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Diffuse ultrasonic wave-based structural health monitoring for railway turnouts

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ABSTRACT

Real-time damage evaluation is a critical step to warrant the integrity of turnout systems in railway industry. Nevertheless, existing structural health monitoring (SHM) approaches, despite their proven effectiveness in laboratory demonstration, are restricted from *in-situ* implementation in engineering practice. Based upon the continued endeavors of the authors in developing SHM approaches and exploring real world applications, an *in-situ* SHM approach, exploiting active diffuse ultrasonic waves (DUW) and a benchmark-less method, has been developed and implemented in a marshalling station in China. When trains passing a railway turnout, the train-induced loads on the rail track can lead to the growth of defects in the rail, and such growth disturbs the ultrasound traversing at the defect and gives rise to discrepancies between the DUW signals acquired before and after the train's passage. On this basis, a damage index, making use of the defect growth-induced changes in DUW signals, is proposed to identify the presence of defect. The probability of defect growth induced by the train-related load can be used to assess the severity of the defect. Via an online diagnosis system, conformance tests are implemented in Chengdu North Marshalling Station, in which defects in switch rails are identified and the health status of in-service rail tracks are continuously monitored. The results have demonstrated the effectiveness and reliability of DUW-driven SHM towards real world railway turnout applications.

1. Introduction

With intense use, heavy loads, and harsh environmental conditions, the integrity of rail tracks has been a paramount concern in railway industry, and this concern is particularly accentuated for turnout systems. As critical components of railway infrastructure, turnout systems are used to guide a train to other directions or other tracks. Unlike stock rails, a turnout system assembles diverse components including switches, crossings, insulators, fasteners, stock rails, etc. Considering the irregularity of the structure, the turnout system is more prone to the initiation and propagation of fatigue damage than stock rails in the railway network, as typified by the switch rail, see Fig. 1, because their geometrical features engender stress concentration in local regions [1]. Furthermore, the discontinuity in the wheel/rail running surface (the contact patch) is usually remarkable, as shown in Fig. 1, and the wheel/rail interaction at this imperfect contact leads to the generation of intense impact loads [2] that severely jeopardize the health of the rails. Taking the impact load-induced damage and the fatigue damage induced by passing trains and thermal variation into consideration, defects in railway turnouts can be developed and lead to catastrophic disasters. As reported elsewhere [3], turnout component failures account for the vast majority of derailments. As an example, a derailment occurred near Hilversum station on 15 January 2014, and subsequent investigation showed that a fatigue fracture in the ring of the switch, owing to overdue switch maintenance, was the culprit.

With integrity a paramount concern for railway turnouts, a number of non-destructive evaluation (NDE) methods have been advocated for inspection of rail defects. Prevailing NDE techniques that are readily available for rail maintenance are represented by those using eddy current [4,5], visual cameras [6], magnetic testing [7], and ultrasonic inspection [8–12], to name a few. Among these techniques, the ultrasonic inspection-based technique is the most prevalently applied, with

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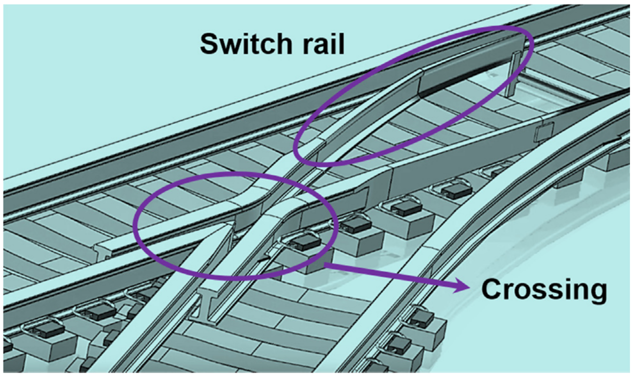


Fig. 1. Turnout system comprising switch and crossing.

the aid of which routine inspection and maintenance has been conducted. Despite their merits in perceiving gross damage, with a nature of off-line manipulation and a high degree of human interaction, most of the aforementioned NDE approaches are inherently unwieldy for timely awareness of rail defects and continuous monitoring of deterioration. Implemented at scheduled intervals after normal service of an inspected railway has been terminated, they are costly, time-consuming, and labor-intensive. Most importantly, when applied to the inspection of the turnout system, these ultrasonic inspection-based techniques are infeasible because they cannot provide efficient access to parts of the turnout system, due to the irregular structure at the turnout system, such as the switch rail as displayed in Fig. 1.

