An Impact Location Method Based on Transmission Coefficient Weighted Impact Intensity

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ABSTRACT The stiffened plate has complex influences on the propagation characteristics of Lamb waves, which causes difficulties for the impact location. In order to realize the impact location in stiffened plate, this paper proposes a transmission coefficient weighted impact intensity (TCWII) method. The method uses cross-correlation curves to calculate impact intensity maps and reduce the location error by superposing the maps of different filter bands. The transmission coefficient weights for different bands are applied to compensate for the effect of the stiffeners on the signal propagation. By finding the maximum impact intensity point in the transmission coefficient weighted impact intensity map, the impact point can be located. To evaluate the performance of the TCWII method, 130 sets of experiments have been taken. The location result shows the TCWII method can achieve good performance in stiffened plate with an average error of 2.29 cm in 50cm × 50cm testing range. The comparison with the traditional TDOA method shows the TCWII has improvement on accuracy in stiffened plates.

INDEX TERMS Impact, location, stiffened plate, cross-correlation, impact intensity, transmission coefficient.

I. INTRODUCTION With the development of the petrochemical industry and aerospace industry, the pressure vessels have been used widely such as storage tanks, pipelines, ship hulls, aircraft and space stations. Structure health monitor technology for these pressure vessels is important for the safety of the equipment and staff. In recent years, various accidents happened in these pressure vessels. In August 2018, the Soyuz space ship was impacted by space debris. The impact formed a 2 mm leak hole, which seriously threatened the safety of the spacecraft [1]. In order to respond to the impact event and perform rapid inspection and repair, many researchers spend effort on the impact location technology.

For impact location, various methods based on different theories have been proposed. The schemes commonly used are infrared imaging method [2], resistance film method [3], fiber grating method [4], acoustic emission method [5] and so on. The infrared imaging method uses the infrared disturbance of the test specimen’s surface to locate the impact location [6], but due to the need of infrared camera, the application scope of this method is restricted. The resistance film method can locate the impact and leakage by arranging a large number of thin film sensors, to monitor the resistance or capacitance change caused by the shape change of the structure. Some researchers have developed this kind of sensor with PVDF material which can be applied to many structures with good sensitivity [7]–[9]. However, the system would be too complicate in large range applications. The fiber grating method also needs large amounts of sensors to monitor the parameter change of the structure. The advantage of the fiber grating method is the fiber Bragg grating can be embedded inside the structure [10], which is usually used for composite material structures. Among these methods, the acoustic emission (AE) method has been used wildly because its simple structure, high sensitivity, fast detection speed, online detection and so on advantages.

Among the impact location technology based on the acoustic emission method, the time difference of arrival (TDOA) is the most traditional method [5]. The impact signals collected...
by different sensors have different arrival times due to the difference of the propagation paths. By calculating the time difference of the arrival time, in the condition of known the wave speed, the location of the impact can be obtained.

The traditional TDOA method uses a fixed threshold to obtain the arrival time, but this method may have large location errors because of the low accuracy of the arrival time. To solve this problem, some improved TDOA methods have been proposed. Matoušek et al. [11] proposed a correlation-based TDOA algorithm, realized impact location in low signal to noise ratio conditions. Mohd et al. [12] proposed an improved TDOA method based on wavelet transform analysis and modal location theory, to improve the accuracy. Li et al. [13] proposed a regularized constrained total least square (RCTLS) algorithm with good robust. It uses the prior knowledge of TDOA measurement error and considers the noise when solving the pseudo-linear equations.

For normal plate-like structures, the above methods can achieve ideal location results. However, more and more complicated structures have been used in pressure vessels such as stiffened structures and composite material structures. For these new structures, the traditional TDOA method lost its usability, due to the complex influence on the acoustic signal caused by the structures. To solve this problem, new methods are proposed in recent years. Sharif-Khodaei et al. [14] established a neural network based on the multi-layer perceptron (MLP) to improve the accuracy of the arrival time in composite plates. Ebrahimkhanlou and Salamone [15] proposed an impact location method for stiffened plates which only need one sensor. They constructed a multipath (MP) model according to the distribution of stiffeners. By comparing the real signal with the MP model, the impact location can be identified. Li et al. [16] proposed an adaptive energy compensation threshold TDOA method. Compare with the traditional method, this method uses energy factors to adjust the threshold according to the signals. With the use of only 3 sensors, this method achieves good performance in a fan-ring shaped stiffened plate, but the stability of the method needs to be improved. The above method can be used for the composite material plate or stiffened plate, but need a complex sensor array or large amount of pre-experiments or calculations.

