EURODYN 2020
XI International Conference on Structural Dynamics
M. Papadrakakis, M. Fragiadakis, C. Papadimitriou (eds.)
Athens, Greece, 23–25 November 2020

DAMAGE FEATURE RECOGNITION BASED ON LAMB WAVES DETECTION

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Keywords: Structural health monitoring, Lamb wave, Damage feature, Damage identification.

Abstract. *Owing to the superiority of lamb waves in the field of Structural Health Monitoring, the Lamb wave-based damage detection and identification technology are widely used. To determine the degree of damage, two damage feature recognitions are proposed in this paper. One is extracted from the time domain, where the lamb wave signals are processed by Hilbert Transform (HT) with the time-domain analysis. According to the law of signal attenuation, the differential signal envelope amplitude procced by the Hilbert Transform is regarded as a damage feature parameter relating to the damage size. The other one is extracted by Fast Fourier transform (FFT) in frequency domain analysis. Two characteristic parameters, the amplitude and probability density in the time domain and the signal roughness parameters in the frequency domain, are defined to characterize the damage size.*

1 INTRODUCTION

With the increase of service time, the plate structure is prone to subject all kinds of damages, such as cracks, delaminations, via holes, corrosion, inclusions, and so on[1]. The Structural Health Monitoring (SHM)[2,3] technology is commonly used in predicting and monitoring structural health conditions. Researchers have been keen to improve the accuracy of determining the damage location[4,5]. Besides the location, the damage size is another important indicator, depending on which different maintenance methods are required. For example, small damage which has little impact on the structure security can be repaired as needed; and the large damage usually needs to be repaired or replaced as soon as possible. Therefore, after confirming the damage location, the relevant characteristic parameters of the damage signal can be extracted and the type/size of the damage can be identified. It will be more beneficial to the long-term use and maintenance of the structure.

Cawley[6,7] studied the effects of notch damage in metals and delamination damage and Lamb waves in composite laminates. In 1992, Wu[8] began to use the Artificial neural network (ANN) to detect structural damage. They explored the application of neural network's self-organization and learning ability in structural damage assessment and trained neural networks to identify damage. Then ANN is widely used to judge the degree of structural damage[9,10]. To accurately identify damage characteristics, it is necessary to select the appropriate damage feature parameters for ANN training and learning. Mares[11] introduced a genetic algorithm into the damage identification and used the residual force method to realize the damage location and quantitative identification. Law[12] selected the sensitivity of wavelet packet transform component energy as damage feature parameter. Li[13] reported a damage identification method based on Lamb wave multi-feature fusion, and determined the damage type by ANN. Sun[14] used energy distribution to identify damage in the structure by ANN. It can be concluded that finding suitable damage feature parameters is the key to improve the success rate of damage recognition.

This work will extract the damage features by analyzing the data based on numerical simulation. The damage size characteristics of the time/frequency domain are analyzed and summarized.

2 ANALYSIS OF ALUMINUM ALLOY PLATE DAMAGE IDENTIFICATION

2.1. Aluminum Alloy Plate Model

The 3D finite element model of the aluminum alloy plate is built with a dimension of 800 mm in length, 800 mm in width and 1 mm in height. The material parameters of the aluminum alloy plate are shown in Table 1, eight PZT sensors are arranged as circular and uniformly distributed with a square damage on the plate. The coordinates of the damage and sensors are as shown in Table 2.**错误!未找到引用源。**.

Table 1. The material parameters of the aluminum alloy plate

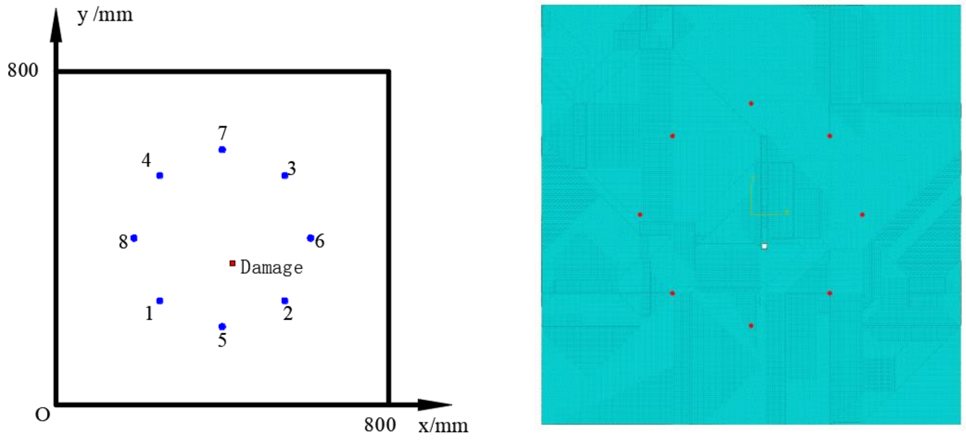
Parameter	Unit	Value
density	kg/m^3	2750
Young's modulus	Gpa	69
Poisson's ratio	--	0.33

