Detection and Quantification of Asymmetrically Located Structural Damages by Mode Converted Guided Waves Using Piezo Electric Elements

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Though damage identification using guided waves generated using ultrasonics is well proven, its usage for structural health monitoring poses difficulties. Piezo electric actuation and sensing overcomes this difficulty to some extent. In this work, usage of such guided waves for damage identification is investigated. Piezo electric wafer transducers are used for generating and sensing the guided waves. Presence of multiple modes and comparatively higher speeds of the guided waves throw up difficulties in damage identification. It is shown here that this problem can be addressed by considering different sensor location with respect to the damage with suitable interpretation of the results. Usage of fundamental antisymmetric (Ao) mode is found to be more suitable in localizing the damage compared to the fundamental symmetric (So) mode. Asymmetrically located damage causes mode conversion. It is demonstrated in this work that the mode converted guided wave (So) could be advantageously used for identification, localization, and quantification of the damage. Damage identification and localization schemes are evolved based on the location of the sensors with respect to the damage. It is shown that the reduction in the magnitude of the mode converted wave can be utilized for assessing the depth of the damage. 3D finite element based numerical models incorporating a PZT sensor are developed and validated with experimental results in terms of the characteristics of the waves, mode conversion due to damage and influence of the defect size on the received signals which are necessary for quantification of the damage.

1. INTRODUCTION

Guided waves have potential for detecting damages in structures as they can propagate over large distances with a little loss of energy. However, their usage for damage detection is extremely challenging due to the dispersive characteristics of the modes, existence of multiple modes in the structure, interaction of the signal with reflected waves from the boundaries, presence of discontinuities etc. Damage detection using guided waves generated through ultrasonics has been in use for decades in Non-Destructive Evaluation (NDE). However, these ultrasonic transducers are not suitable for mounting permanently onboard the structure and hence have found limited usage in Structural Health Monitoring (SHM) applications.

In recent years, piezo electric wafer transducers have been in use for guided wave based SHM.[1–3] Though usage of structurally integrated piezos has been suggested for SHM, relatively less experimental work is reported on guided waves for damage detection. Choice of various parameters such as transducer characteristics and geometry, location and method of excitation, excitation frequency and bandwidth, identification of suitable wave modes for testing, data processing are critical for the successful application of guided waves in damage identification and quantification.[4–6]

Rucka[7] conducted experiments on metallic structures with various types of discontinuities where excitation is achieved by piezo-actuator and the propagating signal is detected by a scanning laser vibrometer. In their work, though the damage was indicated based on changes in the wave propagation characteristics, localization and quantification were not achieved. Damage quantification requires the wavelength of the propagating signal to be much smaller than the size of the damage. Haikuo et al.[8] theoretically demonstrated that when the dimension of a delamination is of the order of the wavelength of the propagating wave, the reflected waves from the left and right end of the delamination are merged into one wave packet and cannot be distinguished. This consideration implies a signal of very high frequency. Further, signal generation from surface bonded piezoelectric actuator (PZT) is governed by its dimensions, material, and strength of the signal.[8,9] Hence, localization and quantification of damage were less successful, especially in metallic structures. Guided waves were reported to have been successfully used for damage identification and localization in composite structural members,[10,11] however damage quantification is not much reported which requires suitable modelling, experiments, and data processing. In some of the works, damages are simulated in some other form as done by Mikhail et al.[12] A metallic block is glued on the surface of a metallic plate and the debond at the interface is the damage. Ao mode is used for the detection and the influence of the block height on the guided wave signal is investigated.

If the damage is in the path of the actuator and sensor, it is rather easier to identify the location of the damage based on the characteristics of the guided waves and information on time-of-flight. However, if the damage is not in the path of the actuator and the sensor, identifying the location of the damage from the time-of-flight information gathered from several sensors and actuators is a complex process. Xianping et al.[13] developed an innovative precise damage identification and localization method for large scale composite laminates and validated through experiments. They used the Levenberg-Marquardt algorithm for the damage localization and damage contour algorithm based on convex envelope of damage reflection points for determining the size of the damage. With advances in neurosciences and high-capability computing devices, recent research is focused on application of machine learning (ML) algorithms based on Artificial Neural Networks (ANN) for guided wave damage identification, localization and qualification including an assessment on the probability of occurrence of damage in metallic and composite structural members.[14–19] Jiahui et al.[20] utilized probabilistic imaging algorithm and statistical method to reduce the impact of composite anisotropy in Lamb wave-based damage localization and quantification in composite plate like structures. The algorithm was validated by experiments and results indicate an accurate prediction of the damage localization and quantification with an absolute error within 11 mm and 2.2 mm respectively for a sensor spacing of 100 mm.

Success of damage identification using guided waves relies significantly on the understanding of the wave propagation and a suitable mathematical model. Several numerical techniques[21] including the Finite Element Method (FEM),[22,23] the Boundary Element Method (BEM)[24] and the Spectral Element Method (SEM)[25,26] have been used to analyze the propagation of elastic waves. Mikhail et al.[12] developed a 2D mathematical model with plain strain assumption to capture the wave scattering due to presence of damage and validated with experimental results. Commercial FE packages like ABAQUS have the capability to solve the multi-physics problems arising from the use of PZT transducers in a structure. Most of the reported works present the characteristics of the waves propagating through a pristine structure and a few works are reported on the wave propagation in a structure with damage.[24,27] Sikdar and Banerjee[28] have reported on the characteristics of the wave that travel through structures which encounter a change in density. Studies on the mode conversion and scattering of guided waves at cracks in isotropic beams are carried out based on a time domain Spectral Finite Element Method (SFEM).[27] Parametric studies with various depth and width of the crack indicate variation in amplitude of the reflected and transmitted waves at the defect. However, works validating the theoretical findings with experimental results are seldom reported.

The transducer localization and the number of transducers required for damage identification were also investigated through experimental and numerical analysis.[29] Experimental illustration of the measurement technique, number and localization of the sensors is shown to accommodate the basic assumption and SHM system requirements which include damage identification, localization, and quantification. In a recent work,[30] a comprehensive approach including experimental and FEM has been used to determine the interaction of guided waves with the crack like defect originated under loading in an Aluminum plate structure with a hole. An array of PZT sensors could identify the origin and growth of the crack along with its orientation. The process of damage identification and quantification by guided waves become complex especially in situations where there are multiple reflections from the boundaries and wave interactions.

Admittedly, the most common defects in many components are surface damage like cracks, notches etc., which are asymmetrically located along the depth. The mode conversion of the guided wave occurs when it interacts with these non-axisymmetric discontinuities.[27,31] Group velocity of the mode converted wave is different from the primary propagating wave and therefore it should be possible to distinctly identify the damage by detecting and interpreting the mode converted wave. Therefore, an option thought to overcome the present limitations is to use the mode converted guided wave generated due to the interaction at the damage, instead of the primary propagating wave. The usage of mode converted wave in experimentally detecting a debond is not reported.

The objective of the present work is to develop a methodology to identify, localize and quantify the damage in structure by advantageously employing a mode converted guided wave in presence of multimode wave propagation. To achieve the above, suitable positioning the sensors with respect to the damage needs to be developed. This aspect has been demonstrated experimentally by introducing an asymmetrical damage in the form of notch and suitable placement of actuators and sensors on the specimen with respect to damage location and their interpretations. The damage can be identified based on the change in the response characteristics of the waves, however the quantification of the damage in the presence of multimode wave propagation is difficult and needs special attention. This aspect has been demonstrated experimentally in this work by considering selective sensor locations with respect the damage. In the experiment, the guided waves are generated and sensed by PZT patches. A Finite Element based numerical modeling is adopted as a suitable theoretical model. The practical concerns regarding the generation and sensing of guided waves using PZT, selection of PZT, excitation frequency, data processing and quantification of small sized defects in structures are addressed. It is shown in this work how the mode converted wave can be advantageously used for identification, localization and quantification of the damage.