To circumvent the deficiencies described, structural health monitoring (SHM) tailor-made for rail tracks emerges to warrant continuous/real-time and automated surveillance of the integrity of rail tracks. In this regard, acoustic emission (AE)-based SHM methods [13–17] that passively utilize the abrupt energy release when a crack grows have proven their effectiveness. Although a number of AE-based techniques have been reported, this group of techniques is demonstrably effective only in laboratory environments. When applied in engineering practice, they are principally confronted with a twofold bottleneck: (1) the acoustic signals caused by various practical factors such as wheel/rail interaction, impact load, and wheel/rail creep are usually overwhelming, and therefore the damaged-related AE can be obfuscated or masked; (2) when dealing with damage that grows at a low rate (e.g. imperceptible fatigue crack growth or low load-induced growth), AE-based approaches may lose their effectiveness – because such damage growth would not lead to a notable energy release, and this will result in the deficiency stated in (1). Although researchers have exhaustively attempted to discern the damage-related signals from the noise, even with the aid of powerful artificial intelligence methods [16], this group of techniques often shows unsatisfactory performance in engineering practice, in terms of their fidelity, reliability, adaptability, and environment tolerance.

To tackle the deficiencies of passive AE-based methods, SHM approaches using active guided ultrasonic waves (GUWs) in rails are attracting increasing research efforts [18–23]. The effectiveness of this category of approaches lies in the premise that defects in the rail disturb the propagation of inspecting waves and, by evaluating the changes in wave propagation features, defects can be identified. Nevertheless, when extended to rail tracks, particularly the turnout system, these approaches that utilize specific wave modes lose effectiveness because of the perplexing wave scattering/reflections at irregular boundaries, high complexity of wave propagation as a result of multimodal and dispersive features (e.g., GUWs, longitudinal waves, surface waves) and modes overlapping. Therefore, it is challenging to isolate and extract damaged-associated features using existing GUWs-based methods, precluding their application in SHM for railway turnout systems.

To provide continuous and automated surveillance of structural health conditions without suspending the normal operation of the railway turnout system, an active approach based on diffuse ultrasonic waves (DUWs) is developed in this study. In this approach, the rail track is treated as a diffusive medium in which incident acoustic wave energy is rapidly reverberated, resulting in a diffuse ultrasonic wave field that encompasses multiple wave modes such as GUWs, longitudinal waves, and surfaces waves. Despite its complex appearance, the DUW features high repeatability and is sensitive even to subtle change in material or structural properties [24–27]. Via processing DUWs as a whole, instead of isolating and discerning specific wave modes, the health condition of the railway turnout system can be evaluated holistically.

On this basis, damage indices that calibrate the health condition of rail tracks can be constructed by making use of the features of DUWs. To this end, a benchmark-less method is proposed. In this method, the presence of a defect is identified via the effect of newly growing defect, rather than the existing defect, on the propagation of DUWs. This method exploits the contrast between DUWs acquired before and after a train passage, rather than using contrast against an outdated baseline, and this leads to enhancement of the precision and the robustness of defect detection. The proposed DUW-driven approach is deployed and implemented on a railway turnout in a marshalling station in China via a previously developed online diagnosis system. To prove the effectiveness and reliability of the proposed approach, rail tracks bearing a defect are examined and health monitoring of intact, in-service rail tracks is performed. Using integrated sensors, pre-developed devices, and proper signal processing techniques, the proposed DUW-driven SHM approach is capable of enhancing the safety of turnout systems in a robust and economic fashion.

2. Methodology

2.1. DUWs in railway track

Considering the complex geometrical manifestation of rail track and the practical constraints on instrument installation, the incident waves are multimodal which are multi-scattered by boundaries. Therefore, the acoustic energy is rapidly reverberated and adequately disseminated throughout the entire rail track section (see Fig. 2). In this context, although the material properties of the rail track are distinct from those of diffusive medium such as concrete, the rail track can be deemed a one-dimensional diffusive medium along the train's running direction. In this one-dimensional diffusive medium, the DUWs propagating in the rail track are extremely sophisticated, owing to the fact that multiple wave modes coexist, including bulk waves, surface waves, and GUWs, and they are intricately overlapped and intertwined. It is fairly challenging therefore, to isolate and discern each wave mode from such a complex DUW waveform. With this backdrop, the DUWs in the inspected rail section are treated as a whole and processed holistically to extract features that are capable of identifying and characterizing defects in the rail.

In conventional methods, a benchmark process against baseline signals that highlights defect-related changes in wave signals is required to characterize the defect, and the baseline signals are pre-

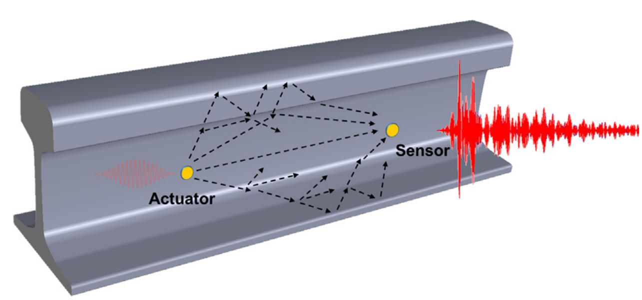


Fig. 2. DUWs in a rail after multi-scattering and mode conversions.

collected from an intact specimen under given conditions [28–30]. Although this method is effective in principle, the detection philosophy is prone to contamination from noise introduced by diverse practical factors. Typically, wave signal acquisition can be influenced significantly by factors such as instrument error, system malfunction, condition variation, and atrocious climate. These practical factors can lead to baseline drift even without the presence of defect, and this drift is often overwhelming above defect-associated changes in DUW signals. As a result, false-positive alarms can be produced, and existing defects can be obscured. With this backdrop, a benchmark-less method is proposed to isolate defect-associated changes in DUWs, enhancing the robustness and reliability of health condition evaluation using DUWs.

