Influence of Crack Parameters on Wavelet Energy Correlated Damage Index

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ABSTRACT

This paper illustrates a Wavelet Coefficient based approach using experiments to understand the sensitivity of ultrasonic signals due to parametric variation of a crack configuration in a metal plate. A PZT patch sensor/actuator system integrated to a metal plate with through-thickness crack is used. The proposed approach uses piezoelectric patches, which can be used to both actuate and sense the ultrasonic signals. While this approach leads to more flexibility and reduced cost for larger scalability of the sensor/actuator network, the complexity of the signals increases as compared to what is encountered in conventional ultrasonic NDE problems using selective wave modes. A Damage Index (DI) has been introduced, which is function of wavelet coefficient. Experiments have been carried out for various crack sizes, crack orientations and band-limited tone-burst signal through FIR filter. For a 1cm long crack interrogated with 20 kHz tone-burst signal, the Damage Index (DI) for the horizontal crack orientation increases by about 70% with respect to that for 135^o oriented crack and it increases by about 33% with respect to the vertically oriented crack. The detailed results reported in this paper is a step forward to developing computational schemes for parametric identification of damage using sensor/actuator network and ultrasonic wave.

1. INTRODUCTION

Extraction of damage-sensitive features from measured signals and statistical analysis of these features through parametric representation in an *integrated* manner are of great challenges while developing Structural Health Monitoring (SHM) systems. There are several advantages to using a SHM system over traditional nondestructive testing, such as reduced down time, elimination of component tear down inspections and the potential prevention of failure during operation [1-5].

Guided ultrasonic wave have been employed over the last several decades for identifying crack location, mainly using the information regarding wave arrival time. Recently, Rajagopalan, *et al.* [6] have studied the concept of PZT sensor/actuator network for guided ultrasonic wave based structural health monitoring of large isotropic plate structures identification of crack location and sensitivity of the edge reflection.

Here, one PZT patch is used as an actuator, which launches Lamb wave plus other types of mixed ultrasonic waves in the plate. The scattered waves in a plate without crack and with crack are measured by an array of PZT sensor patches, which are identical to the actuator patches. The advantage of using identical actuator and sensor patches is that a dynamic correlation over the network is possible through a sequence of phase-conjugated actuation and synchronous sensor measurements without much of a calibration for the dynamic stress localization due to the bonded patch interfaces. Also the computational method, by which one can estimate the damage parameters, should have the capability to extract the parametric information regarding damage from the complex signals.

Deng and Wang [7] applied the discrete wavelet transform to locate a crack along the length of a beam. Quek *et al.* [8] used wavelet analysis for crack identification in beams under both simply supported and fixed–fixed boundary conditions. However, in the related context, no attempt has been made till date to study the signal sensitivity against the variation of crack parameters. Douka *et al.* [9] estimated the depth of the crack and defined an intensity factor to relate the coefficients of the wavelet transform to the depth of the crack. Study of signal sensitivity in terms of time-frequency localization against various crack parameters (crack size and orientation), dealing with noise, filtering the boundary effects are important aspects that need to be addressed.

In the present paper, an experimental study using ultrasonic lamb wave methods for detection of crack and estimation of parametric sensitivity in the diagnostic signal for metallic plate is presented. PZT patches are employed for both the actuation as well as the sensing.

2. EXPERIMENTAL SETUP

The cracked plate specimens are 60cm x 30cm rectangular aluminum plates of 3 mm thickness with three types of crack, namely (1) vertically aligned crack (aligned along the sensor-actuator path as shown in Fig. 1(a) and (b)) (2) 135^o oriented crack (oriented with respect to the incident wave propagation direction) and (3) horizontal crack (oriented perpendicular to the sensor-actuator path). At present, these cracks are made by machined slots. Cracks of various lengths (1cm to 5cm) are considered. Lead-Zirconate-Titanate (PZT) patches of 2cm x 2cm planer area and 2 mm thickness are used as sensors and actuators. PZT patches are bonded to each specimen using phenyl salicylate salt, so that they are firmly attached during experiments, but could be removed afterwards to recover the specimens for future tests. Fig. 1 (a) shows the experimental set up used. Here a_1 indicates the actuator patch, where as s_1 and s_2 indicate the sensors. Both the actuation and the data acquisition were performed using a portable NI PCIe 6529 multifuntional DAQ system and a computer running Labview program as a virtual controller. A Labview code was created for this purpose, which launches a programmed waveform from MATLAB (e.g., a tone-burst signal with known frequency content and amplitude). To remove the unnecessary noises in the signal, a band-pass filter was used. Wavelet based time-frequency localization map is employed as the basic tool to study the parametric sensitivity of the ultrasonic signal in the presence of a crack.

