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REAL-TIME HEALTH MONITORING SYSTEM AVAILABLE FOR ANY ANISOTROPIC CONDITION OF CFRP

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ABSTRACT

In this work, we manufactured the piezoelectric ceramics transducers embedded CFRP and its more exact source location method on microcracking was investigated. Especially, we studied the way to determine the arrival time when high level noise is included and to use wavelet transformation when the amplitude of symmetric mode is so small that searching the arrival time is difficult. The transducers were able to detect the signals without any amplifier well. Control of oscilloscope by personal computer made real-time health monitoring possible. When a signal included a large noise in front of the real response, backward searching method (BSM) was useful to eliminate it. Wavelet transformation (WT) method was useful to determine the arrival time of the symmetric mode Lamb wave as well as that of anti-symmetric mode.

Keywords

Smart structure, Acoustic emission, Health monitoring, Piezoelectric ceramics, Source location, Lamb wave

INTRODUCTION

A large portion of the recent studies on smart materials and structures are concentrated on CFRP [1-5]. CFRP has so high specific strength and rigidity that it is used at important parts in aeronautic and astronautic field. Therefore, if it fails the loss is also so large. In order to prevent such failure, real-time health monitoring on microcracking like matrix cracking, debonding, delamination, transverse cracking and fiber breakage is required.

If the microcracking takes place, the released energy propagates as elastic wave. The elastic wave consists of symmetric mode Lamb wave and anti-symmetric mode Lamb wave. In the case of the study to identify the source of external shock similar to vertical shock, to deal with anti-symmetric mode is useful because out-of-plane component is dominant. Contrarily in the case of identifying a microcrack, symmetric mode is available as it has in-plane component.

So, in this work, we manufactured the piezoelectric ceramics transducers embedded CFRP and its more exact source location method on microcracking was investigated. Especially, we studied the way to determine the arrival time when high level noise is included and to use wavelet transformation when the amplitude of symmetric mode is so small that searching the arrival time is difficult.

WAVE VELOCITY IN CROSS PLY LAMINATES

In orthotropic plates, the Hook's law can be written by Equation (1) [6]. The Q_{ij} are the reduced stiffness components and x-axis is defined as in the fiber direction, y-axis transverse to the fiber, and s denotes shear component.

$$\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} Q_{xx} & Q_{xy} & 0 \\ Q_{xy} & Q_{yy} & 0 \\ 0 & 0 & Q_{ss} \end{bmatrix} \begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{bmatrix} \tag{1}$$

The reduced stiffness components can be expressed with some engineering constants as follows:

$$\begin{aligned} &Q_{xx}=E_x/(1-\nu_x\nu_y) \\ &Q_{yy}=E_y/(1-\nu_x\nu_y) \\ &Q_{xy}=\nu_xQ_{yy}=\nu_yQ_{xx} \\ &Q_{ss}=E_s \end{aligned} \tag{2}$$

where E_x is Young's modulus in the longitudinal direction, E_y means Young's modulus in the transverse direction, E_s indicates shear modulus, and ν_x and ν_y are major and minor Poisson's ratios individually.

On the other hand, the reduced stiffness components in the rotated coordinate-system can be transformed as follows:

$$\begin{aligned} &Q_{11}=m^4Q_{xx}+n^4Q_{yy}+2m^2n^2Q_{xy}+4m^2n^2Q_{ss} \\ &Q_{22}=n^4Q_{xx}+m^4Q_{yy}+2m^2n^2Q_{xy}+4m^2n^2Q_{ss} \\ &Q_{12}=m^2n^2Q_{xx}+m^2n^2Q_{yy}+(m^4+n^4)Q_{xy}-4m^2n^2Q_{ss} \\ &Q_{66}=m^2n^2Q_{xx}+m^2n^2Q_{yy}-2m^2n^2Q_{xy}+(m^2-n^2)^2Q_{ss} \\ &Q_{16}=-m^3nQ_{xx}+mn^3Q_{yy}+(m^3n-mn^3)Q_{xy}+2(m^3n-mn^3)Q_{ss} \\ &Q_{26}=-mn^3Q_{xx}+m^3nQ_{yy}+(mn^3-m^3n)Q_{xy}+2(mn^3-m^3n)Q_{ss} \end{aligned} \tag{3}$$

where, m =cos(θ) and n=sin(θ). θ is the rotated angle.

