BACKSCATTERED GUIDED WAVE DETECTION OF RAIL BASE DEFECTS

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ABSTRACT

Conventional ultrasonic flaw detection can easily inspect defects in rail head and web during service. By contrast, defect detection of rail base is still a challenge because web obstructs the sound path. The guided waves are cross-sectional resonances traveling in the waveguide and appear multimodal and dispersive. The dispersions are more complex in real rails since different worn conditions frequently result in varying cross sections. This work presents experimental and analytical investigations on guided wave detection of rail base defects. The guided waves transmitted by an acoustic probe of 150 kHz are recorded by an air-coupled ultrasonic (ACU) sensor in B-scan over the region between transmitter and defects. Elastic guided waves are inherently scattered from the defects in the regions below the rail head. The scattering signals are generally very small compared to the forward propagation. A spatio-temporal directional filter is used to decompose the forward and backward propagating signals from the total waveforms of B-scan. The backscattered field could be in the form of either bulk waves or guided modes depending on the distance from defects to the receivers. The natures of both forward and backscattered guided modes can be identified through the measured B-scan images and dispersive spectrograms. The backscatter coefficient defined by the ratio of reflected wave amplitude to that of forward propagation indicates defect size and severity.

KEYWORDS: backscatter, defect, directional filter, guided wave, rail base

1. INTRODUCTION

Guided-wave non-destructive testing and structural health monitoring techniques for defect detection in rails have received intensive attention [1-5]. Guided wave inspection has been shown to have the great potential for practical applications. It is most difficult to detect defects in rail bases compared with those in heads and webs using conventional ultrasonic flaw detectors. The rail base defects are generally resulted from imperfections in the weldment such as lack of fusion, heterogeneous inclusions, etc. The guided waves are sensitive to transverse cracking under shelling in rail [3]. The scattered signals from defects are of smaller amplitude than forward propagations. Theoretical prediction of guided wave propagation has a practical limitation since routine maintenance usually changes the cross-sections of rails. The specific resonances cannot be sustained in varying cross sections. This work demonstrates a possibility to extract the backscatter signals from the measured waveforms of guided-wave detection of rail base or web defects using a directional filter based on spectral analysis.

2. METHODS

A tone burst rather than a short pulse is frequently used as a transmitted signal in guided-wave inspection for intensity concern. Longer duration in a tone burst obscures the small backscattered signals. A directional filter based on spectral analysis [6] has been used to decompose waveforms propagating in both opposite directions. The wave field can be represented as a two-dimensional Fourier transform in the form of

\[ u(x,t) = \int \int U(k,\omega)e^{j(kx-\omega t)}d\omega dk \]  

(1)

where \( \omega \) and \( k \) are angular frequency and wavenumber. The wavenumber \( k \) is a product of the spatial frequency \( 1/\lambda \) and \( 2\pi \). The two-dimensional Fourier transform of time history of guided wave response recorded at a series of equally spaced positions along the propagation path can be used to determine phase velocity dispersion curves [7]. The positive and negative values of \( k \) represent the propagating waves towards the positive and negative x-axis, respectively. The forward propagation can be suppressed by erasing the spectra in the associated quadrants of the angular frequency and wavenumber.
In elastic scattering theory, the total wave field can be represented as the sum of incident waves and scattered waves due to defects. The latter are generally much smaller than the former. The B-scan waveforms captured in the area between the transmitter and rail defects can be separated into the forward and backward propagating waves using directional filter. The forward waves in the far-field denote the incident waves. The backward waves are the waves scattered from the defects. The backscattered signals alone can enhance contrast for detection of defects.

The experimental setup is illustrated in Fig. 1. The guided-wave inspections were conducted on two 4.5 meter long UIC 60 rails. One of the rails is defect-free and used to be a control specimen. The other has two transverse notches fabricated by electric discharge machining (EDM) spaced far enough apart. One notch has dimensions of 15×15×1 mm at the bottom center of rail base. The other is a 15 mm long through-thickness notch in the middle of web. A 150 kHz resonant-type acoustic emission transducer (Vallen VS150-M) was used to be a guided wave transmitter driven by a 10-cycle tone burst. The transmitter locates far enough from either end of the rail. An ACU transducer (Ultran Group NCG200-D13 with focal length 38 mm) was employed as the non-contact receiver. The receiving signals were gained 80 dB through two-stage preamplifiers, Olympus/Panametrics 5660B (not shown) and 5800PR. A distance L of 1.2 m between the transmitter and the target defect is reserved for far-field detection. The ACU transducer linearly scanned over the rail head to record a number of waveforms with a space interval of 2.5 mm. Every space interval is 2.5 mm. Each scan moved horizontally toward the defect from a distance to the transmitter in a range of 0.72 m to 0.96 m.

