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Beam forming of Lamb waves for nondestructive testing of plates

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Abstract. For wide range defect detection in plate, acoustic beam optimization technique was investigated. The synthesis wave field obtained from the basic phased-addition is prone to be influenced by the noise and the resolution is low. To improve the performance of beam forming of array, the synthesis acoustic field is processed with amplitude weighting. The experimental data have been processed with phase shift and amplitude weighted optimization. It is shown that the proposed beam forming technique with transducer array can recognize the features in plate.

Introduction

Lamb wave techniques have been utilized for structural health monitoring of simple plate and shell structures [1]. However, most aerospace structures are significantly more complex, and Lamb waves are dispersive and multi-mode. Therefore advanced techniques may be required [2-3]. An array of spatially distributed transducers is one of the most powerful solutions for complex structure health monitoring [4-6]. Traditionally, acoustic array data have been processed by means of beam forming [7-8], or spatial filtering [9-10], to obtain an image of the scattering objects. Beam forming is the process of adjusting the signals in an array of transducers to highlight signal and suppress noise. Beam forming can be performed efficiently using delay-line operations in real time or using post processing as in synthetic aperture systems.

A conventional beam forming can be a simple beam former known as delay-and-sum beam former. All the weights of the antenna elements can have equal magnitudes. The beam former is steered to a specified direction only by selecting appropriate phases for each antenna [11-13]. One drawback is that the resolution of traditional delay-and-sum beam forming methods is determined by the product of the transmitted and received beam patterns. These beam patterns are determined by the position-dependent point spread functions associated with the array system. These are determined by the aperture size, element size, and transmit pulse; hence resolution is directly related to the physical size of the array. Classical beam forming can, therefore, not achieve higher resolution than the so-called diffraction limit.

In principle the basic-phased addition algorithm can be applied to any array geometry, but its performance is good only for a limited number of cases. For example, it produces acceptable results for a linear array, but in the case of a circular array a large number of elements are required to obtain acceptable resolution [14]. This paper is concerned with finding optimal phase coefficients, which allow the best resolution to be achieved for any array geometry with the minimum number of array elements. In this paper an amplitude weighted algorithm is explore to improve the focusing performance of annular array.

Beam forming optimization by amplitude weighting

The synthesis wave field obtained from the processing of basic phased-addition has directional steering and focusing in spatial, as shown in following

$$E_{ij} = \sum_{p=1}^{n_k} A_{pj} \exp(\mathrm{i} k_p r_i) \tag{1}$$

Where r_i is the radial distance associated with a row in E. However the focusing performance is prone to be influenced by the noise and the resolution is low. To improve the performance of beam forming of array, the synthesis acoustic field is further processed with amplitude weighting,

$$G_{ij} = E_{ij} \times w_{ij} \tag{2}$$

Where w_{ij} is the amplitude weighting coefficient, and $0< w_{ij} <1$. The value of amplitude weighted factor w_{ij} mainly depends on the wave field of reflector in far field. Since the elements in annular array behave as point sources, the annular array has uniform resolution in different circumferential directions, and it means that the array is omni-directional. Therefore in far field the responses of reflectors at same circumference are independent on the circumferential position of reflectors, and are far bigger than the noise level at same distance. Therefore the amplitude weighting w_{ij} is expressed as

$$\begin{cases} w_{ij} = 1 & EdB_{ij} \geq m \times Eave_i \\ w_{ij} = \dfrac{1}{1+n\delta} & EdB_{ij} < m \times Eave_i \end{cases} \tag{3}$$

Where Eavei is the averaged acoustic intensity at same distance from the center of array, m is the weight coefficient, δ is step of the amplitude weighting, EdB_{ij} is the normalized acoustic intensity at any spatial location, and it is calculated as following,

$$EdB_{ij} = -20\log\left(\frac{E_{ij}}{\max(E_{ij})}\right) \tag{4}$$

n is integer, which is determined by optimizing the spatial distribution of acoustic field of array.