Table 2. The coordinate of damage and sensors

	Coordinate		Coordinate
Sensor1	(250，250)	**Sensor2**	(550，250)

Sensor3	(550, 550)	**Sensor4**	(250, 550)
Sensor5	(400, 188)	**Sensor6**	(612, 400)
Sensor7	(400, 612)	**Sensor8**	(188, 400)
Square damage	(425, 340)		

The locations of PZT sensors and damage are shown in Figure 1. Eight sensors served as an actuator to excite Lamb waves in turns while the other PZT sensors act as receivers to collect the Lamb wave signals.



(a) (b)

Figure 1. Finite Element Model of The Aluminum Alloy Plate. (a) Sensor and damage location; (b) Simulation model

2.2. Damage Feature Extraction Based on Time Domain

As shown in Figure 2, when there is a damage in the aluminum plate, the lamb wave signal goes along with the route "exciter 1-damage-receiver 2". The reflection wave can be obtained by subtracting the non-damage signal from the damage signal.

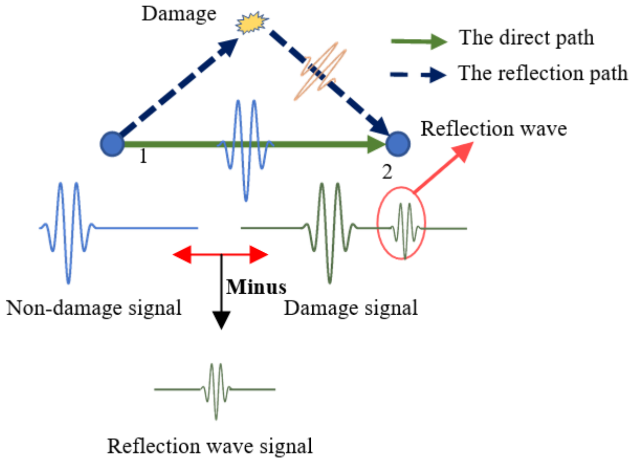


Figure 2. The propagation of damage reflection signal

Taking the square damage as an example, PZT sensor 1 excites a Lamb wave of 200KHz, and PZT sensor 2 receives that signal. The signal is shown in Figure 3.

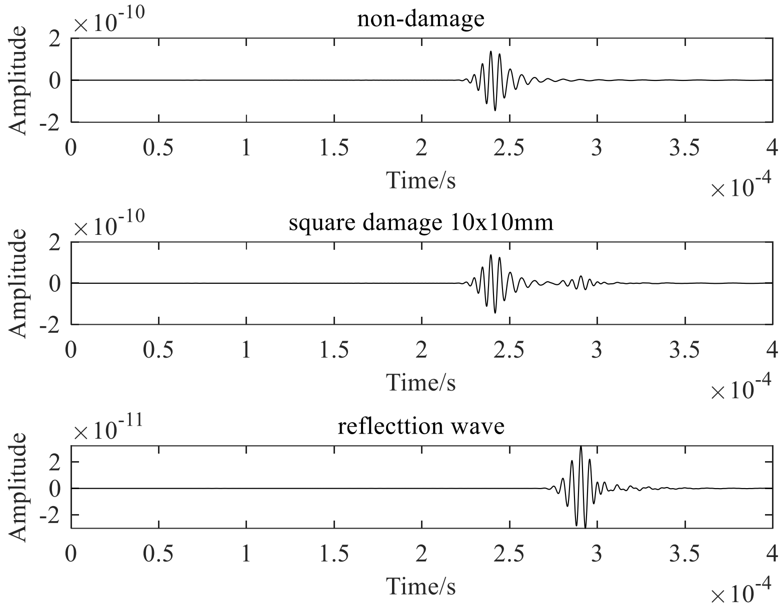


Figure 3. The damage reflection and differential signal

When a wave propagates in medium, its amplitude will gradually decrease with the increase of distance. Generally, the relationship between wave amplitude and propagation distance is

$$A = A_0 e^{\alpha D} \tag{1}$$

where, A_0 denotes the amplitude of excitation, α denotes the attenuation coefficient, and D denotes the propagation distance. To determine the coefficient of the lamb wave, the wave amplitudes in different lengths are collected in the aluminum plate, and the results are shown in Figure 4.

