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Simulation of ultrasonic array inspection of composites with side drilled holes

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Abstract
In this paper we ultrasonic signals from array transducers are simulated using the Thompson and Gray measurement model. The measurement model consists of a beam model, a system efficiency factor which characterizes the response of the electro-mechanical and electrical components of the system, and a flaw scattering model. To inspect layered composite structures with complex geometries such as curvature, a beam model which is non-singular is required. Hence a multi Gaussian beam model for an ultrasonic array which includes the slowness surface parameters for unidirectional CFRP is investigated. The system functions of the ultrasonic array are modelled using a system efficiency model for a rectangular array. The Kirchoff approximation and separation of variables method for far field scattering in anisotropic materials is used to model the far field response of scatterers such as side drilled holes (SDH) in unidirectional CFRP. In summary the ultrasonic measurement model developed is able to predict the signals from scatterers such as side drilled holes (SDH) in transversely isotropic CFRP.

1. Introduction

Over the last decades the use of composite structures in industry has been on a steady rise. To ensure quality of these structures, non-destructive testing using ultrasonic techniques have been applied and recently there has been an increase in the use of phased array ultrasonic instruments for the inspection of composite structures. The inspection of such structures poses a challenge due to their inherent anisotropic nature and scattering by multiple layers. It is highly beneficial to model the inspection of composite structures using the phased array to understand the factors affecting the generated signal including the diffraction of the ultrasonic beam and the scattering of the wave from defects present in the structure.
Hence once the diffraction of the ultrasonic beam is understood, in the next step it is important to understand the scattering of the ultrasonic wave from defects in such structures. A common defect used for calibrating the setup is the use of side drilled holes(SDH). In this paper the response of a side drilled hole in a composite structure is simulated. This is carried out by creating a measurement model for inspection of composites. This measurement model consists of three parts 1) a beam model for inspection of composites using phased arrays 2) a far field scattering model for a flaw 3) A system efficiency factor. The beam model used is the multi Gaussian beam to include the anisotropic velocity in composites [1] which is then expanded for phased arrays in this work. The far-field scattering of flaws can be calculated by using the kirchoff approximation or by the method of separation of variables [2]. The predicted signal from side drilled holes of different diameters is then calculated using the ultrasonic measurement model.

2. Ultrasonic measurement model

For prediction of phased array ultrasonic signals in composite structures, a phased array ultrasonic measurement model for composites is developed. In the phased array ultrasonic measurement model, the contribution of the elements of the model can be considered as a simple multiplication of the beam model, system efficiency factor and flaw scattering model in the frequency domain [3]. Hence the measurement model can be given as show in Eq. (1)

$$\begin{aligned}\tilde{V}(\omega) = \sum_{n=1}^{N}\sum_{m=1}^{N} \beta^{m;n}(\omega) v_n(\omega) v_m(\omega) \left[A^{p;p}\left(e_i^n; e_s^m\right).\left(I_m^p\right)\right] \\ \left(-\frac{2\pi}{ik_2^p S_m}\frac{\rho_2 c_2^p}{\rho_1 c_1^p}\right)\exp(i\omega t_n)\exp(-i\omega t_m)\end{aligned} \quad (1)$$

where $\tilde{V}(\omega)$ is the amplitude of the received voltage, I_m^p is the identity matrix, ω is the angular frequency, p stands for longitudinal wave, $\beta^{m;n}(\omega)$ is the system efficiency factor, $A^{p;p}\left(e_i^n; e_s^m\right)$ is the far field scattering amplitude for the flaw, $v_n(\omega)$ and $v_m(\omega)$ are the velocity field amplitudes, S_m is the area of the element, $t_{n,m}$ is the time delay applied to the elements, k_2^p is the wavenumber in the solid, ρ_2 and ρ_1 are the densities of the solid and water respectively, c_2^p and c_1^p are the group velocities in the solid and water respectively.
The velocity amplitudes are given in Eq. (2) and Eq. (3)

$$v_n(\omega) = T_{12}{}^{p;p}\cos\theta_i^{n;p}\exp\left[i\left(k_1^p d_1^n + k_2^p d_2^n\right)\right] L\int_{-L/2}^{L/2} C_n^p(\omega)\,dL \quad (2)$$

$$v_m(\omega) = T_{12}{}^{p;p}\cos\theta_i^{m;p}\exp\left[i\left(k_1^p d_1^m + k_2^p d_2^m\right)\right] L\int_{-L/2}^{L/2} C_m^p(\omega)\,dL \quad (3)$$