2.2. Benchmark-less evaluation method using DUWs

To circumvent the interference linked with diverse practical factors, a pair of DUW signals from an inspected rail turnout, which are respectively acquired before and after the passage of a train, are contrasted. The passing train exerts a load on the rail track, and if any defect exists, such as a fatigue crack, the load exerted by the passing train can lead to the growth of the defect. This defect growth induces disturbance in the DUWs traversing at the defect, thereby producing a remarkable deviation of the DUWs after the train passage from those ascertained before the train passage, as illustrated schematically in Fig. 3. Usually, the passing of a train takes only a short period (e.g. less than a few minutes), during which the service conditions, the system, and the instrument are invariant. Therefore, interference induced by those practical factors is negligible. In this context, changes in the pair of DUW signals are linked with the defect alone and, if no defect exists in the inspected turnout, the variation between the pair of DUW signals is insidious.

On this basis, to assess the variations in DUWs induced by growth of a defect, a damage index is defined that calibrates the level of decorrelation between the pair of DUW signals and reads

$$Rcc = 1 - \frac{\int X(t)Y(t)dt}{\sqrt{\int X(t)^2 dt \int Y(t)^2 dt}}. \tag{1}$$

In Eq. (1), $X(t)$ and $Y(t)$ denote the DUW signals acquired before and after the passage of a train, respectively. Rcc denotes the remnant cross correlation. It is envisioned that the more severe the defect in the rail turnout, the greater will be the growth of the defect when subjected to a train passage induced-load, producing a higher Rcc.

It is worth noting that the probability of defect growth increases with its severity. Therefore, the proposed Rcc can be used to identify the presence of a defect and to evaluate its severity in a quantitative manner. This method can alleviate dependence on the baseline, thereby enhancing the environment tolerance, adaptability, and robustness of health condition evaluation, providing the basis for application in reality.

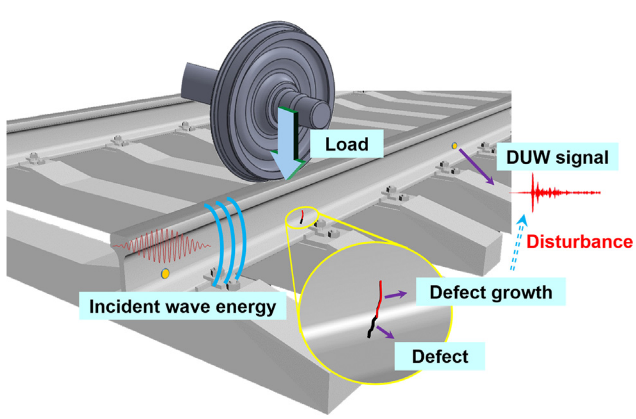


Fig. 3. Load induced by passage of train leads to defect growth causing disturbance in DUWs.

3. Implementation of SHM on turnout in a marshalling station

3.1. System set-up

To implement the developed SHM approach, an integrated online diagnosis system [19] previously designed by the authors is exploited, which is developed on a PCI extension for instrumentation (PXI) platform with the virtual instrument technique. Through the PXI bus and in-house software, the compact system embraces modules including an arbitrary wave generation module, a multi-channel data acquisition module, and a central control and data processing module [31]. In conjunction with the use of an active sensor network, the diagnosis system is capable of performing automatic and online surveillance of the health condition of a rail turnout. For the sensor installation on the rail turnout, lead zirconate titanate (PZT) wafers are appropriate for the practical application (see Fig. 4), owing to several advantageous features: substantial weight saving over conventional ultrasonic actuating and sensing devices, negligible footprint, ease of integration into host structures, high operating frequency, dual roles as actuator and sensor, as well as low cost.

Owing to the holistic monitoring capability of the DUW-based method, a sparse sensor network consisting of two PZT wafers is sufficient to enable DUW excitation and acquisition in a rail turnout, realizing implementation of the developed approach in an economical and convenient fashion. The positioning of PZT wafers does not entail exhaustively prudent selection, thus providing an effortless and universal solution to DUW excitation and acquisition in rail turnout systems with different designs, in which the geometry of the turnout system can vary remarkably.