Fig. 1: Experimental Setup

3. WAVELET BASED ESTIMATE

In continuous wavelet transforms, a given signal of finite energy is projected on a continuous family of frequency bands (or similar subspaces of the function space $L^2(R)$) for instance on every frequency band [*f*, 2*f*] for all positive frequencies $f > 0$. Then, the original signal can be reconstructed by a suitable integration over all the resulting frequency components.

The frequency bands or subspaces are the scaled versions of a subspace at scale *1*. This subspace in turn is in most situations generated by the shifts of a generating function $\psi \in L_2$ called the *mother wavelet*. For example, the mother wavelet for a scale one frequency band [1,2] is,

$$\psi(t) = 2\sin c(2t) - \sin c(t) = \frac{\sin(2\pi t) - \sin(\pi t)}{\pi t} \qquad \ldots (1)$$

which is the superposition of two normalized sinc function. The subspace of scale *a* or frequency band [1/a, 2/a] is generated by the functions (sometimes called *child wavelets*),

$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right) \qquad \ldots (2)$$

where *a* is a positive real number and defines the scale and *b* is any real number and it defines the shift. This shifting process at each scale is the key to localize non-stationary process or parametric influences on a time-frequency map. The projection of a function *x* onto the subspace of scale *a* has the form,

$$x_a(t) = \int_R WT_\psi \{x\}(a,b) \cdot \psi_{a,b}(t)db \qquad \ldots (3)$$

with wavelet coefficients,

$$WT_\psi \{x\}(a,b) = \langle x, \psi_{a,b} \rangle = \int_R x(t)\overline{\psi_{a,b}(t)}dt \qquad \ldots (4)$$

With the definition of wavelet transform above for a signal *x*(*t*) with scale *a* (localized over the frequency axis for our problem) and shifts *b* (localized over the time axis), next we consider the usual application of the estimated Lamb wave dispersion curves and subsequent calculation of arrival time as follows. The following equations are used to predict the lamb wave phase velocity (c_p) in the plate structure: For symmetric Lamb wave modes, one has,

$$\frac{\tan(qd/2)}{\tan(pd/2)} = \frac{-4k^2 \cdot pd}{(q^2 - k^2)} \qquad \ldots (5)$$

For antisymmetric Lamb wave modes, one has

$$\frac{\tan(qd/2)}{\tan(pd/2)} = \frac{(q^2 - k^2)}{-4k^2 \cdot pd} \quad \text{… (6)}$$

Here d is the plate thickness, k is the wavenumber and it is given by

$$k = \frac{2\pi f}{C_p} \quad \text{… (7)}$$

where f is the frequency in Hz. The quantities p and q in Eqs. (5) and (6) are calculated as

$$p = k^2 - \left(\frac{2\pi f}{C_L}\right)^2, \; q = k^2 - \left(\frac{2\pi f}{C_T}\right)^2 \quad \text{… (8)}$$

where C_L is the longitudinal ultrasonic bulk wave velocity, C_T is the shear wave velocity. The group velocity C_G is computed as

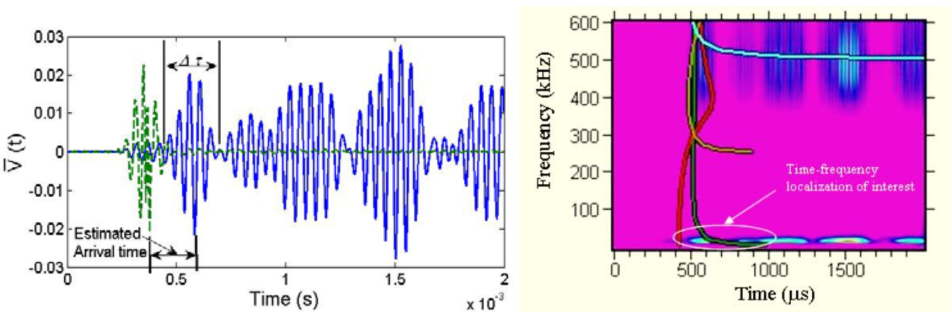
$$C_G = C_p\left(1 - \frac{1}{1 - \frac{C_p}{\alpha}}\right), \; \alpha = fd\frac{dC_p}{d(fd)} \quad \text{… (9)}$$

While applying the group velocity information along with known frequency content in the measured signal for estimating the scattered wave arrival time, it is essential to eliminate the all other information that is present in the signal, which are due to the baseline structure (boundary, joint details etc.). That is, first we perform identical measurement on an uncracked plate and measure a signal voltage $V(t)_{\mathrm{uncracked}}$ (transmitted signal from s_1 or reflected signal from s_2 as indicated in Fig. 1). After the signal $V(t)_{\mathrm{cracked}}$ from the cracked plate is measured, we obtain the non-dimensional and background noise-free signal $\bar{V}(t)$ as,

$$\bar{V}(t) = \frac{\mathrm{FIR}[V(t)_{\mathrm{crack}}]}{V_0} - \frac{\mathrm{FIR}[V(t)_{\mathrm{uncrack}}]}{V_0} \quad \text{… (10)}$$

where, FIR[.] indicates a band-pass FIR filter, V_0 is the maximum amplitude of the filtered signal from actuator a_1.