Generally in-plane stiffness for the entire plate that consists of k layers can be calculated by integration of the reduced stiffness components in the range of thickness and the phase velocity of symmetric Lamb mode in 1-axis can be determined with A_{11}, density(ρ), and thickness(h).

$$A_{ij} = \int_{-h/2}^{h/2} Q_{ij}^{(k)} dz \qquad v_1 = \sqrt{\frac{A_{11}}{\rho h}} \tag{4}$$

In the case of cross ply laminates, however, the calculation of velocity is simplified. We can calculate the Q_{xx} and Q_{yy} by measuring the velocity in 0 degree direction. If we assume that (Q_{xy}+2Q_{ss}) = c (constant), the value of c can be obtained by measuring a velocity (v_α) in another direction. Then, the velocity in a direction can be expressed by Equation (7).

$$Q_{11} = Q_{xx} = Q_{yy} = \rho v_0^2 \tag{5}$$

$$Q_{11} = (m^4 + n^4)Q_{xx} + 2m^2n^2c = \rho v_\alpha^2 \tag{6}$$

$$v_\theta = \sqrt{\frac{A_{11}}{\rho}} = \sqrt{\frac{hQ_{11}}{\rho h}} = \sqrt{\frac{(m^4+n^4)Q_{xx}+2m^2n^2c}{\rho}} \tag{7}$$

$$c = \frac{\rho v_\alpha^2 - (m^4+n^4)Q_{xx}}{2m^2n^2} \tag{8}$$

WAVE VELOCITY IN ARBITRARILY LAMINATED PLATES

In the case of arbitrarily laminated plates, for example [0/10/20/30/.../90], we should first calculate $Q_{ij}^{(1)}$, $Q_{ij}^{(2)}$, $Q_{ij}^{(3)}$, ..., $Q_{ij}^{(10)}$. Of course, for the calculation we needs E_x, E_y, E_s, ν, ρ and h in each layer. Then, all velocities can be calculated by Equation (4).

ARRIVAL TIME DETERMINATION

Backward Searching Method

Because the detected AE signals include some noise in front of main signal, the conventional threshold method sometimes makes mistake on determination of arrival time. Therefore we use Backward Searching Method (BSM) which is not influenced by the front noise. In BSM, as shown in Figure 1, when some points group that proceeds backward from maximum peak enters into a limited range, the last point of the group becomes the first arrived point.

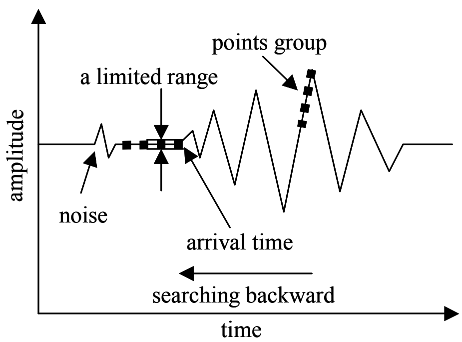

Figure 1: Backward Searching method

Wavelet Transformation Method

The definition of the continuous wavelet transformation (WT) of a function f(t) is as follows [7]:

$$(Wf)(b,a) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\overline{\Psi\left(\frac{t-b}{a}\right)}dt \tag{9}$$

where $a > 0$ and the overbar means the complex conjugate. From WT we can get the information of behavior of a particular frequency component in time domain. The calculation can be carried out at high speed by FFT. The mother wavelet used in this work is Gabor function (Equation (10)). Its Fourier transform is expressed as Equation (11). Here, ω_0 is the center frequency and γ is positive constant.

$$\Psi_g(t) = \frac{1}{\sqrt[4]{\pi}}\sqrt{\frac{\omega_0}{\gamma}}\exp\left(-\frac{(\omega_0/\gamma)^2}{2}t^2\right)\exp(i\omega_0 t) \tag{10}$$

$$\hat{\Psi}_g(\omega) = \frac{\sqrt{2\pi}}{\sqrt[4]{\pi}}\sqrt{\frac{\gamma}{\omega_0}}\exp\left(-\frac{(\gamma/\omega_0)^2}{2}(\omega-\omega_0)^2\right) \tag{11}$$

Generally WT method has been applied to anti-symmetric mode Lamb wave for calculation of velocity or determination of arrival time. It is not, however, impossible to apply to symmetric mode Lamb wave. Especially when the amplitude of symmetric mode is similar to that of noise, WT is very useful.

SOURCE LOCATION

Suppose that T_i and t_i are the true and measured arrival times of *i*-th transducer respectively. The true arrival time is expressed as follows:

$$T_i = \frac{\sqrt{(x-x_i)^2+(y-y_i)^2}-r_i}{v_i} \tag{12}$$

where (x, y) is a source position, (x_i, y_i) is a transducer position, r_i is a radius of transducer, and v_i is the velocity in the direction. If f_i is defined as Equation (13), we can find the (x,y) that satisfies Equation (14) by nonlinear least-square method.

$$f_i = (T_i - T_j) - (t_i - t_j) \tag{13}$$

$$\sum f_i^2 < \varepsilon \tag{14}$$

Here ε is convergence limit.