3.2. In-situ SHM of railway turnout in marshalling station

The developed SHM technique, deployed via the online diagnosis system, was installed on the turnout system in the Chengdu North Marshalling Station in China in December 2018, for *in-situ* monitoring of the health condition of the turnout system.

The Chengdu North Marshalling Station, as photographed in Fig. 5, is the largest freight classification yard in Southwest China, featuring a hump and over 100 tracks. In this station, around 10,000 freight trains consisting of isolated cars with a combined weight of more than 90 million tons are separated, classified, and made into trains according to their destinations every day. In the classification process, the cars are shunted several times along their route through turnout systems, as photographed in Fig. 6. Such frequent passing of heavy freight trains exerts intense loads on the turnout systems. In addition to the intense load induced by trains, they are also exposed to a wide array of hazards such as detrimental impacts, atrocious climate, complex rail conditions, and unexpected events. Therefore, the turnout systems are highly prone to structural damage, and a number of damaged rail tracks in the turnout systems are produced every year.

To implement the developed SHM approach on the selected turnout system, a pair of PZT wafers (PI®, P51, diameter: 12 mm and thickness: 1 mm) were surface-mounted on the rail track prior to the conformance testing. Considering practical constraints, the PZT wafers were located at the rail web at a distance of 70 mm from the rail bottom. The sensor network was then connected to the online diagnosis system, which was accessible to an operator. *In-situ* SHM was performed in the manner of periodic scans. In the DUW test, five-cycle sinusoidal tone bursts modulated by a Hanning window were generated by the waveform generation module at a central frequency of 250 kHz at which strongest responses can be obtained, and the collected data from 128 consecutive scans were averaged so as to increase the signal/noise ratio. Given a propagation speed of ~5 km/s of the longitudinal waves in steel, the

Fig. 4. Online diagnosis system and the PZT wafers used to construct sensor network.

ultrasonic energy could be diffused sufficiently within a time span of 10 ms for a rail with length up to 10 m. Therefore, the DUWs in 10 ms were collected with the PZT wafers at a sampling rate of 25 MHz through the data acquisition module, to encompass desirably rich information pertaining to the status of the overall rail track.

To comprehensively evaluate the developed approach and the online diagnosis system, both the damaged rail tracks and in-service rail tracks were examined.

Fig. 6. The hump and the turnout systems in the marshalling station.

3.3. Application on damaged rail track

To validate the detection capability of the proposed method, damaged rail tracks dismantled from the turnout system in the marshalling station were first examined. As already explained, the switch rail is usually subjected to the impact force owing to the passage of the train, leading to the initiation and evolution of fatigue damage. With an ultrasonic flaw detector maneuvered by an operator, the fatigue damage can be detected. The ultrasonic flaw detector which emits probing ultrasonic waves into the rail and acquires the reflected waves scans along the surface of rail head. At the section in which a defect exists, strong reflection can be detected, as shown in Fig. 7(a), and ignorable reflection is generated in intact regions. Once damage is identified and confirmed, the damaged rail track is immediately replaced by an intact track. Fig. 7(b) displays damaged rail tracks, denoted #1 and #2, that were disassembled from the marshalling station and measured 4.5 m and 5.5 m in length respectively.

A pair of PZT wafers was surface-mounted on the rail track. For illustration, a photograph of the rail with integrated sensors is shown in Fig. 8. The PZT wafers (denoted by PZT1 and PZT2) were positioned 3 m apart. To instigate load-induced defect growth, a hydraulic press was used to apply a load of 100 kN, as displayed in Fig. 8, which was consistent with the load exerted by a passing train in the marshalling station. DUWs were excited and acquired using the PZT wafer-based sensor network before application of the load and after removal of the load. This DUW test was repeated 15 times on each rail track.

With the DUW signals acquired in each DUW test, the defined damage index could be constructed with Eq. (1). From the authors' previous research, it is concluded that in an intact rail track, the load induces no defect growth, and the signals ascertained before and after the