2. EXPERIMENTAL AND THEORETICAL METHODOLOGIES EMPLOYED

2.1. Experimental Setup

The experiments were conducted on a cantilever beam. The beam considered had a length of 1000 mm, width 35 mm and thickness of 2 mm and was made of Aluminum alloy. The damage was introduced asymmetrically in the form of a through-width notch on the surface of the beam. The notch had a depth of 1 mm with a length of 6 mm and was located 700 mm from the fixed end of the beam. Figure 1 shows the schematic and photograph of the specimen along with the sensors and the location of the damage.

The beam was excited near its free end by square shaped PZT actuators of dimensions 25 mm having a thickness of 0.4 mm. They are mounted on either side of the beam at locations E1 and E2, as shown in Figure 1. Two PZT sensors S2 and S1 are placed along the length of the cantilever beam at 412 mm and 865 mm respectively from the fixed end. PZT patches were surface bonded on a central line along the length

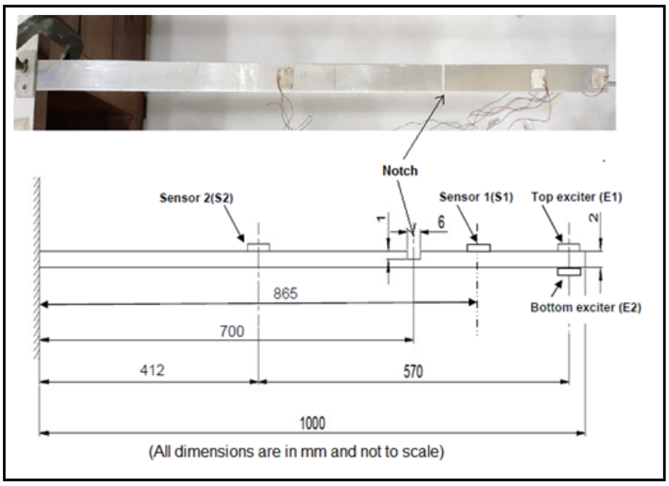


Figure 1. Schematic and photograph of the structure under study.

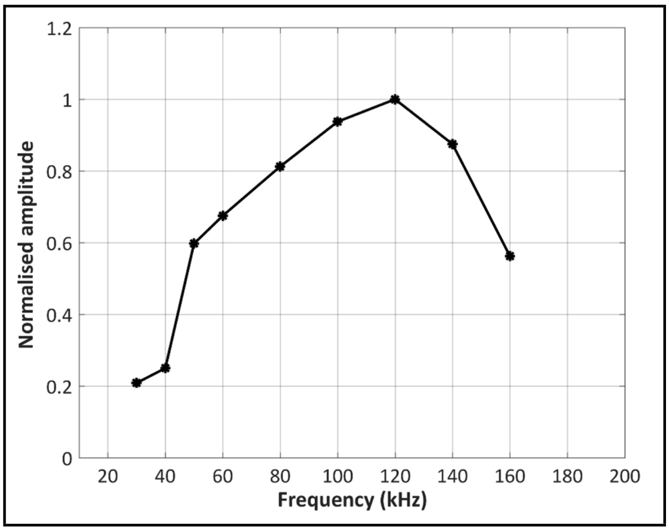


Figure 2. Response of piezo at various frequencies.

of the beam using cyanoacrylite adhesive. The distances and the length of the beam are chosen such that the reflected waves from the damage and fixed end reach the sensors at instances where they are distinguishable. Initially the experiments were conducted on a pristine beam and later the beam with the damage.

A voltage signal having a peak value of 10 V was applied to the PZT exciter through a NI 6251B system interfaced through LABVIEW. The signal is a modulated five cycle sine pulse of 120 kHz. The response of PZT sensors is acquired by the same system.

Some experiments were conducted by exciting only the top piezo exciter, E1 and in the other experiments both E1 and E2 exciters were excited simultaneously. Actuating only E1 generated both flexural and longitudinal waves. When E1 and E2 were actuated simultaneously, an elongational (S_o) mode was generated when the excitations are in phase, If the excitation voltages are out of phase, a flexural (A_o) mode is generated.[8] The excitation sensor location scheme selected is elaborated in the later sections.

2.2. Selection Of Excitation Frequency

To counter the dispersive effects of the propagating guided wave, a modulated sine wave was considered.[32] An input pulse $v(t)$ in the form of five-cycle sine pulse with a Hanning window around a central frequency, f_c, was applied. The input pulse can be expressed as:

$$v(t) = \frac{1}{2}\{1 - \cos(\frac{f_c t}{5})\} \sin(f_c t). \tag{1}$$

Giurgiutiu[24] showed that when the dimension of the PZT actuator is an odd integer multiple of the half wavelength of a particular Lamb wave mode, a strong force causing significant response in the corresponding Lamb mode will act.

PZT patches give optimum results in a certain frequency range. To determine this frequency range, two such PZTs mounted on the beam at a distance of 540 mm were evaluated for actuation and receiver characteristics at various excitation frequencies. The frequency response graph shown in Fig. 2, was obtained by plotting the peak value of the received time domain signal generated from an input pulse at a certain frequency. It is observed that the efficiency of the piezo was optimum at around 120 kHz.

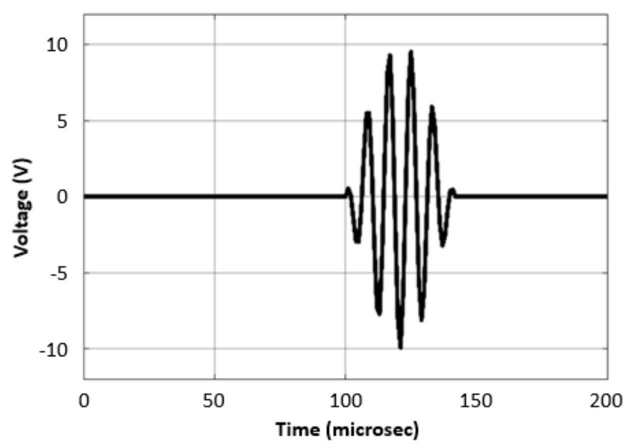
Therefore, a modulated 120 kHz sine pulse having 5 cycles was chosen for all further experiments. The excitation pulse and the corresponding spectrum are shown in Fig. 3. The duration of the pulse is 41.67 microseconds (μs).

The number of cycles selected was five. If the number of cycles was larger, a larger time gap between the two pulses reaching a location was needed to be able to distinguish the two sigmnals. Therefore, an excitation signal with minimum number of cycles was selected.[33] To quantify the damage size, the wavelength should be comparable to this size and therefore, usage of higher frequency excitation was better. The higher frequency results in higher speeds for the A_o mode. As time for five cycles should elapse between the arrival of two waves the higher wave speed translates to longer lengths and hence the sensors should be at greater distance from the source as well as defect. Considering all the above factors, a frequency of 120k Hz was selected.

