Online Damage Monitoring for High-Speed Train Bogie Using Guided Waves: Development and Validation

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ONLINE DAMAGE MONITORING FOR HIGH-SPEED TRAIN BOGIE USING GUIDED WAVES: DEVELOPMENT AND VALIDATION

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ABSTRACT

The high-speed railway industry has enjoyed a rapid development in the past decade, especially in Greater China. The safety of high-speed trains has therefore become a key concern not only in the design process but also in their operation. Usually, plenty of testing jobs are performed through periodical maintenance to ensure the integrity of train structures, using offline nondestructive evaluation methods with relatively low cost-effectiveness. Based on the group's efforts in the past ten years, a guided wave based damage detection and monitoring technique was developed to provide an online structural damage inspection approach, aiming to increase the safety of bogie structures and improve train operation efficiency. Miniaturized standard PZT sensors were developed to compose a pitch-catch based active sensor network for guided wave excitation and acquisition in the train bogie, and a compact system built with the proposed technique was implemented online to inquire information on structural health conditions. As a part of the conformance testing of China's latest high-speed train model, experiments on a bogie frame of the train were carried out, especially when the train was running at a high speed, to validate the proposed technique and system, taking into account the complicated working states and the highly variable circumstances of the train, which are usually hard to be simulated in the lab. Several practical experiments were involved in the testing, including the survival rate of the sensor network, disturbance of mechanical vibration to signals, influences of actions of train (such as urgency brake), artificial damage detection, and so on. After running and testing for more than 1500 km, the experimental results from different conditions demonstrated high reliability and accuracy of the technique and the system.

KEYWORDS : *structural health monitoring, compact system development, train bogie, online damage detection and monitoring.*

INTRODUCTION

Benefiting from the developments of modern transportation techniques, trains now run faster and faster to accommodate people's travelling needs. In recent decades, development of the high-speed railway industry in China has been rapid. Yet, with a rising train speed, safety issues have been concerned about more and more intensively. Painful lessons in the past have told us that damage that occur to running high-speed train structures, such as fatigue, cracks or bolt looseness, may lead to disastrous consequences. In order to avoid such accidents, periodic examination and testing on key structures using traditional nondestructive testing (NDT) techniques have been popularly implemented, even though safety is already significantly accounted for during the design process. Considering the limitations of space, efficiency, operating time, and working conditions of NDT methods, online damage monitoring methods and application systems are necessary to be developed and validated. In this sense, structural health monitoring (SHM) is a new technique that can achieve the goals of increasing the safety level and reducing maintenance costs for engineering structures [1, 2]. It was proposed first in the early 1990s for aerospace vehicles and has made rapid progress in the past two decades. An SHM system typically consists of a sensor network for data acquisition and some central controller to evaluate the structural health online by using stored knowledge of structures and the information obtained in the current situation [1, 3]. Among the existing SHM methods, Lamb wave based damage detection has been widely acknowledged as one of the most effective and promising techniques, due to its wave-guiding characteristics and sensitivity to small damage [1–3]. However, most of the current Lamb wave based SHM methods were developed on simple structures, such as flat plates or tubes, in lab-controlled environments. Real-world engineering structures are usually complicated with varied thickness, geometries and materials. At the same time, working conditions of these structures are changing and sometimes complicated due to external vibration and loading. While such problems are always expected when Lamb waves are applied on highly dynamic mechanical structures in practice, few studies in the current literature have elaborated their applicability in this regard, either strategically or tactically.

Aimed at real-world engineering applications, efforts in the present work focus on the development of a practicable online damage detection technique, based on Lamb waves and active sensor networks, for high speed train structure monitoring in real time. First, an online Lamb wave based damage monitoring system was developed. In conjunction with a long-distance test of a new high-speed train model of China, the developed system and technique was validated experimentally on the train bogie, and some fundamental issues were concerned, including standard PZT sensor and its installation, Lamb wave exciting in complex structures, data acquisition and pre-processing, damage detection method, and so on.