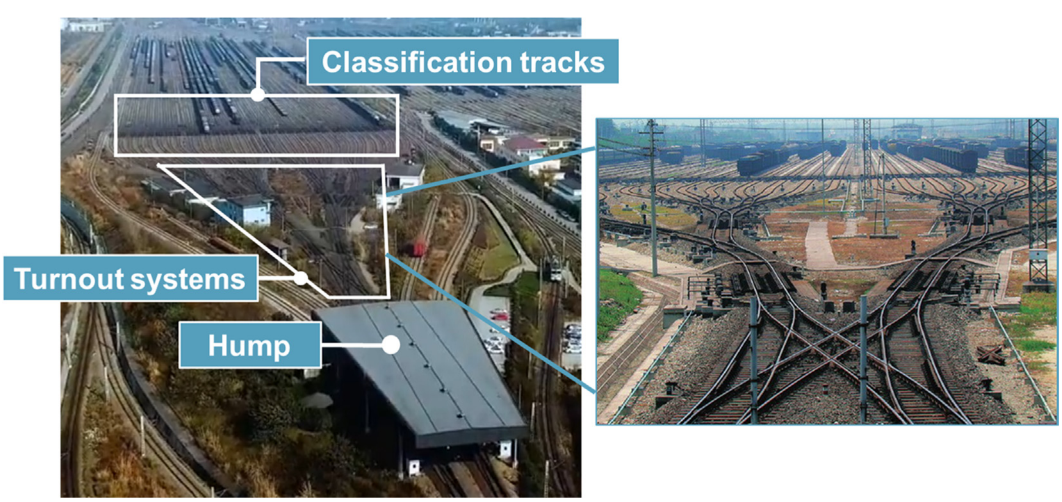
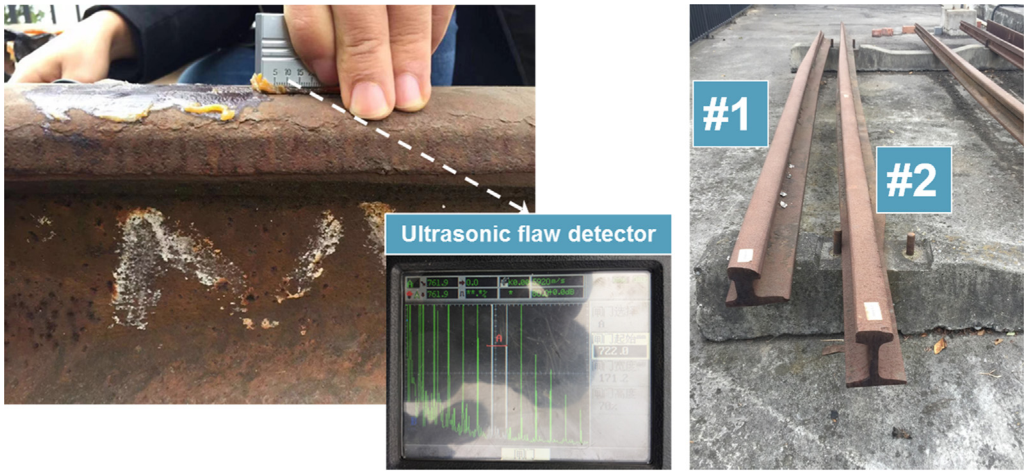


Fig. 5. Chengdu North Marshalling Station.



(a) (b)

Fig. 7. (a) Damage detection using ultrasonic flaw detector; (b) damaged switch rails from the Chengdu North Marshalling Station.

Fig. 8. The hydraulic press used to exert load on the rail and the sensor network on the web of the rail.

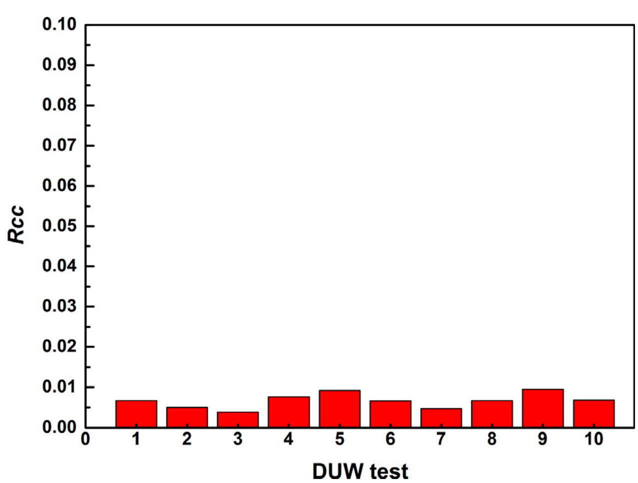
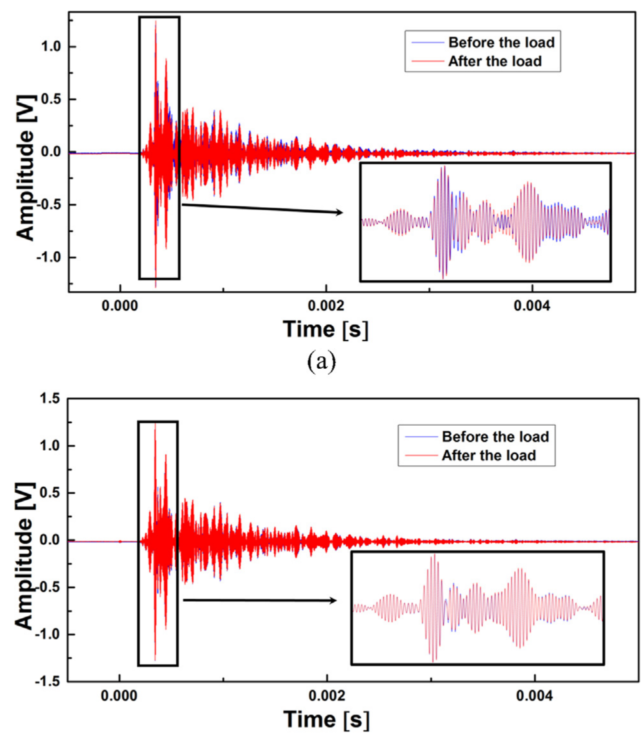


