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Frequency dependent directivity of periodic permanent magnet electromagnetic acoustic transducers

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ABSTRACT

Beam steering has been achieved using shear horizontal waves generated using a periodic permanent magnet (PPM) electromagnetic transducer (EMAT). Unlike phased arrays, where steering is achieved by carefully controlling the firing of individual elements, the spatial periodicity of the PPM EMAT is utilised to steer the beam whilst exciting all elements simultaneously. Due to the periodic nature of the array, the interference of individual waves from each of the elements creates a highly frequency dependent angle of propagation, allowing the directivity to be changed by simply varying the frequency of the input signal. Simultaneous excitation precludes the need for complicated and expensive phased array hardware. A frequency domain model is developed so that the beam characteristics, such as steering angle and beam width, can be calculated, allowing for investigation into the beam steering qualities of the PPM transducer. Broadband pulsed generation is also demonstrated, showing how a wave is generated over a large range of angles, meaning a large area can be covered with a single pulse. Interesting properties of this wave, such as a variation of frequency as a function of angle, and how this can be useful, are also discussed.

1. Introduction

Shear Horizontal (SH) waves are a form of ultrasonic shear wave that has particle displacement polarised in the plane that is parallel to the surface layer of a sample, and exist as both a family of guided waves, as well as a bulk wave [1]. SH guided waves have been applied to a range of ultrasonic inspections, both for plate-like [2] and pipe-like structures [3]. Due to the fact that they are polarised parallel to the surface boundary, SH waves are less likely to mode convert to shear vertical (SV) or longitudinal waves [4] than either of the other two waves. This means less energy is lost at the boundary and analysis of the signal is easier, when compared to SV or longitudinal waves, as it is more likely that only one kind of wave will be present in the experimental signal. Also, as austenitic welds are generally isotropic in the direction of the particle displacement, SH waves can also pass through welds with limited distortion when compared to longitudinal and SV waves [5]. The relative simplicity of the SH dispersion curves on flat plates (when, for instance, compared to Lamb waves [1]) means that analysis and interpretation of SH signals are far simpler. SH waves can also exist in the bulk of a sample, travelling non-dispersively at a speed equal to the bulk shear speed, c_s, in the medium. Due to these beneficial characteristics, SH waves have proven very useful in a range of non-destructive testing (NDT) techniques: from inspecting welds [5,6], pipes [7,8] and plates for defects [9–11], as well as being used to measure thickness changes in samples [2]. However, the use of SH waves in NDT was held back due to the inability to efficiently generate SH waves using piezoelectric transducers. Shear energy cannot propagate through a low viscosity fluid, such as those used for ultrasonic couplant between the transducer and the sample. Horizontal polarisation shear waves are also difficult to excite via mode conversion from a wedge. This makes it difficult, although not impossible, to use piezoelectric transducers to excite SH waves [4].

However, SH waves can be easily generated using a periodic permanent magnet (PPM) electromagnetic acoustic transducer (EMAT) [12,4]. A PPM EMAT consists of an array of magnets, which alternate polarity with their nearest neighbours, and a racetrack coil that is excited with an alternating current. The exact configuration can be seen in Fig. 1. The alternating polarity of the magnet array means that, in non-ferromagnetic samples, the PPM EMAT sets up an alternating Lorentz force within the skin depth of the sample. It is this Lorentz force arrangement, caused as a result of the interaction between the induced eddy currents and the static magnetic field, which generates the SH wave. The generated SH wave has a wavelength on the surface equal to the periodic distance of the array, d, which is twice the pitch of the PPM array. It should be remembered that due to the (anti-) symmetry of the

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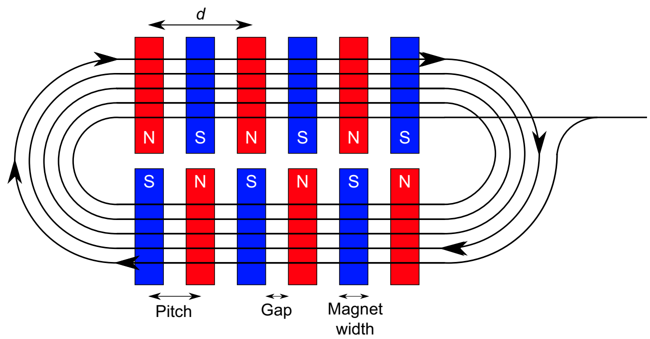

Fig. 1. PPM EMAT configuration, showing the layout of the magnets and racetrack coil.

transducer, two SH waves are produced, travelling in opposite directions to each other. The transducer also has all the traditional benefits of EMATs, such as not requiring any direct contact with the sample, and, when driven by suitably narrowband signal, the ability to generate an ultrasonic wave with the desired polarisation [13].