Aiming to solve the problem of impact location in a stiffened plate, this paper proposes the transmission coefficient weighted impact intensity (TCWII) method. The cross-correlation curves between different sensors are used to calculate impact intensity maps with different filter bands. Considering the influence of the stiffeners on the wave transmission ability, these maps are superposed with the transmission coefficient, and a transmission coefficient weighted impact intensity map can be calculated. The impact point is located by finding maximum impact intensity on the map.

The remainder of this paper is organized as follows. In section 2, the process of the TCWII method is proposed. In section 3, the experiment platform and relative pre-experiment is introduced. In section 4, the result of experiments is discussed. The conclusion of this paper is in section 5.

II. METHOD

The transmission coefficient weighted impact intensity method can be separated into two parts: impact intensity method and transmission coefficient weighting. Multi-sensors are used to collect impact signals at different positions. After calculating the cross-correlations of different signals, an impact intensity map can be performed. The transmission coefficient weighting aims to improve the accuracy of impact intensity method. By using different filter bands, a serial of impact intensity map can be obtained, and by superposing these maps with transmission coefficient weight, a transmission coefficient weighted impact intensity map with more accuracy can be obtained.

A. IMPACT INTENSITY METHOD

Impact signals received by sensors can be regard as copies of original impact signal with different time delay. As a result, the time delay where the cross-correlation curve peaks are the time delay where the cross-correlation curve peaks are the arrival time of the impact signals received by sensors.

\[ t_i = \frac{1}{\nu} \sqrt{(x_p - x_i)^2 + (y_p - y_i)^2} \]  

where \( S(t) \) is the original impact signal, \( \nu \) is phase velocity of Lamb wave.

The cross-correlation curve between signals of sensor \( i \) and \( j \) can be calculated by:

\[ C_{ij}(t) = \int_{-\infty}^{+\infty} S(t' - t_i) \cdot S(t' - t_j + t) \, dt' \]  

In ideal condition, the curve peaks when \( t = \Delta t_j - \Delta t_i \). This characteristic gives the possibility to find the impact point by finding common maximum point of the cross-correlation curves, realized by calculating impact intensity according to (4) and (5):

\[ I(x, y) = \frac{1}{N} \sum_{i \neq j} C_{ij}(\Delta t_j - \Delta t_i) \]  

\[ \Delta t_i = \frac{\sqrt{(x - x_i)^2 + (y - y_i)^2}}{\nu} \]  

where \( N \) is the number of cross-correlation curves, \( I(x, y) \) is the impact intensity of assumed impact point \( (x, y) \).

It can be seen from (4) and (5) that only when \( x = x_p, y = y_p \), the impact intensity \( I(x, y) \) can reach maximum value. As a result, by searching the maximum impact intensity on test plate, the impact point can be located.
The procedure of impact intensity method can be divided into three stages:

a) Gaussian curve calculation.
b) Impact intensity map calculation.
c) Impact point location.

The flow chart of Gaussian curve calculation is shown as Figure 1.

First, a short signal is cut off from the original signal to make the calculation faster. Then, the cross-correlation curves between any different short signals are calculated. As the number of sensors is \(n\), \((n-1) \times n/2\) cross-correlation curves can be obtained. Since only the amplitude of the curve is concerned, the curves are absolutized. Because the absolute cross-correlation curve contains multiple peaks which will affect the algorithm’s accuracy, Gaussian fitting is used to obtain a more property curve. At the last, all curves will be normalized to eliminate the influence of the different distance on the curve’s amplitude.

The flow chart of impact intensity map calculation is shown as Figure 2.

Before impact intensity map calculation, a grid system needs to be established. The test plate is divided into small grids with a size decided by required resolution. The central position of each grid is regarded as the grid’s position. The impact intensity of each grid on the test plate can be calculated according to (4) and (5). Note that due of the operations during Gaussian curve calculation, the formula needs some changes. The final impact intensity formulas for grid \((x_p, y_p)\) are shown as follows:

\[
I(x_p, y_p) = \frac{\sum_{i \neq j} G_{ij}(\Delta t''_{ij} - \Delta t'_{ij})}{N} \tag{6}
\]

\[
\Delta t''_{ij} = \sqrt{(x_p - x_i)^2 + (y_p - y_i)^2} - \frac{p_i}{fs} \tag{7}
\]

where \(G_{ij}\) is the Gaussian curve of \(C_{ij}\), \(p_i/fs\) is the time delay caused by signal cut off, \(p_i\) is the cut off position, \(fs\) is sampling frequency.

