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Investigation of Surface Damages in Composite Materials Using Ultrasonic Lamb Waves

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Abstract: In this research, it was aimed to figure out the damages in composite materials using the air-coupled ultrasonic method. The ultrasonic lamb waves were used to obtain C-scan images of damaged materials. A couple of planar air-coupled transducers (500 kHz-Ultran Group-USA), and an air-coupled scanning system (MISTRAS-EPA, France) were used for obtaining the data from the surfaces of materials used in this research. These transducers were located at different incidence angles for obtaining the lamb waves. The data obtained as A-scan signals was saved in txt data. This data was processed with the MATLAB codes for drawing C-scan images of the surfaces of materials. The results obtained from this research showed that the surface damages in composite materials can be characterized by using ultrasonic lamb waves.

Keywords: Non-destructive testing, air-coupled ultrasonic, surface damages, lamb waves, composites.

Ultrasonik Lamb Dalgaları Kullanılarak Kompozit Malzemelerde Yüzey Hasarlarının İncelenmesi

Öz: Bu araştırmada kompozit malzemelerdeki hasarların hava temaslı ultrasonik yöntemle belirlenmesi amaçlanmıştır. Hasarlı malzemelerin C-tarama görüntülerini elde etmek için ultrasonik lamb dalgaları kullanılmıştır. Bu araştırmada kullanılan malzemelerin yüzeylerinden veri elde etmek için bir çift düzlemsel hava temaslı transduser (500 kHz-Ultran Group-ABD) ve hava temaslı bir tarama sistemi (MISTRAS-EPA, Fransa) kullanılmıştır. Bu dönüştürücüler, lamb dalgalarını elde etmek için farklı geliş açılarında yerleştirildi. A-tarama sinyalleri olarak elde edilen veriler, txt formatında kaydedildi. Bu veriler, malzemelerin yüzeylerinin C-tarama görüntülerini çizmek için MATLAB kodlarıyla işlendi. Bu araştırmadan elde edilen sonuçlar, kompozit malzemelerdeki yüzey hasarlarının ultrasonik lamb dalgaları kullanılarak karakterize edilebileceğini göstermiştir.

Anahtar Kelimeler: Tahribatsız test, hava temaslı ultrasonik, yüzey hasarları, lamb dalgaları, kompozitler.

1. Introduction

Many errors and discontinuities such as missing plies, cracks, air gaps, voids, ply damages, matrix cracking, porosities, shrinkage, hail damages, fiber waviness, and fiber wrinkling can be seen in composite materials. These errors can be formed during production, cutting, transportation processes, or during usage of the materials. Some of these results occur because of human factors, while some of them occur because of uneven curing process as well [1]. All kinds of these defects should be figured out. If their size is over an acceptable size, they should be repaired or replaced. Otherwise, these errors can cause very big accidents, which may cause the loss of very important

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life and property. Therefore, the requirement for the quality control and structural health monitoring of materials has been a very important necessity nowadays. On the other hand, new types of composite materials such as metal matrix [2, 3], ceramic matrix [4, 5], and polymer matrix [6-9]. These newly produced materials need to be determined in different physical properties as well as quality controls.

There are different types of quality control techniques such as destructive (DT), semi-destructive and non-destructive testing (NDT) techniques. These techniques are the basic methods for the quality control of produced materials. The DT techniques have been carried in different types of composites [6, 10, 11]. However, the DT techniques damage the materials during the tests, and this increases the cost of the products. Thus, non-destructive testing methods are preferred to destructive testing methods. There are different types of quality control techniques that can be performed non-destructively such as liquid penetrant testing, eddy current testing, magnetic particle testing, radiographic testing, and ultrasonic testing[12, 13].

Ultrasonic testing (UT) has been proven as one of the best non-destructive testing methods for materials [8,14,15]. Traditional UT techniques are carried out to investigating metals, fiber-reinforced composites, polymers, and many different materials [7, 9, 14, 16, 17]. However, most of the conventional ultrasonic techniques use couplings such as water, glycerin, honey, etc. for transmitting the ultrasonic waves through the materials. Using these liquids might not be appropriate for the inspection of certain materials. Because that the inspected materials can absorb the couplings, which can cause some contaminations, corrosions, or damages. Recently, air-coupled ultrasonic techniques have been introduced as an alternative way to inspect materials in NDT of materials characterization. This method eliminates the usage of external coupling media from the measurement process. Air-coupled ultrasonic also figure out a faster and more convenient examination possibility to the researchers, who control the materials. The main advantage of this method is that air is all around us every time and the air is free of charge. The air is very useful for highly damping materials and certain composites, where the traditional C-scan methods can be difficult to apply. The Air-Coupled Ultrasonic Testing (ACUT) became increasingly desirable for the quality control of different materials such as plastics, rubbers, composites, foams, and similar materials [18-22].

Air-coupled ultrasound has many advantages compared to traditional ultrasonic techniques [23]. However, the difference between the acoustic impedance of the air and solid materials is a limitation for using ACUT. Thus, the production of ultrasound in the air is an important problem that should be solved. The ACUT has been used for a long time [21,22, 24-26].

Using air as a coupling medium is useful for materials such as foams, and different types of polymer composites. Because that the attenuation amount is proportional to the square of the frequency, the lower frequencies are preferred in ACUT applications. It is known that ACUT transducers can be directed at different angles to obtain different wave modes for UT inspections [27]. Nowadays, different kinds of ACUT transducers have been used in air- coupled ultrasonic applications without using any liquid coupling medium. The through transmission and one-sided pitch-catch techniques are mostly used in air-coupled ultrasonic testing [28]. These techniques are carried out generally with two transducers separated from each for sending and getting ultrasonic waves. Longitudinal, Shear, and Guided waves (Rayleigh and Lamb waves) are used in these techniques.