Where $T_{12}{}^{p;p}$ is the transmission coefficient from the water into solid, $\theta_i^{n.m;p}$ are the incident angles from the *m* and *n* elements, *L* is the length of the side drilled hole, and $C_{n,m}^p(\omega)$ are the diffraction corrections from the nth and mth elements. Hence the prediction of the phased array signals using the measurement model requires the calculation of the beam fields, the time delay laws for focusing and steering, the system efficiency factor and the far field scattering amplitude of the flaw. The next section describes the calculation of these components.

2.1 Ultrasonic beam model

For anisotropic media such as composites, the ultrasonic beam model can be calculated by combining the multi Gaussian beam model for phased arrays [4] with the multi Gaussian beam for anisotropic media [5]. As the velocity of the ultrasonic wave differs in different directions in the anisotropic media, the multi Gaussian beam model for phased arrays can be modified as shown in Eq.(4)

$$\begin{aligned}C_{n,m}^p(\omega) = d_\alpha \sum_{n=1}^{N}\sum_{m=1}^{N} A_n A_m \sqrt{\frac{1}{1+v_\alpha z\left[M_{mn}(0)_{11}\right]}} \\ \sqrt{\frac{1}{1+v_\alpha z\left[M_{mn}(0)_{22}\right]}}\exp\left[\frac{i\omega}{2}X_j^T M_{mn}(z) X_j\right]\end{aligned} \quad (4)$$

Where d_α is the polarization vector of the wave type α (p and s) and , v_α is the group velocity, $A_{n,m}$ is the Wen and Breazzle coefficient, z is the distance travelled in the solid medium X_j is the position vector, ω is the angular frequency and j is the element number. The M matrices are complex valued square matrices given below

$$\left[M_{mn}(j)\right]_{11} = \frac{\left[M_{mn}(0)\right]_{11}}{1+\frac{c_\alpha}{v_\alpha} z\left(v_\alpha - 2C\right)\left[M_{mn}(0)\right]_{11}}$$

$$\left[M_{mn}(j)\right]_{22} = \frac{\left[M_{mn}(0)\right]_{22}}{1+\frac{c_\alpha}{v_\alpha} z\left(v_\alpha - 2E\right)\left[M_{mn}(0)\right]_{22}}$$

$$\left[M_{mn}(j)\right]_{12} = \left[M_{mn}(j)\right]_{21} = 0$$

And at the face of the transducer

$$\left[M_{mn}(0)\right]_{11} = \frac{iB_m}{v_\alpha D_{r1}}, \left[M_{mn}(0)\right]_{22} = \frac{iB_n}{v_\alpha D_{r2}}$$

$$\left[M_{mn}(0)\right]_{12} = \left[M_{mn}(0)\right]_{21} = 0$$

$$D_{r1} = \frac{ik_p a_1^2}{2}, D_{r2} = \frac{ik_p a_2^2}{2}$$

Where $B_{n,m}$ is the Wen and Breazzle coefficient, c_α is the phase velocity, k_p is the wavenumber in the solid, a_1 is the width of the element and a_2 is the length of the element[4]

As composite structures are inherently anisotropic, the group velocity and phase velocity are different at different angles of propagation in the structure.