In the final stage, the impact point can be located by finding maximum impact intensity in the impact intensity map.

**B. TRANSMISSION COEFFICIENT WEIGHTED IMPACT INTENSITY METHOD**

Due to the influence of dispersion phenomenon, the phase velocity of Lamb wave changes with frequency. As a result, on condition that filter bandwidth is large, the accuracy of the algorithm will decrease because of the inaccurate phase velocity. To avoid this, filter bandwidth should be small to reduce the effect of dispersion. However, small bandwidth will also reduce the accuracy and stability of the algorithm. To solve this problem, this paper proposes a TCWII method.

The flow chart of this method is shown in Figure 3. The method utilizes many narrow filter bands to obtain a series of impact intensity maps. By using narrow bandwidth, each impact intensity map can be given an accurate phase velocity during calculation. As the bandwidth is small enough, the phase velocity of each frequency in the band can be regarded as the same with the central frequency’s phase velocity.

The impact intensity maps will then be superposed with different weights which determined by the transmission coefficient. The transmission coefficient can reflect different characterization of the effect of stiffener on the energy of different frequency Lamb waves, which is first proposed by Reusser et al. [17]. It can be calculated by (8):

\[
R(f) = \frac{E_A(f)}{E_B(f)} \tag{8}
\]

where \(E_A(f)\) is the wave energy after passing stiffener, \(E_B(f)\) is the wave energy before passing stiffener.

After getting the transmission coefficient weighted impact intensity map, the locating of the impact point can be determined by finding maximum impact intensity.

The advantages of TCWII method are as follows:

1. Compared with the traditional TDOA method, this method uses impact intensity maps to locate impact point, exclude the need of threshold setting and adjusting, reduce dependence on accuracy of arrival time, improved algorithm’s stability and accuracy.
2. By using narrow filter bands, the influence of the dispersion phenomenon is reduced. The phase velocity of different filter bands used for calculation can be determined individually.
3. The superposition operation can reduce the effect on accuracy when some individual filter bands get unsatisfactory location results. The transmission coefficient weighting operation can increase the influence of frequency bands whose location results are better on the final result and improve the accuracy of the algorithm.

III. EXPERIMENTS IN LABORATORY

A. EXPERIMENT PLATFORM

The schematic diagram of the experimental platform is shown as Figure 4. The experimental platform can be divided into three parts: signal generating system, signal acquire system and test plate.

The signal generating system uses a laser debris generator to generate a simulate impact signal. The laser debris generator consists of a laser generator and a piece of aluminum foil. The laser generator can generate a beam of high energy laser, by shining the laser on the aluminum foil, a piece of aluminum debris will fly out from the aluminum foil with a high speed. The speed of the aluminum debris can reach 5 km/s and can use to simulate the impact event.

The signal acquire system is used to acquire impact signals. Its’ main parts are 8 sensors (PAC: Nano-30), 8 amplifiers (Softland Times: AE Amplifier), an acoustic emission instrument (Softland Times: DS2-16B) and a computer. During the experiment, the signals first acquired by the sensors, after amplified with the amplifiers, the signals will be transformed to digital signals by the acoustic emission instrument and finally saved in the computer.

The test plate is made of 5A06 aluminum. The test plate has several stiffeners on the back. To reduce the influence of boundary reflection, at the edge of the test plate, a kind of sound absorbing medium is used. The size of the plate and the stiffeners is shown in Figure 5.

In the stiffened plate, the difference of impact signals acquired by different sensors is mainly influenced by the propagation path from the impact point to sensors. To evaluate the performance of the method. Total 13 impact points are select to perform the experiment, and each point carries out 10 repeated experiments. The position of impact points and sensors are shown in Figure 6, with a testing range of 50cm × 50cm.

B. TRANSMISSION COEFFICIENT CALCULATION

The stiffeners have different influences on the Lamb wave at different frequencies. As mentioned above, Holland S D proposes transmission coefficient to reflect this characterization. The transmission coefficient can be calculated by (8). And the energy of Lamb wave under different frequency can be calculated by (9):

$$E = \int_{f_c-5}^{f_c+5} FFT^2(f) df_c$$

$$E = \int_{f_c-5}^{f_c+5} FFT^2(f) df_c$$

(9)
where $f_c$ is the central frequency, $\text{FFT}(f)$ is the FFT of Lamb wave.