There are two types of propagation of Lamb waves (ant-symmetric and symmetric) as dispersive waves. Lamb waves' propagation characteristics in isotropic materials have been defined by different scientists [29-31]. The phase and group velocity of Lamb waves are related to structural stiffness. The phase and group velocities of lamb wave decreases, when they travel through a media have reduced stiffness. The phase and group velocities of an ultrasonic wave depend on the orientation angle of the reinforcing fibers in composites [32]. Therefore, damages in materials can be figured out by analyzing the difference between the phase and group velocities. Lamb waves are very useful waves for characterizing errors, which are on the surface, and close to the surface of the thin materials, such as large panels. Because lamb waves can propagate during the surface, they have been used in the characterization of anisotropic plates for several decades [33]. The one-sided pitch-catch technique is carried out using two transducers, which are placed on the same side of the specimen. Therefore, this technique is useful for large and thin plates. The high-quality images obtained with air-coupled applications using lamb waves have proved the one-sided pitch-catch technique. The principle of acoustic imaging is to monitor arrival times/amplitude of acoustic pulse through the structure to investigate. The presence of a defect will delay/diffract the wave. Representing different times of flights (TOF) or amplitudes within the selected gate will give the data related to the presence of the flaws in the mediums. The quality of the signal depends on a lot of experimental parameters. Tian and Yu [34] have investigated Lamb waves using the frequency–wavenumber filtering applications to crack characterizations in an aluminum plate. Chennamsetti et al. [35] were carried a numerically and experimentally research on glass-fiber reinforced plastic (GFRP) with TOF of Lamb waves using the one-sided pitch-catch ACUT and figured out a good prediction about the damage dimensions.

On the other hand, it should be stated that Lamb waves' propagations in composite materials are more complex due to anisotropy. The fiber volume fractions, reinforcements, layup, and type of matrix strongly affect the propagation velocity of lamb waves in composite materials. This is one of the disadvantages of the Lamb waves. Except this also there are some disadvantages of ACUT such as the acoustic impedance mismatch, and the divergence of ultrasonic waves. The divergence problem is eliminated by using focused ACUT transducers, while the acoustic impedance mismatch problem is eliminated by using ACUT transducers having lower frequencies. On the other hand, the ACUT C-scanning measurements should be carried out in the best conditions for obtaining high-quality c-scan images. In this research, the lamb wave application was carried out to figure out the defects and disbands in composite laminate and honeycomb composite samples. Thus, the main aim of this research was to find the best scanning conditions with lamb waves for getting high definition c-scan images of the Carbon/Epoxy and Composite samples, which figure out the defects in these materials.

2. Experimental Methods

2.1. Materials

An air-coupled system (MISTRAS Group SA-EPA, France) (Figure1) and a couple of non-contact ultrasound probe (NCG 500 D13- Ultran Group-USA) made from Gas Matrix Piezo (GMP) material with a central frequency of 500 kHz, a honeycomb sandwich composite sample and a carbon/epoxy composite sample (Figure2) were used in this research.

2.2. Air-coupled Ultrasonic Scanning System

The air-coupled ultrasonic scanning system (Figure1) is based on the use of powerful electronic cards for the generation of signals (up to 280 V peak-peak) and reception. The emission card allows generating a different type of signals, like sin function, square signal, and arbitrary waveform generation. The reception card allows setting an adjustable gain (+20 dB/+40 dB/+60 dB) and involves pre-designed filters.