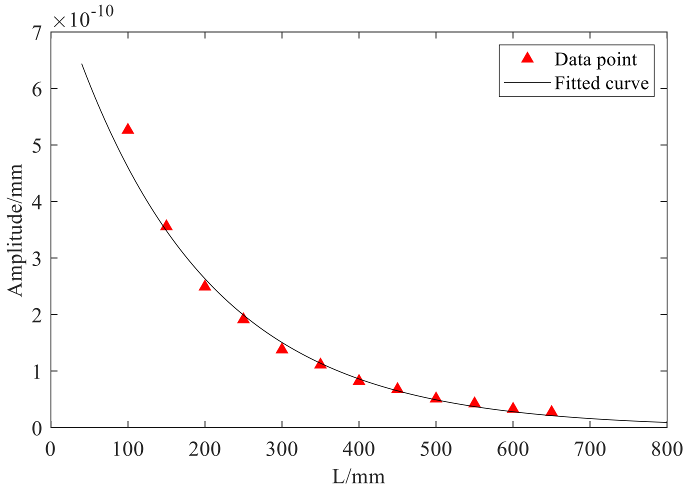
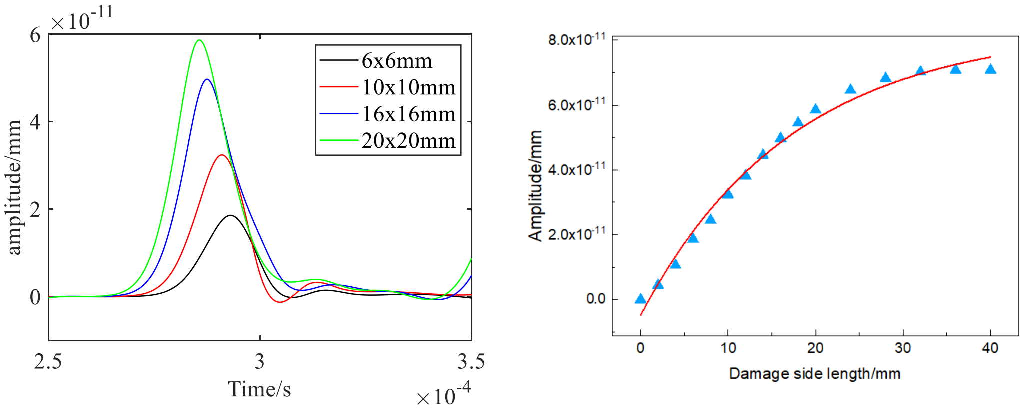


Figure 4. The attenuation of Lamb wave

By use of curve fitting, the attenuation coefficient is obtained as α = -179.1. Then the amplitude attenuation function of the lamb wave in the aluminum plate is shown as

$$A = 8.05\times 10^{-10} e^{\frac{-D}{179.1}} \tag{2}$$

In order to analyze the dynamic regularity of the reflected wave signal with the degree of damage, the envelope processings are performed on the difference signals of various damage size based on Hilbert Transform(HT), as shown in Figure 5-(a). It is easy to observe that the reflection wave gradually stronger as the size of the damage increases. The energy distribution feature of the signal in the time domain is represented by the HT envelope, and the damage characteristic of size is reflected by extracting the amplitude magnitude. The different sizes of damage are simulated, and the amplitude of the reflected wave signal is plotted in Figure 5-(b).



(a) (b)

Figure 5. Lamb wave feature in time domain. (a) The upper envelope of different damage size; (b) The amplitude of the envelope with different damage size

In Figure 5 (b), it can be seen that as the degree of damage increases, the amplitude of the envelope gradually increases to the upper limit value. As the spread of lamb wave energy has limits, the strength of the reflected wave also has a limit and will not increase unlimitedly. Through curve fitting, the functional relationship of the envelope amplitude along with different damage size is

$$y = 8.36\times10^{-11} - 8.83\times10^{-11} e^{\frac{-x}{17.34}} \tag{3}$$

2.3. Damage Feature Extraction Based on Frequency Domain

Based on the frequency domain analysis, the Fast Fourier transform (FFT) is used to extract the frequency domain features from the Lamb waves signal. Frequency components and amplitude characteristics of lamb wave signals are obtained to identify the damage features of an aluminum plate. The amplitude-frequency curve with different damage size are shown in Figure 6.