To calculate the transmission coefficient, a relative experiment was carried out. As shown in Figure 7, three sensors are arranged on the test plate: an exciting sensor and two receiving sensors. The distance between two receiving sensors to the exciting sensor are both set to 10 cm to exclude the influence of the distance.

To calculate the transmission coefficient of a wide frequency band, the excitation signal is set as a wide band signal. The signal consists frequencies from 50 kHz to 500 kHz and last 20 $\mu$s. The expression of the signal is as follows:

$$y(t) = \begin{cases} \sum_{f=500kHz}^{50kHz} \sin(2\pi f), & t \in [0, 20 \mu s] \\ 0, & t > 20 \mu s \end{cases}$$

The excitation signal in time domain and frequency domain is shown in Figure 8 (a) and (b) respectively.

The transmission coefficient calculated by (8) and (9) is shown in Figure 9. The curve of transmission coefficient is comb-shape, and shows no obvious trend with the increasing of frequency. The transmission coefficient between 100-164 kHz and 385-400 kHz is below 0.4, between 251-295 kHz and 347-360 kHz is above 0.8.

### C. WAVE VELOCITY DETERMINATION

As mentioned in section 2, the phase velocity of Lamb wave is an important parameter for the calculation of the TCWII method. The phase velocity is determined according to the dispersion curve shown as Figure 10. Because A0 mode Lamb wave is chosen for processing during the experiment, the phase velocity of A0 Lamb wave is used to construct phase velocity matrix. For each narrow filter band, the phase velocity of its central frequency is regard as its phase velocity.

### IV. RESULTS

#### A. SIGNAL PROCESSING

In this section, the procedure of the TCWII method will be reintroduced.

In the signal processing procedure, 30 narrow filter bands between 100-400 kHz are used to filter the signals. The filter bands have a bandwidth of 10 kHz and 10 kHz interval with adjacent bands.

The impact point ($-15$, $-5$) is used for example. Figure 11 shows filtered signals collected by sensor 2 and sensor 4, with a filter band of 200-210 kHz. The figure shows signals collected by both sensor 2 and sensor 4 have significant spikes at the beginning of the signal. Because the distance between sensor 4 and impact point is larger than that between sensor 2 and impact point, the signal collected by sensor 4 has a significant amplitude drop and time delay compared with sensor 2’s signal. Considering that S0 Lamb wave is too short which is unfit for cross-correlation calculation, A0 mode Lamb wave is chosen for processing. The short signal cut off from the original signals are shown as Figure 11, with a lasting time of 20 $\mu$s (400 points).

The cross-correlation curves after getting absolute value, Gaussian fitting and normalizing are shown in Figure 12, calculated with the signals in Figure 11.

By calculating impact intensity using (6) and (7), the impact intensity map can be obtained. The grid size is 1 mm
in this paper. Figure 13 shows several impact intensity maps of different narrow filter bands. Figure 13 (a) and (b) are the most common result: the location result has an acceptable deviation from the impact point, and there is still relatively larger impact intensity at the impact position. Compare with Figure 13 (a), Figure 13 (b) have extra bright spots away from the impact point called secondary bright spots in this paper. Because the secondary bright spots have lower impact intensity than the bright spot at impact point, the location result didn’t be affected by it. Figure 13 (c) is an ideal location result, which usually happens under filter bands whose transmission coefficient is larger. Figure 13 (d) shows an extreme case: the location result has large location error because the secondary bright spots have largest impact intensity. But at the impact position, there is still observable impact intensity which can contribute to weighted impact intensity map.

Before the superposition of the impact intensity maps, the weight of each narrow filter band needs to be determined. As the transmission coefficient has been obtained, the weight of each band can be determined by its transmission coefficient. The weight of each narrow filter band is calculated by summing the transmission coefficients of frequency it contains and then be normalized, as shown in Figure 14.