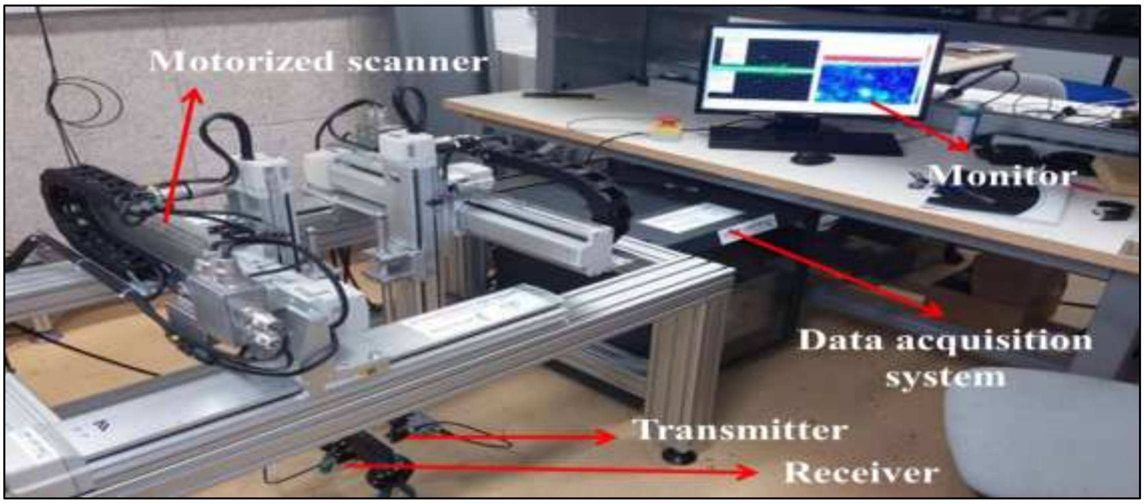

Figure 1. Air-coupled scanning system

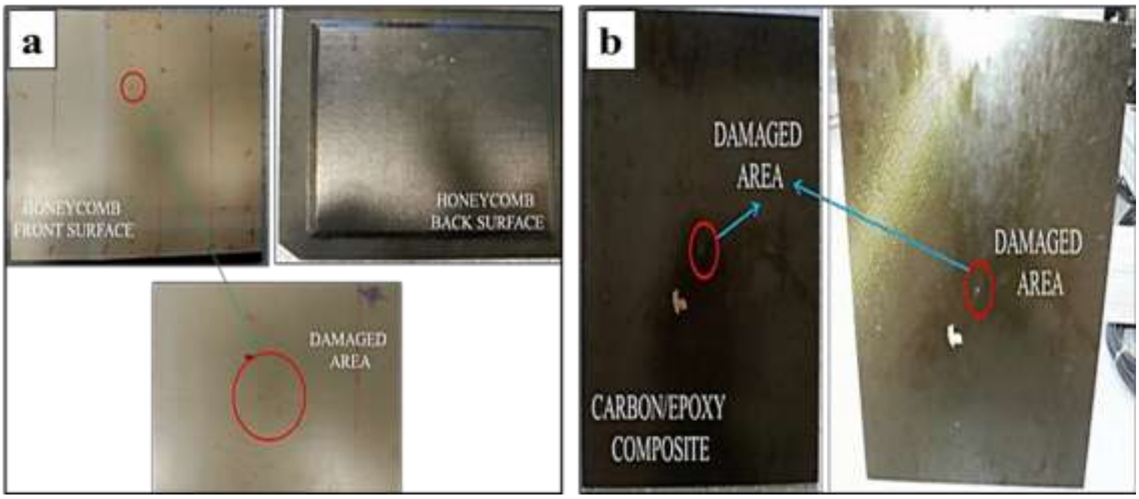

Figure 2. The materials used for air-coupled C-scan measurements: (a) Damaged honeycomb sample, (b) Damaged carbon/epoxy composite sample

A couple of planar narrow-band piezoelectric air-coupled ultrasonic transducers made of Gas Matrix Piezo material (Ultran®group-USA) were used for all applications. The central frequency of these unfocused ACUT transducers was 500 kHz with 25% bandwidth. Their diameters were 12.50 mm. All experiments were carried out using the one-sided pitch-catch technique. In this technique, one transducer is used as a transmitter while the other one is used as a receiver of ultrasonic waves. The transducers were oriented on the surface of the samples with an angle of about 400. The position and angle of each transducer were adjusted manually as shown in Figure3.

The most of ultrasonic energy reflects because of acoustic impedance mismatch between air and testing samples. However, a small amount of ultrasonic energy propagates along the surface of the samples as Lamb waves when the suitable angle is adjusted. When these ultrasonic Lamb waves reach the receiver transducer, they were converted back to electrical energy. The received signals were amplified by the inbuilt amplifier. They were amplified about 20 dB with a low noise auxiliary preamplifier. After that these waves were directed through a 60 dB preamplifier as well.

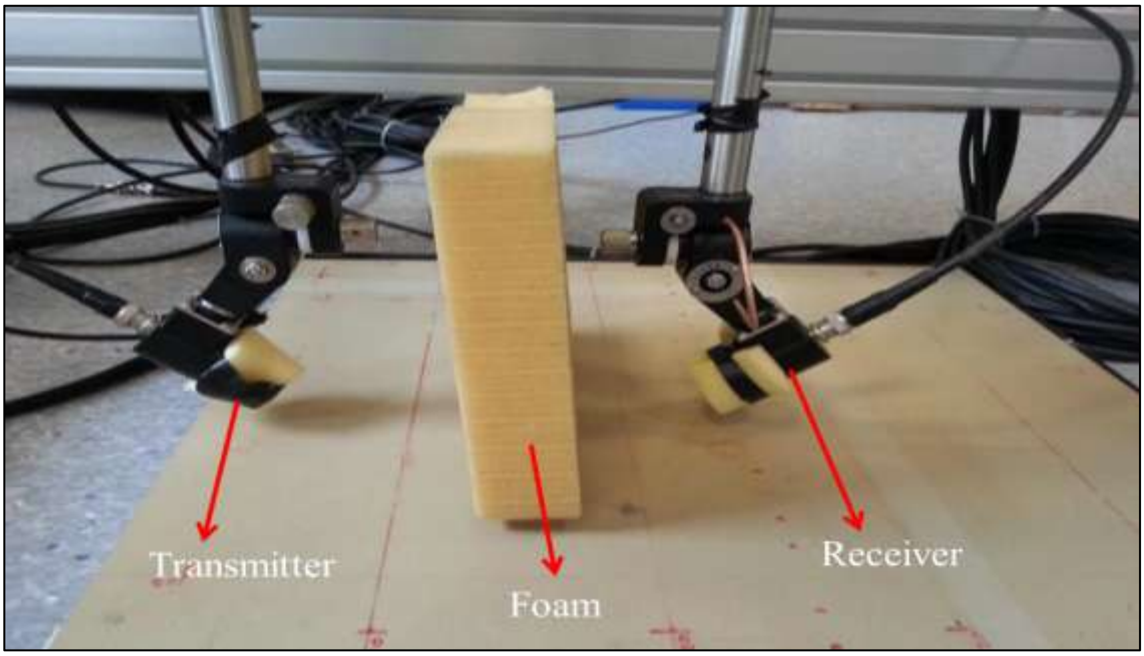

Figure 3. The air-coupled ultrasonic testing system using lamb waves

3. Findings

The ultrasonic lamb wave applications were carried out on carbon/epoxy composite laminate and honeycomb composite samples. Different angles were tried with emitter and receiver transducers on the surface of composite materials for forming lamb waves to investigate the defects on their surface and near the surface as well. Therefore, the A-scan signals obtained from each of the incidence angles were analyzed using MATLAB codes. The data obtained from these studies were given in Figures 4-16.

