Damage Detection and Structural Health Monitoring of ST-37 Plate Using Smart Materials and Signal Processing by Artificial Neural Networks

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ABSTRACT

Structural health monitoring (SHM) systems operate online and test different materials using ultrasonic guided waves and piezoelectric smart materials. These systems are permanently installed on the structures and display information on the monitor screen. The user informs the engineers of the existing damage after observing the signal loss which appears after damage is caused. In this paper, monitoring is done for plate shaped structures made of ST-37 steel. After conducting the experimental tests, the stored signals by the multi-layer artificial neural network algorithm are processed and the damage caused in the plate is detected. By analyzing the graphs, it becomes clear that after causing damage the signal amplitude decreases. In the experimental test, two piezoelectric discs are used on a steel plate which has been installed using a strong adhesive. Using a strong adhesive improves wave propagation in the structure. Developing innovative testing methods for the SHM system has caused better control in structures after assembly.

1-Introduction

Monitoring and damage detection of structures are considered an important process in sensitive industries. This system is a growing trend of periodic nondestructive tests (NDT) which is permanently installed on structures and is referred to as structural health monitoring (SHM).

Gazis [1] conducted the structural health test on a structure immersed in lead and at a temperature of 4500°C. After conducting this test, an approach is proposed for optimal conduction of the test and also for solving the problems which occurred at high temperature. In this research, methods such as the ultrasonic test and measurement with a laser beam are used. The purpose of the test, final evaluation, and improvement is in damage detection, which has been achieved using a laser beam with high precision. Transferring the signals of each test to the screen is done by using piezoelectric sensors installed on the piece. After the signals are transferred, the damage detection process is conducted by analyzing the obtained graphs.

In a research Farrar et al. [2] analyzed elements with a probability of high damage. In an experimental test by reducing the difference between energy levels through comparison of external and internal forces exerted upon each element, a mathematical model was estimated. The emergence of damage during the life span of structures such as bridges, oil rigs and all structures in general is inevitable. So far, numerous examples of different damages in various engineering structures have been recorded which, in the wake of their occurrence,

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lots of life and property damages have occurred. Most of these damages can be revealed, modified and repaired by initial analysis of structures and thus the spread of damage in structures and their collapse can be prevented. This matter doubles the importance of structural health monitoring in earthquake zones where local damages in elements of the structures can be the source of overall damages. Therefore, damage detection in structures and their accessories is an important and necessary matter, after which the safety and reliability of the existing state of structures will emerge. If the damage in structures is detectable in some way, by repairing or replacing the damaged elements, the occurrence of overall damages in structures can be prevented. As a result, health monitoring systems can play a crucial role in securing and improving structures. Furthermore, they prevent life and property damages caused by the collapse of structures. The main focus of this paper was on structures with a high probability of failure, and old structures were used as the evaluation criteria which caused limitations in the application of the testing method. Similar to the previous research, no analytical data software has been used for automatic damage detection.

Staszewski et al. [3] used conventional NDE techniques, such as C-scan, radiographic inspection, eddy current, acoustic emission, vibration-based analysis, using eigen-frequency and mode shapes, and ultrasonic inspection, which are still widely used to inspect structural integrity.

Wandowski et al. [4] conducted health monitoring on four points in a structure. Ultrasonic guided waves on the structure were sent to the aid of piezoelectric and then recorded by a laser vibrometer. Different frequencies of the actuator were also analyzed in this test. They used two types of the actuator in order to compare the results of both actuators and select the best one. Nowadays, new devices with high sensitivity are used in the structural health monitoring systems. Furthermore, in order to process the stored signals, computer programming is used. In this paper, programming in MATLAB and C++ is utilized. In this test, ultrasonic waves are used in structural health monitoring in order to create high sensitivity in damage detection. In this paper, a laser vibrometer is used, and its use is evaluated. Additionally, due to measurement using a laser vibrometer, software codes were not used for analysis of data and automatic damage detection.

Lehfeldt et al. [5], Ball et al. [6], Mansfield [7] and several other researchers have recognized the advantages of using Lamb waves for fast inspection, where some reduction in sensitivity and resolution compared with that obtained in standard, high-frequency ultrasonic inspection can be tolerated. For example, Lamb waves have been used to carry out coarse, quick inspection on a variety of different strips and plates.

Payo et al. [8] used PKI- 502, commonly known as “Navy type II," similar with PZT5A, by Piezo Kinetics Inc. and acrylic paint base provided by Rohm and Haas with various additives required for a viable paint. The piezoelectric coating was poled with an electric field of 5kV/mm at room temperature for 10 s. Ricles et al. [9] monitored the structural health and analyzed the damages caused in the structure by the weight of the structure. Their research focused on the analysis of increasing the load applied on structures. High complexity in design and attention towards durability and longevity in structures in the fields of road and structure, mechanical components and aerospace structures, highlights the importance of structural health monitoring more than ever. The extensive methods of nondestructive tests by utilizing strain gauge, penetrating fluids, ultrasonic waves, visual inspections, etc. are the available methods for damage detection in structures. Unfortunately, all the aforementioned methods require a long time and high costs for inspection. In this paper, the proposed method was specific to heavy structures and had limited application in light structures.

Rose et al. [10] have reported investigations using Lamb waves to inspect K-joints in off-shore structures and the Welding Institute in the U.K. had been developing an acoustic pulsing technique to monitor crack growth in large plate-like structures [11].

Optimal baseline subtraction sought to minimize the impact of harmless changes in reflections by using a pool of baseline signals, which were collected under different operating conditions comprising all the typical ones of the structure that were monitored. The temperature difference between two locations along the pipeline could reach several degrees, which would result in varying changes to wave packet arrival time. In order to increase the chances of a successful baseline subtraction approach, the aforementioned effect was compensated for.

