Research on Active and Passive Monitoring Fusion for Integrated Lamb Wave Structural Health Monitoring

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Abstract. Lamb wave based active and passive monitoring technologies are both hot points in structural health monitoring (SHM). However, active and passive monitoring methods were usually worked independently. The interaction and complementarity between Lamb wave active and passive monitoring techniques was analyzed. According to the advantages and disadvantages of active and passive monitoring methods, the active and passive cooperative working mechanism was proposed which combined the active and passive monitoring approaches. In the new method, active scanning and monitoring was set to be trigged by passive acoustic emission event, and the scanning interval could be greatly extended to save the energy consumption and improving monitoring efficiency as the evolution of damages caused by service and external erosion were usually very long. Meanwhile, the results and diagnosis information of active and passive monitoring method could be fused to improve the monitoring accuracy. In addition, the hardware implementation and software frame of the new integrated system were given. The experimental validation showed that the new approach combined the advantages of active and passive monitoring methods, and improved the damage monitoring efficiency and accuracy.

Keywords: Structural health monitoring (SHM) · Cooperative working mechanism · Passive acoustic emission event · The scanning interval

1 Introduction

The large-scale engineering structures, such as aerospace vehicles, civil engineering, ship railways, oil pipelines etc., are affected from external environmental loads, fatigue, corrosion, material aging which would cause damages. On the surface or inside of the structures [1]. In order to avoid unexpected accidents and even heavy casualties, structural health monitoring technology was proposed in the aviation field and has been widely concerned and developed in the early 1990s [1]. Structural health monitoring (SHM) is one kind of the real-time on-line monitoring technology without destroying

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the structure and ensuring the integrity of structural parts. Professional equipment were usually designed and adopted to analyze structural responses continuously to determine the occurrence, location and extension of possible damages [2, 3].

Lamb wave based structural damage monitoring technology is one of the hotspots and frontier technologies in the field of SHM with broad application background. This technology includes two categories, namely active monitoring methods and passive monitoring methods. In the passive monitoring mode, acoustic emission signal would be captured and analyzed to extract the damage related information and locate the damage online [4–6]. In the active monitoring mode, an excitation with certain form which usually was narrowband signal was inspired in the structure firstly through preset actuator, and at the same time the structural responses would be acquired using several distributed sensors around. The received response signals were analyzed by comparing with the ones before damage so that the changes of the responses could be extracted to evaluate the damage features and complete the damage monitoring and diagnosis. No matter active methods or passive methods, most of the existing studies are usually focused on one of the above-mentioned categories; however, less attention was drawn on how to take into account the advantages of these two categories to improve the monitoring effect and accuracy. Based on the existing efforts in Lamb wave based SHM, the cooperative working mechanism of the active and passive categories was proposed which also included the fusion method of active and passive SHM technology. Experimental validation was carried out to verify the improvement of the new method.

2 The Analysis of Lamb Wave Based Active and Passive Monitoring Fusion SHM Mechanism

2.1 The Principle of Mechanism

For the active Lamb wave damage monitoring methods, the certain forms of Lamb waves are firstly excited in the structure, and usually single mode Lamb wave was preferred. The structural responses would be collected and analyzed to extract the information related to the damage and to diagnose the damaged area. So it is more sensitive to the changes of the structural state, but it can't detect the accidental damages timely, such as impact and fracture. Thus, it is necessary to scanning the structure periodically and the interval between two adjacent scanning should be short to avoid missing the possible damages caused by impact, and the shorter the time interval, the greater the power consumption. For the passive monitoring methods, the monitoring system would work only if impact or acoustic emission events occurred. So it is sensitive to the accidental damages, but is not effective for evolutionary damage, such as fatigue, corrosion. At the same time, the signals from the possible damages may be very complicated due to the dispersive nature of Lamb wave and the sensor network should be preset very carefully because the acoustic emission events may occur at any place. Limited sensors would lead to monitoring accuracy, but more sensors would increase equipment costs greatly. Actually, these two categories will effective for most of the damages at different stages. For example, impact may cause the delamination in composite and perforation in metal structure. At the moment of the impact, the passive Lamb wave monitoring methods would be activated to capture the impulses from the damage location and point out the approximate damage position, and then the active Lamb wave monitoring methods can realize the evaluation about the possible damage by using specified excitation. The same sensor network was used in both of the two methods. Thus, in order to combine the advantages of active and passive Lamb wave monitoring mechanisms, a new monitoring methodology was proposed in which the two monitoring methods were functionally combined in time series to realize the full-time monitoring. The principle of the new monitoring methodology can be shown in Fig. 1.