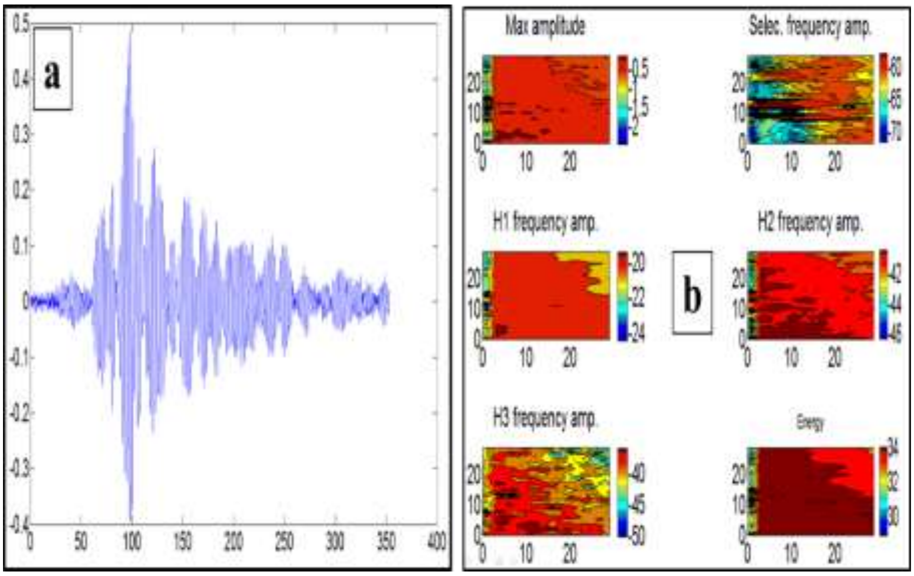

Figure 4. Ultrasonic lamb wave C-scan images of honeycomb composite obtained by an unfoamed transducer (a: A-scan signal of scan 0, b: Scan 0 data around peak-1)

3.1. Finding Related to Honeycomb Composite Sample

Nine different orientations namely Scan-0 (without foam), Scan-1 (with foam), Scan-2 (Figure6), Scan-3 (Figure7), Scan-4 (Figure8), Scan-5 (Figure9), Scan-6 (Figure10), Scan-7 (Figure11), and Scan-8 (Figure12) for honeycomb composites, while five different orientations called Scan-1, Scan-2, Scan-3 closer (the transducer was kept closer to the surface), Scan-4 far (the transducer was kept far from the surface) and Scan-4 far2 (the distance to the surface was increased) for carbon/epoxy composite were carried out as well. This process was carried out to find the best angle to form lamb waves for detecting the damaged regions in composites.

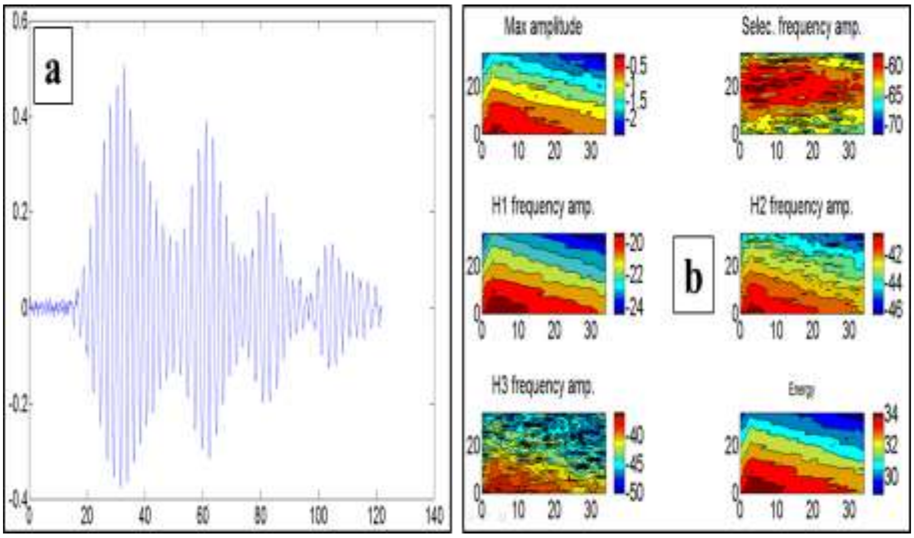

Figure 5. Ultrasonic lamb wave C-scan images of honeycomb composite obtained by a foamed transducer (a: A- Scan signal of scan1, b: Scan 1 data around peak-1)

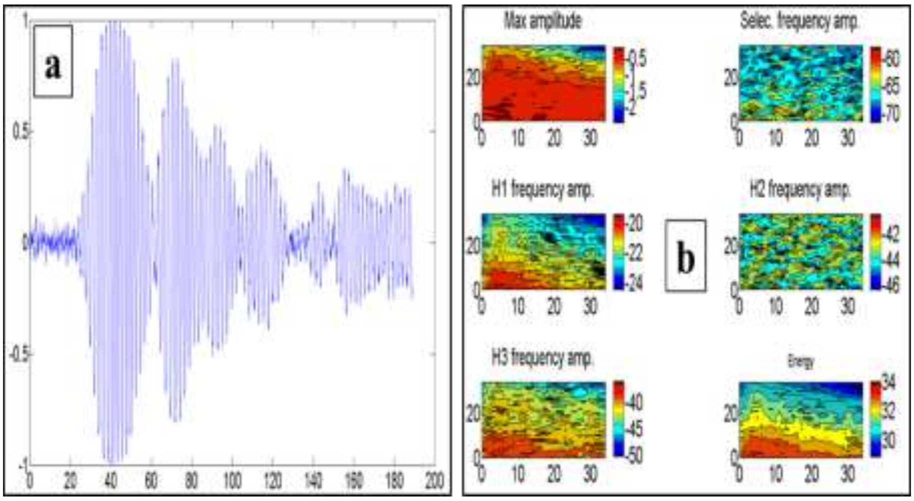

Figure 6. Ultrasonic lamb wave C-scan images of honeycomb composite obtained by a foamed transducer (a: A-scan signal of scan 2, b-Scan 2 data around peak-1)

As it can be seen from Figure 4 and Figure 5, the c-scan images obtained with foamed transducer are clearer than the images obtained with an un-foamed transducer. Therefore, all the other one-sided pitch-catch applications were carried out with foamed transducers.

