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Localisation of defects with time and frequency measurements using pulsed arrays

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ABSTRACT

The frequency dependent directivity of the periodic permanent magnet transducer is used to extract information about the position of any discontinuities present in a sample. Two approaches are used: narrowband excitation and broadband pulsed generation. Simultaneous narrowband excitation, with the appropriate frequency, can be used to steer the ultrasound to a particular angle. Broadband excitation emits a wavefront that extends over a large range of angles, with the frequency of the wavefront varying smoothly as a function of angle. Using these two approaches, two-dimensional maps of any defects present in the sample can be obtained.

1. Introduction

Recently published work has demonstrated how a wavefront with a frequency dependent angle of propagation can be generated by simultaneously activating a periodic array of ultrasonic emitters [1]. By utilising this physical phenomenon, the location of a discontinuity can be ascertained by measuring the frequency of the scattered signal, as well as the time-of-flight. A new send–receive configuration is presented here, whereby the data obtained from such a broadband pulsed array can be processed to form a two-dimensional map of the location of defects that may be present in a sample. This broadband approach is compared to the established narrowband excitation technique. This narrowband approach can steer an ultrasonic beam to a particular angle by exciting the array with a low bandwidth signal of a particular frequency [2–4]. The ultrasonic beam can be swept over a range of angles by simply varying the excitation frequency. The accuracy and the precision of the localisation of defects obtained from these approaches are compared using calibration and realistic samples by interrogating them with Shear Horizontal (SH) waves.

SH waves are becoming a useful tool for ultrasonic inspection applications as they have a number of advantageous qualities. For instance, if a SH wave is obliquely incident on a free surface, it will not mode convert to either longitudinal or shear vertical (SV) waves [5]. This means that the received signals are easier to analyse, as there is only one type of wave present, as well as minimising energy loss at the boundary of the sample. It has also been shown that SH waves can pass through austentic welds with limited distortion when compared to longitudinal and shear vertical (SV) waves [6], as a consequence of the typical microstructure [7]. However, the widespread utilisation of SH waves in non-destructive testing has been limited by the inability to efficiently generate SH waves using piezoelectric transducers [5]. Shear energy cannot easily propagate through a low viscosity fluid, such as those used for ultrasonic couplant between a piezoelectric transducer and the sample. Horizontal polarisation shear waves are also difficult to excite via mode conversion from a wedge.

However, SH waves can be easily excited using electromagnetic acoustic transducers (EMAT), specifically using a periodic permanent magnet (PPM) EMAT [8,5]. 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. For a non-ferromagnetic sample, the Lorentz force dominates [9]: setting up alternating forces, arising as a result of the interaction between the induced eddy currents and the static magnetic field, within the skin depth of the sample [10]. It is these alternating Lorentz forces that generate the SH wave, which will have a wavelength on the surface equal to the periodic distance of the array, d, which is twice the pitch of the PPM array. The PPM transducer also benefits from the usual advantages of EMATs, such as not requiring any direct contact with the sample, and the ability to generate ultrasound of a single polarisation [11].

It is possible to use the periodic structure of the magnet array in a PPM EMAT to control the angle at which the SH waves propagate [2,3,12]. Phased array methods [13,14] rely on precisely activating the individual array elements with a time delay in order

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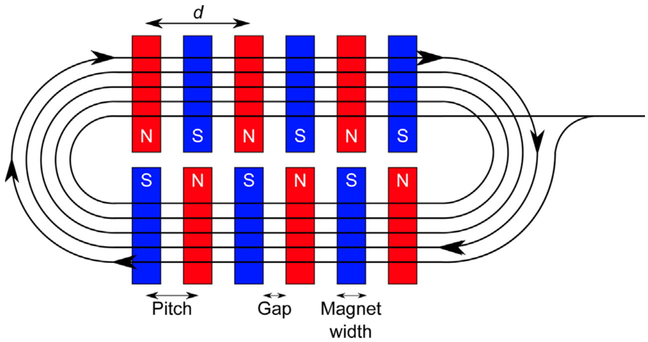

Fig. 1. PPM EMAT configuration, showing the magnet array and racetrack coil.