After the superposition of the impact intensity maps with weights in Figure 14, a transmission coefficient weighted impact intensity map can be obtained, as Figure 15 shows. The location result of the weighted impact intensity map is (−15.15, −5.35) with a location error of 0.39 cm. The Figure shows the secondary bright spots in Figure 14 (b) didn’t influence final impact intensity map, but the secondary bright spots in Figure 14 (d) have left traces in the final map. The main reason is the secondary bright spots in Figure 14 (d) have larger impact intensity and other impact intensity maps have some similar secondary bright spots at the same position of Figure 14 (d). In general, the TCWII map reduces the
TABLE 1. Location errors.

| No. | Impact point (cm) | Average location error (cm) |
|-----|------------------|-----------------------------|
| 1   | (0, 0)           | 1.98                        |
| 2   | (10, 10)         | 2.36                        |
| 3   | (-10, 10)        | 1.22                        |
| 4   | (10, -10)        | 2.10                        |
| 5   | (-10, -10)       | 1.69                        |
| 6   | (15, 5)          | 2.14                        |
| 7   | (-15, 5)         | 1.93                        |
| 8   | (15, -5)         | 2.60                        |
| 9   | (-15, -5)        | 2.05                        |
| 10  | (20, 15)         | 3.37                        |
| 11  | (-20, 15)        | 2.90                        |
| 12  | (20, -15)        | 2.57                        |
| 13  | (-20, -15)       | 2.91                        |

FIGURE 15. Transmission coefficient weighted impact intensity map of impact point (-15, -5).

influence of the secondary bright spots in impact intensity maps, achieves better location results.

B. LOCATION RESULTS

Table 1 shows the location errors of 13 impact points. The total average location error of 13 impact points is 2.29 cm. Furthermore, location results of impact points 2-5 located at the crossover point of stiffeners achieve high accuracy, with an average error of 1.84 cm. The result shows the TCWII method can realize accurate impact location in stiffened plates.

To verify the rationality of the transmission coefficient weighted superposition, the average location error using the impact intensity method with different narrow filter bands is shown in Figure 16, compare with the transmission coefficient. As shown in the Figure, the average location errors are smaller, of narrow filter bands whose transmission coefficients are larger. The trend of the average location error curve is roughly consistent with the transmission coefficient. This shows that weighting with the transmission coefficient is reasonable and effective.

C. COMPARISON WITH TRADITIONAL TDOA METHOD

The traditional TDOA method is used to compare with the TCWII method. Signals collected by sensors 1-4 are used for TDOA method. The filter frequency band is set to 250-300 kHz. The threshold is set to 150 mV to catch the arrival time of A0 mode Lamb wave. The wave velocity is set to 2132 m/s for calculation. The location errors are shown in Table 2. The Table shows the location results obtained using traditional TDOA method have larger average location error at all impact points than TCWII method. The total average location error of TDOA method is 8.77 cm. The comparison shows the TCWII method has much improvement on accuracy than the traditional TDOA method. This is mainly because the TCWII method doesn’t depend on accurate arrival time detecting, which TDOA method very depends on. Influenced by the stiffeners the signals collected by the sensors have large attenuation on amplitude. As the number of stiffeners between different sensors and the impact point is different, the attenuation of the signals is different, causing for the same threshold, the arrival time detected by different signals don’t point to the same position of the original impact signal. This causes errors of time difference of arrival and affecting the accuracy of the TDOA method. However, the TCWII method doesn’t use arrival time directly, which makes the method perform better than the TDOA method.

The TCWII method uses impact intensity map to locate the impact points. It has potential to be combined with other methods. For example, the cross-correlation curves can be replaced by other curves, such as Gaussian curves generated according to the time difference of arrival. By this way, the TCWII method can be combined with other novel arrival time
gaining method. Because the number of cross-correlation curves is large, the calculation time of this method is long. It can be further improved by finding a proper method to reduce the number of cross-correlation curves without affecting the location accuracy.

V. CONCLUSION
This paper proposes the TCWII method which can realize accurate impact location in stiffened plates. The method firstly calculates the cross-correlation curves of the signals collected by different sensors. Then impact intensity maps are calculated using the curves according to the impact intensity formula. Finally, a final impact intensity map is obtained by superposing impact intensity maps of different filter bands weighted by transmission coefficient, and the impact point is located by finding maximum impact intensity in the map.

To evaluate the TCWII method, 13 impact points are selected for experiments. As each impact point processes 10 repeat experiments, a total of 130 experiments have been taken. According to the results, the TCWII method achieves good accuracy with an average location error of 2.29 cm in 50cm × 50cm testing range, which is 70% less than that using traditional TDOA method (8.77 cm). And the tending of location errors of impact intensity method using different number of cross-correlation curves without affecting the number of cross-correlation curves can be further improved by finding a proper method to reduce the number of cross-correlation curves.

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