WAVELET-BASED ACTIVE SENSING FOR QUANTITATIVE ASSESSMENT OF THROUGH-THICKNESS CRACK SIZE AND ANGLE IN COMPOSITE PLATES

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Abstract

Cost-effective and reliable damage detection is critical for utilization of composite materials. This paper utilizes PZT piezoelectric disks to excite the first symmetric Lamb wave (S_0 mode). The interaction of Lamb wave mode with a through-thickness crack of different lengths and angles in $[0/45/-45/90]_s$ CF/EP laminate plates is analyzed in terms of finite element method. This study contributes to the damage detection by developing an improved wavelet-based signal processing technique that enhances the visibility and interpretation of the Lamb wave signals related to defects. Based on the amount of energy dissipated by the damage, a damage index is defined as the function of an electric signal's attenuation for a limited time span and at the input frequency of the signal.

Introduction

The demand for use of composite materials has seen considerable growth in many industry sectors from the latter part of the twentieth century, due to their performance factors, such as higher strength and stiffness to weight ratio, resistance to chemical attack and tailorability. Disadvantages, however, is that composite materials present challenge for design, manufacturing, maintenance and repair over metallic parts since they tend to fail by distributed and interacting damage mode [1,2]. Furthermore, damage detection in composites is more difficult than in metallic structure due to anisotropy of material, the conductivity of fibers, the insulative properties of the matrix and the fact that much of damage often occurs beneath the top surface of laminate and is therefore not readily detectable (the threshold of detectability is often termed barely visible impact damage, or BVID). Currently successful composite non-destructive testing (NDT) techniques for small laboratory specimens, such as X-radiography detection (penetrant enhanced X-ray) and hydro-ultrasonic (C-scan), are impractical for in service inspection of large components and integrated vehicles. Some other methods, such as eddy-current and single-sided ultrasound are expensive, time consuming and can be unreliable when applies to composites by comparison to techniques used for metals. It is clear that new reliable approaches for damage detection in composites need to be developed to ensure that the total cost of ownership of critical structure does not become a limiting factor for their use.

Structural Health Monitoring (SHM) involves real-time monitoring of structures by means of sensors embedded or mounted externally to the structure. In the case of an aircraft, the sensors must be right at the place where an area is to be monitored to ensure the structural integrity. SHM may alleviate the cost of maintenance and repairs by replacing scheduled maintenance with as-needed maintenance, thus saving the cost of unnecessary maintenance, on one hand, and preventing unscheduled maintenance, on the other hand. In case of damage, its signature, will dictate the type of sensors that are required, which in-turn determines the requirements for the rest of the components in the SHM system. Several techniques have been researched for detecting damage in composite materials, however lamb wave methods have recently re-emerged as a reliable way to locate damage in these materials. Lamb waves, a.k.a., guided plate waves, are a type of ultrasonic waves that are guided between two parallel free surfaces, such as the upper and lower surfaces of a plate. Internal damages can be detected based on the Lamb wave propagation in a plate and the examination of the response signals. Because the Lamb waves travel long distances and can be applied with conformable piezoelectric (PZT) actuators/sensors that require little power, they may prove suitable for online structural health monitoring.

2 Lamb wave based damage detection

As a lamb wave propagates through a plate structure, energy is transferred back and forth between kinetic and elastic potential energy. When this transfer is not perfect because of heating wave leaking and reflection, attenuation occurs. In particular, the attenuation is increased by presentence of the through-thickness crack and the energy of input force spills over the driving frequency to neighboring frequency values. Based on this phenomenon, a damage index can be defined as a function which measures the degree of the test electric signal's energy dissipation compared to the baseline electric signal for cracks of different lengths in form of Eq.-1. Note that the value of DI increases as a result of damage from zero and remains range-bounded between 0 and 1.

$$DI = 1 - \frac{\int_{t_0}^{t_1} (E_f)_d dt}{\int_{t_0}^{t_1} (E_f)_p dt} \qquad (1)$$

where E_f is the energy of filtered signal component corresponding to the input frequency, t_0 and t_1 represent the starting and ending time corresponding to the first packet of baseline signal. Also subscrpits d and p denote damaged and pristine structure respectively.

However, in practice with limited transducers, the crack is not generally perpendicular to the propagation path of Lamb wave and therefore the collected signal may contain different information in different angles measured to the propagation path for the same crack. In this study, effect of the length parameter of a through-thickness crack on received signal by a PZT sensor, the interaction between oblique-incident Lamb waves and the crack is investigated using ANSYS finite element model.