Fig. 9. The damage indices *Rcc* from each DUW test on intact rail.

load are almost invariant. Fig. 9 displays the damage index obtained using the DUW signals from the tests in intact rail tracks which are performed using the same set-up and repeated 10 times. It is clearly demonstrated that the proposed damage index is not greater than 1%. With this background, a threshold (1%) for the damage index *Rcc* was proposed, and defect growth was deemed to have occurred when the



(a)

(b)

Fig. 10. The DUW signals in scenarios: (a) when defect growth occurs and (b) when no defect growth occurs.

threshold was reached.

Fig. 10(a) and (b) representatively display the DUWs from two DUW tests on #1 rail. In Fig. 10(a), a remarkable difference is clearly demonstrated between the signals acquired before and after the load, whereas no discernable change is exhibited in the signals shown in Fig. 10(b). It is worth noting that the crack growth is in nature a local event, and thus only the propagation of certain wave modes that traverse at the crack is alternated. As a result, the acquired signals in certain time windows are changed, as displayed in the inset in Fig. 10(a). Using Eq. (1), the damage indices *Rcc* in each DUW test are ascertained and displayed in Fig. 11 for #1 rail and Fig. 12 for #2 rail. It is clear that in the DUW tests denoted by 1, 4, and 11 for #1 rail and

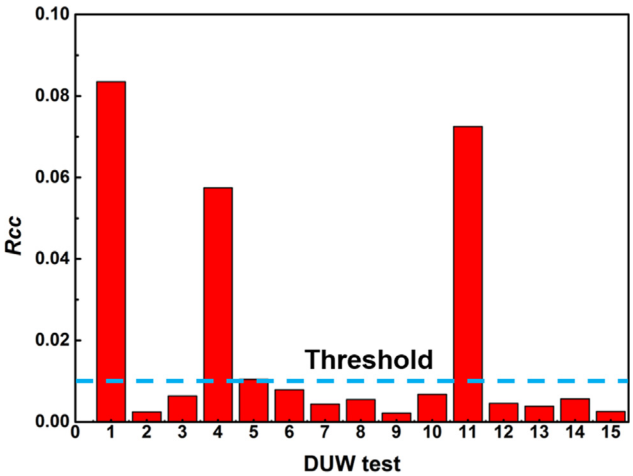


Fig. 11. The damage indices *Rcc* from each DUW test on #1 rail.

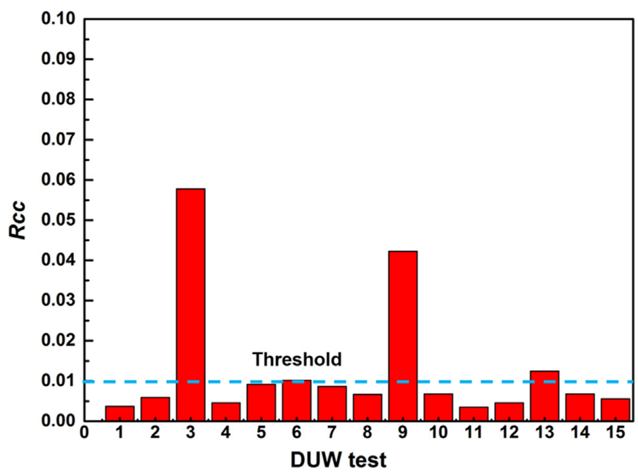


Fig. 12. The damage indices *Rcc* from each DUW test on #2 rail.

those denoted by 3 and 9 for #2 rail, a remarkable increase in *Rcc* is generated, whereas in other tests the *Rcc* are lower than the threshold. These phenomena indicate that in these tests (1, 4, 11 for #1 rail and 3, 9 for #2 rail) the defect growth that leads to disturbance in the probing DUW is induced by the load. To verify the defect growth, the ultrasonic flaw detector is used to measure the amplitude of reflection of probing ultrasonic waves in #1 rail, and the increasing in amplitude of the reflection induced by each exertion of the load is obtained. It is clearly demonstrated that remarkable increasing is only detected in the DUW tests denoted by 1, 4, 11 for #1 rail, corroborating with the evaluation results using the proposed approach.

Taking a step further, among 15 DUW tests, defect propagation is identified in three tests for #1 rail and two tests for #2 rail. These results assert that, compared with the scenario in which the defect is of small scale and the probability of defect growth is low (usually lower than 1%), the probability of defect growth under the load is high. Therefore, it can be concluded that a severe defect exists in both inspected switch rails.