C^α , D^α and E^α are the slowness surface curvatures of the wave type α which are measured in the slowness coordinates. These are obtained by expanding slowness vector s_α using a Taylor series expansion as shown in Eq.(5).

$$s_3 = s_0 + As_1 + Bs_2 + \left(C - \frac{1}{2s_0}\right)s_1^2 + Ds_1 s_2 + \left(E - \frac{1}{2s_0}\right)s_2^2 \tag{5}$$

A phased array transducer is a multi-element transducer and the array elements have smaller dimensions. Hence the radiated field from an element is not considered as a quasi-plane wave but as a spherical wave. A synthetic beam field of all the elements with the time delays is perfectly collimated and this velocity field satisfies the quasi plane wave condition. Hence the velocity field from a phased array can be written as shown in Eq.(6)

$$\mathbf{v}^\alpha = \sum_1^j \mathbf{v}_j^\alpha \exp\left(i\omega t_j\right) \tag{6}$$

2.2 Far-Field Scattering Model

2.2.1 Kirchoff approximation method for side drilled holes in composite structures

The 3-d pulse echo scattering amplitude for a SDH using the kirchoff approximation is given in equation Eq.(7)[2]

$$A(\omega) = -\frac{ik_\alpha L}{2\pi} \int_{C_{lit}} \left(e^\alpha \cdot n\right) \exp\left[2ik_\alpha\left(e^\alpha \cdot x\right)\right] ds \tag{7}$$

L is the length of the side drilled hole, e^α is the unit vector in the direction of propagation in the solid. The integral can also be calculated analytically as given in Eq.(8)

$$A(\omega) = -\frac{k_\alpha Lb}{2}\left[J_1(2k_\alpha b) - iS_1(2k_\alpha b)\right] + i\frac{L(2k_\alpha b)}{\pi} \tag{8}$$

Where J_1 and S_1 are the Bessel and Struve functions.

2.2.2 Separations of variables method

Using the separation of variables method, the far field scattering for a SDH can be given as in Eq. (9)[2]

$$\begin{gathered} A(\omega) = \frac{1}{L}\sqrt{\frac{2i}{\pi k_p}}\sum_{m=0}^{\infty}(2-\delta_{0n})M_n(k_\alpha b)\cos(n\theta)e_r \\ M_n = \frac{i}{2k_p b}\left\{1 + \frac{C_n^{(2)}(k_p b)C_n^{(1)}(k_s b) - D_n^{(2)}(k_p b)D_n^{(1)}(k_s b)}{C_n^{(1)}(k_p b)C_n^{(1)}(k_s b) - D_n^{(1)}(k_p b)D_n^{(1)}(k_s b)}\right\} \end{gathered} \tag{9}$$

In the above equation

$$\begin{gathered} C_n^{(i)}(x) = \left(n^2 + n - (k_s b)^2/2\right)H_n^{(i)}(x) - xH_{n-1}^{(i)}(x) \\ D_n^{(i)}(x) = \left(n^2 + n\right)H_n^{(i)}(x) - nxH_{n-1}^{(i)}(x) \end{gathered}$$

Where *H* are the Hankel functions

2.3 System Efficiency factor

System efficiency factor is calculated by the deconvolution of an experimental signal captured from a reference experimental setup to the model predicted system efficiency factor. For a phased array system the system efficiency factor has to be determined for each firing and receiving element. Extracting only the firing and the receiving signal from the reference signal is not easy. It demonstrated that instead of determining a matrix of system functions for each pair of firing and receiving elements, one single system efficiency factor is enough to characterize the array[6]. Hence the efficiency factor is given in Eq. (10)

$$\beta = \frac{v_{\exp}(\omega)}{v_m(\omega)}W(\omega) \tag{10}$$

Where $v_{\exp}(\omega)$ is the measured voltage, $v_m(\omega)$ is the velocity obtained from the beam model and $W(\omega)$ is the Weiner filter.