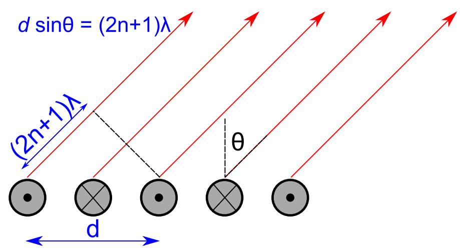

Fig. 2. Array configuration showing the condition for constructive interference.

to manipulate the ultrasonic beam. However, with a PPM EMAT, beam steering can be achieved by exciting all of elements simultaneously, with a narrow-band signal [15]. Consequently, it is possible to steer the ultrasonic beam without having the complication of requiring the individual control of each element in the array. 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, with a frequency dependent on the angle of propagation. Experimental data is presented in Section 3 to demonstrate how PPM EMATs and SH waves can be used to detect and locate defects. For the frequency steered array, the beam can be used to sweep through a range of angles, by changing the driving frequency, in order to create a 'sector scan' image, whilst time–frequency analysis can be used to interpret data obtained from the pulsed array. Due to the frequency variation as a function of angle, any wave that has been scattered from the original pulsed array wavefront will have a unique arrival time and frequency. This can be used to locate the defect by converting the time of flight to a radial distance, with the frequency of the scattered wave being related to the angle of the defect [1].

2. Theory

2.1. Frequency steered arrays

The alternating Lorentz forces generated by the PPM EMAT act to generate SH waves on the sample surface, with the periodicity of the EMAT array defining the wavelength of the generated waves. The spatial periodicity of the PPM EMAT can also be used to generate SH waves that are steered so that they propagate at an angle to the sample surface. Ultrasonic steering using simultaneous excitation is achieved due to interference effects [15]. This constructive interference occurs when the path length difference between waves from two neighbouring elements of the same polarity is equal to an odd-integer number of wavelengths. This is a condition that changes with frequency, and hence the SH beam can be steered by simply varying the input signal frequency. The condition for constructive interference can be calculated as

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

Here, d is the periodic distance of the array, λ is the ultrasonic wavelength, n is the order of interference and θ represents the angle at which the ultrasonic beam is steered. Therefore it is possible to direct the ultrasonic beam to an angle θ by driving the PPM EMAT with a tone-burst signal of a particular frequency, ν (associated with a wavelength: $\nu = c/\lambda$). The ultrasonic beam can be swept over a large range of angles, simply by varying the input frequency. The beam can be steered from 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 $\lambda = d/3$ [1]. 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. Frequency domain models can be constructed to calculate not only the steering angle, but also the other important parameters such as the beam shape and width, as well as other characteristics such as side lobes [15]. Knowing the total frequency dependent directivity of the array means that any received signal can be correctly interpreted.

The ability to steer the ultrasonic beam provides 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

When simultaneously exciting all the elements of the array with a pulse of the correct frequency bandwidth, a wavefront is generated over a large solid angle. The frequency of the wavefront varies with the angle of propagation, with the same dependence between frequency and angle as was seen for the frequency steering. As with the frequency steered arrays, 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 continuously over a wide range of angles. As this change in frequency is continuous and monotonic, it can be used to locate the position of a scatterer. This is because the frequency encapsulates the angular position of the scatterer, whilst the time of flight can be used to determine the radial distance of the scattering 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.

Analytic and finite element (FE) modelling techniques can be used to gain more information about the wavefront, such as how it evolves in time, as well as confirming the angular dependence of the frequency [1]. The analytic model, using a simplified Huygens approach, has the advantage of being able to extract the key physical characteristics of the wave. The simulated wave displacement is shown in Fig. 3 as an SH wave generated by an array with $d = 10$ mm operating on aluminium ($c_s = 3111$ ms^{-1}). It demonstrates that the wavefront extends over a large angular region, from the surface, at $\theta = 90^\circ$, up to around $\theta = 20^\circ$. In this angular range, the frequency of the wave is changing: from low frequency ν_0 on the surface, up to $3\nu_0$ at $\theta = 20^\circ$. This means that an angular region of around 70° can be covered with a single pulse. The exact frequency variation can be seen in Fig. 4, which is in accordance with the expected diffraction grating behaviour. This allows us for easy conversion between the measured peak frequency of any scattered signals and the angle from which they originated.