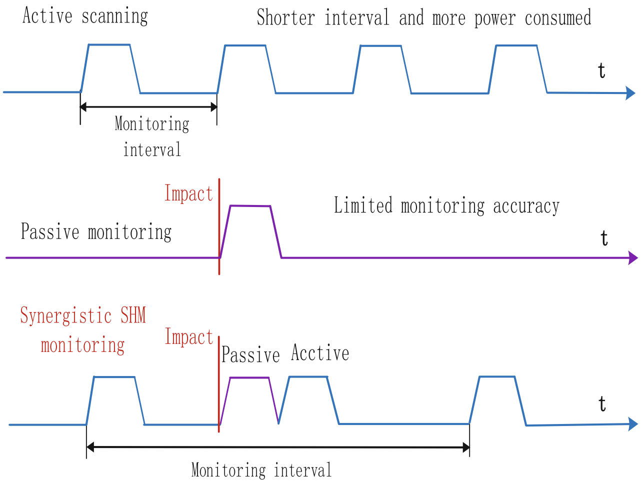


Fig. 1. Principle of the active and passive fusion monitoring methodology

According to Fig. 1, in the new monitoring method the passive monitoring mode would monitor the state of the structures during the active scanning interval. The active monitoring mode would be activated by the impact events or it only worked at the presented time periodically. So the passive monitoring mode was used as the trigger of active monitoring mode. The scanning interval of the active monitoring can be extended greatly to reduce power consumption and improve monitoring efficiency. When the impact or acoustic emission occurred, the passive monitoring mode can sense and locate the damage immediately, after that the active monitoring mode was triggered to start the monitoring process to evaluate the size and extension of damage. Furthermore, the two monitoring information can be fused to achieve more accurate damage diagnosis.

2.2 Lamb Wave Monitoring Information Fusion

The fusion of active and passive monitoring information was based on the probabilistic localization and imaging algorithm. The characteristic parameters of Lamb waves of active and passive monitoring mode were extracted and analyzed respectively. The surface coordinate of the measured structure can be transformed to pixels of an image which can be calculated by the contrast value at each pixel. And two images can be obtained by active and passive monitoring modes. The fusion of damage information was achieved though these two images.

The value assignment of each pixel in passive monitoring mode could be expressed as

$$\alpha_{mn} = \sum_{a=1}^{K-1} \sum_{b}^{K} \beta_{ab} \left| \frac{S_{mn}^{a} - S_{mn}^{b}}{(t_a - t_b)v} - 1 \right| \tag{1}$$

Where K was the number of sensors, β_{ab} was the weight coefficients of sensor a and sensor b, t_a and t_b were the impulse response times, S_{mn}^{a} and S_{mn}^{b} were the distance of the pixel to sensor a and b. In conjunction with the contrast of each pixel, $M \times N$-order matrix A_{MN} can be obtained.

The value assignment of each pixel in active monitoring mode can be expressed as

$$\beta_{mn} = \frac{1}{(K-1)(K-2)} \sum_{a=1,a\neq z}^{K} \sum_{b\neq a,b\neq z}^{K} \frac{\left| \frac{\Delta t_a}{\Delta t_b} - \frac{S_{mn}^{z} + S_{mn}^{a}}{S_{mn}^{z} + S_{mn}^{b}} \right|}{\frac{\Delta t_a}{\Delta t_b}} \tag{2}$$

Where K was the number of sensors, Δt_a, Δt_b was the arrival time of the Lamb wave scattering signals received by sensor a and b, and S_{mn}^{a}, S_{mn}^{b}, S_{mn}^{z} were the distance from the pixel (m, n) to the sensor a, b and c. In conjunction with the contrast of each pixel, $M \times N$-order matrix B_{MN} can be obtained.

The elements in the matrixes were mapped to [0, 1] by the min-max normalization. After the normalization processing, we can get the positioning and imaging matrix as A_{MN}^{*} and B_{MN}^{*} by the active and passive monitoring mode respectively, and the fused image can be obtained by using the followed formula.

$$C_{MN}^{*} = \delta_p A_{MN}^{*} + \delta_a B_{MN}^{*} = \frac{K}{2(K-1)} \left[\alpha_{mn}^{*}\right] + \frac{K-2}{2(K-1)} \left[\beta_{mn}^{*}\right] \tag{3}$$

δ_a, δ_p were the weights of respectively active and passive monitoring information.