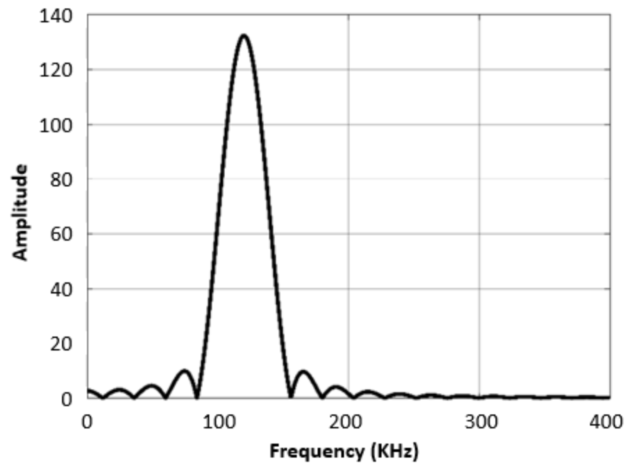
2.3. Numerical Modeling

Results from a theoretical analysis will enhance the understanding of the wave propagation. Therefore, a numerical model which is Finite Element (FE) based, is developed to simulate the test conditions and to validate with the experimental results.

The numerical modeling and simulations are carried out using the commercial FE software ABAQUS v6.12. The dimensions of the test article are as given in Fig. 1. The beam was modeled with 8-noded, linear brick elements (C3D8R) with reduced integration, and the PZTs were modeled using standard linear piezoelectric brick element (C3D8E). The piezo and beam elements were assembled together (node to node) by tie elements based on master-slave formulation in ABAQUS. The voltage signal shown in Fig. 3 was used as input to the exciter PZT and applied on the top surface of the PZT. In addition to the fixed boundary condition applied at one end of the cantilever beam, a zero voltage was applied to the bottom surface of the piezo transducer. The voltage output from the top surface of the receiver sensor was captured from the analysis. Length of the element was dictated by the excitation frequency and the wavelength of the lamb wave to ensure that 8-10 elements are included in one wavelength. The FE model of the beam with piezo transducer is shown in Fig. 4. Young's modulus $(E) = 70$ GPa, density $(\rho) = 2800$ kg/m^3 and Poisson ratio $(v) = 0.3$ were the material properties of Aluminum considered. The electromechanical material properties corre-



(a)



(b)

Figure 3. 120 kHz modulated excitation pulse: (a) Time domain (b) Frequency spectrum.

sponding to PZT-5H based on the data provided by the manufacturer were:

$$[e] = \begin{bmatrix} 0 & 0 & 0 & 0 & 17 & 0 \\ 0 & 0 & 0 & 17 & 0 & 0 \\ -7.7 & -7.7 & 31.5 & 0 & 0 & 0 \end{bmatrix} \times 10^{-3}\text{N/m/V}; \tag{2}$$

$$[c] = \begin{bmatrix} 12.6 & 7.95 & 8.41 & 0 & 0 & 0 \\ & 12.6 & 8.41 & 0 & 0 & 0 \\ & & 11.7 & 0 & 0 & 0 \\ & & & 2.3 & 0 & 0 \\ & \text{Symmetry} & & & 2.3 & 0 \\ & & & & & 2.35 \end{bmatrix} \times 10^{10}\text{Pa}; \tag{3}$$

$$[\epsilon] = \begin{bmatrix} 1.505 & 0 & 0 \\ & 1.505 & 0 \\ & \text{Symmetry} & 1.302 \end{bmatrix} \times 10^{-8}\text{C/V/m}. \tag{4}$$

where $[e]$ was the piezoelectric stress matrix, $[c]$ the stiffness matrix and $[\epsilon]$ the piezoelectric permittivity matrix. The density of the piezoelectric material was 7500 kg/m^3.

In the case of the beam with the defect, the notch geometry was modeled and meshed as shown in the enlarged view around the notch of Fig. 4. Sensitivity of the results on the parameters of the mesh were studied by varying the element size and number of elements in the notch area.

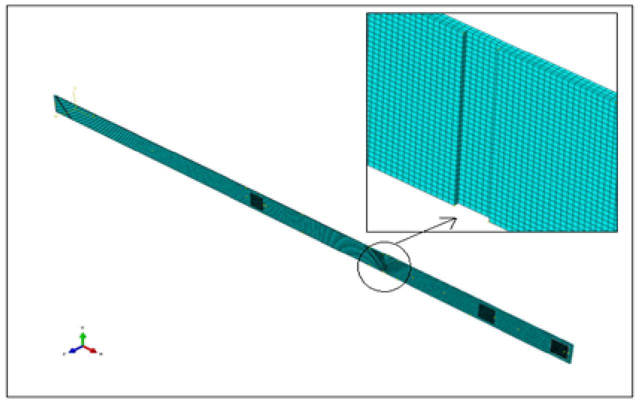


Figure 4. FE model of the beam with PZT sensors and the damage.

3. DAMAGE DETECTION USING PRIMARY PROPAGATING GUIDED WAVE

3.1. Results Of Pristine Structure

Lamb waves comprising Symmetric (*S*), Antisymmetric (*A*) and Shear Horizontal (*SH*) modes are commonly used for damage identification in structures. The S waves, also described as extensional modes, have dominant displacements in the longitudinal direction which is the direction of propagation. In antisymmetric type waves, which are also known as flexural modes, the displacements are dominant along the normal to the direction of propagation. In a structure, multiple wave modes exist simultaneously.

To establish the methodology and experimental technique adopted in the present study, results of the wave propagation in a pristine beam are presented initially. Excitation by piezo electric exciter E1 which is placed on the top surface of the beam generates both A_o and S_o modes. The excitation signal is a five-cycle modulated 120 kHz sine pulse as shown in Fig. 3.

The voltage measured at the sensor S2 is shown in Fig. 5. Sensor S2 is placed sufficiently away from the exciter such that waves arriving at S2 are distinct on the time scale. The theoretical group velocity of the S_o mode in the beam is 5000 m/s. If the specimen is considered as a plate, the theoretically estimated group velocity is 5175 m/s at 120 kHz. Based on the Time of Flight (ToF) measurements and the distance that wave needs to travel, the group velocity of the So mode is determined to be 4954 m/s. Similarly, the theoretical group velocity of the A_o mode in the beam is 2950 m/s at 120 kHz. Based on the Time of Flight (ToF) measurements and the distance that wave needs to travel, the group velocity of the A_o mode is determined to be 2900 m/s. The difference in the group speeds determined using various methods are negligible. Though these results are well expected, they are briefly presented as the same methodology will be used for further experiments. A value of 5000 m/s for S_o mode and 2950 m/s for A_o mode are considered as the group velocity for further discussions.

If the response at S1 were used for identifying the modes, it would have been difficult to distinguish the wave pulses as the propagating wave is mixed with the reflected wave from the free end. Detection using the sensor at S1 necessitates that the speed of the wave shall be lower. This could be possible by generating only the A_o mode whose speed is lower. The primary A_o mode can be generated by simultaneous excitation of E1 and E2 with the voltage signals applied in opposite phase.

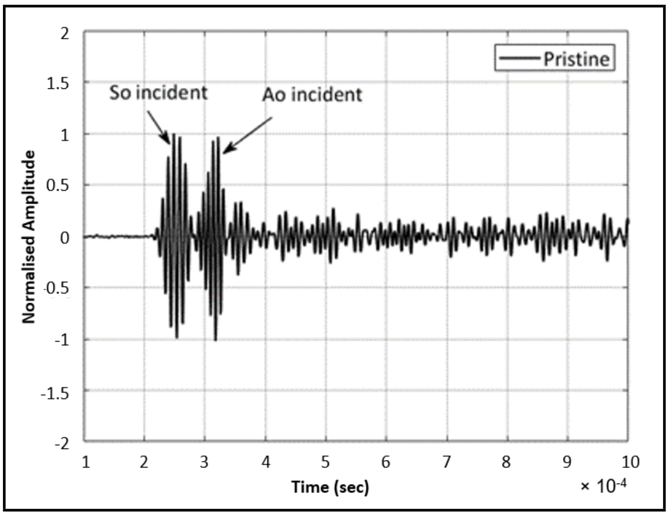


Figure 5. Response signal of piezo sensor (S2) for pristine beam.