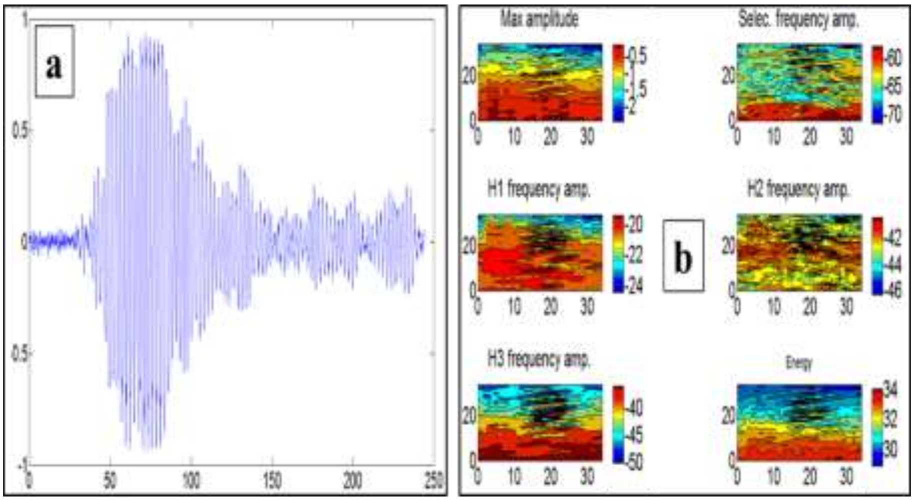

Figure 7. Ultrasonic lamb wave C-scan images of honeycomb composite obtained by a foamed transducer (a: A- scan signal of scan3, b: Scan 3 data around peak-1)

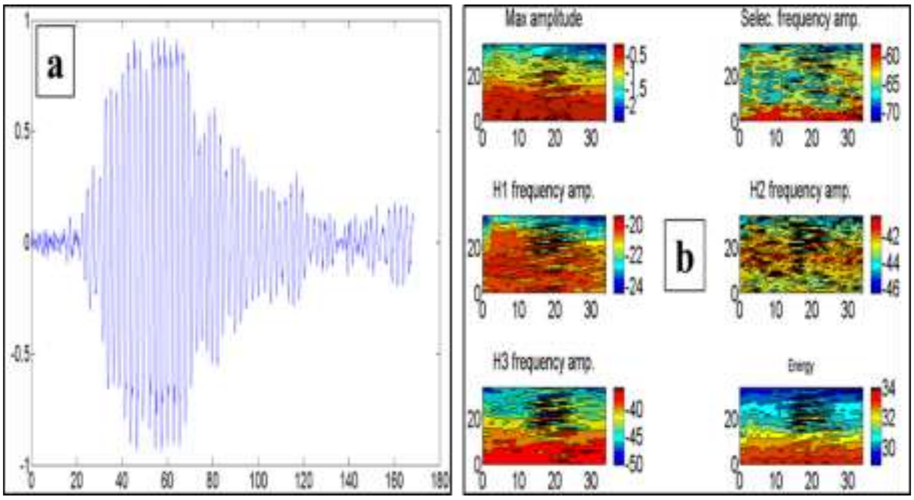

Figure 8. Ultrasonic lamb wave c-scan images of honeycomb composite obtained by a foamed transducer (a: A- scan signal of scan 4, b: Scan 4 data around peak-1)

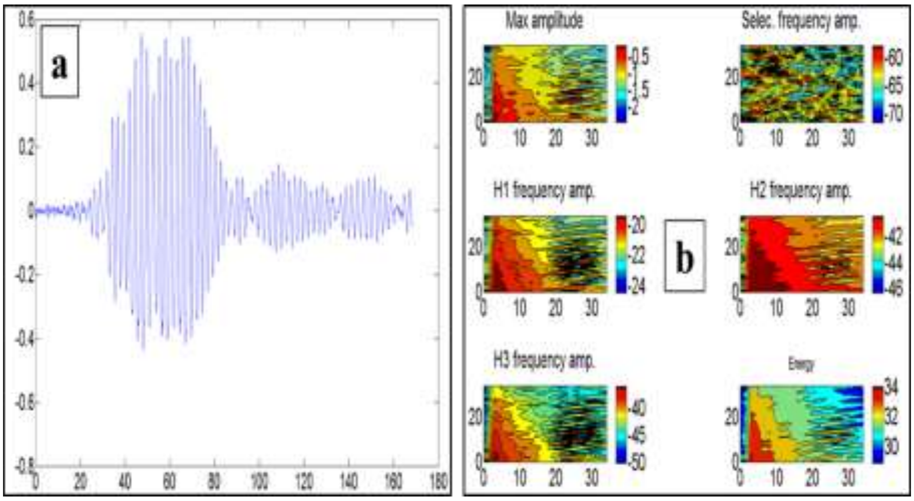

Figure 9. Ultrasonic lamb wave c-scan images of honeycomb composite obtained by a foamed transducer (a: A- scan signal of scan 5, b: Scan 5 data around peak-1)