3 SHM Validation System Design Based on New Monitoring Methodology

According to the Lamb wave principle of the active and passive fusion monitoring methodology, a functional verification of the monitoring mechanism was carried out, which used the standard module and was developed to integrate the fusion of the active and passive monitoring methods. The system included man-computer interaction interface and hardware device modules as shown in Fig. 2.

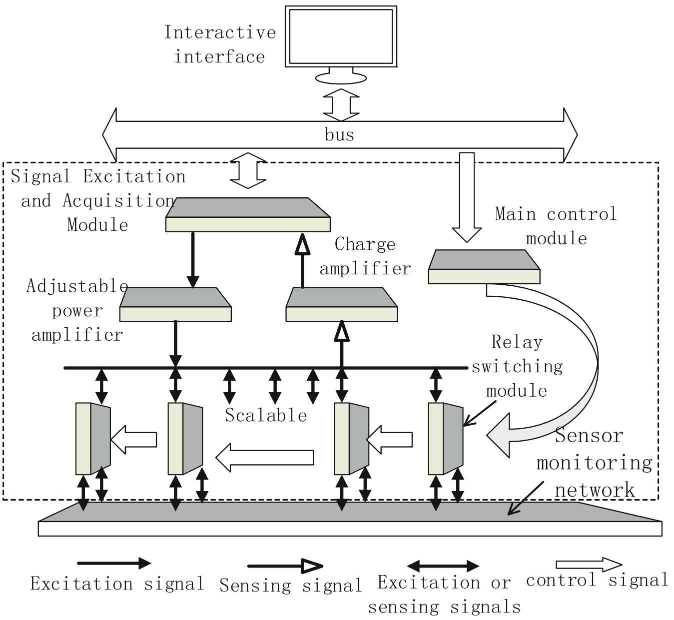


Fig. 2. The integrated system based on new monitoring methodology

3.1 The Hardware Framework of Integrated Systems

The hardware framework of the integrated system was shown in Fig. 2. The main components were the control module, relay switching module and the signal conditioning module. The signal conditioning module included signal excitation and acquisition equipment, power amplifier and charge amplifier. All parts of the hardware were connected through the bus. The bus based interconnection of the integrated system makes it compatible with other systems, and can be extended with more monitoring channels and sensor network. So it was possible to realize the large-area monitoring for the engineering structures.

The control module communicated with the PC through the bus, buffered, processed and transformed the control instruction issued by the man-machine interface. In this way, the system can switch between the active and passive monitoring modes, select the

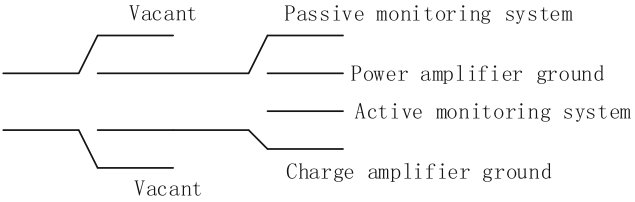


Fig. 3. Topology diagram of channel switching

acquisition channel. The signal conditioning module achieved the Lamb wave excitation signal generation, power amplification, acquisition and storage of sensing signals.

Relay switching module was the core of hardware system design, which solved the switching of piezoelectric array freely in active and passive monitoring modes. The designed relay switching topology (two relays to form a channel) was shown in Fig. 3.

According to Fig. 3, the passive monitoring mode worked during the active scanning interval. The switches of the second level relay were connected with the signal inputs and the ground of the charge amplifiers. When the active scanning or events triggered switch to the active monitoring mode, the switches of the second level relay were connected to the output and ground of the power amplifier. Time-sharing control over time series was used to switch the system working states between the active and passive monitoring modes freely.

3.2 The Software Framework of Integrated Systems

According to the collaborative working mechanism and hardware design of the integrated system, the software framework of the monitoring system was divided into the application and the driver layers which interacted with each other through the man-machine interface. The software design framework was shown in Fig. 4.