It has also been shown that PPM EMATs can be used to control the angle at which the SH waves propagate [8,14,15], without having to use any phase array methods [16,17]. It is achieved by exciting all of elements in the array with a narrowband signal of a particular frequency. Consequently, it is possible to steer the ultrasonic beam without having the complication of having to control each element in the array individually. This is described in more detail in Section 2.1. Section 2.2 explains how an array can be pulsed with a broadband signal to create a wavefront that covers a large angular region, and has an angularly dependent frequency. A frequency domain model is discussed in Section 2.3 that can calculate the directionality of the generated wavefront, which will help aid inspections. Whilst the peak position of the beam in such frequency steering cases has been extensively discussed in the literature, other key parameters, such as the beam shape and beam width, are also important. The frequency domain model allows the directivity of a PPM EMAT, when driven by a particular signal, to be calculated. Hence, the intensity of the generated wavefront over the entire half-space can be calculated, not just the peak steering angle. Experimental data is presented in Section 3 to verify the model with the directivity of a PPM EMAT shown for many narrowband frequencies, as well as for the pulsed case.

2. Theory

2.1. Frequency steered arrays

The periodic structure of the PPM EMATs, with regular elements of alternating polarity, can be used to generate SH waves on the surface. The alternating polarity of the elements leads to a similar force distribution of the surface of the sample; the periodicity of this distribution defines the wavelength of SH waves along the surface. This spatial periodicity can also be used to generate a steered SH beam that propagates at an angle to the sample surface. All SH waves, regardless of sample thickness, can be analysed by the consideration of the SH dispersion curves. However, if the sample thickness is greater than the SH wavelength, and for propagation distances less than the order of the sample thickness, the generated wave can be viewed as a bulk wave. By driving the array with a narrowband toneburst signal, the individual waves from each element in the array interfere with each other leading to constructive interference at a particular angle. This constructive interference occurs when the path length difference between waves from two neighbouring elements of the same polarity is equal to an integer number of wavelengths. This is a condition that obviously changes with frequency, and hence the SH beam can be steered by simply varying the input signal frequency [18]. This is analogous to a diffraction grating, but with an alternating polarity structure, as can be seen from Fig. 2. From this, the condition for constructive interference can be calculated as

$$d\ \sin\ \theta = (2n+1)\lambda \qquad (1)$$

Therefore, by driving the PPM EMAT with a toneburst signal of a particular frequency, ν (associated with a wavelength: $\nu = c/\lambda$), it is possible to direct the ultrasonic beam to an angle θ. By varying the input frequency, it is possible to sweep the beam over a large range of angles; starting on the surface, at $\theta = \pi/2$, up to an angle at which the first grating lobe appears. For the array shown in Fig. 2, the next order of interference occurs when $\lambda = d/3$ [18]. So, in the angular range $20^\circ \le \theta \le 90^\circ$, only the lowest order diffraction term is satisfied, meaning that there is only one main beam.

The ability to steer the ultrasonic beam can lead to the opportunity to create ultrasonic images. For example, it is possible to perform a sector scan by simply repeating the measurements at different frequencies. By varying the frequency between c/d and $3c/d$, the main beam will be steered from 90° to 20°. The resultant A-scans obtained from the frequency sweep can be combined into a single 'image', showing two dimensional information (time–frequency, or radial–angular position) about any defect that may be present.

2.2. Pulsed arrays

Whilst frequency steering has been previously achieved in a number of scenarios, a novel way of exciting the array is to pulse all of the elements simultaneously with a broadband pulse. When this is done with a pulse of the correct frequency bandwidth, a wavefront is generated over a large solid angle with the frequency varying over the angular range [18]. The frequency varies in a smooth and continuous fashion, and can be explained in a similar way as the frequency steered arrays. As before, constructive interference occurs at an angle for which the diffraction grating equation (Eq. (1)) is satisfied. However, as the input signal contains a range of frequencies, this condition is satisfied many times, meaning that instead of being a steered beam the wavefront is spread over a large range of angles with the varying frequency as described by Eq. (1). This change in frequency can be used to locate the position of a scatterer, as the frequency encapsulates the angular position of the scatterer, whilst the time of flight can be used to determine the radial distance of the body. The wavefield can also be used to interrogate a large section of the sample in a single pulse due to the large angular area that it covers.

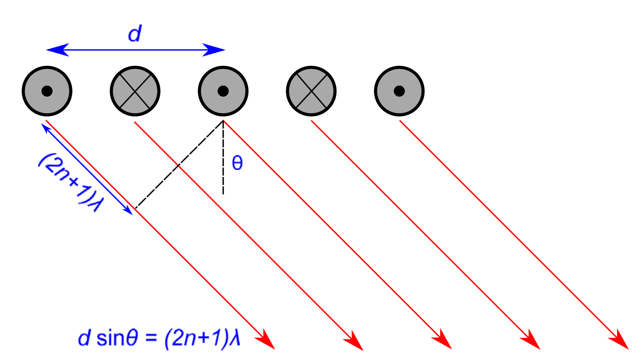

Fig. 2. Array configuration showing the force applied on the surface due to the PPM EMAT is represented as the filled circles, and illustrates the alternating polarity of the array and how it leads to condition for constructive interference.