Ultrasound induced by a single transducer placed on top surface of a rail generally propagates in different directions. Multimodal guided waves are formed by the interference of multiple reflections from the boundaries of waveguide. The height of a real rail is much larger than the thickness of a plate or pipeline. The test specimen in this work is UIC 60 rail which has a height of 172 mm. Hence longer traveling distance is required to construct guided waves compared with those in plates or pipelines. The far-field distance is about 0.8 m for guided waves in UIC 60 rails. The first arrival shown in Fig. 2 has a constant phase velocity and group velocity of about 2,936 m/sec. It is called as the rail-head mode since most deformations appear in the head of rail. The measured value of its attenuation coefficient is about 2.671 Np/m.

Both 8-bit digital oscilloscope (LeCroy WaveSurfer 424) and a 14-bit A/D converter (National Instruments PXIe-5122) were used to record the ultrasonic signals. The comparison shown in Fig. 2 indicate that the 14-bit converter has better signal to noise ratio (SNR). Fig. 3 shows that the 14-bit converter holds the same SNR in filtering the backward signals from the original B-scan images. Thereafter, the 14-bit converter was considered for recording B-scan image and filtering backscattering images.
3. RESULTS AND DISCUSSION

The spatio-temporal directional filter is based on 2D-FFT, which can be used to determine phase velocity dispersion curves of multimodal guided waves [7]. Additionally, not only the B-scan images but also the dispersive spectrograms of both forward and backward propagations can be decomposed. A first, we characterized the guided waves transmitted from a contact transducer placed on the top surface of the rail head by measuring the dispersive spectrograms along the rail head, web, centerline of the bottom, and toe of the base. The measured spectrograms are compared with the spatial frequency response functions calculated by the semi-analytical finite element (SAFE) method. Secondly, the backscatter images and its spectrograms for the defects at the center of rail base and web are explored. Those defects can be definitely detected through their clear backscatter images.
3.1 DISPERSIVE SPECTROGRAMS

Fig. 4 depicts both the B-scan image and its corresponding spectrogram measured from the rail head. In experiment, the axial distance from the transmitter to the starting point of each linear scan was 1.2 meters. The first arrival is again the rail-head mode, and its arriving time is 512 µs. The relatively large responses occur in the spatial frequency range from 0.015 to 0.04 mm\(^{-1}\) and at 0.05 mm\(^{-1}\). The maximum response happens at 0.03 mm\(^{-1}\) rather than the rail-head mode at 0.05 mm\(^{-1}\).

The ACU sensor was focused in the web middle to detect the transient response induced by the top surface transmitter spaced 1.2 m apart. Fig. 5 denotes the B-scan image and its spectrogram. The B-scan image is much smaller than that of Fig. 4. The rail-head mode does not appear since it has deformation only at the head. Larger responses occur at spatial frequencies ranging from 0.015 to 0.04 mm\(^{-1}\). The greatest response also appears at 0.03 mm\(^{-1}\).

The rail was raised to measure the dispersive spectrogram of guided wave propagation along the bottom. The B-scan image of Fig. 6(a) is a bit vague. The legible signals arrived at about 700 µs. The greatest value of the image is larger than that shown in Fig. 5(a). A similar spectrogram to Fig. 5(b) can be found in Fig. 6(b). Larger responses happen in the spatial frequency range from 0.015 to 0.04 mm\(^{-1}\). Again, the greatest response appears at 0.03 mm\(^{-1}\). It seems that the same guided mode with large deformation appears in the web and on the centerline of the bottom.

Fig. 7 denotes that the B-scan image and spectrogram of guided waves propagating along the toe of the rail base. The image comprises several wave packets. Each packet has uniform, clear image. The maximum value is close to that of rail bottom.
addition, the response does not concentrate at spatial frequency of 0.03 mm$^{-1}$. Instead, Fig. 7(b) reveals the responses distribute to 0.02 and 0.04 mm$^{-1}$. The former has larger response than the latter. The spectrogram shows that the guided modes with long wavelength up to 50 mm can propagate along the rail toe.