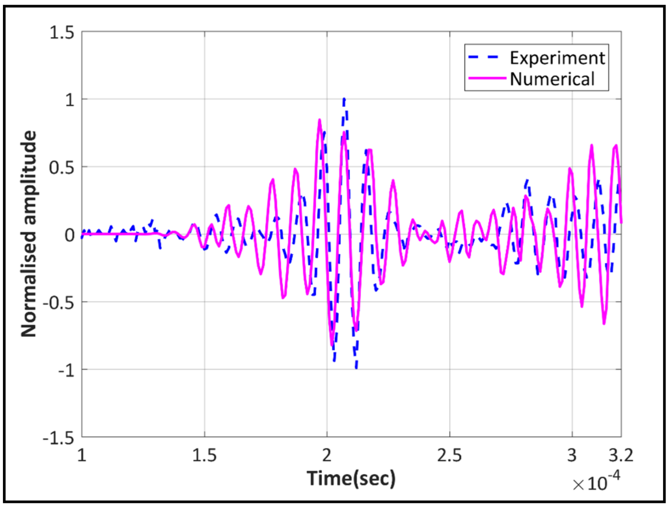


Figure 6. Analytical and experimental response at S1 in pristine beam.

This is attempted and the results are given in Fig. 4. The response of pristine beam at S1 is shown in Fig. 6, where the incident A_o mode is distinctly noticeable. To identify the damage using the response at S1, one needs to excite the pure A_o mode.

The predictability of the theoretical model is also verified here with the results of pristine beam. The response at S1 is obtained through finite element simulations and compared with the experimental results, as shown in Fig. 6. The experimental and numerical results match well. Though the magnitudes of the response in the experimental results are slightly less than the results obtained through simulation, the nature and characteristics of the response are identical. Perhaps the difference can be reduced further incorporating a more accurate values for damping factor. In this context, as the absolute value of the magnitude of the response is not of importance, the same model is used for further investigations.

In all these experiments, the sampling frequency is 1 MHz though the frequency of the excitation is 120 kHz and the resolution of the voltage signal is about 30 μV. Therefore, the signal captured is not expected to be having any noticeable digital processing error.

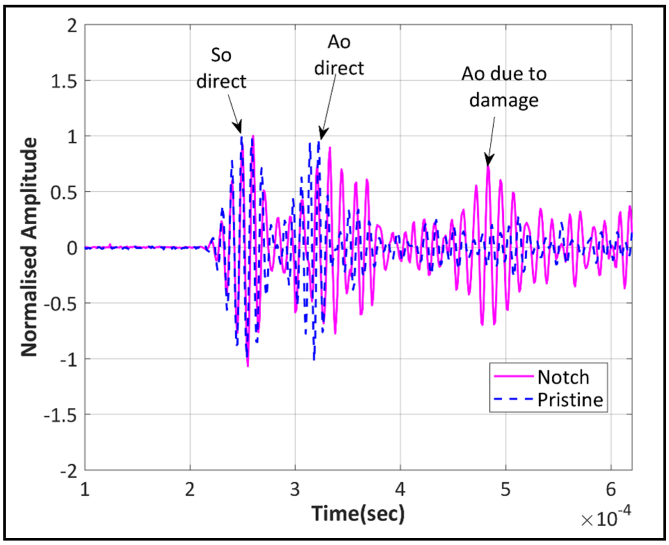


Figure 7. Experimental response at S2 for pristine and notch beams.

3.2. Damage Identification

Investigations are now carried out on a beam with the defect as described in the previous section. The pulse as shown in Fig. 3 is applied at the exciter piezo and the response signals are captured by the piezo sensors mounted on either side of the defect.

E1 piezo actuator, which is mounted on the top of the beam alone is excited and the response of sensor S2 as shown in Fig. 7 is captured. It is noticed that both S_o and A_o modes at 120 kHz are generated. A part of them are reflected by the notch. These reflected waves undergo further reflections at the free end of the beam and reach sensor S2. In other words, the response at S2 will have pulses that are reaching directly and the that reflected from the damage and the free end. Both S_o and A_o waves are present.

The responses of S2 in the pristine beam and the beam with damage are plotted on the same graph (Fig. 7) for easy interpretation. The first pulse seen is the S_o mode, the magnitude of which is slightly diminished compared to that in the pristine beam since a part of it getting reflected at the notch. This reduction in the amplitude of the first pass transmitted signal clearly indicates the presence of the defect in the wave transmission path between exciter E1 and sensor S2. The second pulse seen at S2 is the A_o mode reaching S2 with a part being reflected due to the damage. A similar observation of amplitude reduction in the response of the notched beam is seen with A_o mode too.

The third pulse which is seen at about 475 μs, is the part of Ao mode reflected from the damage and reaches S2 after getting reflected at the free end. Such a pulse is expected to reach S2 at 490 μs. This is calculated taking the speed of A_o mode as 2900 m/s and considering the wave travel distance travelled by the wave after reflecting from damage and then at the free end. This is absent in the pristine beam and very much distinguishable in the beam with the damage. Thus, the damage can be detected in two ways. One approach is to consider the wave pulse reaching S2 due to S_o and A_o modes reaching directly, with a part being reflected at the damage. The damage can be distinguished by the reduction in the magnitude of the pulse. The other way is by sensing the third pulse which is absent in the pristine beam. The second method is more effective and distinguishable. From the third pulse, even the location of the damage can be identified. Based on the Time of Flight and

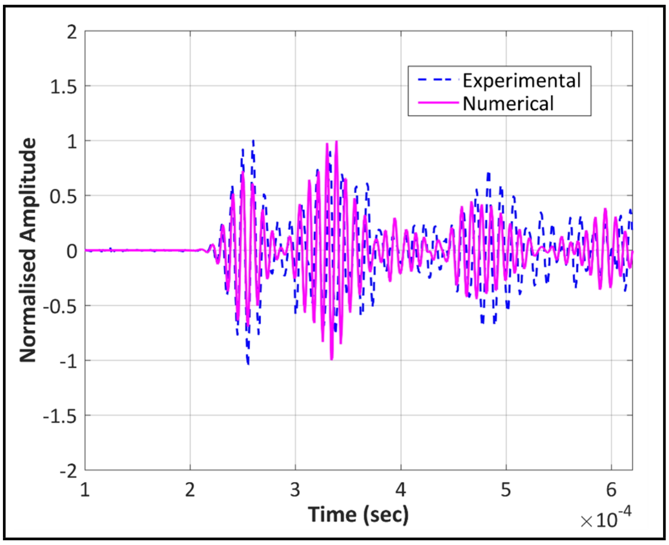


Figure 8. Analytical and experimental response at S2 in the beam with defect.