The proposed method to compensate for localized as well as global temperature variations involved a multi-step stretch procedure. In the initial step, the baseline stretch was applied to compensate for global temperature variations of the pipeline, as mentioned by other authors [12].

Once a new reading was collected, the optimal baseline within the pool was chosen to be the one that minimizes the RMS value of the residual signal. In this way, the extent of the non-damage related the residual signal decreased by reducing the difference in the structure operating conditions between the baseline signal and the current signal [13].

Furthermore, some pieces cannot be inspected as they are not accessible. This leads to damage increase to a critical level in the intervals between periodic inspections. This major flaw made the engineers think about developing new methods to continuously monitor the structures. Methods implemented based on vibration response provide the chance to extract meaningful data from time or frequency areas and attends to calculating the change in structure features and modals such as resonance frequencies, attenuation and shape of the modes and employs them in developing reliable methods to detect, locate, and decrease damages.

One of the important points in damage detection in plates is that gradually damage will occur on the plate. The results have caused structures today to be equipped with measurement tools. Other results from this study are as follows: with the change in non-elastic behavior in the structure parts, no physical damage was observed. Also, in structures that have high weight, the occurred damage will spread and serious damages such as the impacts of an earthquake can be hidden in the structure and with the force of its weight, the structure will collapse. Thus, monitoring in these structures is vital.

Atashipour et al. [14] performed an experimental health monitoring test on a steel beam by causing an intentional damage. In the test, an actuator and a ceramic piezoelectric sensor were installed on the steel beam. This actuator created ultrasonic guided waves, and the sensor saved the reflected signals of surface and deep damages in the beam. To process the saved signals artificial neural network algorithm was used. The result of this test showed that the suggested criteria for structure health monitoring together with artificial neural network are strong tools in damage detection in structures. This is especially useful in thin-walled structures. The main focus in this paper was damage detection on the data extracted from software simulations, and the simulated data were used for automatic damage detection, which were slightly different from real environment and no valid results could be gathered from them.

In the present work, taking the research history into account and having identified the deficiencies of conducted researches, damage detection is done on an ST-37 plate made from stainless steel. The material of the plate is chosen considering the high usage of steel in different industrial structures. In this experiment, steel glue is used in order to further reinforce the sensor and actuator to the structure which is estimated to yield better results than experiments conducted until now. The main innovation of this paper is in utilizing multi-layer artificial neural network in structural health monitoring. After identifying the base line signal of a healthy structure, this optimal and multi-layer artificial neural network algorithm automatically performs the structural health monitoring and damage detection process and in case any damage exists it will automatically warn the operator. The use of a multi-layer artificial neural network makes the process of damage detection much more accurate as compared to the past.

However, regarding structural health monitoring, developing a setup on the structure and receiving a correct response and also performing automatic damage detection on structure is considered an important innovation. This significant matter is performed in the Smart Systems and Structures Laboratory of Islamic Azad University, Najafabad Branch.

In this paper, the damage detection and SHM system are performed on sample sheets in test setups. For the first time, the sheets are chosen from stainless steel ST-37 and also in the experimental tests of this study, an actuator and a ceramic disk sensor are used. To process the saved signals and perform automatic damage detection, a multi-layer artificial neural network algorithm is used.

2-Problem statement

In all the existing definitions of smart structures, the emphasis is put on them being alive and their artificial intelligence. The structures have the power to sense (measurement) and act. The AI of the smart structures is given to them by electronic circuits that have the ability to choose a proper response in the environment and alien actuators. Fig. 1 presents a schematic of the smart structure used in the experimental tests of this study. It can be seen that the actuator and sensor are installed on the outer surface of the sheet. The function generator that is connected to the actuators propagates in the structure by sending waves, and then the returning waves reach the sensor and first pass a hardware filter to remove the noise and then the signals are saved by an oscilloscope. After saving the signals, the process begins and the damage detection output is done by a smart algorithm.

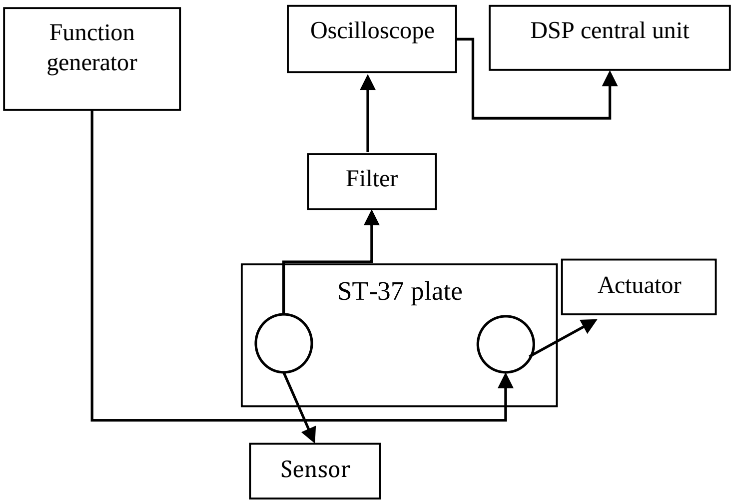

Fig. 1. Schematic representation of the smart system used in the experimental tests.