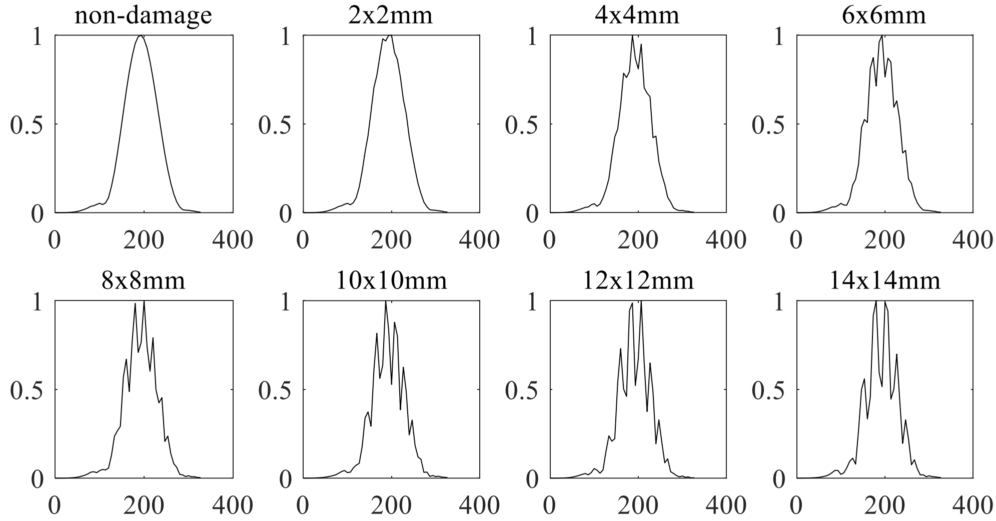


Figure 6. The frequency-domain image of different damage size

In Figure 6, as the damage size increases, the frequency range of the signal becomes decentralized. The larger the damage, the more uneven the frequency distribution. The reason is that when Lamb wave propagates to the position of damage, waveform reflection and modal conversion occur due to the sudden change of structure, which causes the waveform frequency domain signal to fluctuate. The larger the size of the damage, the higher the fluctuation, so the signal concentration level of the frequency-domain image can be used as one of the damage features for determining the damage size.

When there is no damage, the signal received by the receiving sensor is only a 200 KHz Lamb wave signal modulated by the Hanning window. The frequency-domain image of non-damage is similar to the frequency-domain figure of the excitation Lamb wave, and the frequency-domain model conforms to the law of the Hanning window rising first and then falling. Due to the existence of damage, the - reflected wave causes fluctuations in the frequency domain of the received signal. The fluctuations are closely related to the damage size. The above results in multiple frequency peaks in the signal spectrum, as shown in Figure. 5.

In order to characterize the degree of signal decentralization, the signal roughness is introduced in this paper to describe the degree of influence of impairments on frequency-domain signals. The equation of signal roughness is defined as

$$\mathrm{R}=\sum_{i=1}^{i=n-2}\left|\frac{y_{(i+2)}-y_{(i+1)}}{\Delta x}-\frac{y_{(i+1)}-y_{(i)}}{\Delta x}\right| \tag{4}$$

where, R denotes the signal roughness and Δx represents a single increment of the frequency-domain signal, y denotes the corresponding amplitude. When the peak value or the sudden change in the graph increases, the signal roughness increases; when the signal gradually concentrates and the sudden change coefficient decreases, the signal roughness decreases.

As shown in Figure 7, the signal roughness of the frequency-domain figure increase with the expansion of damage. Therefore, the signal roughness of the frequency-domain image is a an effective damage feature indicator.