3 Signal processing and damage diagnosis

Processing a signal consists of transforming a signal in a certain manner in order to get specified information. Before signals can be processed with a computer, analog signals must be converted to digital signals which operate in discrete-time domain. An analog-to-digital (A/D) convertor is used to convert a signal from analog to digital. According to Nyquist sampling theorem the sampling frequency should be at least twice the highest frequency contents of analog signal to avoid aliasing [4]. In particular, The Fourier transform, the Short-Time-Fourier transform, the Wigner-Ville distribution and the wavelet transforms has been widely use in structural health monitoring.

The Fourier transform is a frequency-based transform which breaks down a signal into constituent sinusoid of different frequencies. Therefore, it provides a general method for examining the global energy-frequency distribution of the analyzed signal and can be used for damage detection. Melhem, et. al. [5] showed that the Fourier transform can detect the progression of an impact damage in a beam. Unfortunately, in transforming to the frequency domain, the time information is lost and it is impossible to determine when a particular event took place.

In order to overcome the problem with localizing the frequency components on time, the Short Time Fourier Transform (STFT) was designed to analyze the signal in a time-frequency domain. The STFT transform, with a Gabor window in which a fixed length window is swept over the data, analyzes temporal variations of the frequency spectrum. The drawback of STFT is its poor frequency resolution. According to the uncertainty principle, the product of the standard deviations in time and frequency (i.e., time and frequency resolutions) has a limited value. Therefore, a high resolution in time and frequency cannot be obtained simultaneously since once the window size is chosen, it is the same for all frequency.

The wavelet transform uses multi-resolution technique by which different frequencies are analyzed with different resolutions. Since high frequency signals require short time-domain windows and low frequency signals require long ones, good resolution low frequency analysis can be achieved using long ones in wavelet transform. The opposite is true for high frequency analysis.

Wavelet transform has been used in this study to gain insight as how the intensities of the signal input energy have been shed into sideband frequencies as a result of a through-thickness crack in a composite plate.

3.1 The wavelet transforms

The wavelet transform was developed by Grossman and Morlet in the early 1980s to provide a time-frequency representation of the signal. Wavelets are localized waves that extend for a finite time duration compared to the sine waves in Fourier transform which extend from minus to plus infinity. Wavelet analysis starts by selecting a basic wavelet function, called 'mother wavelet'. Many functions can be used as mother wavelet, if they have some properties which are given by Rao and Boparadikar [6]. Actually, if a function f(t) is continuous, has null moments, decreases quickly toward 0 when t moves to +/− infinity, or is null outside a segment of τ, then it can be a candidate for being a mother wavelet[7].

The mother wavelet *Ψ(t)*, is then dilated (stretched or compressed) by *a* and translated in time by *b* to generate a set of daughter wavelets $\Psi_{(a,b)}(t)$ as follows:

$$\Psi_{a,b}(t) = \frac{1}{\sqrt{a}}\Psi\left(\frac{t-b}{a}\right) \tag{2}$$

The translation parameter, *b*, indicates the location of the moving wavelet window in the wavelet transform. Shifting the wavelet window along the time axis implies examining the signal in the neighborhood of the current window location. Therefore, information in the time domain will still remain, in contrast to the Fourier transform, where the time domain information becomes almost invisible after the integration over the entire time domain. The dilation parameter, *a*, indicates the width of the wavelet window. If $|a| < 1$, the wavelet is the compressed version (smaller support in time-domain) of the mother wavelet and correspond mainly to higher frequencies. On the other hand, when $|a| > 1$, $\Psi_{(a,b)}(t)$ has a larger time-width than *Ψ(t)* and corresponds to lower frequencies[8].

The continuous wavelet transform (CWT) uses inner products to measure the similarity between a signal and the scaled and shifted wavelets by using the *c(a,b)* coefficients as follows:

$$c(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} f(t)\Psi_{a,b}^{*}(t)dt \tag{3}$$

Where * denotes the complex conjugate. The factor $1/\sqrt{a}$ is introduced for energy normalization at different scales.