2-1-Finite-element method simulations for database development

In this study, at first the plate is simulated by software. The simulation reveals the pattern of wave spreading in the plate. Then the capacities of the excitation signal in the damage detection process are assessed using ultrasonic waves before the experimental test. Furthermore, the best methods for placement and installation of the actuators and sensors are determined. In these simulations, the pieces are modeled using the ABAQUS software. Under most circumstances, the currently available commercial FEA software can provide only a single modeling interface for a specific geometry. Such a procedure is extremely laborious and repetitive with various geometric parameters, since the whole system should be remodeled. This becomes even more challenging when the damage parameters involved are also varied [15]. Choosing the proper place of installation for the sensor results in receiving better data from the structure.

In this paper, the goal of performing a simulation is to choose the best installation site for the sensor and actuator which causes the most optimal state in conducting the experiment. Due to the fact that in this experimental test, the sensor and actuator are glued using steel glue, the reproducibility and probability of testing different installation sites would not be possible and because of this, a reproducible simulation is used. The main data for signal processing are also extracted from the experimental tests.

2-2-Equations

Generally, the movement of elastic stress waves in a continuum can be represented by the following matrix relation [16-17]:

$$\mu \vee^2 (\lambda+\mu)\vee\vee.u = \rho \frac{\partial^2 u}{\partial r^2} \quad (1)$$

where μ and λ are lame coefficients, ρ is density, and **u** is the displacement vector. For an isotropic matter, lame coefficients can be shown as follows [16-17]:

$$\mu = \frac{E}{2(1+v)} \quad (2)$$

$$\lambda = \frac{Ev}{(1-2v)(1+v)} \quad (3)$$

where *E* represents the Young modulus and *v* represents the Poisson's ratio. By using displacement potential method, which is based on Helmholtz's theorem, and by defining two potential functions ϕ and equation (1) can be placed as [16-17]:

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}+\frac{\omega^2}{c_1^2}\phi=0 \qquad (4)$$

$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}+\frac{\omega^2}{c_l^2}\psi=0$$

(5)

In the above relations x represents the wave propagation direction, y perpendicular to propagation direction, frequency on the wave c_l, longitudinal wave velocity, and c_t shear wave velocity. Wave spreading velocities can be demonstrated as the following coefficients [16-17]:

$$c_l^2=\frac{\lambda+2\mu}{\rho},\; c_l^2=\frac{\mu}{\rho} \qquad (6)$$

3-Experimental procedure

To set up structural health monitoring system and performing experimental tests to detect damage and monitor the health of plate lines, ultrasonic guided waves are used. To choose the plate, at first the curve for wave dispersion in the plates is drawn and the best choice is a plate with 2 mm thickness. In the experimental tests of this study, initially, a plate of 300x200 mm is used. Then two piezoelectric transducers with a distance of 170 mm are placed on the plate. One of them is for the sensor and the other for activating. The piezoelectric transducers are installed on the edges of the plate and in its width. According to Fig. 2, the dispersion curve for the steel plate is extracted, and the best frequency for the vector sample is chosen. The frequency of the vector sample for this test is 200 kHz. The thinner the plate is, the better the output results will be, and the wave will transmit better, too. The actuator and the sensor used in the tests are piezo-ceramic type. These piezoelectric transducers are the piezo-disc model, and each has a thickness of 0.9 mm and a diameter of 15 mm. One of these piezoelectric transducers is installed as actuator and the other as a sensor. The experimental test begins when the created wave by the function generator is sent to the actuator piezoelectric transducers, and it propagates in the structure. Then the sensor piezoelectric receives the response signals and displays them on the oscilloscope, then storing is done on a flash drive.

After the wave is sent by the actuator and ultrasonic waves spread across the plate, the transmitted and reflected waves reach the sensor, and the function of the sensor is to display and store the responses in digital signal form. Fig. 2 displays the dispersion curve of Lamb waves for steel plate.

In order to store information of the received signals from the oscilloscope, it is required that the storage be programmed automatically because this experiment is conducted within the short time of 200 microseconds. The experimental test begins when the created wave by the function generator is sent to the actuator piezoelectric transducers, and propagates in the structure.

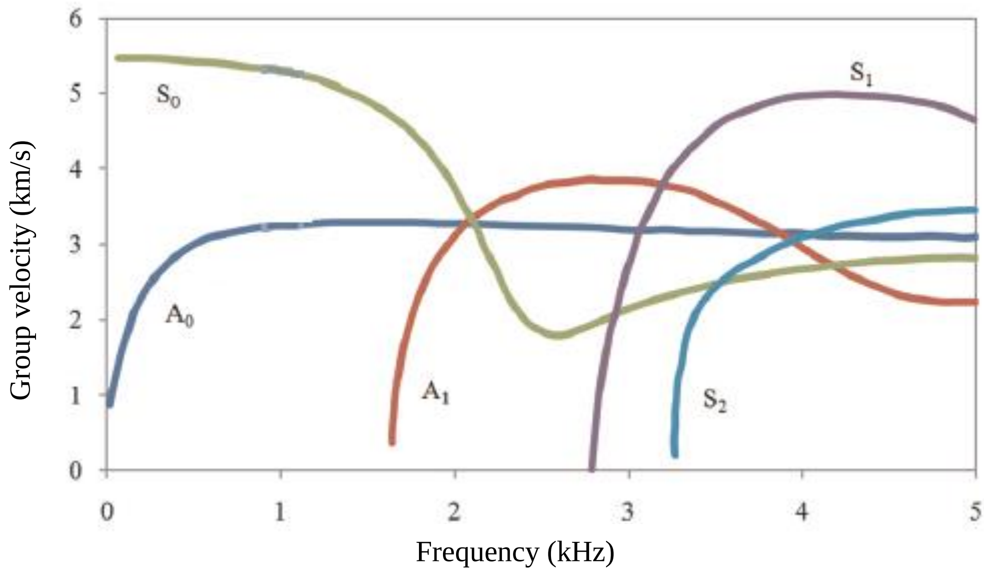

Fig. 2. Dispersion curves of the Lamb waves for steel plate [15].