In this work, the guided waves were excited by a contact pressure sensor of 150 kHz. The response of rail by application of a point load is a function of not only frequency but also spatial frequency. Fig. 8 denotes the spatial frequency response functions (SFRF) at the points on top surface of the rail head and bottom, respectively. The earlier mentioned rail-head mode occurs at the greatest value of spatial frequency, 0.05108 mm$^{-1}$. Numerical results indicate that the rail-head mode only appears near head and cannot be found in base. The magnitudes of SFRF vary at different spatial frequencies. Partial guided modes have weak responses so that they are illegible in Fig. 8. Compared with the measured dispersive spectrograms, we can calculate the deformations of guided modes having relatively large SFRF. Fig. 9 shows deformations of four guided modes corresponding to those significant responses measured in the above four cases. Except the rail-head mode, many other modes have deformations in rail head, web, and base. This discovery overthrows the argument in [5] that guided waves cannot pass through the cross-section of rail.

Fig. 6 (a) B-scan image and (b) its corresponding spectrogram measured along centerline of the rail bottom.

Fig. 7 (a) B-scan image and (b) its corresponding spectrogram measured along toe of the rail base.
3.2 DEFECT DETECTIONS

In the experiments of defect detection, the distance between the defect and transmitter is arranged to be $L = 1.2$ m; the starting point of linear scan to the defect is $d = 0.36$ m. There remains an important issue that the far-field range of the wave backscattered from the defect. There is no need for multiple reflections. Hence the near-field distance of the scattered wave from a defect is less than a pressure actuator. Fig. 10 and Fig. 11 denote the forward propagating and backscattered B-scan images with their corresponding spectrograms for the central defect in the rail base. The forward propagation is composed of a legible rail-head mode and guided modes in the spatial frequency range from 0.015-0.035 mm$^{-1}$ as shown in Fig. 10(b). The latter modes hit the rail base defect and the backscattered modes are in the same spatial frequency. No other mode-converted guided wave has been found in Fig. 11(b). The clear backscatter image shown in Fig. 11(a) indicates the existence of a defect.

Fig. 12 and Fig. 13 depict the forward propagating and backscatter image associated with their spectrograms. The web defect can be also detected through the backscatter image. As mentioned earlier, the forward propagation in far-field can be considered as the incident wave which is independent of the properties of scatterer. Hence, the forward propagations shown in Fig. 10 and Fig. 12 have very close similarity except a bit of magnitude difference. In Fig. 12(b), the incident waves are short of stronger responses in the spatial frequency range from 0.015-0.035 mm$^{-1}$. The backscatter image of the web defect has less contrast than the base defect with the same crack length $a = 15$ mm. A quantitative index value is needed to distinguish the size and severity of a defect. The backscatter coefficient is defined by the ratio of backscattered wave amplitude to that of forward propagation. The rail-head mode has been considered to be the reference in definition of the backscatter coefficient. The coefficient is 0.21 and 0.17 for the defect in the rail base and web, respectively.
Fig. 10 Forward propagating (a) B-scan image and (b) its spectrogram for the base central defect ($a = 15$ mm).

Fig. 11 Backscattered (a) B-scan image and (b) its spectrogram for the base central defect ($a = 15$ mm).

Fig. 12 Forward propagating (a) B-scan image and (b) its spectrogram for the web defect ($a = 15$ mm).
4. CONCLUSION

It has been reported that the energy carried by the guided waves almost does not penetrate from rail head to base, and vice versa [5]. The measured results of dispersive spectrograms indicate that the rail web is not a perfect barrier to partition guided waves. Most guided modes have simultaneous deformation in every region of the rail. Their responses can be detected by air-coupled ultrasonic transducers. However, the rail-head mode has deformations only in the head. Its phase velocity and group velocity are constant and close to the surface wave speed. The far-field distance of rail-head mode excited by a pressure sensor on the top surface of rail is beyond 0.8 meter. The attenuation coefficient is about 2.671 Np/m.

Various guided modes can be used to inspect the defects in different regions. The elastic waves backscattered from the defect in web and base are of smaller amplitude than the rail-head mode. The defect can be successfully detected by guided waves using the directional filter based on 2D-FFT. Both backscatter image and its corresponding spectrogram can be definitely used to detect defect in rails. The backscatter coefficient defined by the ratio of backscattered wave amplitude to that of forward propagation is used to be an indication for defect size and severity. Further investigations are required to establish a quantitative rule. The backscattered guided wave imaging system has a great potential in automatic inline inspection for defect in rails.

REFERENCES


Fig. 13 Backscattered (a) B-scan image and (b) its spectrogram for the web defect (a = 15 mm).