1 LAMB WAVE BASED STRUCTURAL HEALTH MONITORING

1.1 Fundamentals of Lamb waves

Lamb waves are a kind of guided elastic waves propagating in plate-like structures. Unlike bulk waves, Lamb waves are complicated due to their dispersive and multimodal features [4]. Theoretically, these two features can be investigated by solving the Rayleigh–Lamb equations defined by the symmetrical and anti-symmetrical modes on an infinite plate with a thickness of $2h$ [4]:

$$\left(k^2 + s^2\right)^2 \cosh\left(qh\right)\sinh\left(sh\right) - 4k^2 qs \sinh\left(qh\right)\cosh\left(sh\right) = 0 \ , \tag{1a}$$

$$\left(k^2 + s^2\right)^2 \sinh\left(qh\right)\cosh\left(sh\right) - 4k^2 qs \cosh\left(qh\right)\sinh\left(sh\right) = 0 \ , \tag{1b}$$

where $q^2 = k^2 - k_l^2$ and $s^2 = k^2 - k_t^2$. Here, k denotes the wave number, and k_l and k_t are the wave numbers for the longitudinal and shear modes, respectively. The dispersion curves can be determined by solving Equations. (1a) and (lb), and expressed in terms of the frequency-thickness product versus the group velocity C_g, which is defined as

$$C_g = \frac{d\omega}{dk}, \tag{2}$$

where $\omega$is the angular frequency. For a plate with a constant thickness, a dispersion curve can be represented as a function of frequency. The dispersive nature of Lamb waves causes the different frequency components of Lamb waves to travel in the plate at different speeds, thus altering the shape of the wave packet. It should be noted that multiple wave modes can be extracted from Equation (1). The symmetric modes are designated S_0, S_1, S_2, *etc.*, while the antisymmetric are designated A_0, A_1, A_2, *etc.*

1.2 Lamb wave based SHM

Thanks to their relatively long propagation distance and high sensitivity to small damage, Lamb waves have been utilized to realize structural damage detection and health monitoring [2, 3, 5]. The basic principle of active Lamb wave-based damage detection is shown in Figure 1. First of all, a sensor network is installed on or in the structure to actuate and sense Lamb waves. Narrowband signals are usually selected for the excitation of a dominant single mode (to the extent possible) to simplify structural responses. Since Lamb waves are sensitive to structural damage, the structural condition can be monitored and evaluated by comparing current responses and stored benchmark responses. Advanced signal processing techniques and tools, such as the theory of time reversal and phased arrays [6-9], can be adopted and refined for a further analysis to evaluate damage location, size, and severity.

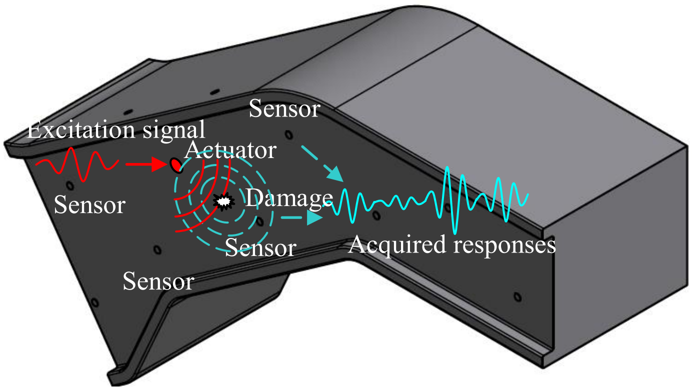

Figure 1: Basic principle of active Lamb wave-based damage detection

Considering the advantages of Lamb wave-based SHM and its progress so far, an online damage detection technique and system were developed first. Some fundamental issues were then investigated to provide a new approach for safe operation of key components of high-speed trains.