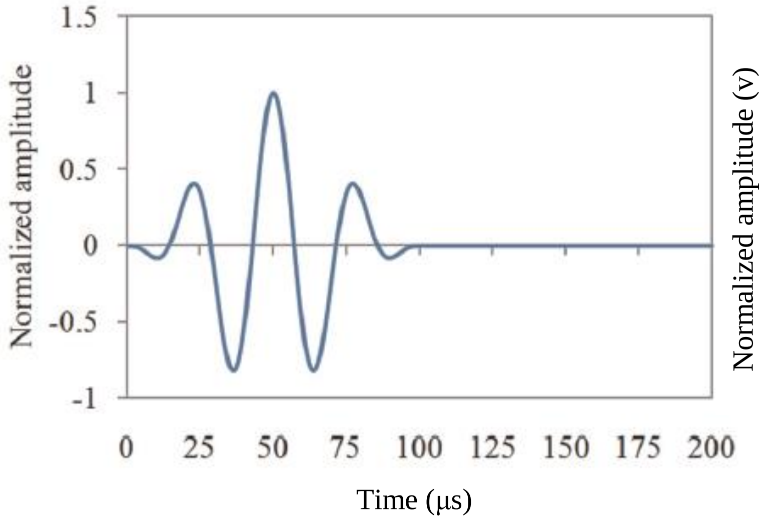

Fig. 3. Tune burst created by the function generator.

Afterwards, the response signals received by the piezoelectric sensor are displayed on the oscilloscope display and are stored on a flash drive. Then the wave is sent by the actuators and ultrasonic waves propagate across the plate, the transmitted and reflected waves reach the sensor, and the function of the sensor is to display and store the responses in digital signal form. Fig. 3 displays tune burst created by the function generator.

After performing an initial test and becoming assured of the test response, all actuators are attached to the plate using HL twin glue as shown below. Considering the high rigidity of this adhesive, using this glue would cause a better propagation of waves in the plate. Also, concerning the sensor it amplifies the received signals. In conclusion, by increasing the rigidity of attachment, in addition to a better propagation of the wave in the structure, the received signals by the sensor improve as well. Fig. 4 shows the piezoelectric transducers attached to the steel plate. Fig. 5 shows the experimental test setup.

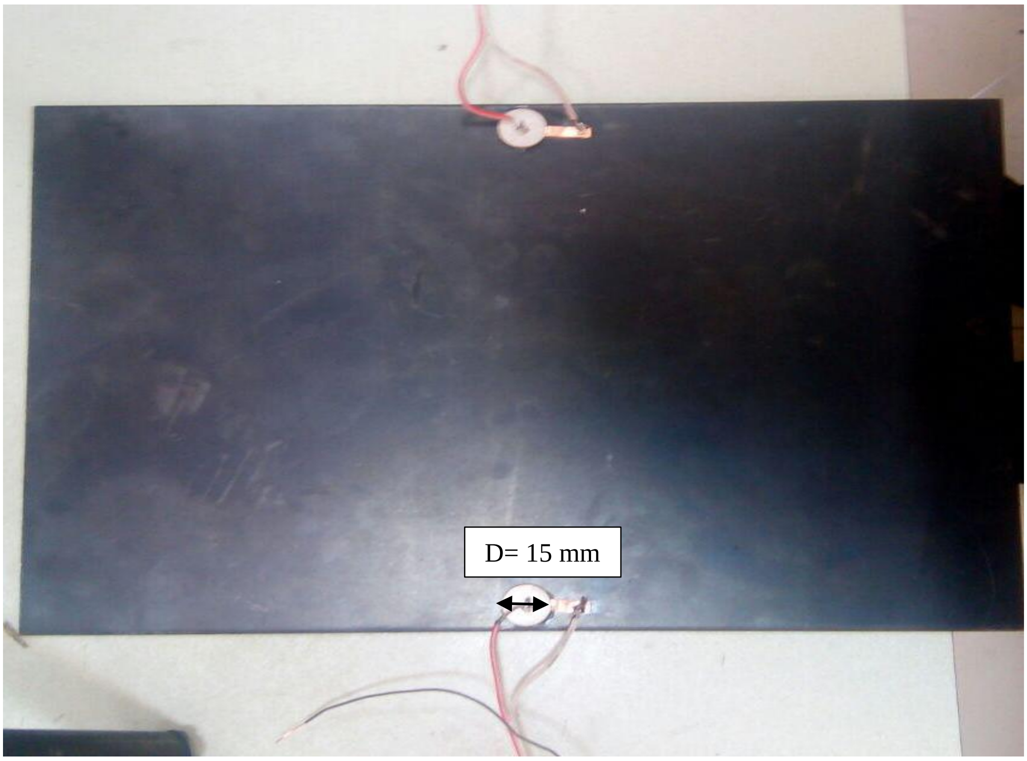

Fig. 4. The piezoelectric transducers attached to the steel plate.