According to the expression (3), the determination of amplitude weighting can be divided into two groups. If the normalized acoustic intensity EdB_{ij} is greater than or equal to the averaged acoustic intensity Eavei at same distance, it is believed that there is reflector at this location, and the value of amplitude weighting is set 1; otherwise it is supposed that there is no reflector at the location, and the acoustic intensity is the results of noise. The amplitude weighting is set as $w_{ij} = \dfrac{1}{1+n\delta}$, and n is determined by meets the following condition:

$$(1+n\delta)EdB_{ij} \leq Emin_i \tag{5}$$

Where E_{mini} is the minimum of the acoustic intensity at the distance. According to equation (3) and (5), the beam forming optimization is to find the minimum n which meets the equation (5).

Then the optimal amplitude weighting coefficient w_{ij} is applied to the synthesis acoustic field to eliminate the influence of noise on defect detection.

Experimental system of lamb transducer array

Experiment in plate using lamb transducer array were conducted after beam forming optimization. The experimental system is shown in Fig.1. It includes signal generator, amplifier, annular array, oscilloscope, computer and the plate to be tested. The excitation signal is a ten-cycles hanning-windowed burst at 180kHz, which amplitude is 300mV. A 20×2mm defect has been processed on the plate to be tested, which dimensions are 1000mm×1000mm×1mm.

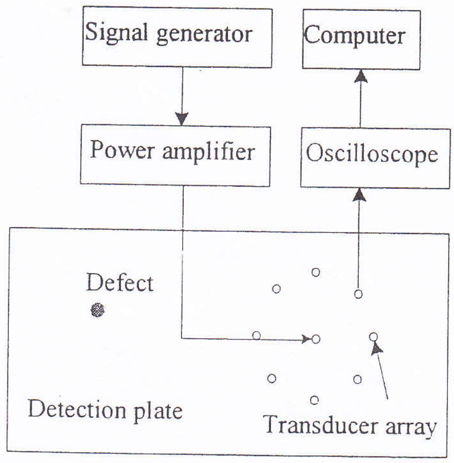


Fig 1 Experimental devices

Fig. 2 shows the operating principle of electromagnetic acoustic transducer (EMAT). The direction of magnetic field produced by permanent magnet is vertical with the plate. And Lorentz force produced by loop coil is along the radial direction of transducers and parallel with the plate. Then guided waves in mode S0 will be excited and transmitted with an angle of 360°. So this transducer has the same sensitivity to defects in different directions.

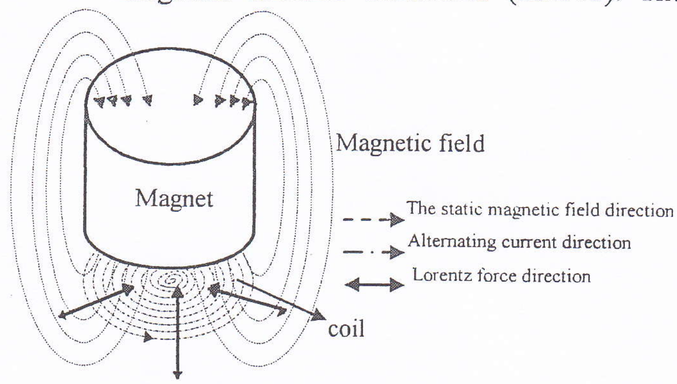


Fig 2 EMAT Schematic

The EMAT consists of coil, permanent magnet and supporting frame. The coil was made by PCB plate of 0.5mm thick with a external diameter of 32mm. The permanent magnet's surface intensity of magnetic field is 4300 gauss. It is made of NdFeB and was processed to a cylinder, of which the diameter is 35mm and the height is 20mm. Supporting frame is made of PVC to avoid eddy current.

According to the result of numerical simulation, the inter-element spacing should be less than the half wave length of lamb wave to avoid the effect of side lobe. The wave length of lamb of mode S0 at 180kHz is 30mm, and the diameter of receiver array is 300mm. So there should be at least 63 receiving elements in the array according to the calculation. In the experiment, one excitation transducer was stabilized at the original point. Signal receiving at 64 locations along the circumference with same spacing was achieved by move the receiving element on a circle of which the radius is 150mm, therefore the dimension of the receiving signal matrix is 64.