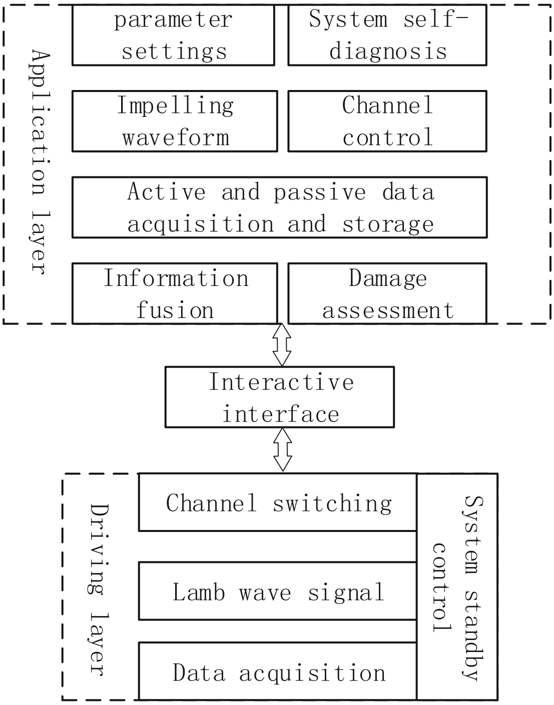


Fig. 4. The framework of the software

The interactive interface implemented functions, such as input of system parameters and user's commands, presentation of damage monitoring results, and so on. The input of the user's instruction was convenient to switch the working state of the system between the active and passive modes, expand the monitoring channels and the sensor network.

The design of application layer included the generation of excitation waveform, the control of monitoring channel, the fusion of active and passive acquisition information, the damage monitoring and evaluation. The monitoring channel control realized the selection of the actuator and the sensor under the active and passive modes, and extension of the channels according to the scope of the monitored structures. The fusion of the active and passive information was based on the extracted characteristic parameters of the damage information from the active and passive Lamb wave responses, and it can be integrated in the imaging algorithm. Driving layer achieved the control of hardware devices, including the channel switching, Lamb wave signal excitation, data acquisition and system standby drive.

4 Experimental Validations

4.1 Object and Platform of Experiment

The experimental specimen and platform were shown in Figs. 5 and 6. The specimen was made of reinforced glass fiber composite material with dimensions of 1000 mm * 500 mm and thickness of 3 mm. PZT sensors were distributed over the structure to compose a sensor array network. The distance between the PZT sensors was 250 mm. The sensor was numbered as shown in Fig. 5. The monitoring area was divided into three parts, named area A, B and C which composed with sensors No. 1, 2, 7, 8, sensors No. 2, 3, 6, 7 sensors and sensors No. 3, 4, 5, 6 respectively.

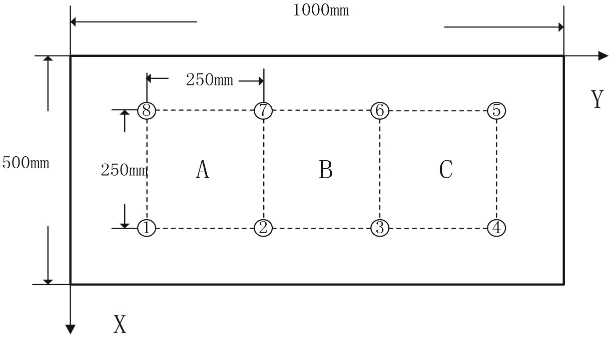


Fig. 5. Schematic diagram of the experimental object

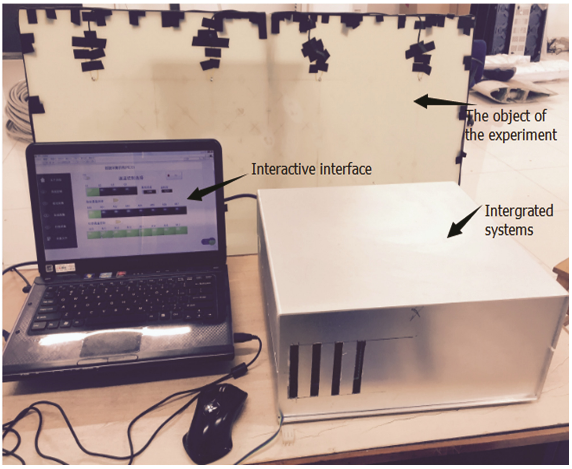


Fig. 6. Experimental platform of integrated system

In the integrated system, the impact damage in the passive monitoring was achieved by the impact hammer knocking the surface of the structure. Cracks and delamination damage were simulated by pasted masses on the structure. The experimental integrated system platform was shown in Fig. 6.