The signal *f(t)* may be recovered or reconstructed by an inverse wavelet transform as defined by

$$f(t) = \frac{1}{c}\int_{a=-\infty}^{+\infty}\int_{b=-\infty}^{+\infty}\frac{1}{|a|^2}c(a,b)\Psi_{a,b}(t)da\,db \tag{4}$$

An important drawback which affects the continuous wavelet transform is its high level of redundancy which results from the fact that both the dilation parameter *a* and the translation parameter *b* are continuous quantities. In practical signal processing a discrete version of wavelet transform is often employed by discretizing the dilation parameter *a* and the translation parameter *b*. In general, the procedure becomes much more efficient if dyadic values of *a* and *b* are used, i.e.,

$$a = 2^j; \quad b = k2^j \quad j,k \in Z \tag{5}$$

Table 1: Material properties of CF/EP (T650/F584) UD laminates (ϴ=0°)

E_{11}(GPa)	E_{22}(GPa)	E_{33}(GPa)	G_{12}(GPa)	G_{13}(GPa)	G_{23}(GPa)	ν_{12}	ν_{13}	ν_{23}	ρ(kg/m^3)
153.7	9.49	9.49	4.26	4.26	3.44	0.295	0.295	0.381	1528

Table 2: Material properties of PZT disks

S_{11} (m^2/N)	S_{22} (m^2/N)	S_{33} (m^2/N)	S_{12} (m^2/N)	S_{13} (m^2/N)	S_{23} (m^2/N)	S_{44} (m^2/N)	S_{55} (m^2/N)	S_{66} (m^2/N)	ρ (kg/m^3)
16.4e-12	16.4e-12	18.8e-12	-5.74e-12	-7.22e-12	-7.22e-12	44.3e-12	47.5e-12	47.5e-12	7750

Table 3: Electromechanical characteristics of PZT disks (IEEE index convention)

d_{31} (C/N)	d_{32} (C/N)	d_{33} (C/N)	d_{24} (C/N)	d_{15} (C/N)	k_1 (F/m)	K_2 (F/m)	K_3 (F/m)
-171e-12	-171e-12	374e-12	584e-12	584e-12	1730	1730	1700

where Z = set of positive integers [9].

3 FEM simulation

In this paper, the application of finite element method (FEM) to simulate Lamb wave propagation and interaction with a through-thickness crack in a quasi-isotropic graphite/epoxy laminated composite plate is investigated. The lay-up of this quasi-isotropic plate contains 8 plies stacked according to the sequence $[0/45/-45/90]_s$. Each layer is made of CF/EP (T650/F 584) unidirectional prepreg. The material properties of CF/EP (T650/F584) unidirectional prepreg are given in Table 1 [10].

In order to generate S_0 mode only, dual PZT actuators on the upper and lower surfaces of the plate are excited by tone burst signals with the same phase. The physical properties of the PZT disks are listed in Table 2 and Table 3[10].

Two PZT disks, as the actuators, are located at the center of the host plate, surface-bonded on the top and bottom surfaces, while the other PZT disk acted as the sensor for collection of Lamb wave is located at the actuator's top right quarter schematically shown in Fig. 1. The dimensions of the composite plate are 300 mm × 300 mm × 1.28 mm and the PZT disks have a diameter of 6.9 mm and a thickness of 0.5 mm.

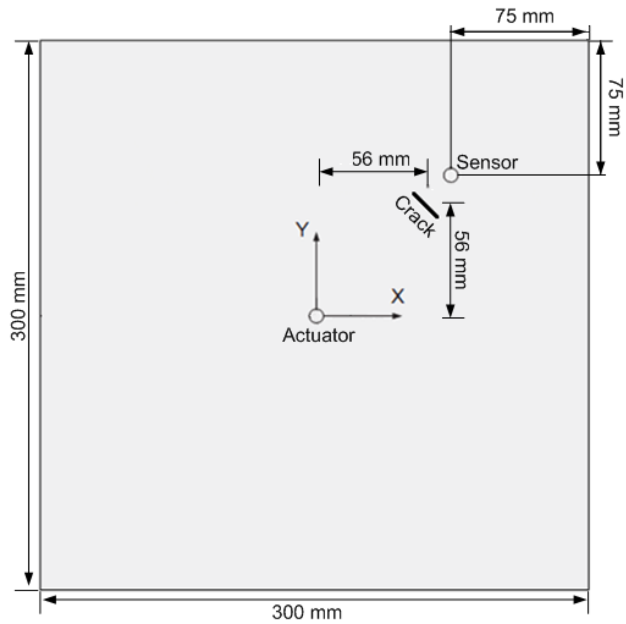

Fig 1: Square quasi-isotropic plate with PZT discs

The host quasi-isotropic composite laminate and PZT disks were discretized using the rectangular 4 nodes FEM shell elements and 3-D brick coupled filed elements, respectively. The composite laminate is divided into eight layers through its thickness using the general shell section to define the composite laminate structure. The modeling of the crack was achieved by unmerging the appropriate nodes and definition of a non-penetrating contact between two sides of crack.