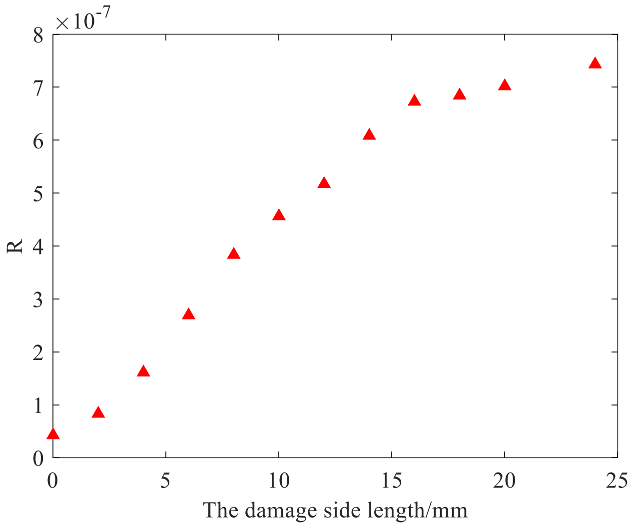


Figure 7. The signal roughness of different damage size

3 THE VERIFICATION OF THE DAMAGE FEATURE PARAMETER

To further verify the damage feature parameters' usabilities, the location of the damage changed while the transmitter and the receiver changed at the same time. As shown in Figure 8, the Lamb signal is excited by the sensor 2 and received by the sensor 3.

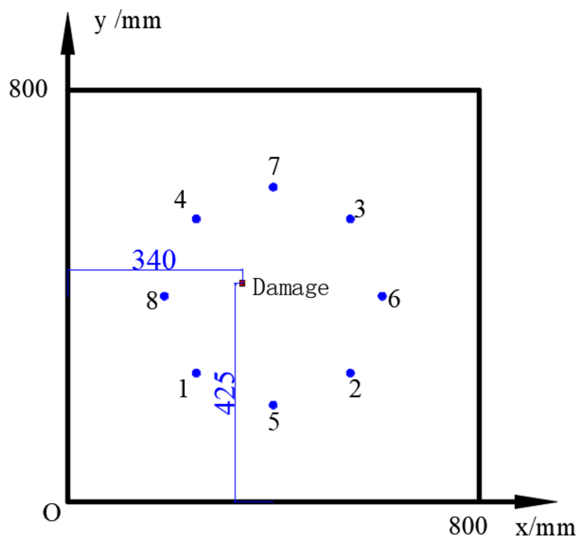


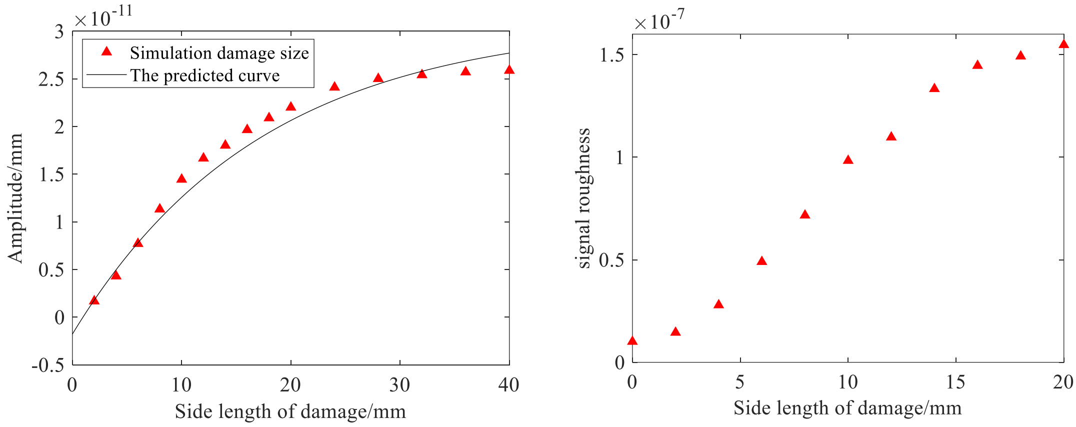
Figure 8. Change the location of the damage

When the lamb wave arrives at the damage location, according to the Huygens-Fresnel principle, the damage will become a new wave source, and the amplitude of the new wave will be lower than the arrival amplitude. The new vibration source wave amplitude is linearly related to the arrival amplitude.

The damage location is shown in Figure 1-(a) and the propagation path length of the reflected wave $L_{1\text{-}D\text{-}2}$ is 322 mm. Another damage location is shown in Figure 8 and the propagation path length of the reflected wave $L_{2\text{-}D\text{-}3}$ is 517 mm. By substituting 322 and 517 into eq. (3), the theoretical amplitude of path $L_{2\text{-}D\text{-}3}$ is 2.9 times that of path $L_{1\text{-}D\text{-}2}$. In Figure 8, the curve-fitting function in Figure 5-(b) is divided by 2.9 so we can get the relationship between the amplitude and the size of the damage as folllows:

$$A_1 = \frac{\left(8.05\times10^{-10} e^{\frac{-L}{179.1}}\right)}{2.9} \quad (5)$$

The relationship between the actual damage size and amplitude is shown in the Figure 9-(a), the simulation damage size coincides with the theoretical predictive value calculated by the eq. (5). Therefore, the amplitude of the reflected wave can be used as a parameter to characterise damagesand the damage size can be successfully predicted.