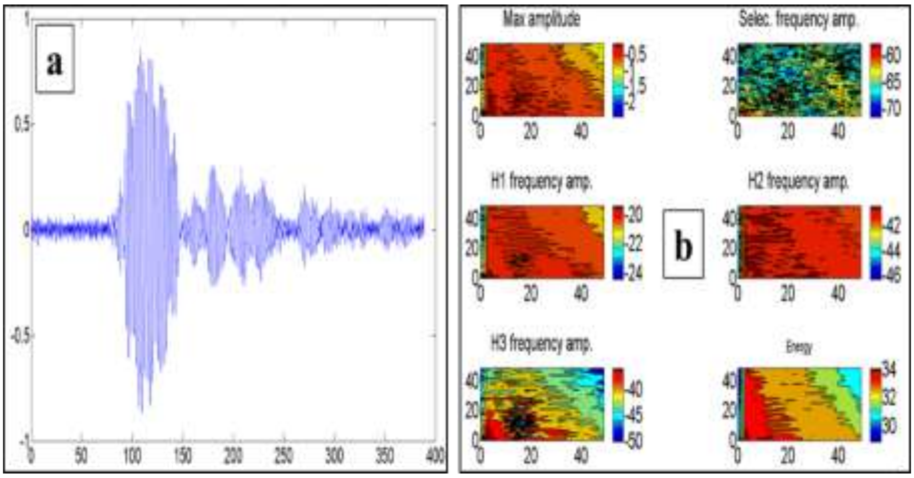

Figure 10. Ultrasonic lamb wave C-scan images of honeycomb composite obtained by a foamed transducer (a: A- scan signal of scan 6, b: Scan 6 data around peak-1)

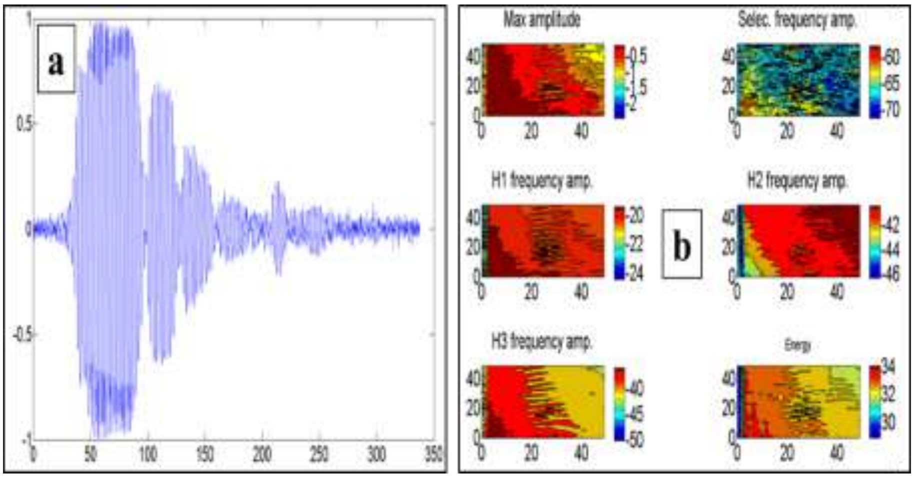

Figure 11. Ultrasonic lamb wave C-scan images of honeycomb composite obtained by a foamed transducer (a: A- Scan signal of scan7, b: Scan 7 data around peak-1)

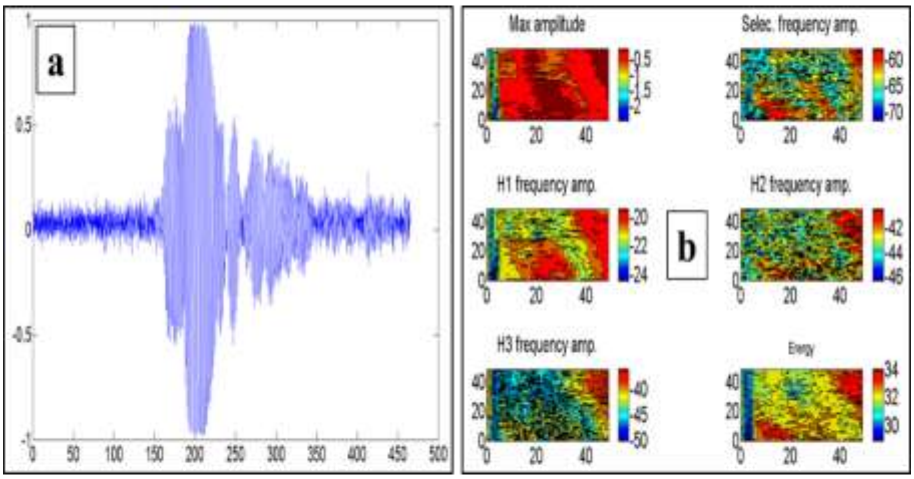

Figure 12. Ultrasonic lamb wave C-scan images of honeycomb composite obtained by a foamed transducer (a: A- scan signal of scan 8, b: Scan 8 data around peak-1)

According to the C-scan images obtained for the honeycomb composite, it is seen that Scan 3 (Figure 7), Scan 4 (Figure 8) and Scan 5 (Figure 9) images are better than others. It is believed that these three A-scan signals are lamb wave signals and the images obtained by processing these signals with MATLab give some information related to the surface of the honeycomb composite sample. When these three images data are carefully analyzed, it can be realized that the image obtained by the transducer's orientation of scan 4 is better than of scan 3 and scan 5, because that the defected area can be defined more clearly from Figure 8.

3.2.Finding Related to Carbon/epoxy Composite Sample

Five different orientations, called Scan 1, Scan 2, Scan 3 closer (the transducer was kept closer to the surface), Scan 4 far (the transducer was kept far from the surface), and Scan 4 far2 (the distance to the surface was increased) for carbon/epoxy composite, were carried out. The data obtained for Carbon/epoxy composite samples were given in Figures 13-17.