The excitation signal considered in this study consists of a smoothed tone burst to reduce the excitation of frequency side lobes associated with the sharp transition at the start and the end of a conventional tone burst. The smoothed tone burst is obtained from a pure tone burst of frequency 500kHz filtered through a Hanning window, as shown in Fig. 2. The input signal is applied to actuators with 45 V amplitude.

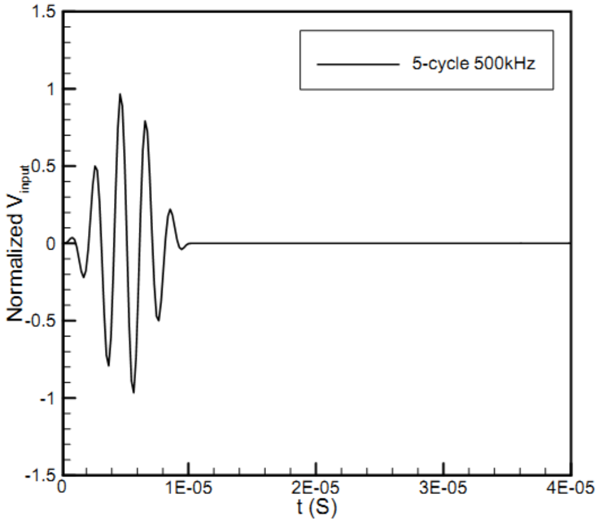

Fig 2: Input excitation signal at time-domain

4 Wavelet methodology for damage detection

In this study, the real Morlet wavelet is used as mother wavelet. This wavelet, $\psi(t)$,is defined as follows:

$$\Psi(t) = e^{-t^2/2} \cos 5t \tag{6}$$

Once the wavelet coefficients are computed, they can be plotted on a colored 2D plot which the color at each x-y point represents the magnitude of coefficients, the x-axis represents the position along the signal (i.e. time) and the y-axis represents scale, as shown in Fig. 3.

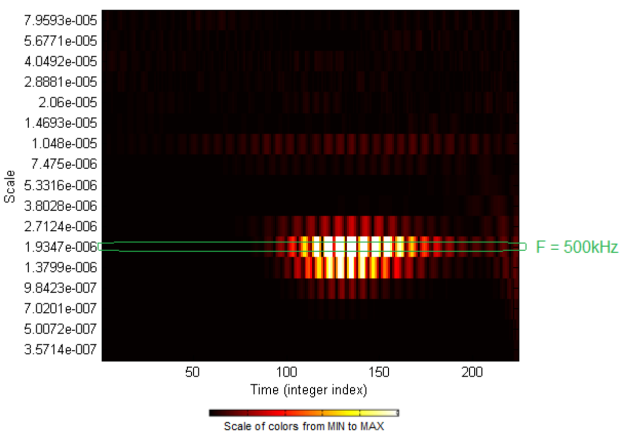

Fig 3: Time-scale representation of the Picked-up Signal with the wavelet transform

From this time-frequency representation, it can be concluded that the signal component corresponding to the input frequency (i.e. 500kHz) is dominant through the first recived signal packet, as expected. This component can be filtered via recostruction of signal with using coefficients correspond to this scale. Fig. 4 shows picked up signal from pristin specimen and its filtered component at 500kHz.

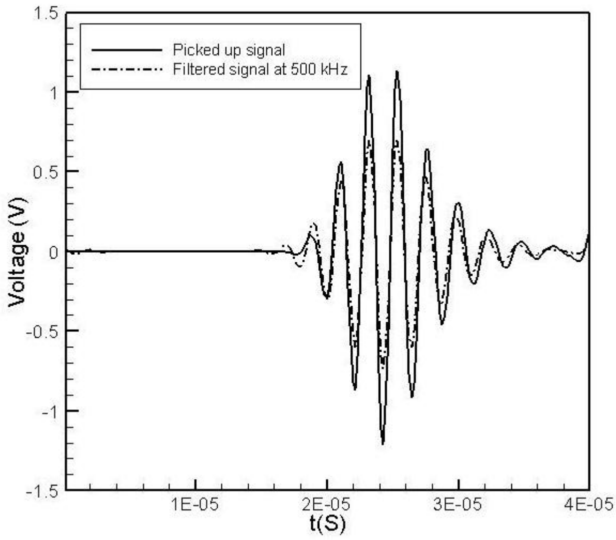

Fig 4: Filtering the Picked-up Signal using wavelet transform at the input frequency

5 Results and discussion

This paper investigates a wavelet-based approach for SHM and detection of through-thickness crack in different lengths and angles in quasi-isotropic composite plate utilizing ANSYS finite element method (FEM) software and digital signal processing technique utilizing MATLAB software. Damage index (DI) is calculated for different models which in all of them crack center passes through the connecting line between the actuators and the sensor.