3. Prediction of the signal response from side drilled holes in unidirectional CFRP

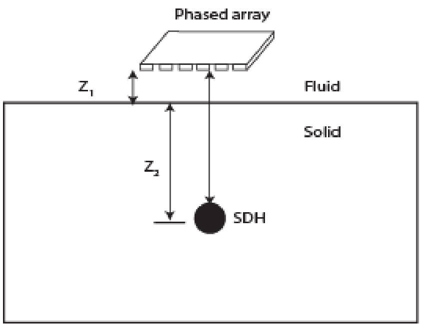


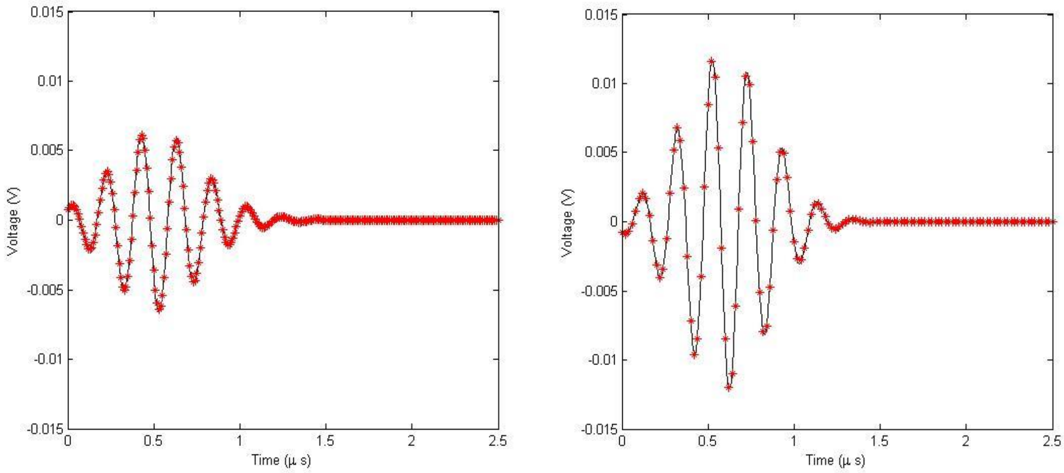
Figure 1. **Simulated setup containing one SDH**

For prediction of the response of side drilled holes in unidirectional CFRP, we need to find the slowness surface, the group velocity and phase velocity of the ultrasonic wave. The unidirectional CFRP composite considered is transversely isotropic with its properties given as C_{11}=C_{22}= 15, C_{12}=7.7, C_{23}=C_{13}=3.4, C_{33}=87, C_{44}=C_{55}=7.8, C_{66}=3.65 GPa and $\rho = 1595$ kg/m^3 [1]

For this study, the Centre frequency was taken at 5 MHz, and the bandwidth as 1.5 MHz The side drilled hole is at a depth of 40 mm from the surface and the length of water path is 20 mm The composite laminate has been considered homogeneous through the thickness and scattering from individual layers has been neglected.
The system efficiency factor has been modelled using a Gaussian pulse.
Figure 1 shows the simulated setup in which the signal response from one SDH is predicted. The setup is am immersion setup where z_1 is the distance in the fluid and z_2 is the distance from the top layer of the composite to the centre of the side drilled hole. The number of elements used in the phased array is 32 elements with widths of 0.8 mm and with an element spacing of 0.1mm.

The results presented are the voltage responses for side drilled holes of diameters 0.5, 2 mm using the kirchoff approximation and the method of separation of variables. Results are also presented when the wave is travelling along the fibre direction, at 45° and perpendicular to the fibre direction.

3.1 Model predicted signal when fibre orientation is 0°



(a) (b)

Figure 2. Model predicted signal for (a) 0.5 mm SDH (b) 2 mm SDH (Solid line: Kirchoff approximation, Starred: Separation of Variables)

In Figure 2 the model has predicted the signal from a SDH at a depth of 40 mm from the surface. The ultrasonic beam is propagating along the fibre direction and it can be seen that both the kirchoff approximation and the method of separation of variables predict the signal. Also while traveling along the fibre direction the magnitude of the velocity of the quasi longitudinal wave is more than twice the velocity of the quasi shear waves. A change in amplitude of the voltage is also observed between the 0.5 mm and 2 mm SDH.