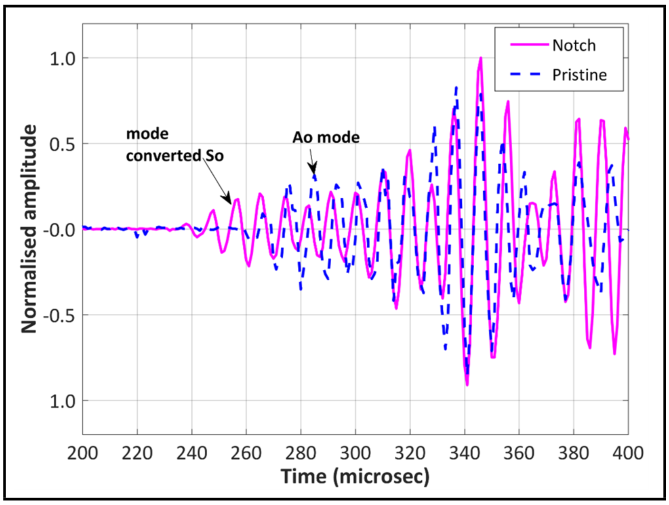


Figure 9. Response of S2 for pristine and notch beams excited by A_o mode.

the known velocity of A_o mode, the distance travelled by the wave can be determined. This distance is equal to the sum of the distance of the defect from the exciter, the distance of the defect from the free end, and the distance of S2 from the free end. However, the damage location estimation from response at S2 by exciting E1 alone is not accurate as discussed in the next section.

Numerical simulations are also carried out for the beam having the defect. The results for location S2 are shown in Fig. 8. Signature of the defect is captured in the response. However, due to close presence of both wave modes in the reflected signal added to the reflections from the fixed end of the beam, distinct localization of the defect could not be done.

3.3. Limitation Of The Methodology

It is to be noted that the damage was identified using the response at S2 and not by using the response at S1. Response at S1 was not used as it is closer to the source and distinguishing various wave pulses was not feasible since they arrive in a short duration of time. These results are not provided here for brevity. Even the identification by using the response at S2 is difficult because of the presence of several pulses such as the direct pulse, reflected pulse from the fixed end, those reflected by the notch and subsequent reflection from the free end etc. The damage identification by exciting the top PZT actuator (E1) and observing the response for damage signature, thus involves multiple reflections from the notch as well as free end before reaching S2. Estimation of damage location from this method is prone to errors as the propagating path of the damage-reflected wave includes one more reflection from the free end. The multiple reflections and possible interactions with the other wave modes can induce large errors in ToF calculations. It is expected that one can, to some extent, overcome this difficulty by adopting A_o mode as its speed is significantly lower compared to S_o mode. In the next experiment, the damage detection using A_o mode is investigated.

4. DAMAGE DETECTION USING MODE CONVERTED GUIDED WAVE

In the next experiments, a pure A_o mode is generated by simultaneous excitation of E1 and E2 with voltage signals in out of phase. The A_o mode is chosen over S_o to obtain a distinct reflected wave pulses on time scale. Interaction of the incident A_o mode with notch type damage generates additional S_o guided wave. A_o wave and mode converted S_o wave are emanating from the damage upon A_o wave incidences the notch.

The waves are generated by using two piezo patches, one on the upper (E1) and the other on the lower (E2) surface of the beam. When these two forces are in phase, the active wave mode is S_o mode. When these two shear forces are out of phase an Ao mode is generated.[8] Hence to generate pure A_o mode, the voltages applied on these piezo patches should be in out of phase. In the present experiment, the output of the amplifier is tapped in to two lines. For the upper piezo patch, ground and the signal are connected to the ends. For the lower piezo, they are connected in the reverse order, that is signal and ground. This simple arrangement generates out of phase forces. If the forces are not exactly out of phase, it will generate S_o mode too but the magnitude will be very low. This S_o mode will be distinguishable as its speed is quite high compared to the speed of the A_o mode and can be neglected. Also, as the magnitude of this wave mode is quite low, it will decay soon and will be invisible.

Figure 9 shows the response at S2 for the pristine and notch beams. It is observed that the mode converted S_o wave is present in the response of the notched beam before the incident (propagating) A_o wave. The presence of S_o mode indicates the presence of damage in the wave propagation path from exciter PZT to S2. The ToF calculation indicate the presence of damage at distance of 280 mm from S2 which matches within seven percent of the measured position of the defect.

The responses of sensor S1 in pristine and the damaged beams are depicted in Fig. 10. The first pulse is the incident A_o mode at 140 μs. The incident wave is seen spread for larger duration as it involves another pulse which is the reflected wave from the free end of the beam. The mode-converted So guided wave, generated at the damage and travelling back is seen at 230 μs and is clearly absent in the response of the pristine beam. The A_o pulse reflected from the damage seen at 251 μs is not distinguishable due to its interaction with reflected modes from beam ends. Time of Flight calculation for the mode converted S_o guided wave indicates the presence of the defect at 166 mm from the sensor which agrees well with the physical measurement of the defect which is 165 mm. This estimation is more accurate compared to the one done in the first experiment with only E1 excitation, as the pulse used

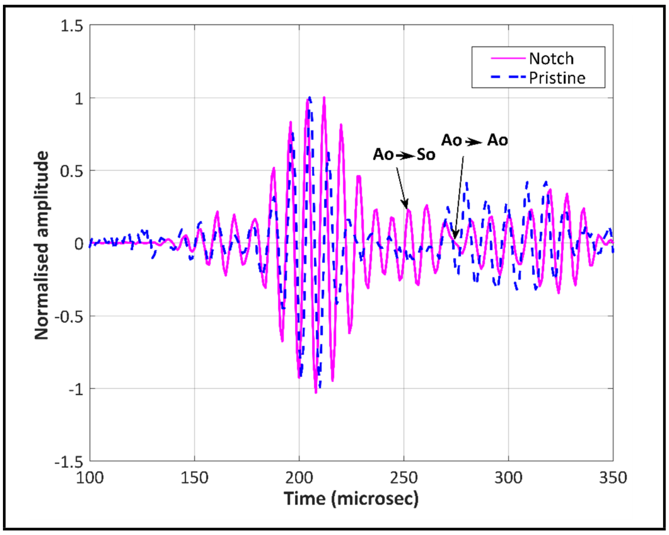


Figure 10. Response of S1 for pristine and notch beams excited by A_o mode.

for estimation does not involve any multiple reflections. As shown in Fig. 10, the mode converted S_o guided wave does not mix with other reflected wave modes. This is because the group velocity of the mode converted S_o guided wave is much higher than that of an A_o guided wave. It is demonstrated that by exciting the A_o mode and by measuring the response which includes damage reflected mode converted wave, the location of the damage in a beam can be accurately determined.

Thus, an asymmetrically located damage is well identified as well as localized through the converted wave mode. It is known that such damages causes conversion of the wave type and in this work it is demonstrated that the converted mode can be conveniently used for the identification and localization of the damage. The damage in a beam type structure can be detected and localised through either of the two experiments. The sensor could be on any side of the damage and the defect can be located through proper interpretation of the results. Though one type of experiment is sufficient to detect the damage, results of the two types of tests complement each other. Data from both the locations can reinforce the identification of the damage.

The temperature of the environment is kept constant around 24°C and no external load is present. However, ultrasonic guided wave propagation is significantly affected by the temperature and load conditions and can lead to false conclusions if these effects are not addressed. The damage identification and quantification can be in error if these environments change in the path of the guided wave. They affect the amplitude as well as phase of the signals. If both the environments get changed simultaneously, the influence on the guided wave could be even nonlinear. There are techniques developed to compensate for these effects.[34–36] The method includes matching with a reference signal using suitable algorithms.