It is worth noting that in reality the load applied on the railway track is caused by moving trains with low frequency vibration. Considering that the proposed method identifies the fatigue damage in the rail track by assessing the load-induced damage growth, and features of the load (static load or low-frequency cyclic load) impose insignificant influence on DUW signals acquired before the load and after the removal of the load. Therefore, despite that the static load applied in the experiment is different from the load induced by moving trains in reality, the evaluation of crack growth is not influenced by the load type.

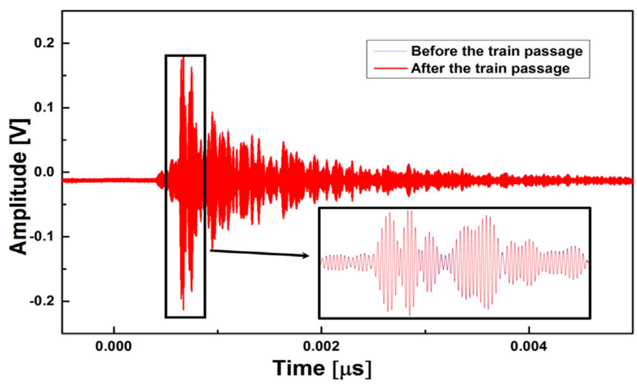
3.4. Application on in-service rail track

To examine the reliability and robustness of the developed SHM technique, *in-situ* monitoring for the health condition of in-service rail tracks in a turnout system was performed. Two rail tracks in a turnout system were selected as the monitoring object, denoted by #1 and #2. During the suspension window period of the marshalling station, a pair of PZT wafers was installed 5 m apart on the web of each track, as demonstrated in Fig. 13, to excite and acquire DUWs in the rail. This pair of PZT wafers was then connected with the diagnosis system (see Fig. 14). Load exerted on the rail by a passing train can lead to the growth of a defect, if any, in the rail. By evaluating the train-induced defect growth, the health condition of the monitored rail track can be assessed using the developed SHM method.

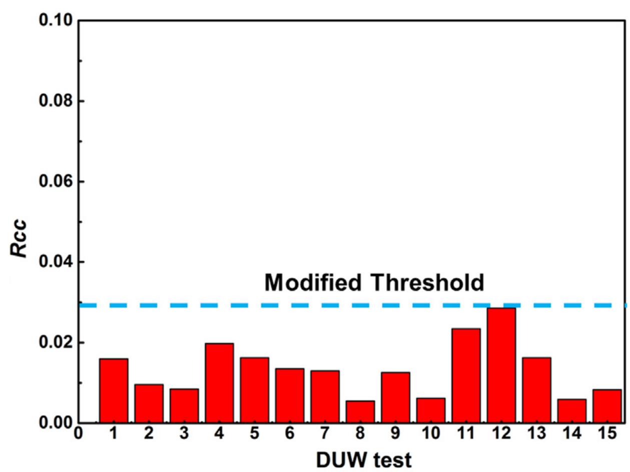
The DUW signals were acquired before and after the passing of a train and, in conjunction with Eq. (1), the proposed damage index *Rcc* was ascertained. Fig. 15(a) displays the DUWs from #1 rail acquired before and after the passing of a freight train weighing 96 t, and the damage index obtained using Eq. (1) is 2.8%. Fig. 16(a) displays the representative DUWs from #2 rail. The damage indices in 15 DUW tests are exhibited in Fig. 15(b) for #1 rail and Fig. 16(b) for #2 rail, from which it is observed that no remarkable increase in *Rcc* is generated in these tests. Therefore, it can be concluded the rail tracks in-service were in an intact status. It is worth noting that the conformation tests were performed on a rainy day in winter when the temperature was below 5℃ and the humidity was high. Despite these harsh climate conditions, the evaluation results exhibited the effectiveness and reliability of the proposed approach, proving its environmental adaptability.

Fig. 13. The sensor network installed on the turnout system.

Fig. 14. The online diagnosis system used for the *in-situ* health monitoring of in-service rail track.



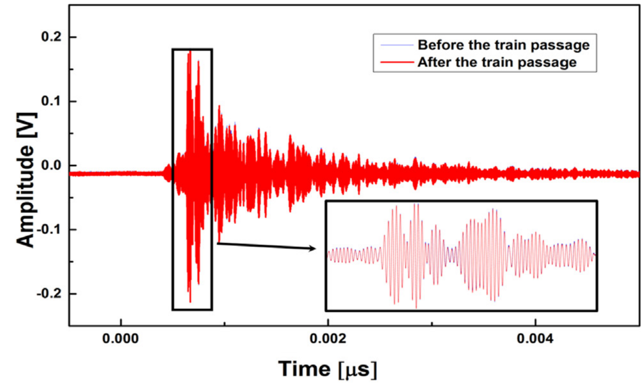
(a)