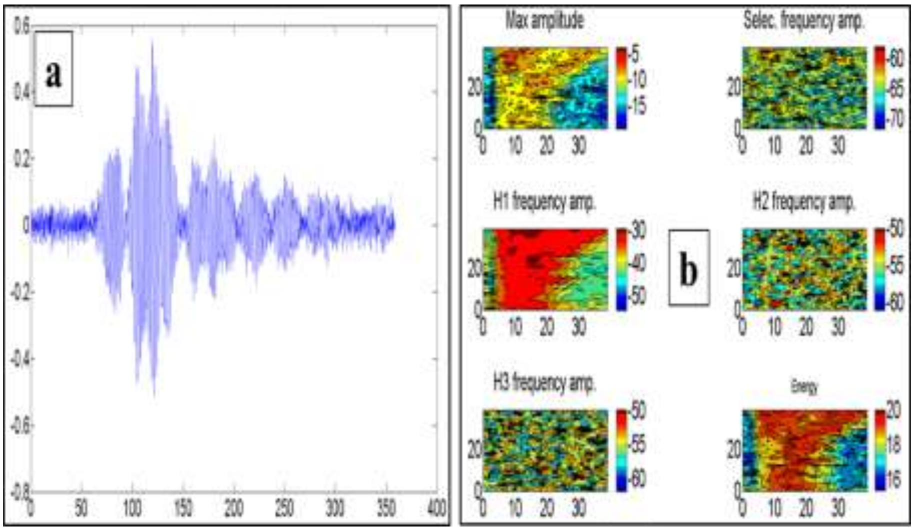

Figure 13. Ultrasonic Lamb wave C-scan images of carbon composite obtained by foamed transducer (a: A-Scan signal of scan 1, b: Scan 1 data around peak-1).

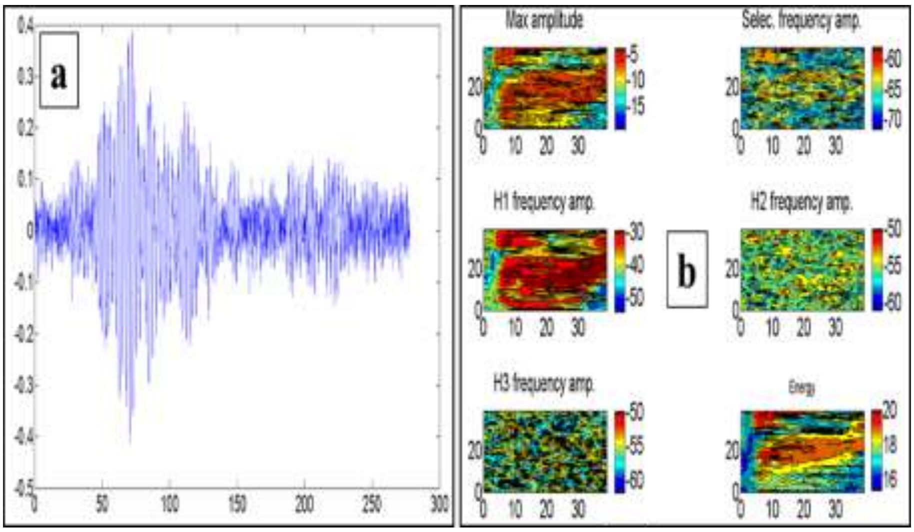

Figure 14. Ultrasonic lamb wave C-scan images of carbon composite obtained by a foamed transducer (a: A-scan signal of scan 2, b: Scan 2 data around peak-1)

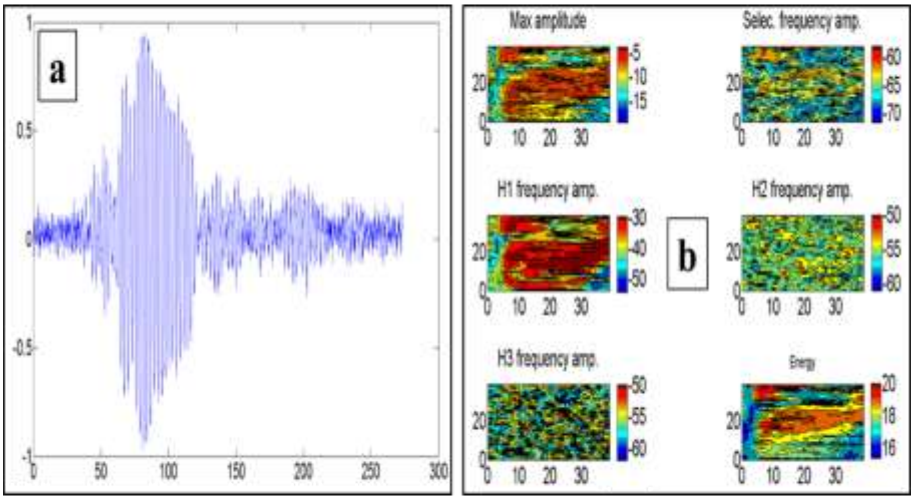

Figure 15. Ultrasonic lamb wave C-scan images of carbon composite obtained by a foamed transducer (a: A-scan signal of scan 3 closer, b: Scan 3 closer data around peak-1)

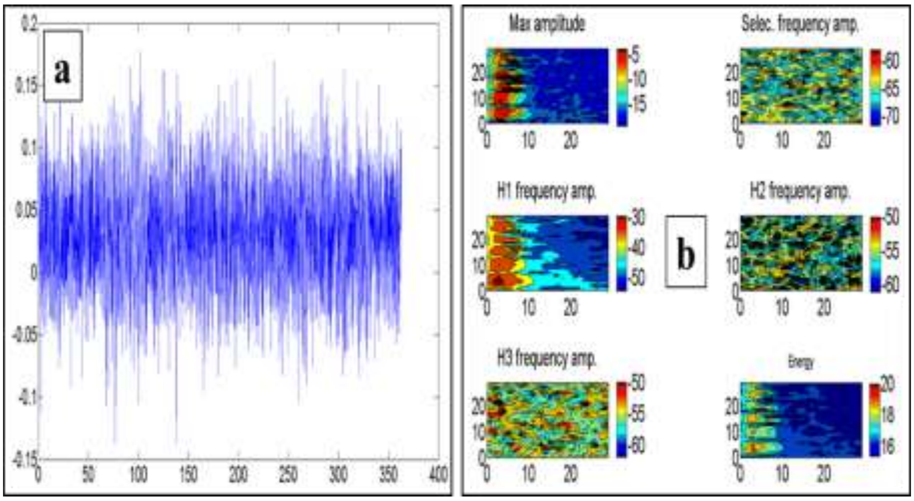

Figure 16. Ultrasonic lamb wave C-scan images of carbon composite obtained by a foamed transducer (a: A-scan signal of scan 4 far, b: Scan 4 far data around peak-1)