2 ONLINE DAMAGE DETECTION TECHNIQUE AND SYSTEM FOR HIGH-SPEED TRAIN

The investigation of the technique included mainly the development of an active sensor network and the design of an integrated online monitoring system. In addition to the common functions of wave actuation and acquisition, the sensor network required in this investigation should also address more practical issues such as the sensor size, package, protection, and so on, to accommodate rough working conditions of high-speed trains and other engineering structures. PZT elements have been widely used as actuators and sensors in Lamb wave-based SHM because of its two-way piezoelectric effects. However, PZT elements are also fragile and their connecting wires can be long, disordered, and unstable, which is impractical for real-world applications. Therefore, the flexible printed circuit (FPC) technique was adopted in this study to design the standard PZT sensing units. A polyimide film was used to embed the printed circuit and the PZT element and its poles for protection, and the preset circuit could provide uniform electric connection between each PZT element and the monitoring system, improving the performance consistence of the sensing units. To minimize the influence of sensors on the integrity of the host structure, selected PZT elements were only 0.2–0.5 mm in thickness, and 5–10 mm in diameter, as shown in Figure 2(a).

Allowing for the fact that the number of sensors in a configured sensor network could be much greater than that of the signal acquisition channels in a data acquisition system, a time division multiplexing method was introduced for the management and control of the sensor network. As shown in Fig. 2(b), all standard sensing units in the network were connected with a switch array, which could simultaneously select two of the units in the network to act as the actuator and sensor respectively, setting up one monitoring path.

According to the aforementioned Lamb wave-based SHM principle (Figure 1), a compact online damage detection system was designed, residing on the virtual instrument technique and the PXI (PCI extension for instrument) platform [10, 11]. The hardware frame of the system is illustrated in Figure 3(a), which consists of four basic components: the switch controller of active sensor networks as shown in Fig. 2, wave generation with high-power amplification, high-performance multi-channel data acquisition, and central control and signal processing. These four parts were integrated through the PXI Bus, and controlled by the in-house software. Commands to the hardware components were issued by the software planted into the central control unit, which fulfilled all the major functions for real-time diagnosis, including management of hardware, man-machine interface (MMI), signal processing, damage detection, and presentation of diagnostic results. Figure 3(b) shows the basic software frame and the necessary modules for the integrated system, which consisted of the interface layer, the application layer and the physical layer.

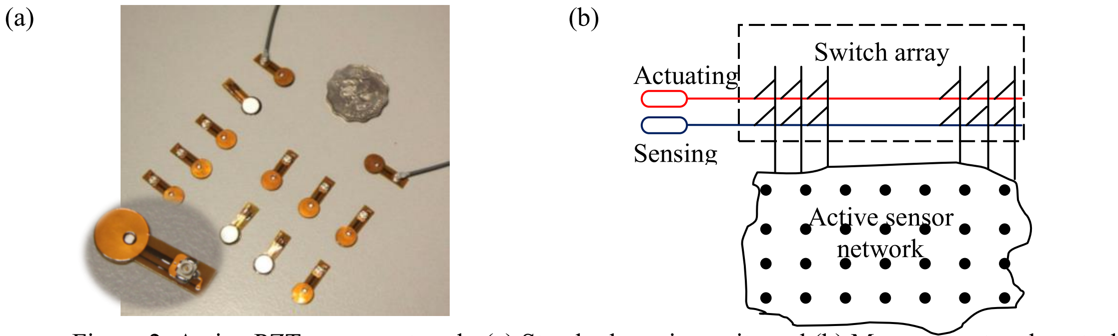

Figure 2: Active PZT sensor network: (a) Standard sensing units and (b) Management and control