(a) (b)

Figure 9. Simulation verification results. (a) The amplitude of the envelope with different damage size by sensor 2 sensor 3; (b) The signal roughness of different damage size by sensor 2 sensor 3

In Figure 5-(b) and Figure 9-(a), it is clear that the trends of the damage size and the envelope amplitude in the two figures are consistent, which can predict the damage size through simulations. From Figure 7 and Figure 9-(b), it can be concluded that the signal roughness is an important parameter to describe the damage size.

4 CONCLUSIONS

The characteristics of the Lamb wave signal corresponding to the degree of damage are studied in this work. Two parameters are defined to describe the damage degree both in the time-domain and frequency-domain. In the time-domain analysis, the differential signal envelope amplitude extracted from the Hilbert Transform is applied as the damage feature parameter related to the damage size. In the frequency domain analysis, the signal roughness is proposed. It is used as the damage size characteristic parameter. The feasibilities of the envelope amplitude and the signal roughness are verified by numerical simulation. The identification of multiple damages using the proposed approaches is under further investigation.

5 ACKNOWLEDGMENTS:

This project is supported by the Program of National Natural Science Foundation of China (Grant No. 51805298), Natural Science Foundation of Shandong Province (ZR201807090390) and YSPSDUWH.

REFERENCES

[1] H. Yan, H. Jin, R. Yao, Prediction of the damage and fracture of cast steel containing pores. *International Journal of Damage Mechanics,* 29(1), 166-183, 2020.

[2] K. Worden, C R. Farrar, G. Manson, et al. The fundamental axioms of structural health monitoring. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 463(2082), 1639-1664, 2007.

[3] Y. Tang H, C. Winkelmann, W, Lestari, et al. Composite structural health monitoring through use of embedded PZT sensors. *Journal of Intelligent Material Systems and Structures*, 22(8), 739-755, 2011.

[4] N. Mori, S. Biwa, T. Kusaka. Damage localization method for plates based on the time reversal of the mode-converted Lamb waves. *Ultrasonics*, 91, 19-29, 2019.

[5] A. De Fenza, A. Sorrentino, P. Vitiello. Application of Artificial Neural Networks and Probability Ellipse methods for damage detection using Lamb waves. *Composite Structures*, 133, 390-403, 2015.

[6] N. Alleyne D, P. Cawley. The interaction of Lamb waves with defects. *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, 39, 381-397, 1992.

[7] N. Guo, P. Cawley. The interaction of Lamb waves with delaminations in composite laminates. *The Journal of the Acoustical Society of America*, 94(4), 2240-2246, 1993.

[8] X. Wu, J. Ghaboussi, H. Garrett Jr J. Use of neural networks in detection of structural damage. *Computers & structures*, 42(4), 649-659, 1992.

[9] C. Su, M. Jiang, S. Lv, et al. Improved damage localization and quantification of CFRP using lamb waves and convolution neural network. *IEEE Sensors Journal*, 19(14). 5784-5791, 2019.

[10] G. Wang. Design of damage identification algorithm for mechanical structures based on convolutional neural network. *Concurrency and Computation: Practice and Experience*, 30(24), e4891, 2018.

[11] C. Mares, C. Surace. An application of genetic algorithms to identify damage in elastic structures. *Journal of sound and vibration*, 195(2), 195-215, 1996.

[12] Law. S S, Li. X Y, Zhu. X. Q, et al. Structural damage detection from wavelet packet sensitivity. *Engineering structures*, 27(9), 1339-1348, 2005.

[13] R. Li, H. Gu, B. Hu, et al. Multi-feature Fusion and Damage Identification of Large Generator Stator Insulation Based on Lamb Wave Detection and SVM Method. *Sensors*, 19(17), 3733, 2019.

[14] D. Sun, Q. Wang, X. Xue, et al. Damage Degree Assessment Based on Lamb Wave and Wavelet Packet Transform. *2019 Chinese Control And Decision Conference (CCDC). IEEE*, 3179-3184. 2019.