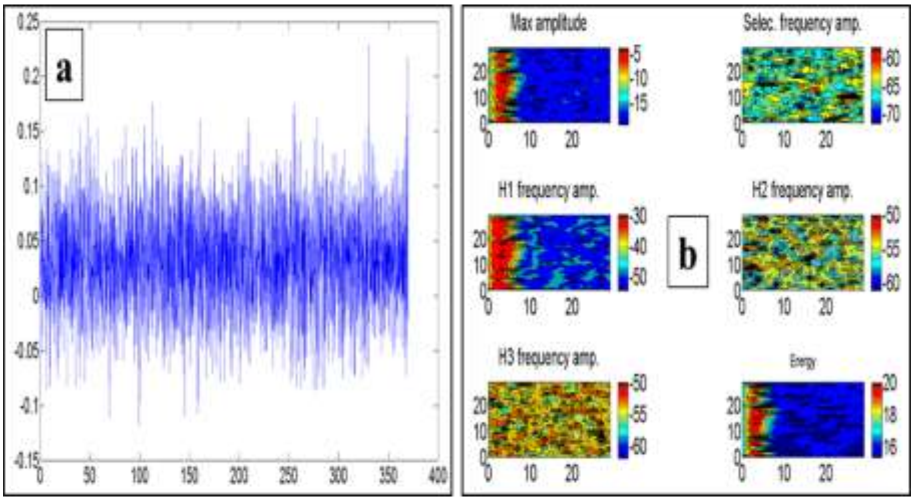

Figure 17. Ultrasonic lamb wave C-scan images of carbon composite obtained by a foamed transducer (a: A-scan signal of scan4 far2, b: C-scan 4 far2 data around peak-1)

It was aimed to figure out the damaged area on the surface of the carbon/epoxy composite sample. Therefore, when the c-scan images obtained for the carbon/epoxy sample were analyzed, it seems that the results of scan-2 and scan-3 are better than the others. But the more detailed investigation on damage zone it can be stated that the image obtained with scan-3 is the best image, which defines the damage very well (Figure14).

4. Results and Discussion

The one-sided pitch-catch ACUT applications have been recently carried out to figure out the damages on the surface and near the surface of different kinds of composite structures [36, 37]. Also, the ply waviness and wrinkles in thick carbon and glass fiber reinforced composites can be detected with this technique. The one-sided pitch-catch ACUT can be used as a non-contact, and portable technique to use in nondestructive evaluations of aircraft composites, as well. The damaged zones in the honeycomb composite sample and carbon/epoxy composite sample were tried to figure out by data obtained using ultrasonic lamb waves. This data obtained with the one sided pitch-catch ACUT technique was analyzed, and the images of these samples' surfaces were imaged with MAT Lab codes. These one-sided pitch-catch ACUT applications were carried out with different incidence angles to form lamb waves on the samples' surfaces. The obtained results were given and discussed in this section of this research.

In one-sided, pitch-catch ACUT applications, the reflected signals, which overwhelm the weak lamb wave signals related to the interior structure of the test sample, should be blocked. Therefore, a foam piece was replaced between transmitter and receiver transducers to block these kinds of reflected signals. To see the effect of this foam firstly the one-sided pitch-catch ACUT experiment was carried out using a foam piece, and without using a foam piece as well. When the c-scan images in Figure4, and Figure 5 were compared with each other, it is seen that the c-scan images obtained with foamed transducer are clearer than the images obtained with an un-foamed transducer. Because of this reason, all of the other experiments were carried out in different orientations of transducers, were carried with using a foam piece between transmitter and receiver transducers.

When the figures obtained for honeycomb sandwich composite sample are analyzed, it is seen that transducer orientation named as Scan 4 (Figure8) define the damaged region better than other orientation. Also, it can be concluded that if the suitable orientation and conditions can be applied in one-sided pitch-catch ACUT, one can found out the surface errors with lamb waves. Also, it can be stated that the c-scanning images adjusted with MAT lab codes can be used to characterize the surface damages of honeycomb composites. Li et al. [26] were carried out the ACUT using lamb waves to detect defects in silicon solar cells. They figured out the cracks from the data of amplitude distributions obtained from solar cells. Bustamante et al. [21] tried two different non- contact air-coupled UT systems to figure out the flaws in CFRP and aluminum plates. They have proved these two ACUT techniques for detection flaws in these kinds of materials. Chakrapani et al. [22] were presented a review about detecting flaws such as slots, delamination, and fiber waviness in wind turbine blades using ACUT. In conclusion, it was proven that the flaws, ply waviness, and porosity in aerospace composite structures and laminates can be figured out by one- sided pitch-catch ACUT using lamb waves with suitable orientations.

5. Conclusions

Based on the findings obtained from this research, the following conclusions can be given:

1- Using foam between transmitter and receiver transducers in one-sided pitch-catch ACUT is beneficial to block the reflected waves to improve the resolution of c-scan images.
2- One-sided pitch-catch c-scan measurements are carried out with lamb waves, which can help us to obtain very important information related to defects near the surface of the samples.
3- The c-scan 3 made by using lamb waves, gave the best c-scan images for both carbon/epoxy and honeycomb composite samples.

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Authors' Contributions

OI carried out the work and wrote up the article.

Competing Interests

The author(s) declare that they have no competing interests.

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