Time-of-flight information is used to determine the location of the damage. The time of arrival of the pulses is considered, if the wave pulses are distinct in the time scale, In the case where the initial waveform is not clear due to interaction with previous wave mode, the time of peak amplitude of the wave pulse is considered for the estimation of the time-of-flight. One can expect an error of 1 μs in the time-of-flight measurement as the data is sampled at a frequency of 1 MHz leading to a resolution of 1 μs. In the present case, this translates to an error of 2.03 mm in the location of the damage. It needs to be

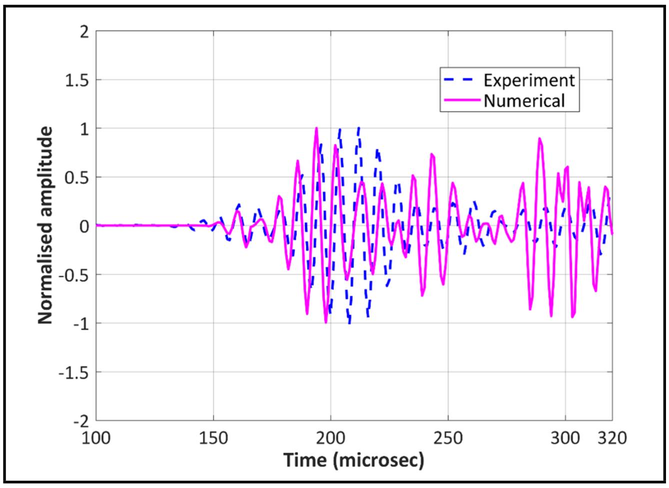


Figure 11. Response at S1 for beam with defect excited with A_o mode.

noted that the travel towards the defect is a A_o mode and the return is S_o mode.

Results from a numerical model are obtained for the beam with defect when excited with an A_o mode and the result at location S1 are as shown in Fig. 11. They match very well with the experimentally obtained results. The numerical model is not essential for identifying the presence of the damage and its localization. However, the model is required for quantifying the damage. The model is built and verified in stages and hence the results corresponding to this condition are presented here.

In practice as the structure could be two dimensional and the damage may not be along the direct sensing path and hence several sensors need to be deployed. Time-of-flight of the mode converted So mode can be extracted for different sensing paths. Localization of the damage needs to be done from these values of time-of-flight. There are algorithms reported[13,20] for this purpose when the structure is excited by S_o mode, like forming the ellipses of possible damage location from various sensor locations and extracting the location using suitable algorithms etc. A similar algorithm could be thought of for mode converted S_o waves when excited A_o mode. It should be noted that travel towards the defect is as A_o mode and the return is S_o mode.

5. DEFECT QUANTIFICATION

Having established the location of the defect, we now aim to find an appropriate way of quantifying the damage. The notch defect is quantified by its width and depth.

Width of the damage can be quantified by the distinct reflections from the ends of the notch and it requires that the wavelength of the propagating wave be comparable with the width of the notch.[8,27] From the time difference between the two reflections and the speed of the wave, the width of the damage can be determined. It is considered that to have clear distinction, the second wave shall arrive after one wavelength of travel. In the present experiment, the pulse has a frequency of 120 kHz. Considering the group velocity of the S_o mode as 5000 m/s, the wavelength is 42 mm. If the width of the notch is 21 mm, the second wave will arrive after one wavelength. If a damage having width of 6 mm is present, the second reflection travels additionally 12 mm. To distinguish it by a shift of one wavelength, the frequency of the wave should be 415 kHz. It is to be noted that if the second reflected wave can be distinguished with a difference of half the wavelength itself, excitation of 210 kHz may be sufficient. Theoretically estimated group speed of S_o mode at 415 kHz is 5075 m/s. For the assessment made above on the frequency of excitation needed, the speed of 5000 m/s itself is considered as the difference is very negligible.

The strength of the Lamb wave signal generated by the PZT transducer is different at different frequencies. The force applied strongly depends on its dimension.[4,6] The dimensions of the PZT used in the present experiment are 25 mm $\times$ 25 mm $\times$ 0.4 mm (thickness). The optimal response of this PZT when mounted on the Aluminum base is experimentally obtained and it peaks around 120 kHz. The guided wave signal generated by the PZT used in the experiment is weak at 415 kHz. PZTs having smaller dimensions need to be used to excite guided waves around 415 kHz. The amplitudes of the waves in terms of voltage, after interaction with the damage should be higher than the instrumentation noise. As the present study aims to identify the depth of the notch as low as 0.25 mm, usage of a still lower sized PZT was not feasible. Also, the amplifier used for the experiments has linear operation up to 250 kHz. This amplifier is not suitable for signals of 415 kHz. To generate and sense the Lamb waves at 415 kHz calls for a different piezo and amplifier.

Considering the limitation of the PZT response and frequency range of the amplifier used in the present experiment, the damage width quantification is not attempted here. However, the depth of the notch is assessed by the change in magnitude of the mode converted reflected wave from the damage.

The depth of the damage may be quantified by observing the change in amplitude of the distinct wave pulse generated due to the presence of damage. It is shown earlier from the responses at S1 and S2 that the reflected wave pulse from the damage gets reflected at the free boundaries and its amplitude is diminished. It is seen from the present experiment that the mode converted S_o wave pulse generated at the damage and travelling to S1 is distinct and its amplitude directly correlates with the depth of the damage and hence more appropriate for quantifying the damage.

Experiments are conducted on specimens with notch depths of 0.25 mm, 0.5 mm, 0.75 mm and 1.0 mm. The piezo actuators E1 and E2 are excited simultaneously by five-cycle modulated pulse at 120 kHz. Figure 12 shows the mode converted S_o wave generated from the damage for varying notch depth. The reflected wave signal from damage having a depth of 0.25 mm depth was detected experimentally. It may be possible to detect damages with still smaller depths but could not be attempted here due to practical difficulties in making such specimens for testing. One shall rely on a theoretical model to arrive at the minimum depth.

The magnitude of the mode converted signal increases with rise in the depth of the notch. It is therefore possible to correlate the magnitude of the signal to the depth of the damage. In the results presented, the voltage of the reflected wave is normalized with respect to the reflected wave for a notch having a depth of 1 mm.

The above relation is established using the measurement at S1. In principle it is possible to establish a similar relation based on the signal measured at S2. However, it faces with some issues in the present context. The response signal at sensor location S2 shown in Fig. 9 depicts the presence of mode converted S_o wave, which indicate the presence of the damage in the wave transmission path from the exciter to S2. The time of arrival of S_o mode is distinctly seen. However, the

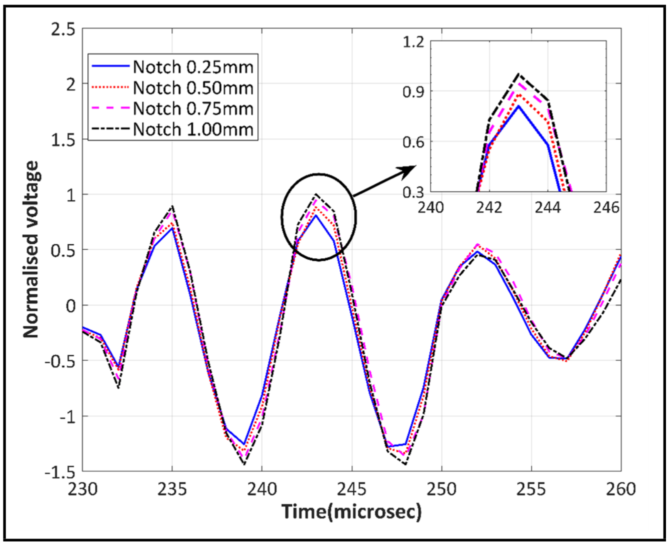


Figure 12. Experimental results for varying notch depth.

peak value of the S_o mode is not distinct due to the presence of the incident A_o mode. Hence, damage quantification based on the mode converted S_o wave reaching at S2 location is not attempted here. This is specific to the distance at which S2 is located from the damage. If S2 was placed slightly away from the damage, it would have been possible to get the amplitude correctly. It should be noted that the damage localization can still be done and the difficulty is in its quantification. In practice, there is a multiple sensor network with sensors distributed and located at different distances from the damage. This could happen only to a very few sensors Using suitable algorithm, location having such issues can be removed from the set of sensors to be used for quantifying the damage and one needs to extract the damage size based on other sensors.