For a hairline or partially closed crack, the signals collected by sensor which is in the shadow of the crack, include the directly transmitted wave signals travelling across the crack and the scattered wave signals originating from the crack tip [11].

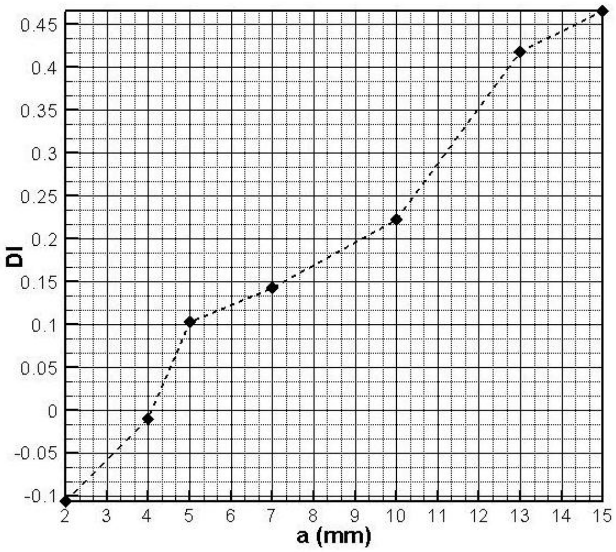

Fig 5: Damage index in term of crack length

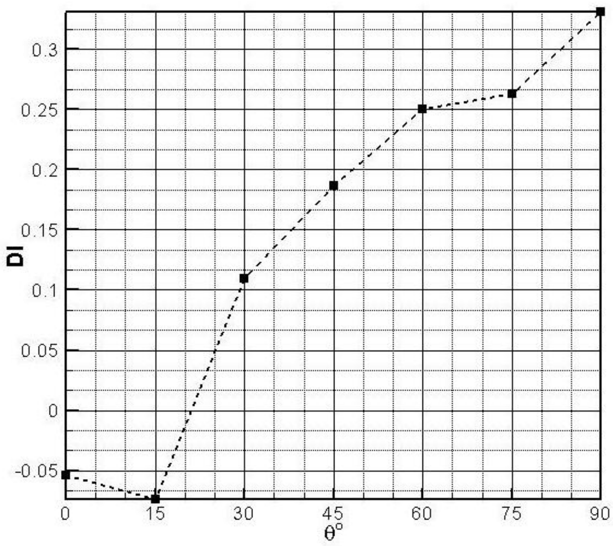

Fig 6: Damage index in term of crack angle for a=10 mm, Aluminum plate

According to the values of DI, which is shown in Fig. 5, by increasing the crack length, more intensities of the input energy have been shed into sideband frequencies. It is acceptable because, when length of crack increases, the propagation path of the scattered wave signals originating from the crack tip will increase. Therefore, the amplitude of the waves received by the sensor is lower. The value of DI undulates around a value of 1.0 before a = 5 mm for a 90° crack angle, where the propagation path of the scattered wave signals is short to some extent that the superposition of the two components of received energy in the sensor is more than pristine plate.

For two-dimensional damage, such as delamination and holes, scattered Lamb waves can be considered in all directions. In the case of cracks, however, the orientation of crack is a critical parameter which has a significant influence on Lamb wave propagation. Ye Lu et al. worked on quantitative evaluation of notch crack orientation in aluminum plates based on Lamb waves [12]. They showed for this case that the transmission coefficient decreases with the increase of angle of incident. Fig. 6 shows the trend in the case that crack is partially closed, which is considered in this paper, in aluminum plate.

From Fig. 6, for hairline crack, the rising trend for the value of DI is also observed, however transmitted signal is stronger. This difference comes from the point that in the case of notch crack, where sensor is in shadow of the crack, signals received at the sensor is only from the scattered waves component in a detour route from the crack tips whereas for hairline crack it also contains the transmitted wave component.