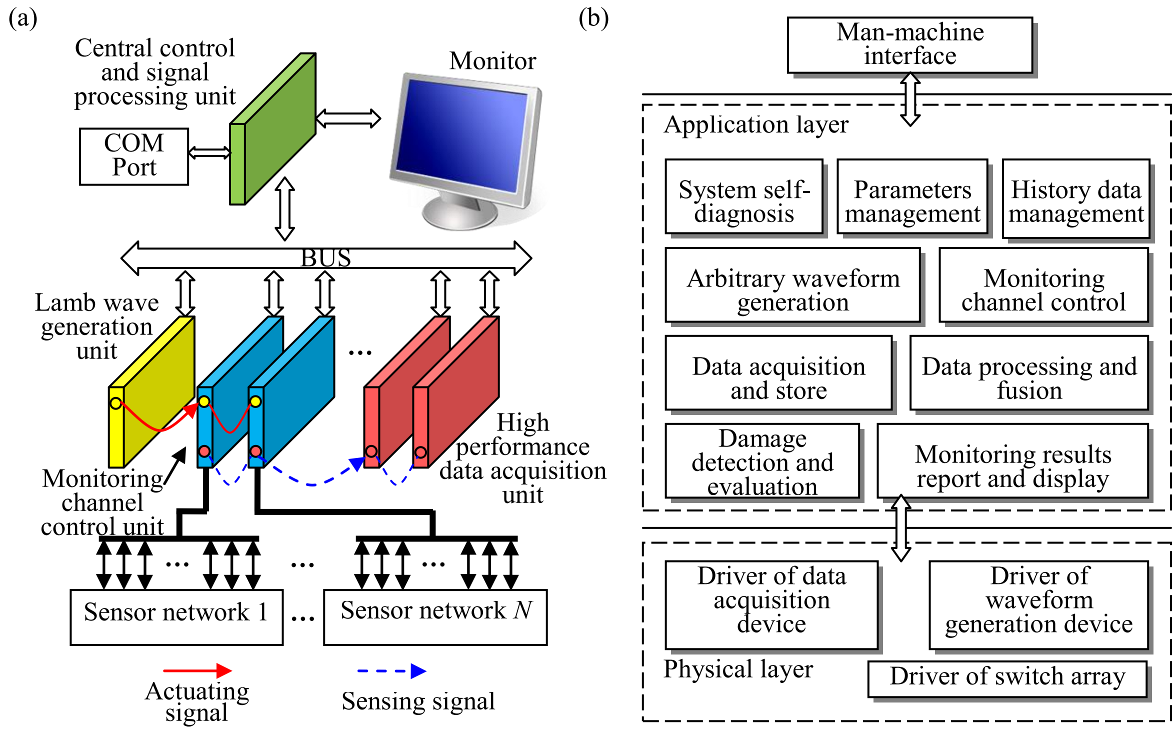

Figure 3: Frameworks of (a) the hardware and (b) software of the integrated online damage detection system

Considering the rugged working conditions of high-speed trains, an aluminum case was designed to protect the equipment. The final integrated system with casing was shown in Figure 4.

3 APPLICATION AND VALIDATION OF THE TECHNIQUE ON HIGH-SPEED TRAIN BOGIE

Bogies are one of the most important structures of high-speed trains. In conjunction with a long-distance conformance test of a new CRH high-speed train model of China, application investigation was conducted to validate the developed Lamb wave-based online damage monitoring technique and system. Some practical issues were focused on primarily, such as active sensor networks, signal excitation and acquisition, monitoring strategy, signal consistency and sensitivity to damage.

Figure 4: The developed online damage monitoring system

3.1 Active sensor network installation

Train structures are composed of thousands of components. In consideration of the integration and wiring, sensors should be installed before the assembling of these parts. Since the train bogie was symmetric both lengthwise and widthwise, focus was placed on a quarter of the bogie as the main monitored region covered by active sensor networks. Each standard sensor unit was bonded to the bogie frame with strong adhesive and protected by epoxy resin. All the sensors were connected to the integrated system through shielded cables with over 30 m in length in total, which were tape-fixed on the bogie as shown in Figure 5. Eleven sensor units were installed on the selected branch among the others.