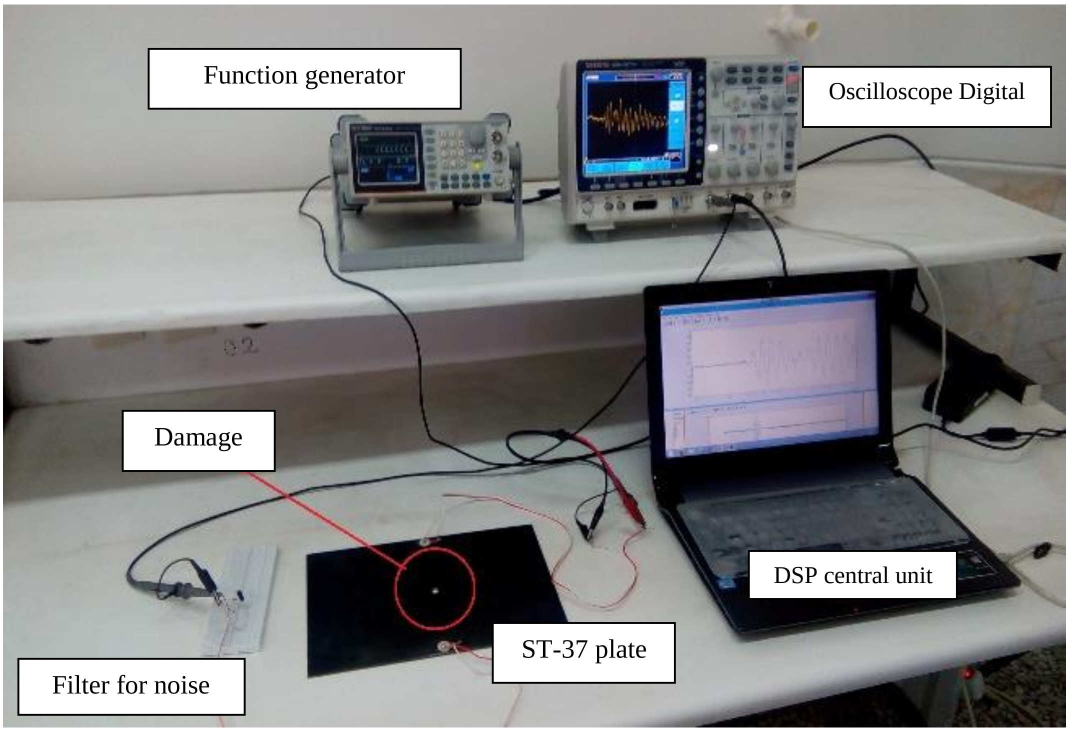

Fig. 5. Experimental test setup.

Initially, the test is conducted on a healthy plate, after conducting the test the reflected wave is extracted from the healthy structure as shown in Fig. 6. Afterwards, the test is conducted on a damaged plate (diameter= 6 mm) as shown in Fig. 5. Then the reflected signals from the healthy and damaged plate are drawn upon one another. This is an initial step to detect damage in a plate in real-world environments. Then in order to accurately detect the damage, the signals are processed by a multi-layer neural network algorithm which will be discussed in the next section.

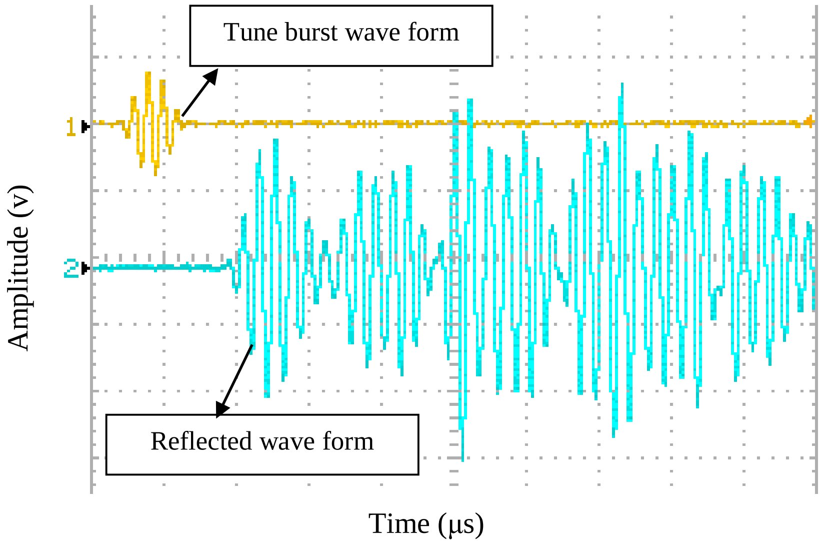

Fig. 6. Reflected wave from structure in oscilloscope monitor.

As can be seen in Fig. 6, the blue signal, which is one of the drawn signals on the oscilloscope, is the stored signal from the plate and the first signal peak is only required because the rest of the signal consists of repetitive signals that are not involved in the damage detection process.

Sampling frequency is adjusted according to the dispersion curve diagram of the plate with a thickness of 2 mm on 200 kHz. This frequency is chosen according to the frequency range of piezoelectric materials, and the frequency obtained from the dispersion curve of waves. The received signal has a 16 mv voltage with a lot of noise. The electronic circuit (hardware filter) which is placed on the way of the sensor extracts this noise, which is mostly caused by municipal electric power and extracts the sine-wave present on the signal and also increases the voltage up to 19 mv. Fig. 6 shows the experimental test and system device.

4-Results and discussion

After performing the experimental tests and saving its signals, there should be an algorithm to remove extra and useless data from the signals in the signal process section. Artificial neural network algorithm is among the most capable algorithms for processing signals. To do this, a command code is written in MATLAB, which after entering the wave data will automatically do the process and demonstrate its results on a graph. Normally, the aim of digital signal processing is to measure, filter, and compress signals. Generally, the aim of signal processing is to identify and sideline extra data and demonstrate and enlarge useful and functional data from the signals that were saved before the test. Signal processing is composed of three main parts, pre-process, process, and post-process. In the first stage, the damaged and healthy sample signals are drawn upon each other as shown in Fig. 7. Then, with damage detection by the signal operator, they will be assessed professionally in later stages.