Every element of the receiving signal matrix G in time domain is expressed as g_{pj}, where p stands for sequence number of data point received when receiving transducer is at one location, and j stands for sequence number of different locations. Zero filling was executed on G to guarantee the accuracy of transformation from frequency to wave number. After DFT on G, matrix S in frequency domain was obtained. The elements of S are shown as:

$$s_{ij} = \sum_{p=1}^{n_t} g_{pj} \exp(-i\omega_i t_p) \tag{6}$$

Then we got matrix W by expressing S using wave number instead of frequency. This can reduce frequency dispersion and guarantee basic-phased addition in the chosen mode. The range of wave number should be determined before the transformation, considering that the Nyquist wave number have to be larger than the wave number at Nyquist frequency in chosen lamb wave mode, namely $k_{Nyq} \geq k_m(\omega_{Nyq})$. Also the transformation distance ought to be large enough to ensure the inversed transformation, which means the quantity in wave number domain satisfied

$$n_k \geq 2k_m n_t \Delta t v_{\max} \tag{7}$$

in which the vmax stands for the fastest group velocity of lamb wave mode. After constructing the wave number vector ki, transformation from frequency domain to wave number domain can be achieved through linear interpolation as:

$$sw_{ij} = s_{p,j} + (s_{p+1,j} - s_{p,j})\frac{(\omega_m(k_i) - \omega_p)}{\omega_{p+1} - \omega_p} \tag{8}$$

In which $\omega_p < \omega_m(k_i) < \omega_{p+1}$.

Result and analysis

Imaging result of sound field on plate is shown in fig.3 by basic-phased addition. Boundary of the plate can be determined according to the reflect signal. And the reflect signal also exist at the defect. But defect on the image is not so obvious because of noise around.

. Characterization parameters of sound field at different locations were studied before amplitude-weighted optimization. As shown in fig. 3, phenomenon that maximum value is larger than the amplitude-weighted mean value of sound field intensity occurs in many locations, which means there are many reflecting objects in the sound field.

Amplitude-weighted optimization was processed, and result were shown in fig. 4. noises decrease greatly after basic-phased addition and amplitude-weighted optimization. Defect and four edges of plate were clearly shown in the reflection sound field. Result of noise elimination became better as the value of m decreasing. (fig. 5)