3.2 Model predicted signal when fibre orientation is 45°

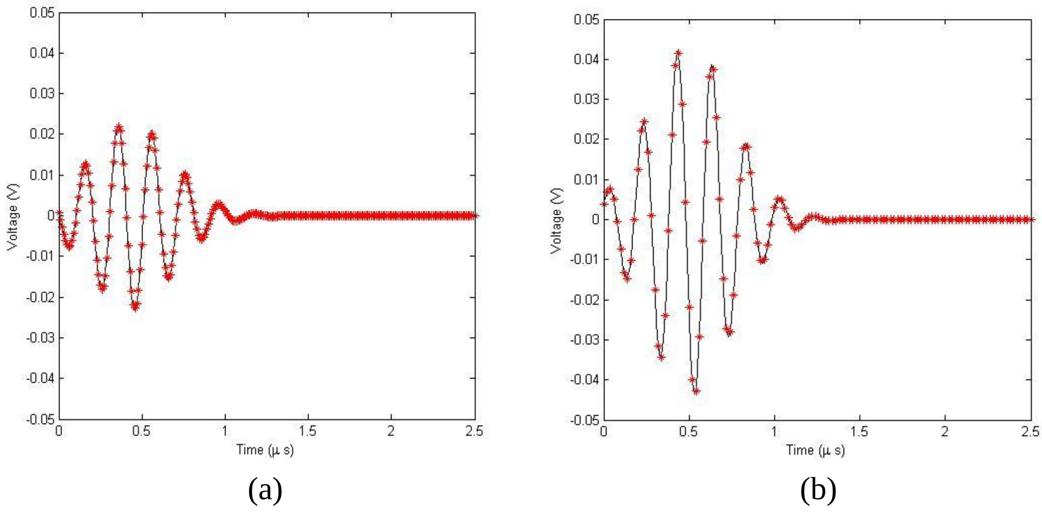


Figure 3.Model predicted signal for (a) 0.5 mm SDH (b) 2 mm SDH (Solid line: Kirchoff approximation, Starred: Separation of Variables)

When the SDH is embedded in the plane in which the fibres are aligned at 45 degrees, the predicted signal using the kirchoff approximation and method of separation of variables agree closely as seen in Figure 3. It is also observed that as the ultrasonic beam is propagating at an angle to the fibres there is an increase in the amplitude of the predicted signal from the SDH.