In Fig. 7, after the initial peak which is important for damage detection is separated, the healthy and damaged structure signals are drawn upon one another. The dashed line diagrams of the healthy and damaged structure signals are indicated by the color blue. In the initial stage, the operator is able to identify the possible damage on the structure by noticing the changes that are drawn on the figure. In the later stages, damage detection is analyzed and evaluated by trained engineers.

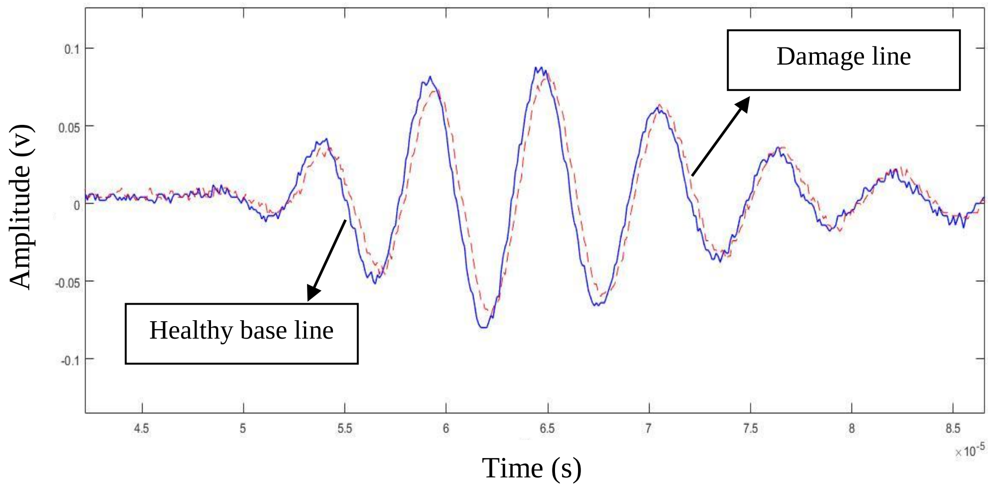

Fig. 7. Damaged and healthy sample signals.

Two-stage sampling: Discretization and calibration are done during the discretization stage. First, the signal environment is divided into equal categories. Then calibration is done by replacing the sample signals with original signals in equal categories. In the calibration stage, the value of the signal is estimated by a subset of a finite set. The Nyquist–Shannon sampling theorem states that the signal can be remade from the sample signal, of course, if the frequency of sampling is bigger than twice the highest frequency component of the signal.

For the next step, the part of the digital signal that contains the required data must be extracted from the rest, because it is impossible to continuously save a signal and also an extended part of the signal is useless and there is no need to save it. To do this, numerous methods can be employed, one of which is the use of threshold. For the next step, the direct part of the signal received from the sensor should be removed and only the periodic part should be kept. The non-periodic part or DC occurs when the positive and negative domain signals are not in uniformity with the dispersion. Normally, it is better when the average signal domain equals zero. In the first method, by using signal gathering hardware, only periodic receiving signals are saved. In the second method, after saving the signal, a high-pass filter can be used. The non-periodic parts of the signal are, in fact, components with zero frequencies. The filter only passes the components with a frequency higher than zero or another small amount. Thus, the DC part can be filtered from the signal. As it is shown in Fig. 8, DC is removed from the healthy structure signal.

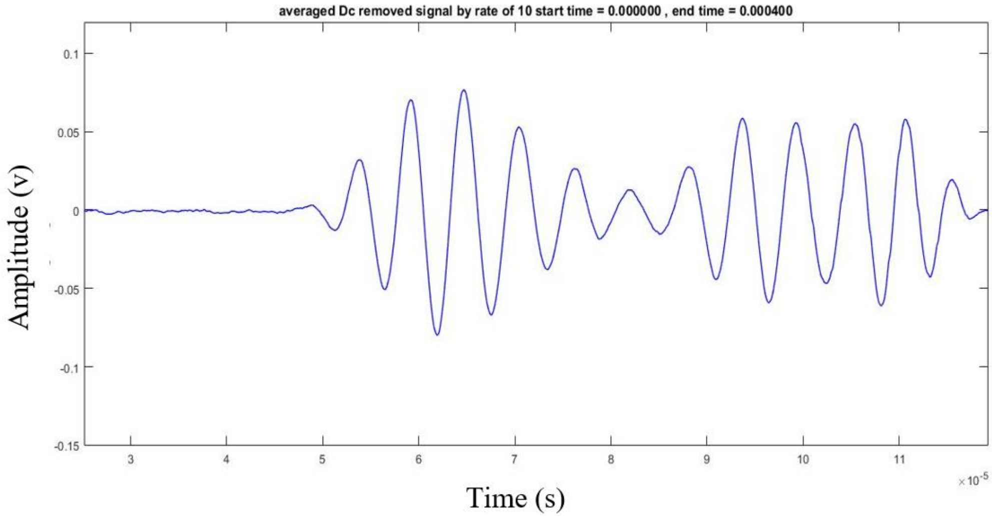

Fig. 8. DC noise is removed from the healthy structure signal.

As can be seen in Fig. 8, after noise reduction we will have a completely clear signal, in comparison to Fig. 7, which causes the features of the structure and noise from the municipal electric power not to be detected as damage so that damage detection can be carried out with high reliability and accuracy.

For the next step, in order to achieve a particular behavior from the signal and perform the noise reduction process, averaging which is an important filter in digital signal processing is performed. There are numerous methods for signal averaging. One of the most common ones which is from the category of synchronous moving filter, is called the periodic averaging method. In this method, averaging for every point on the sample is done in relation to the points before and after it [18].