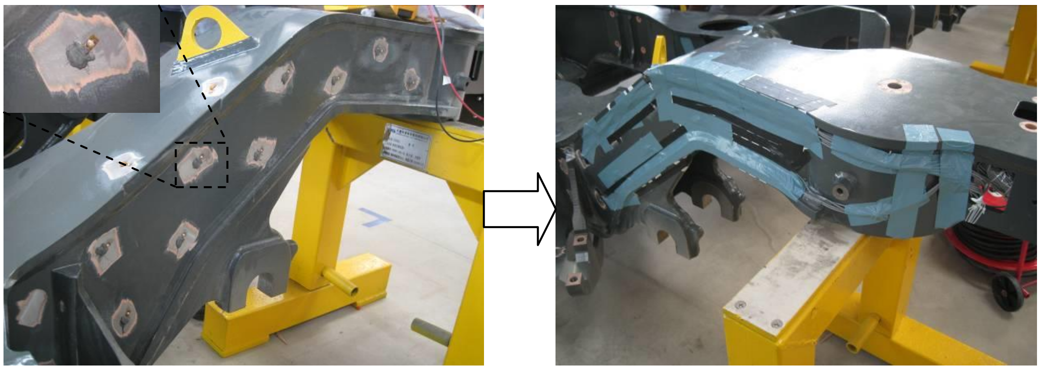

Figure 5: Sensor installation and wiring on the train bogie

3.2 Lamb wave excitation and acquisition

For simple plate or tube structures, a desired Lamb wave mode can be excited and collected using frequency tuning [9], and influences of reflections and mode conversion caused by boundaries are usually small. However, the excitation and propagation of Lamb waves were complicated in the train bogie. It was found that when the central frequency of excitation was below 200 kHz, it was difficult to excite clear Lamb waves. Meanwhile, after a long-distance transmission, sensed signals also attenuated rapidly in this lower band. Thus, the chosen central frequencies of excitation in the testing were over 300 kHz. Typical structural responses amplified and collected in static testing (when the train was stationary) were shown in Figure 6, at a sampling rate of 20 MHz. At least two or more modes coexisted in the responses and it was hard to separate them due to the mode aliasing. In this case, the single mode selection and pulse-echo based damage detection were also challenging for implementation because of the multi-mode responses and complex boundary reflections. Red dotted circles in Figure 6 indicated the probable modes and the mixing.