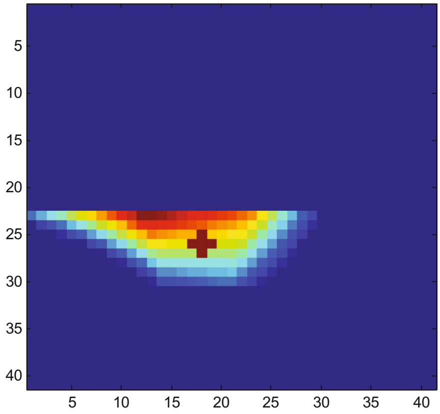
4.2 Localization and Imaging of Integrated System Experiment

A typical 5-wave sinusoidal modulation signal was used as the excitation signal and the central frequency was 60 kHz. Its amplitude was power amplified to100 V. Excited Lamb wave signal was mainly A0 mode [7–9]. In the composite plate, the impact damage was occurred at (125 mm, 187 mm), and the simulated delamination was at the same location. When the impact triggered passive monitoring mode, the acoustic signals were acquired and the damage imaging could be obtained. The coordinates of impact was detect at (124 mm, 182 mm). At the same time active monitoring mode and the data acquisition were triggered after the passive monitoring mode. And the coordinates of the damage were detected at (122 mm, 186 mm) by using the active imaging algorithm. The location coordinates obtained from the active and passive fusion algorithm were (124 mm, 183 mm). The positioning coordinates were shown in Table 1.

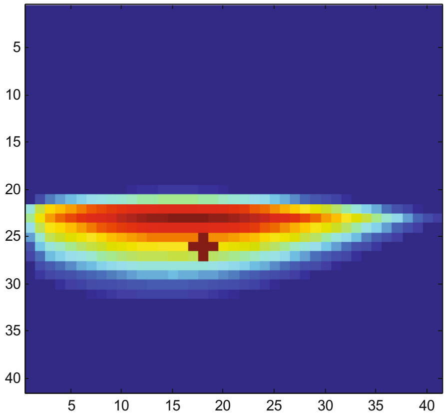
Table 1. Comparison of different monitoring methods (mm)

Actual damage location	(125,187)
Passive monitoring	(124,182)
Active monitoring	(122,186)
Collaborative monitoring	(124,183)

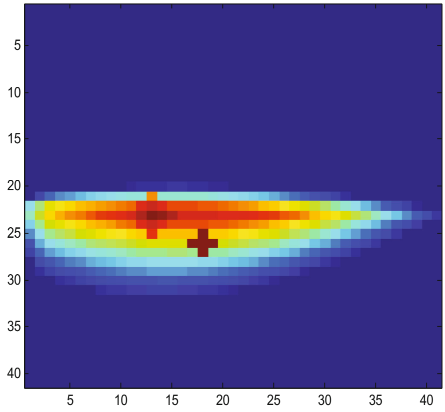
The active and passive monitoring results and fused imaging were shown in Fig. 7. The crosses in the figure were the actual approximate impact and damage location.



(a) passive monitoring imaging



(b) active monitoring imaging



(c) fused monitoring result

Fig. 7. The single and fusion of information by imaging (Color figure online)

From the three imaging results in Fig. 7, the locations of impact damage and the simulated damage can be seen clearly. The brightened part of the color was the passive or active localization area. After the fusion process, the positioning points were relatively more accurate than that of active and passive monitoring mode. From the trend of the color highlighting, the damage expanded from the left to the right.

5 Conclusions

The cooperative working mechanism of the active and passive Lamb wave damage monitoring methods was studies. Integrated system based on the new method was designed, including the hardware and software. Experimental validation showed that the advantages of both active and passive monitoring modes could be retained in the cooperative working mechanism. The hardware of the system integrated the active and passive monitoring functions. It was realized by the design of the topology of switching control. The software platform provided supports for hardware devices, visualization of human-computer interaction interface, information collection, pre-processing and integration. Finally, the experimental results also showed that the new method and system improved the accuracy of damage location and the evaluation.

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