The signals obtained from the propagation of guided supersonic waves are normally collected in unequal working conditions. Thus, normalizing has an important position in the correct interpretation of signals and correct comparison of them. In this part, the signals have been normalized relative to the maximum domain value in a way that all the values are placed in the [-1, 1] range.

Fig. 9 shows the signals made from the damaged plate after normalizing the data. In fact, all dynamic systems have noise or attract surrounding noises towards themselves. Noise reduction is considered one of the most important processes in the field of signal processing. Several methods can be used in this process. One of the most effective methods is the discrete wavelet transform method.

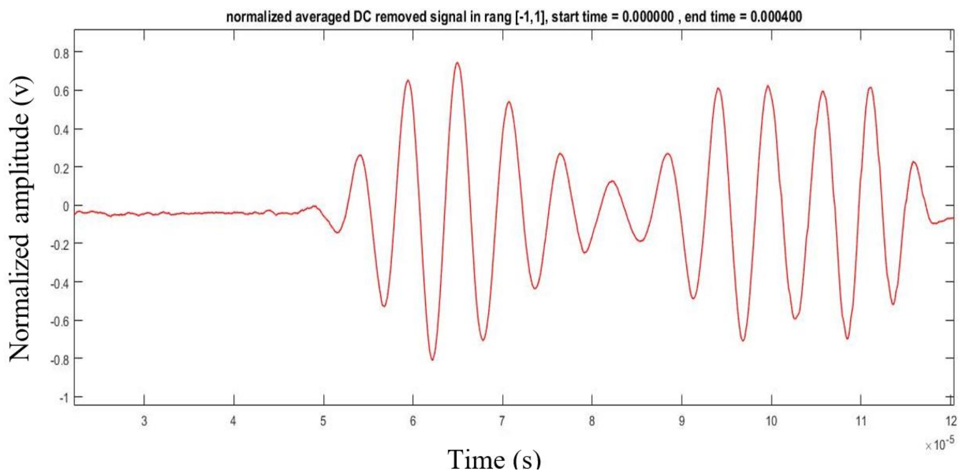

Fig. 9. The signals made from the damaged plate after normalizing the data.

After performing pre-processing and signal conditioning in order to perform the main processing, using continuous wavelet transform, the continuous wavelet coefficients of signals are calculated. In the next step, by utilizing the obtained coefficients, the scale-averaged dispersion wavelet powers of signals are calculated. The time position of signal energy peaks can be obtained by drawing the scale-averaged wavelet power and by calculating the time difference between these peaks, which is called time of flight, determines the group velocity of wave propagation in structure and afterwards the possible damage location. Generally, there are two types of time of flight: time of flight from structure border and time of flight from the damage border. Fig. 10 shows the time of flight from structure border and Fig. 11 shows the time of flight from the damage border.

The boundary conditions in the experimental tests of this paper are selected proportional to the most realistic conditions in industry. In order to increase efficiency and obtain adequate data, the most optimal placement conditions of actuator and sensor from each other and also the most optimal boundary conditions, which are obtained from the simulation, are used in the experimental tests. In case of any change in the boundary conditions of the experimental, enlargement of the plate and increase in the distance of boundaries from the sensor and actuator, it only causes complexity in the received response and in order to better monitor the structural health more sensors and actuators must be used. For example, in monitoring the health of a pipeline if the distance from the actuator ring is more than 8 meters from the structure border, another ring must be added in this distance to propagate better and after that a sensor must be added to receive signals better [19]. This result was also applies for the plate. In Fig. 10, which is extracted from a healthy structure, the borders of the structure will be identified (taking into consideration the initial velocity of the transmitted wave and the distance of the piezoelectric from the structure borders). The peaks that can be seen in Fig. 10 can each be the borders of the structure, but as it was mentioned before, only the initial peak is important to the damage detection process, and the process is carried out in the software code according to the data from the initial wave peak. In Fig. 11 and according to Fig. 10, the peak which can be seen in between structure borders indicates damage. When the process of damage detection is carried out automatically, the source code detects the presence of an extra peak and warns the operator. In fact, the sudden rise of this peak compared to Fig. 10 indicates that a damage has occurred in the building. Afterwards, based on the time when this peak occurred in the wave and considering the velocity of the wave, the exact size and location of the damage can be detected.