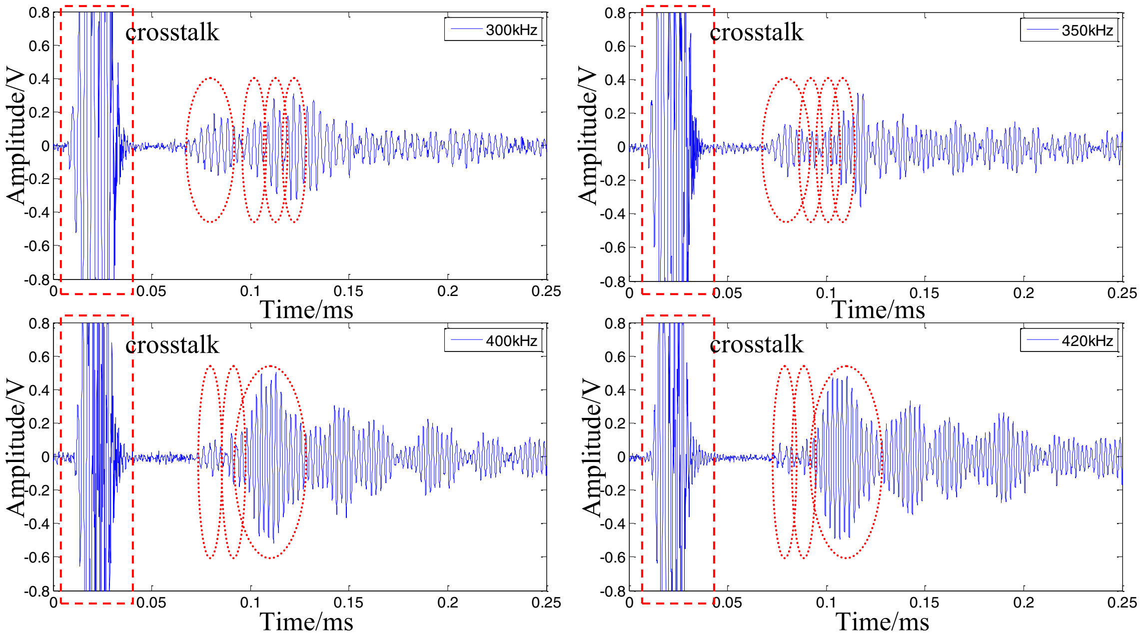

Figure 6: Typical structural responses of the train bogie

3.3 Consistency testing under different working conditions

Unlike a simple specimen in laboratory, train structures usually bear various loads, both static and dynamic. Also, their working conditions may change rapidly according to operational needs. These facts would bring possible disturbance to the monitoring system and acquired signals. At the same time, vibration noises in long-distance operation of the train could be significant and need to be evaluated. In the experiments, structural responses under several typical working conditions were recorded and compared with each other to evaluate the impact of different working conditions of the train bogie in real world on the monitoring technique and system. All the data were collected under the real working conditions, and the maximum speed of the train during the testing reached 300 km/h. Typical signals with noises were shown in Figure 7(a), from which it can be estimated that the noises were limited due to the low pass filter integrated in the data acquisition module. After a secondary low pass digital filter, these signals were shown in Figure 7(b) with good consistency. It can be concluded that the impact of the different working conditions on the system was negligible.

3.4 Damage monitoring strategy and sensitivity

Considering the complex and multi-mode Lamb wave responses, the detection and localization of damage was realized by probing amplitudes variations of signals on the monitoring paths that passed though/by the damaged area, using the pitch-catch mode as illustrated in Figure 8 as an example.

An aluminum mass was plastered on the bogie frame to create the artificial damage in order to test the sensitivity of the monitoring technique and system as shown in Figure 9. The responses before and after damage occurrence from the monitoring paths (red dashed lines in Figure 9) are shown in Figure 10 with their changes. Compared with the benchmark responses from the healthy condition, the changes of the current responses were clear enough to indicate the occurrence of the damage. In other words, the proposed technique and system was sensitive to the small possible damage. Due to different sensitivities of the paths, probability of the presence of the damage within the inspected area could be used to indicate damage location [12], which could be defined based on a variety of signal features (*e.g.*, correlation coefficient) of the acquired and windowed responses before and after damage occurrence, *viz.* the present and the reference signals.

(a)

(b)

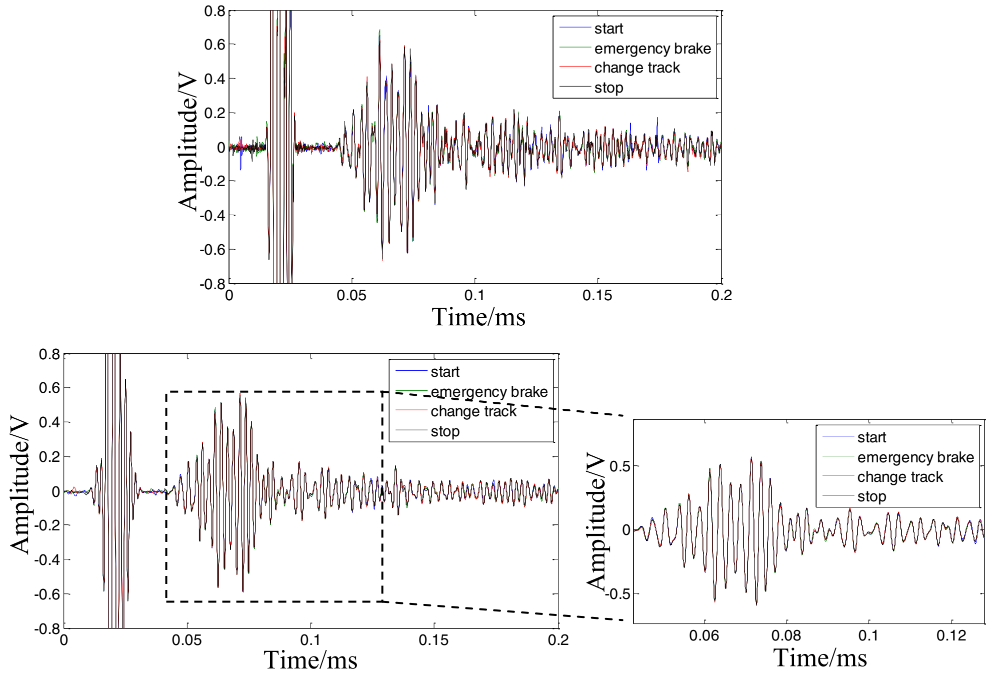

Figure 7: Structural responses under different working conditions (a) with noises and (b) without noises