EXPERIMENTAL SETUP

When we manufactured $[0/90]_{2s}$ CFRP, a polyimide sheet with four embedded piezoelectric ceramics (Figure 2) was inserted between two center layers. The dimension of the composite is 145x200x1.8mm. The thickness and diameter of the piezoelectric ceramics is 200μm and 5mm. For source location test of out-of-plane AE source, pencil lead break test was carried out at the point of x=40, y=90mm. The pencil lead is 0.5mm 2H type. Two velocities (in 0 degree and 45 degree) were measured with pencil lead break for calculation of a velocity in an arbitrary direction. Any amplifier was not used. The block diagram is shown in Figure 3.

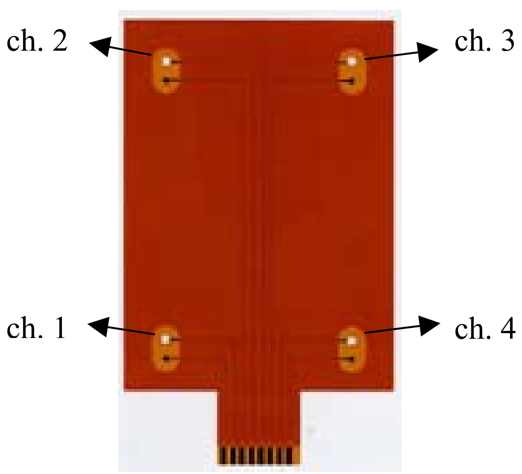

Figure 2: Photograph of the polyimide sheet with piezoelectric ceramics and circuit

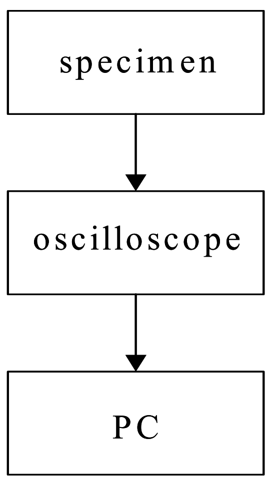

Figure 3: Block diagram of experimental setup

RESULTS AND DISCUSSION

The measured velocities of 0 and 45 degree are 6700 and 5150 m/s, respectively. There are four signals detected at each channel in Figure 4(a). The signals were modified with 0-point correction and noise filtering Figure 4(b). In order to avoid the influence of the residual large noise, arrival times were searched with BSM Figure 4(c). In this case, the source location error is very small, 0.8 mm.

On the other hand, we also tried to test the WT method on the same signals. As shown in Figure 5(a), the center frequency of the symmetric mode of the detected signal (eg., 1 ch.) is 474 kHz. Figure 5(b) shows the WT coefficients of 474 kHz component in time domain. We let the first peak arrival time. The source location error is also very small, 1.1 mm.

