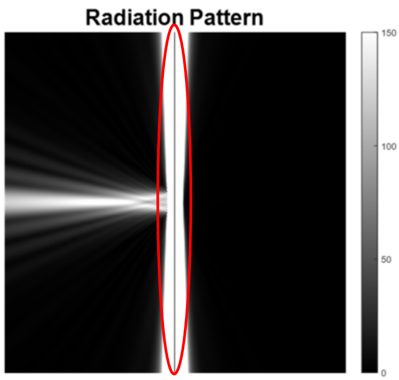

Figure 4. The radiation pattern of the unidirectional Rayleigh waves.

The beam directivity is defined as, at a specific distance away the transducer (which is EMATs in this work), the displacement / velocity fields distribution along different angles. The calculated beam directivity at a distance of 250 mm is shown in Figure 5; only the displacement fields between -30^0 to 30^0 are presented here since most of the acoustic energy are concentrated within such zone. From Figure 5, the unidirectional Rayleigh waves have a main lobe and several side lobes. The main lobe is distributed from -7.5^0 to 7.5^0, and the bandwidth (also refereed as beam angle) of such main lobe is defined as 15^0.

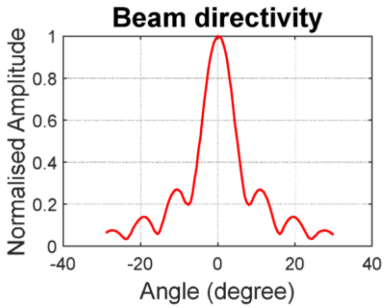

Figure 5. The beam directivity of unidirectional Rayleigh waves for 50mm-long DML.

2.3. The effect of wire length on unidirectional Rayleigh waves' beam features

For a fixed excitation frequency to generate unidirectional Rayleigh waves, the center-to-center distance between adjacent wires of each meander line coil *'W'* and the spacing between two meander-line coils *'S'* are determined. The length of the DML coil *'L'* can be changed and have an effect on beam directivity. In this part, *'L'* is changed from 20mm to 60mm with a step of 10mm, and the beam directivity at different lengths are calculated. The beam directivity comparison between different length DML is shown in Figure 6. From this figure, a longer wire corresponds to a smaller bandwidth of the main lobe; in other words, a longer wire results in a more concentrated unidirectional Rayleigh waves. More specifically, the bandwidth of main lobe are 13^0, 15^0, 19^0, 26^0, and 39^0 at wire length of 20mm, 30mm, 40mm, 50mm and 60mm respectively.

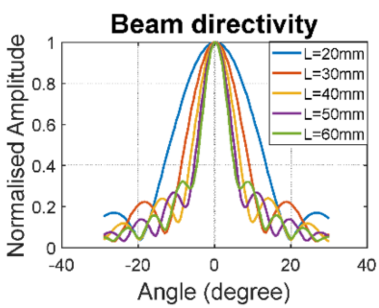

Figure 6. The beam directivity of unidirectional Rayleigh waves for different-length-DML.

3. Conclusions

The beam directivity of unidirectional Rayleigh waves is investigated via a wholly analytical model. Analytical EM model is to calculate Lorentz force distribution while the US model is to calculate the displacement distribution. Results indicate that a longer wire length of the DML coil results in a narrower bandwidth of the main lobe of unidirectional Rayleigh waves. The bandwidth of main lobe with 20mm wire length

DML is three times of that with 60mm wire length DML. This work lays a foundation for unidirectional EMATs design and optimization. Future work will be focused on experimental investigation and focusing Rayleigh waves design and analysis for the small defect detection.

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