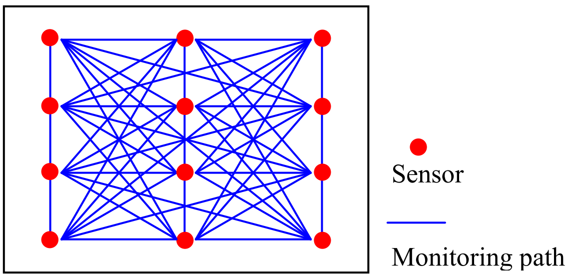

Figure 8: Monitoring strategy for damage detection in the pitch-catch mode

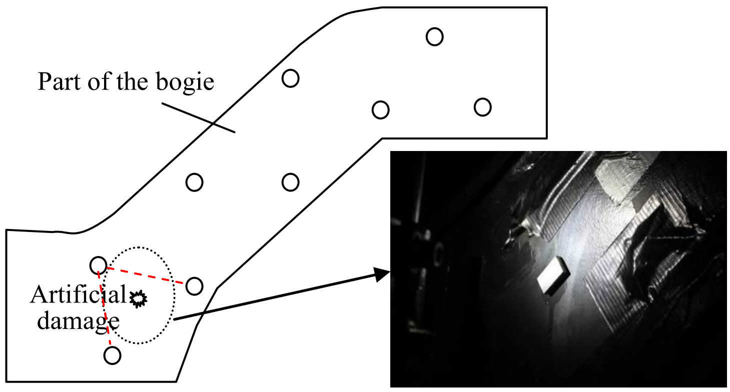

Figure 9: Artificial damage detection

CONCLUSION

In this paper, efforts presented were focused on the application investigation of Lamb wave based structural health monitoring technique for high-speed trains. A compact and integrated system was developed for the field testing of the new high-speed train model of China. A number of fundamental but important issues of using Lamb waves in real-world applications were interrogated, including the active sensor network and its installation, Lamb wave excitation and responses collection, the consistency of the system under complex working conditions, and the damage monitoring strategy and sensitivity. The experimental results on a train bogie showed the expected effectiveness of the developed technique and system. The future work would focus on the damage related signal analysis and the online damage evaluation.

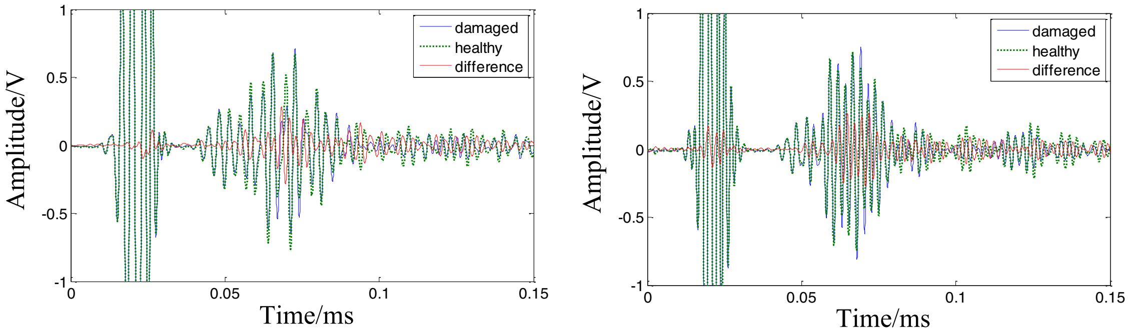

Figure 10: Typical responses before and after damage

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