Figure 2 (a) shows the superposed signals from the actuator patch a_1 and the sensor patch s_1 (see Fig. 1 showing the sensor/actuator locations). Figure 2 (b) shows superposed wave dispersion curves on the time-frequency plot for horizontal crack of 1cm length for input signal frequency of 20 kHz.



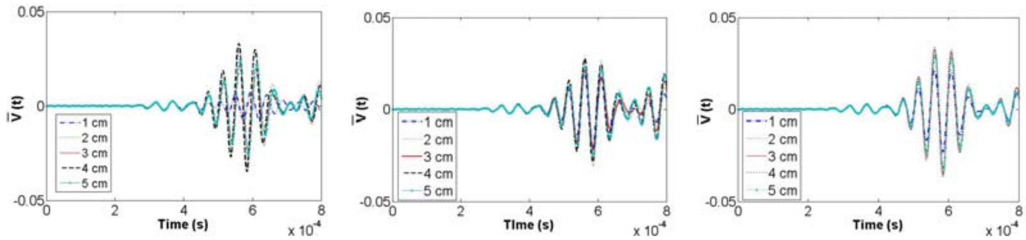
(a) (b)

Fig. 2: (a) Non-Dimensionlised Signals from the Actuator a1 (shown by thin solid line) and Sensor s1 (shown by thick solid line) for a Horizontal Crack of 1 cm. Signal Frequency 20 kHz. (b) Superposed Dispersion Curve on Time-Frequency Plot for Horizontal Crack of 1cm Length. Input Tone-Burst Signal Frequency 20 kHz

In the present study, we have mainly used the antisymmetric mode A_0 for time-frequency localization at the 20 kHz for the results shown in context of Fig. 3. However, it is not straightforward to isolate the individual Lamb wave modes when one uses bonded piezoelectric patches in a sensor/actuator network, since both the dynamic shear strains and the dynamic in-plane strains are introduced by the shear stress transfer from the PZT patch area to the plate surface. Again, the localized natures of these induced waves, which are functions of the square shape of the PZT patch, are important factors that bring more complexity into the diagnostic signal.

4. CRACK PARAMETER SENSITIVITY DUE TO WAVELET BASED ESTIMATE

From Fig. 3, one can see that as the size of the crack is varied for a particular crack orientation, the amplitude changes for different crack size are significant, but phase remains almost unchanged. Also, as the frequency of the input signal is changed for a particular crack orientation, the changes in the scattered signal amplitude changes for different crack size are significant but phase remains unchanged. And as the crack orientation is changed for particular crack size, there is a change in the signal amplitude. Here also, the phase change is insignificant, except for 135^o oriented crack of size 1cm. Such variations in the signal due to varying crack geometry are also reflected in the energy localization on time-frequency plots shown in Fig. 4.



(a) (b) (c)

Fig. 3: Sensor Signal from s_1 for Various Crack Lengths for (a) 135^o Crack Orientation, (b) Horizontal Crack and (c) Vertical Crack for Input Signal Frequency of 20 kHz

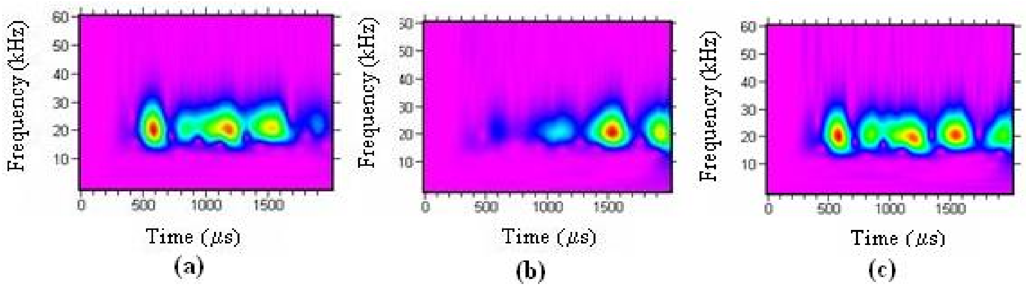
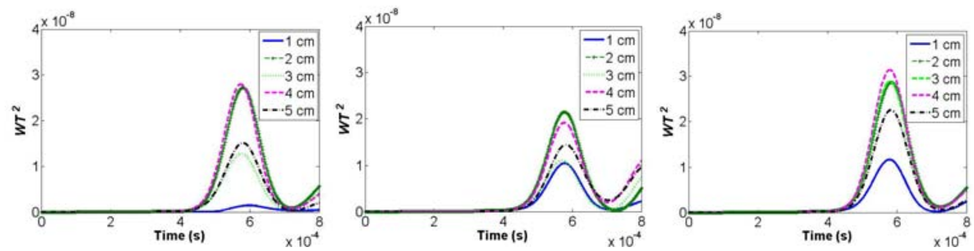