In practice, to determine the depth of the notch, it is necessary to calibrate in advance for different structures and different types of damage. However, this is a difficult task. Therefore, suitable theoretical models need to be developed. The model may be validated with the results of specific experimental cases and then the model could be used for cases where the calibration is not done. In the present work an attempt is made in this direction. Using the finite element based theoretical model described in Section 2, the reflected wave responses at S1 are now theoretically determined for various notch depths and presented in Fig. 13. The theoretical results are consistent with experimental results.

Figure 14 shows the variation in voltage of the mode converted wave signal at S1 obtained by numerical simulations as well as the experimental results for various depths of the notch. The theoretical model gives a reduction in peak voltage of the reflected wave signal with reducing notch depth, as seen in the experiments. The experimental data at very low notch depths of 0.25 mm and 0.5 mm show relatively large reduction in voltage compared to the theoretically predicted values. It is to be noted that as the waves propagate through the medium there are several losses encountered which are not represented in the model. Therefore, the experimental results show a lower value compared to the theoretical values. In case of smaller notch depth, the amplitude of the wave reflected from the notch is very small and the losses are relatively higher and hence causes larger differences in the results. The proposed model can represent the damage in the beam and therefore can be used for further predictive analysis.

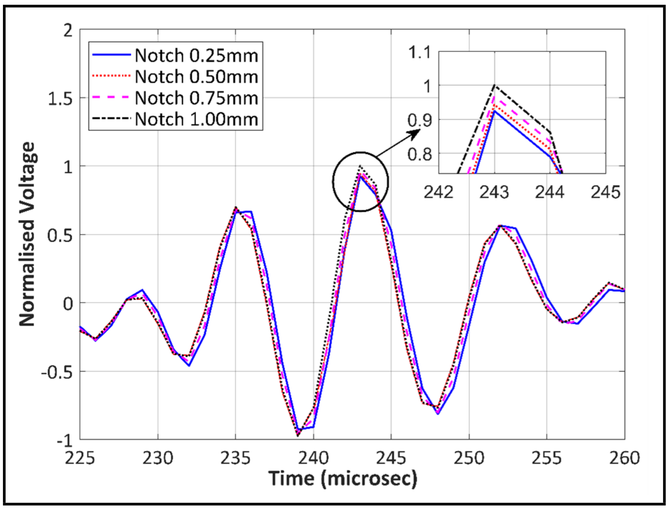


Figure 13. Theoretical results for varying notch depth.

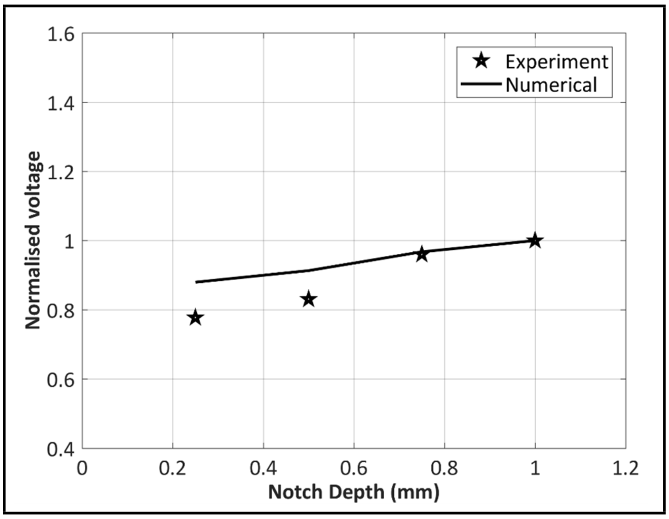


Figure 14. Variation of peak magnitude of S_o signal with notch depth.

6. CONCLUSIONS

An experimental method to detect, localize and quantify an asymmetrically located notch type damage is demonstrated using guided waves generated and sensed through piezo actuators and sensors. A_o mode is found to be more effective in localization and quantification of the damage compared to S_o mode, though it is practically difficulty to generate a pure A_o mode. The presence of multiple modes and reflected waves from the boundaries elevate the difficulty in localization and quantification of the damage. However, excitation by A_o mode generates a S_o mode by a non-symmetric damage and it is shown that the mode converted S_o wave can be advantageously used to identify, localize, and quantify the damage. The sensor could be on any side of the damage and the defect can be located through proper interpretation of the results. The quantification of the damage is demonstrated experimentally based on the amplitude of the mode converted S_o wave. A finite element model that predicts the response behavior in the experiment incorporating the piezo actuation and sensing is developed. It represents closely the characteristics of the waves being propagated across the damage. The model predicts reasonably well the change in characteristics of the propagating waves for varying depth of the defect.

REFERENCES

[1] Joseph, L. Rose, Ultrasonic guided waves in structural health monitoring, *Key Engineering Materials*, 270-273, 14-21, (2004). https://doi.org/10.4028/www.scientific.net/KEM.270-273.14

[2] Giurugiutiu, V. and Zagrai, A. N. Embedded self-sensing piezoelectric active sensors for online structural identification, *Journal of Vibration and Acoustics*, **124**, 116-125, (2001). https://doi.org/10.1115/1.1421056

[3] Mijia Yang and Pizhong Qiao, Modeling and experimental detection of damage in various materials using the pulse-echo method and piezoelectric sensors/actuators, *Smart Materials and Structures*, **14**, 1083-1100, (2005). https://doi.org/10.1088/0964-1726/14/6/001

[4] Ajay Raghavan and Carlos, E. S. Cesnik, Finite-dimensional piezoelectric transducer modeling for guided wave based structural health monitoring, *Smart Materials and Structures*, **14**, 1448-1461, (2005). https://doi.org/10.1088/0964-1726/14/6/037

[5] Zhongqing Su, Lin Ye and Ye Lu, Guided Lamb waves for identification of damage in composite structures: A review, *Journal of Sound and Vibration*, **295**, 753-780, (2006). https://doi.org/10.1016/j.jsv.2006.01.020

[6] Nieuwenhuis J. H., Neumann J., Greve D. W., and Oppenheim I. J. Generation and detection of guided waves using PZT wafer transducers, *IEEE Transactions on Ultrasonics Ferroelectrics and Frequency Control*, 2103-2111, (2005). https://doi.org/10.1109/tuffc.2005.1561681

[7] Magdalena Rucka, Experimental and numerical study of guided wave damage detection in bars with structural discontinuities, *Archive of Applied Mechanics*, **80**, 1371-1390, (2010). https://doi.org/10.1007/s00419-009-0389-8

[8] Haikuo Peng, Lin Ye, Guang, Samir Mustapha and Fucai Li, Concise analysis of wave propagation using the spectral element method and identification of delamination in CF/EP composite beams, *Smart Materials and Structures*, **19**(18), (2010). https://doi.org/10.1088/0964-1726/19/8/085018