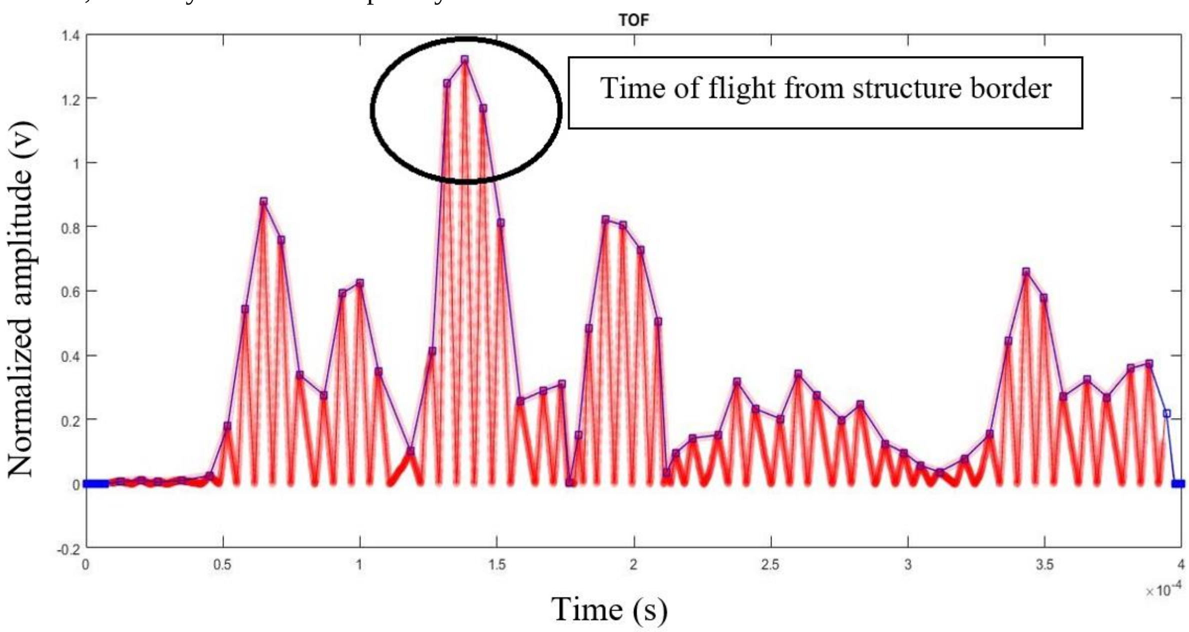

Fig. 10. The time of flight from the structure border.

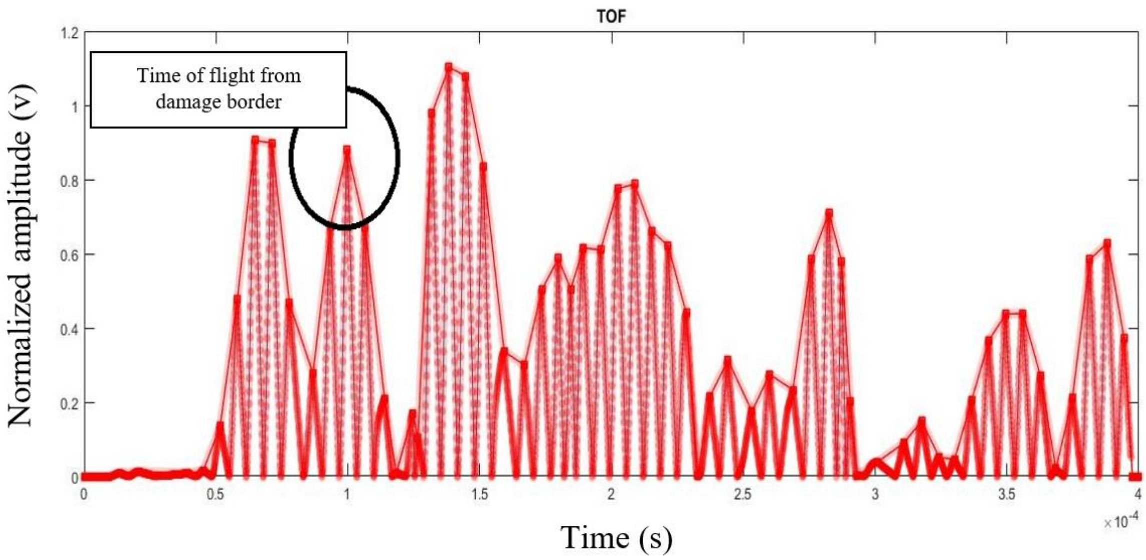

Fig. 11. The time of flight from the damage border.

As it is illustrated in the above figures, by utilization of scale-averaged wavelet power, the times of flight from plate border and damage border emerge. After that, by utilizing the time of flight from the plate border, the group velocity of wave propagation in the plate is calculated. As can be obtained from the diagrams after processing, it is clear that the time of flight from the plate border equals 1.5×10^{-4} s, and the time of flight emerged from the damage border is 1×10^{-4} s. By using this time difference between the emerged time of flight from damage border and healthy structure border and by having the emerged wave velocity from the dispersion curve the difference in distance of damage from sensors and possible damage location can be obtained.

With the steady increase in the amount of damage, the signal amplitude first decreased and then increases. The reason is that in high depth damages, the damage shows a reaction similar to the structure border which causes an increase in the receive signal amplitude. This increase in amplitude causes an increase in the energy of reflected signal and during it, precise determining of the time of flight is done. This increases damage detection accuracy and helps conserve time and expenses. In the experimental test of this paper, automatic damage detection is done. The damage caused, which is in the form of a hole and 6 mm in diameter, is detected in 90 mm distance from the structure border, and its location and size are acceptable and the amount error is negligible.

5-Conclusion

In this paper, the damage detection and structural health monitoring process were conducted on steel plates used in important industrial structures. For the first time, a plate made of ST-37 stainless steel was chosen and an actuator, and a ceramic sensor disc were used in the experimental tests. In order to store the processed signals from the experimental test and automatic damage detection a multi-layer artificial neural network algorithm was used. In the following, some of the major results are presented:

- Rigidity is an important matter in the connection of actuators and wave propagation. After testing several versions of glue it was determined that, by increasing the rigidity of the connection, in addition to an improvement in wave propagation in the structure, the signals received by the sensor improved as well.
- By increasing the number of actuators in addition to separating the signal modes from each other, an increase in the amplitude of received signal also occurred, which facilitated signal processing.
- As the thickness of the plate was reduced, in addition to better wave transmission, better results in the output were achieved. In case the thickness of the plate increased more actuators with more power need to be used.
- By increasing the depth of damage, the signal amplitude first decreased and then increased.
- In the experimental test, after testing various thicknesses of sensor, it was determined that the thinner the sensor is, in addition to the separation of signal peaks, the

more stable signals with higher amplitudes are extracted.

- It was concluded in signal processing that those specifications of signal should be sought after which are connected to damage parameters and also have the highest sensitivity towards change in them.

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