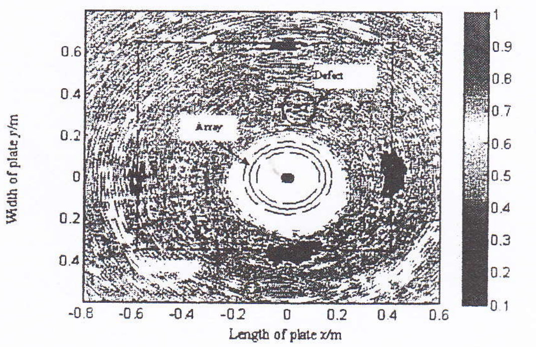


Fig 3 Equal phase superposition principle

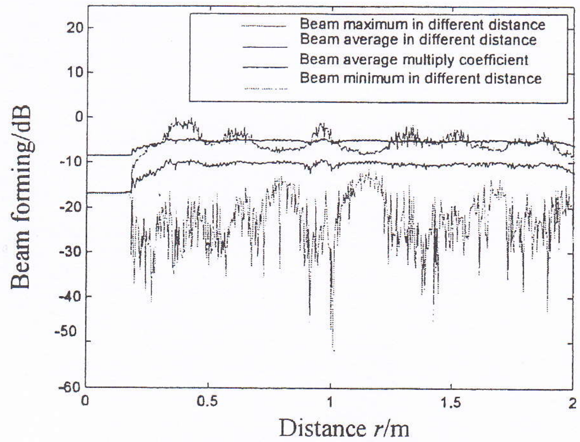
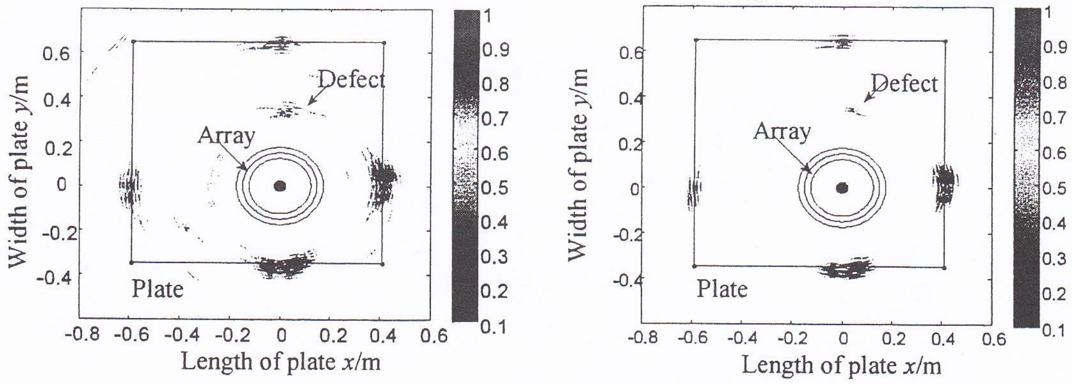


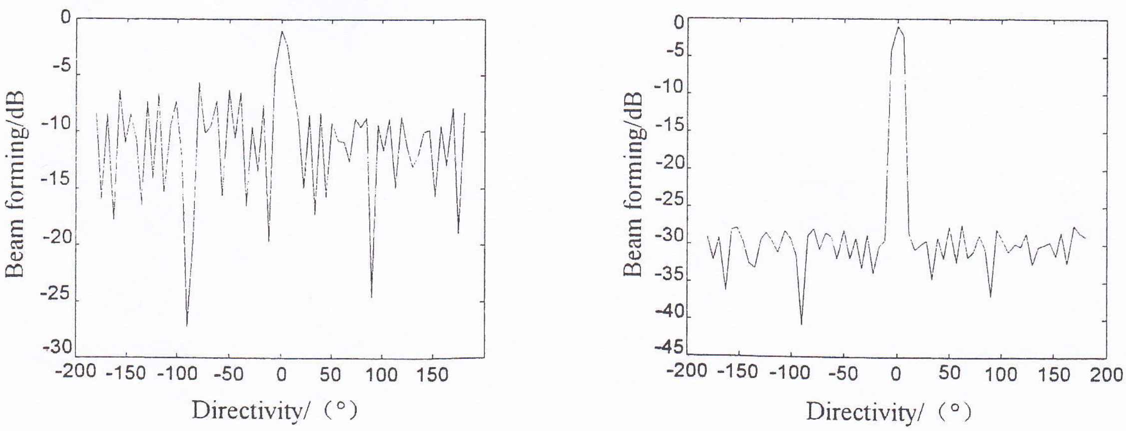
Fig 4 Beam in different distance



(a) m=0.5 (b) m=0.4

Fig 5 Image after amplitude weighing optimization

Fig. 6 shows the distribution of sound field intensity both before and after amplitude-weighted optimization to declare the elimination of side lobes, where the distance is 0.4m. After amplitude-weighted optimization the distribution of sound field pointed obviously at the direction of 0°, thus wiping the noises greatly.



(a) Before amplitude weighted optimization (b) After amplitude weighted optimization

Fig 6 Distribution of sound field in different angles

Summary

Based on phased addition and amplitude- weighted algorithm in phased array, the received data of array is processed and beam of array is directed without the hardware of phased control system. By processing the simulation data with the phased addition algorithm, the influences of diameter of array, the number of elements and number of beam on the directivity of transducer array was studied. It is found that the spacing of elements should be smaller than half-wavelength of Lamb waves in order to avoid the visible side lobe. Amplitude-weighted optimization was processed on distribution of spatial sound field according to weighted mean value and minimum value of sound field intensity after basic-phased addition. Both simulation and experiment show that directly focusing test on plate in large range can be achieved by beam optimization of data from transducer array.

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