[9] Lee B. C., and Staszewski W. J. Modeling of Lamb waves for damage detection in metallic structures: Part I wave propagation, *Smart Materials and Structures*, **12**, 804-814, (2003). https://doi.org/10.1088/0964-1726/12/5/018

[10] Fabrizio Ricci, Ernesto Monaco, Leandro Maio, Natalino D. Boffa, and Ajit K. Mal, Guided waves in a stiffened composite laminate with a delamination, *Structural Health Monitoring*, **15**(3), 351-358, (2016). https://doi.org/10.1177/1475921716636335

[11] Dulip Samaratunga, Ratneshwar Jha and Srinivasan Gopalakrishnan, Wavelet spectral finite element for modeling guided wave propagation and damage detection in stiffened composite panels, *Structural Health Monitoring*, **15**(3), 317-334, (2016). https://doi.org/10.1177/1475921716640468

[12] Mikhail V., Golub, Alisa N. Shpak, Inka Mueller, Sergey I. Fomenko and Claus-Peter Fritzen, Lamb wave scattering analysis for interface damage detection between a surface-mounted block and elastic plate, *Sensors*, **21**(860), (2021). https://doi.org/10.3390/s21030860

[13] Xianping Zeng, Xiao Liu, Jiajia Yan, Yinghong Yu, Bowen Zhao and Xinlin Qing, Lamb wave-based damage localization and quantification algorithms for CFRP composite structures, *Composite Structures*, **295**, (115849), (2022). https://doi.org/10.1016/j.compstruct.2022.115849

[14] De Fenza A., Sorrentino A., and Vitiello P., Application of artificial neural networks and probability ellipse methods for damage detection using Lamb waves, *Composite Structures*, **133**, 390-403, (2015). https://doi.org/10.1016/j.compstruct.2015.07.089

[15] Su Z.,and Ye L., Lamb wave-based quantitative identification of delamination in CF/EP composite structures using artificial neural network algorithm, *Composite Structures*, **66**, 627-637, (2004). https://doi.org/10.1016/j.compstruct.2004.05.011

[16] Qian C., Ran Y., He J., Ren Y., Sun B., Zhang W., and Wang R., Application of artificial neural networks for quantitative damage detection in unidirectional composite structures based on Lamb waves, *Advances in Mechanical Engineering*, **12**(3), (2020). https://doi.org/10.1177/1687814020914732

[17] Dhiraj, Akshit Agarwal, Aviral Agarwal, Viviana Meruane and Sangwan K. S. Development of a machine learning based model for damage detection, localisation and quantification to extended structure life, *Procedia CIRP*, **98**, 199-204, (2021). https://doi.org/10.1016/j.procir.2021.01.030

[18] Xinlin Qing, Yunlai Liao, Yihan Wang, Binqiang Chen, and Fanghong Zhang, Machine learning based quantitative damage monitoring of composite structure, *International journal of smart and nano materials*, **13**(2), 167-202, (2022). https://doi.org/10.1080/19475411.2022.2054878

[19] Donato Perfetto, Alessandro De Luca, Marco Perfetto, Guiseppe Lamanna and Francesto Caputo, Damage detection in flat panels by guided waves based artificial neural network trained through finite element method, *Materials*, **14**(24), (2021). https://doi.org/10.3390/ma14247602

[20] Jiahui Guo, Xianping Zeng, Qijian Liu and Xinlin Qing, Lamb wave-based damage localization and quantification in composites using probabilistic algorithm and statistical method, *Sensors*, **22**(410), (2022). https://doi.org/10.3390/s22134810

[21] Bond L. J. Numerical techniques and their use to study wave propagation and scattering- a review, *Proc. of the Elastic wave and Ultrasonic Nondestructive Evaluation*, North-Holland, Amsterdam, 17-27, (1990).

[22] Koshiba M, Karakida S and Suziki M. Finite element analysis of Lamb waves scattering in an elastic plate, *IEEE transactions on Ultrasonics*, **31**, 18-25, (1984). https://doi.org/10.1109/t-su.1984.31456

[23] Weber R, Hosseini S. H. M., and Gabbert U. Numerical simulation of the guided Lamb wave propagation in particle reinforced composites, *Composite Structures*, **94**(10), 3064-3071, (2012). https://doi.org/10.1016/j.compstruct.2012.04.020

[24] Zhao X., and Rose J. Boundary element method for defect characterization potential in a wave guide, *International Journal of Solids and Structures*, **40**, 2648-58, (2003). https://doi.org/10.1016/s0020-7683(03)00097-0

[25] Doyle J. F. *Wave Propagation in Structures*, Springler- Verlag, New York, (1997).

[26] Murthy M. V. V. S., Renji K., Gopalakrishnan S. A spectral element for wave propagation in honeycomb sandwich construction considering core flexibility, *Composite Structures*, **127**, 28-40, (2015). https://doi.org/10.1016/j.compstruct.2015.02.074

[27] He S., Ng C. T. Analysis of mode conversion and scattering of guided waves at cracks in isotropic beams using time-domain spectral finite element method, Special issue: Structural Health Monitoring, *Electronic Journal of Structural Engineering*, **14**(1), 20-32, (2015). https://doi.org/10.56748/ejse.17214

[28] Shirsendu Sikdar and Sauvik Banerjee, Guided wave propagation in a honeycomb composite sandwich structure in presence of a high density core, *Ultrasonics*, **71**, 86-97, (2016). https://doi.org/10.1016/j.ultras.2016.05.025

[29] Adam Stawiarki and Alexander Muc, On transducer localization in damage detection by wave propagation, *Sensors*, **19**(8), 1937, (2019). https://doi.org/10.3390/s19081937

[30] Marek Barski and Adam Stawiarski, The crack detection and evaluation by elastic wave propagation in open hole structures for aerospace application, *Aerospace Science and Technology*, **81**, 141-156, (2018). https://doi.org/10.1016/j.ast.2018.07.045

[31] Ramadas C., Krishnan Balasubramaniam, Joshi M., and Krishnamurthy C. V. Interaction of guided Lamb waves with an asymmetrically located delamination in a laminated composite plate, *Smart Materials and Structures*, **19**(6), 065009, (2010). https://doi.org/10.1088/0964-1726/19/6/065009

[32] Giurugiutiu V. Tuned Lamb wave excitation and detection with piezo electric wafer sensors for structural health monitoring, *Journal of Intelligent Material Systems and Structures*, **16**, 291-305, (2005). https://doi.org/10.1177/1045389x05050106

[33] Seth S. Kessler, Mark Spearing S. and Constantinos Soutis, Damage detection on composite materials using Lamb wave methods, *Smart Materials and Structures*, **11**, 269-278, (2002). https://doi.org/10.1088/0964-1726/11/2/310

[34] Croxford A. J., Moll J., Wilcox P. D., and Michaels J. E. Efficient temperature compensation strategies for guided wave structural health monitoring, *Ultrasonics*, **50**(4-5), 517-528, (2010). https://doi.org/10.1016/j.ultras.2009.11.002

[35] Mohabuth M., Kotousov A., Ng C. T., and Rose L. R. F. Implication of changing loading conditions on structural health monitoring utilizing guided waves, *Smart materials and structures*, **27**(2), 025003, (2018). https://doi.org/10.1088/1361-665x/aa9f89

[36] Yishou Wang, Geng Wang, Di Wu, Yue Wang, Bingrong Miao, Hu Sun and Xinlin Qing, An improved matching pursuit-based temperature and load compensation method for ultrasonic guided signals, *IEEE Access*, **8**, 67530-67541, (2020). https://doi.org/10.1109/access.2020.2985748