Fig. 4: Time-Frequency Localization in the Transmitted Signal (s_1), (a) 135^o Inclined Crack (b) Horizontal Crack and (c) Verticle Crack for all the Signals, the Excitation Signal Frequency is a 30 kHz Tone-Burst Signal

From Fig. 5, one can see a significant variation in the square of wavelet coefficient $\psi(\omega,t)$ for different crack lengths and different input signal frequencies for different crack orientations. The variation of square of wavelet coefficient $\psi(\omega,t)$ for 30 kHz input signal frequency for horizontal crack compared to 135^o crack orientation and vertical crack is significant. The effect on the wavelet coefficient $\psi(\omega,t)$ is thus useful to develop the parametric sensitivity analysis scheme.

Here we introduce an energy estimate J (Damage Index) on the non-dimensionlised signal $\bar{V}(t) \leftrightarrow \psi(\omega_n,t)$ as,

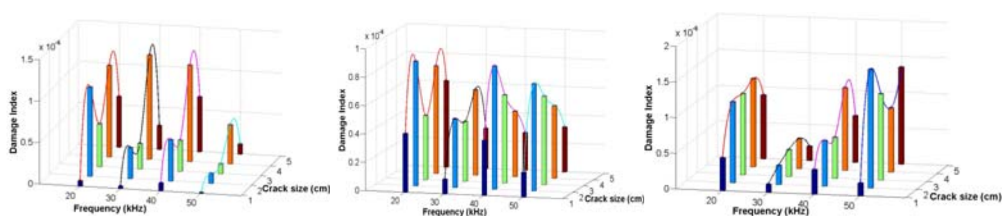
$$J = \frac{1}{\Delta\tau}\sum_{n=n_1}^{n_2}\int_0^{\Delta\tau} |\psi(\omega_n, t)|^2 \, dt \quad , \qquad \dots (11)$$



(a) (b) (c)

Fig. 5: Sensor Signal from s_1 for Various Crack Lengths for 20 kHz (a)135^o Crack Orientation, (b) Horizontal Crack (c) Vertical Crack

Figure 6 shows the variation of Damage Index *J* for the different input signal frequencies and different crack lengths for various crack orientations. At 20 kHz input signal frequency for different crack lengths, maximum variation in the damage index value is 95%, which is for 135^o crack orientation, 55% for horizontal crack and 66% for vertical crack. Thus the effect on the Damage Index *J*, based on energy is useful to develop the parametric sensitivity analysis scheme.



(a) (b) (c)

Fig. 6: Variation on Damage Index, *J* for Different Crack Size and for Different Input Signal Frequencies for Various Crack Orientation (a) 135^o Crack Orientation (b) Horizontal Crack (c) Vertical Crack

In context of Eq. (11), $[\omega_{n_1}, \omega_{n_2}]$ describes the frequency band used for the FIR filter. Hence *J* is essentially the sum of the area under the time-frequency localized spots as shown in Fig. 6. From Fig. 6, one can see that as the crack length increases, for vertical crack the transmitted energy decrease by very small amount, where as for 135^o inclined crack, the transmitted energy increases for 2 cm and 3 cm crack lengths and again decreases for 5 cm crack length. For horizontal crack, the transmitted energy first decreases for 2-3 cm crack and then again increases for 5cm crack. This contradicts the usual intuitive reasoning that a horizontal crack would generally block maximum amount of energy on the wave propagation path. This trend could be true only for few particular crack lengths. For the 1 cm crack length and the 5 cm crack length, a less energy is transmitted for the 135^o inclined crack as compare to vertical and the horizontal cracks.

6. CONCLUDING REMARKS

We report a new approach based on wavelet based estimate for energy spread in the time-frequency plane and a residual force vector correlation to analyze the sensitivity of the scattered ultrasonic signal due to the crack parameters (such as crack length and crack orientations). An integrated sensor/actuator network approach is adopted wherein a complex signal can be dealt with and additional measurements based on laser vibrometer etc. can also be employed for more accurate identification tasks. Experiments using a plate with various crack configurations show that it there exist significant sensitivity of the proposed damage indices due to crack parameter variation and hence is possible to extract various relevant information through model based computation. Such analysis of the parametric sensitivity would help in designing better identification and classification algorithms based on statistical approach and time reversal in a sensor network.

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