Fig. 7 shows variation of DI with crack angle measured with respect to the connecting line between actuators and sensor for a 10 mm crack length in quasi-composite plate.

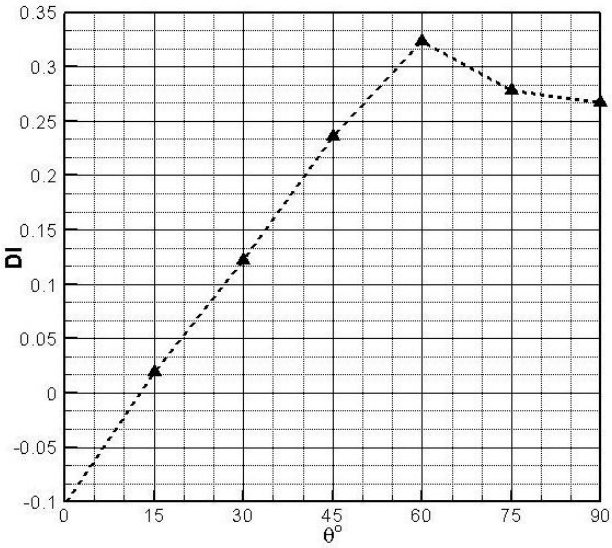

Fig 7: Damage index in term of crack angle for a=10 mm

From Fig. 6 and Fig. 7, it can be observed that for both the aluminum and quasi-isotropic composite plate, the value of DI undulates around a value of 1.0 for small angles. However, after this angle unlike the aluminum plate, the composite plate does not follow a rising trend.

It is apparent that, when incident Lamb waves are oblique to the crack, the length of propagation paths of incident waves to the crack tips and also the length of scattered paths from the crack tips to the sensor are no longer the same. Therefore, the scattered waves received by the sensor are different in two parameters amplitude and phase. In addition, propagation of wave in different directions in composite plate is different. In other word, since the composite plate is stiffer in directions of prepregs' fiber orientations, the lamb wave propagation has directional properties. So, with change of crack angle, waves passing through the crack tips in the composite plate travel paths that are different in properties in addition to the paths' length parameter. Also, despite the composite is quasi-isotropic, since crack is in fact a cut in lay-up of composite laminate, behavior of material in two sides of crack does not resemble isotropy perfectly. These parameters cause the value of DI to have more complex changes with change of crack angle in the composite plate than the aluminum plate.

From Fig. 7, for the composite plate, the value of DI has the global minimum and maximum at $\theta = 0°$ and $\theta = 60°$ respectively. At $\theta = 0°$, since of the transmitted wave component is inappreciable, the scattered waves are dominant component and the effect of this factor is so clear that the strength of energy field near the crack tips causes the DI becomes negative. This phenomenon is also observed in aluminum plate. With the increase of the angle value, the distance between the crack tips and both the sensor and actuator increases and the received signal at the sensor and the crack tips will be attenuated accordingly. In other hand, with the increase of the angle value, the transmitted wave component factor intensifies until it becomes the dominated factor at $\theta = 60°$. Importance of this factor is more emphasized if it is paid attention that at $\theta = 90°$ the 45° plies in the composite lay-up are perpendicular to the crack interface. Because the normal properties of the material is more important in its contact behavior and as mentioned above, the material is now stiffer normal to the crack interface; more energy is transferred through the crack and therefore the DI takes a local minimum at this angle. In other words, in an opposite manner, with more increasing of angle value to 90°, the received signal by the sensor will be stronger and the DI decreases. As result of these parameters compromise, $\theta = 60°$ is emerged as a maximum in Fig. 7.

6 Conclusion

The interaction of normal–incident Lamb waves with a through-thickness crack of different lengths in quasi-composite plate was studied. To this end, a dual-PZT actuation scheme was applied, aimed at generating the S_0 mode at a square composite plate. It was observed that, the value of DI increases when crack length increases. Also, the effect of crack orientation on Lamb wave propagation was evaluated. Under oblique wave incidence with the current specimen and sensor configuration, it was found that, with increase of angle the value of DI increases at first and then decreases. In both of these study, when the projection the crack length in the direction of normal to the connecting line between the sensor and actuators is smaller than an approximate threshold value of 4 mm, the value of DI undulates around a value of 1. Such undulation is attributable to the superposition of the strong scattered waves from the crack tips that travel small paths and the transmitted wave signals traveling across the crack.

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