3.3 Model predicted signal when fibre orientation is 90°

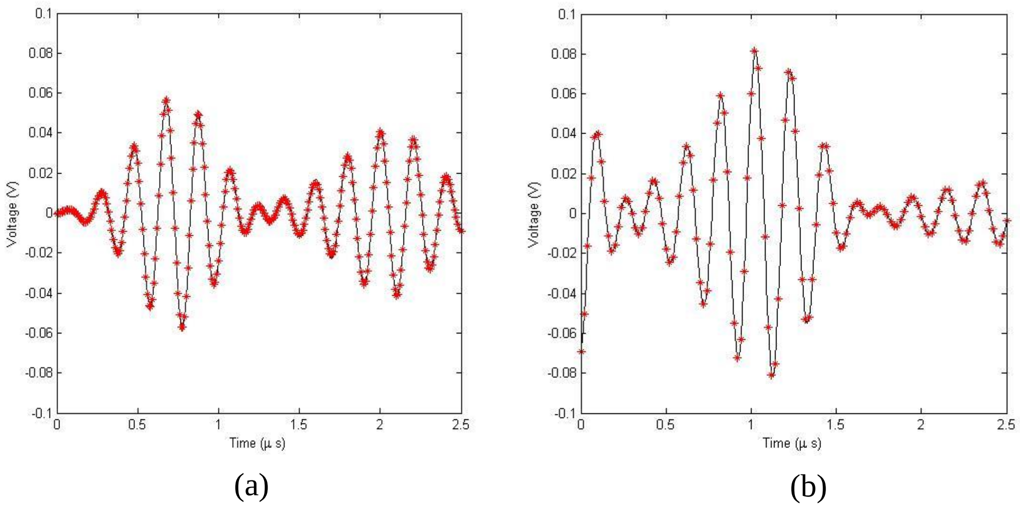


Figure 4.Model predicted signal for (a) 0.5 mm SDH (b) 2 mm SDH (Solid line: Kirchoff approximation, Starred: Separation of Variables)

When the SDH is embedded in the plane in which the fibres are aligned at 90°, there is an increase in the amplitude of the voltage received. Also echoes are predicted caused by the creeping waves as observed in Figure 4. The echoes are of relatively high amplitude as the difference between the velocity of the longitudinal and shear waves is lesser than in the case when the ultrasonic wave propagation is along the fibres.

3.4 Comparison of scattering amplitudes

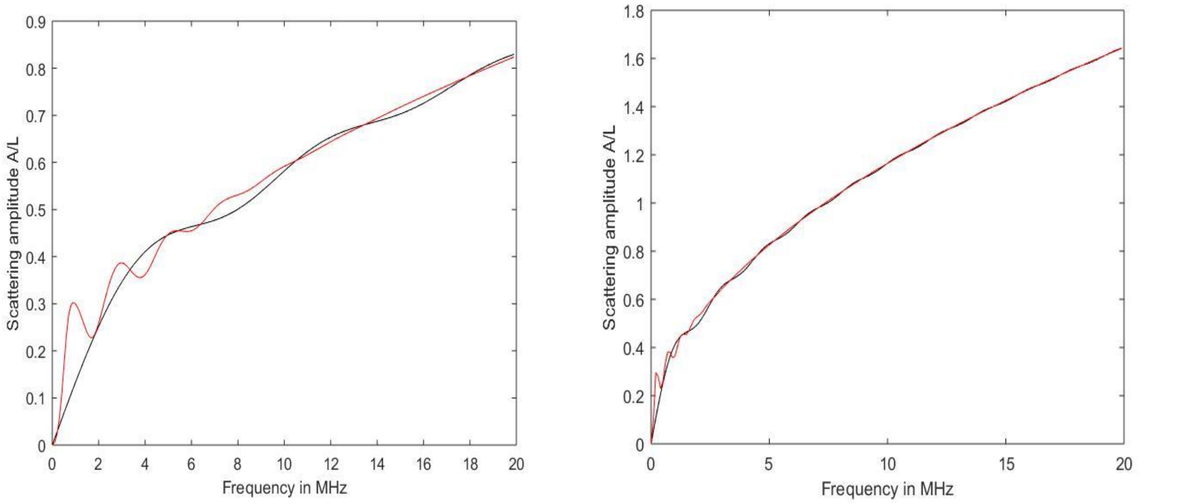


Figure 5. Scattering amplitude for (a) 0.5 mm SDH (b) 2 mm SDH (Black line: Kirchoff approximation, Red line: Separation of Variables)

The scattering amplitudes for the side drilled holes is shown in Figure 5. More oscillations are seen in the scattering amplitude calculated by using the method of separation of variables as the creeping wave effects are also taken into account at the lower frequencies.

4. Conclusion

In this paper, we have proposed a complete ultrasonic measurement model for a phased array testing system to simulate the phased array signals from side drilled hole in composite structure. Using the Multi Gaussian beam model, the radiated beam fields from a liner phased array into a composite structure have been calculated. We have predicted and compared the ultrasonic array signals scattered from a side drilled hole embedded in a composite structure by using the kirchoff approximation and separation of variables solution. It is observed that the predicted signal using both the methods is similar in amplitude and shape of the signal. As a next step these predicted signals will be verified using both experimental data and finite element analysis.

5. References

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