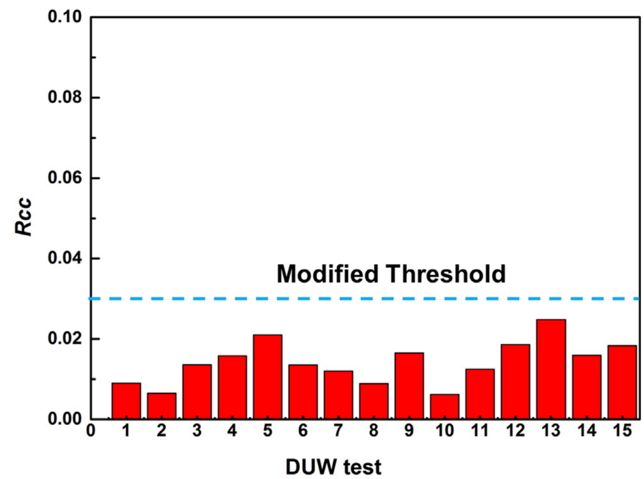
(b)

Fig. 15. (a) The signals in a DUW test and (b) the damage indices *Rcc* from each DUW test on #1 in-service rail.

It is also worth noting that, although the monitored rail track was in an intact status, the damage index was slightly greater than the pre-set threshold (1%). As demonstrated in Figs. 15 and 16, the maximum of the damage index for #1 rail is 3% and that for #2 rail is 2.5%. This is because the train passage leads to changes in the rail structures, such as the rail fastening, which impose an influence on the DUWs in the rail track, and therefore, the damage index is increased. This result implies that, in a practical application, a modified threshold (e.g. 3%), as exhibited in Figs. 15(b) and 16(b), that can be acquired empirically is



(a)



(b)

Fig. 16. (a) The signals in a DUW test and (b) the damage indices *Rcc* from each DUW test on #2 in-service rail.

required to obtain a reliable evaluation of health condition.

The proposed benchmark-less method using DUWs can fulfill *in-situ* health monitoring of the rail track in an online manner. This method is capable of identifying the crack growth induced by each train passage and, via assessing the probability of growth of the defect, can evaluate the severity of the defect. It is also worth pointing out that, provided the influence of practical factors on the DUW testing is consistent over a certain period (e.g. a few weeks), the accumulated growth of a defect in this period that encompasses multiple train passages can be evaluated using the proposed method. Thus, a defect can be identified and evaluated even when the individual crack growth induced by train passage is minimal, such that the AE energy is so weak that it cannot be detected using an existing AE-based method. Moreover, compared with widely studied AE methods, the proposed method features higher reliability because typical AE methods evaluate cracks via their sudden growth which is an instantly occurring event, whereas the proposed method is based on assessment of defect growth that can be performed repeatedly. In addition, the developed method can be readily applied to the monitoring of different rail types and to inaccessible sections of rail by appropriate distribution of PZT wafers (e.g. pitch-catch or pulse-echo configuration). For example, for a switch rail, at the tip of which the installation of an instrument is strictly prohibited, two PZT wafers installed at a certain distance from the tip, forming a pulse-echo configuration, can be exploited to implement the developed monitoring approach. It is also worth noting that the effectiveness of the proposed approach lies in the fact that the defect is detected by assessing its growth when the rail is subjected to external load, and thus the developed approach can also be used to detect defects of diverse types, for example the pitting corrosion, that can expand due to external load and induce changes in DUWs.

Given the appealing merits of the diffuse features of DUWs, this method is capable of monitoring the overall health of the turnout system using a sparse sensor network and does not entail an exhaustively prudent selection of sensor position. The distance of the adjacent PZT transducers is mainly dependent on the amplitude of DUW signals, and using the above set-up, a pair of PZT transducers can be exploited for the effective and reliable monitoring of rail tracks measuring 8 m in length. Thus the method can accommodate practical restrictions in terms of weight, volume, and mounting manner. Most importantly, the utilization of benchmark-less concept in the proposed method alleviates dependence on baseline signals obtained from an intact specimen, thereby rendering immunity to interference induced by various practical factors, warranting the performance of the system in different service conditions. This enhancement of robustness improves the readiness level of the proposed method, benefiting its suitability for application in engineering practice.

4. Conclusions

Targeting *in-situ* health monitoring of railway turnouts, a benchmark-less method that makes use of diffuse ultrasonic waves in the rail track is developed in this study. With this method, diffuse ultrasonic waves are generated and acquired with a sparse sensor network. Wave signals in a rail track are captured before and after the passage of a train. If defect growth is induced by the train passage, discrepancies are introduced between the signals obtained before and after the train passage. By contrasting these signals, a damage index is constructed, whereby the defect can be identified and evaluated. The proposed method is experimentally examined via conformance testing, in which the DUW tests are performed on a switch rail with a defect and an in-service rail turnout from Chengdu North Marshalling Station in China. Utilizing the proposed method, the defect is identified, and the health condition of the rail track can be monitored *in-situ* and automatically.

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