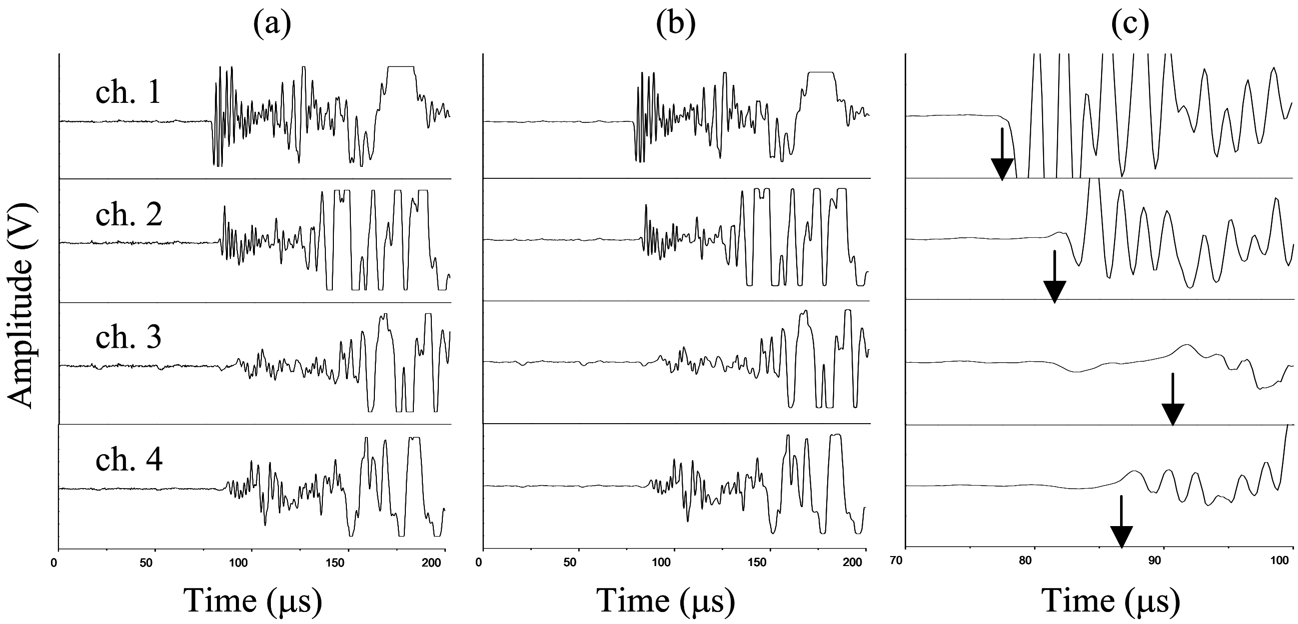

Figure 4: (a) detected signal, (b) filtered signals and (c) arrival times by BSM

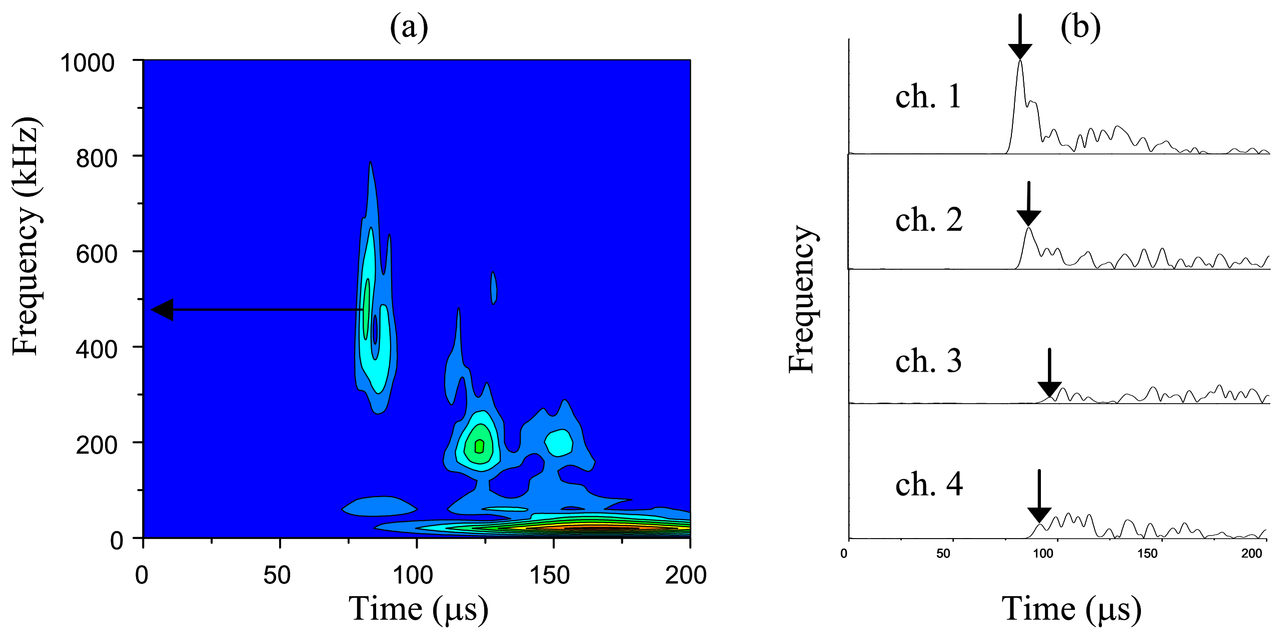

Figure 5: (a) WT of channel 1 and (b) WT at 474 kHz

CONCLUSION

Some piezoelectric ceramics were embedded into CFRP thin plate for sensing the simulated AE signal in this work. The transducers were able to detect the signals without any amplifier well. Control of oscilloscope by personal computer made real-time health monitoring possible. When a signal included a large noise in front of the real response, backward searching method was useful to eliminate it. Wavelet transformation method was useful to determine the arrival time of the symmetric mode Lamb wave as well as that of anti-symmetric mode. We think that the experimental results obtained in this work is in the case of cross ply thin plate but the analysis method can be adopted to any arbitrarily plied laminates.

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