Experimental Study on Crack Detection at Bolt Hole Edge in Rail Joint Using the Third Harmonic

Chuang Wang¹, a, Wei-Wei Zhang ², b* and Hao-Ran Wang³, c

¹ School of Applied Sciences, Taiyuan University of Science and Technology, Taiyuan, Shanxi, 030024, China
² School of Applied Sciences, Taiyuan University of Science and Technology, Taiyuan, Shanxi, 030024, China
³ School of Applied Sciences, Taiyuan University of Science and Technology, Taiyuan, Shanxi, 030024, China

aS20190134@stu.tyust.edu.cn, achuangwang551@163.com, b* zwwps@126.com, c wanghaioran0215@qq.com

Abstract. In this paper, a nonlinear ultrasonic detection method for detecting the hole edge crack in rail joint was proposed. The experimental results show that a single frequency sinusoid wave modulated by Hanning window is input to the rail specimen, there are higher order harmonics in the received signals for cracked rail, but there are no any harmonics for the rail with no crack bolt hole. That is to say the higher order harmonics can be used to indicate the presence of a crack. Furthermore, a nonlinear parameter $\beta$ is defined by the ratio of the third harmonic frequency peaks to the peak of the fundamental frequency. The relationship between nonlinear parameters and crack size is approximately linear, which means that the third harmonic not only can detect the presence of the hole edge crack, but also can assess the size of the hole edge crack.

1.Introduction

Rail joint is usually the weak link of rail line and also the key problem of rail flaw detection. In particular, the bolt holes in the joint often crack due to stress concentration which is a potential threat to railway safety. Therefore, it is of great significance to detect the damage of rail joints in time, and reinforce or repair them at the early stage of crack occurrence in order to avoid traffic accidents and improve railway operation quality[1].

However, since the traditional ultrasonic nondestructive testing (NDT) is based on reflection of ultrasonic wave, the echo from the bolt hole and crack are very similar, which results in the hole edge crack is difficult to be detected effectively[2]. The nonlinear ultrasonic in rail provide some inspiration for solving this problem[3]. This makes it possible to detect small defects in the steel rail. In recent years, many scholars have carried out extensive researches in the field of nonlinear ultrasonic detection. For example, Wan[4] et al. measured the amplitude of the second harmonic and fundamental waves under different experimental conditions and calculated the ultrasonic nonlinear coefficient by fatigue test on the swallowtail notch on the rail section of U71Mn, and verified the effectiveness of ultrasonic nonlinear coefficient charactering the extent of rail fatigue damage. Wu[5] et al. measured the nonlinear parameters of AZ31 magnesium alloy under tensile and fatigue conditions, and the results showed that the nonlinear parameter was very sensitive to the mechanical property degradation of magnesium alloy. Jiao[6] et al.
conducted an experimental study on the thermal aging of organic materials, measured the second harmonic, fundamental wave and nonlinear damage factors, and pointed out that the nonlinear damage factors were closely related to the thermal aging damage degree of organic materials. Although nonlinear ultrasonic NDT has a broad application prospect, the technology is still in the critical period of development and has not been applied to specific engineering practice[7-9].

In this paper, a nonlinear ultrasonic strategy will be discussed for detecting the hole edge crack in a rail joint by experiment. The experimental scheme, signal processing and damage index will be discussed in detail. This study will provide some technical support for detecting the bolt hole edge crack.

2. The experimental scheme

The experimental specimen is the 390mm-in-length segment of a 60Kg/m type rail joint. The main section size of the rail are shown in Fig.1

![Fig.1 the main section size of the 60 Kg/m type rail](image)

There are three bolt holes in the rail web. The excitation signal uses the single-frequency sine signal of a 0.5MHz center frequency modulated by the Hanning window, and the expression is as follows:

$$S = (1 - \cos \frac{2\pi f_c t}{n}) \frac{\sin(2\pi f_c t)}{2} .$$

In addition, n is the cycle number of single signal and $f_c$ is the central frequency. The excitation signal waveform is shown in figure 2(a) and (b). Here, n=10 and $f_c = 0.5$MHz

![Fig. 2 the signal waveform in both time and frequency domain](image)
A piezoelectric pitch whose size is $12\text{mm} \times 5\text{mm} \times 0.5\text{mm}$ resonates in the thickness direction is used to generate the ultrasonic. Moreover, another piezoelectric pitch whose size is $16\text{mm} \times 4\text{mm} \times 1\text{mm}$ resonates in the length direction is used to receive the signal. Both of them are directly attached to the top of the rail by adhesive. The excitation piezoelectric pitch is pasted on the railhead above the bolt hole, and the receiving piezoelectric pitch is pasted at 1cm distance from the excitation one.

The experimental system is composed of computer, signal generator, power amplifier and digital oscilloscope, as shown in Figure 3. In the experiment, the signal generator firstly inputs ultrasonic signal into the power amplifier to amplify it, and then drives the excitation piezoelectric pitch. The receiving piezoelectric pitch receives the ultrasonic signal in the rail, and record by a digital oscilloscope. As a comparison, five cases listed in Table.1 are studied, in which Case1 represents no crack in the bolt hole, and case2-5 showed the crack at the bolt hole edge is gradually increased from 1mm to 7mm with an increment of 2mm, as listed in table 1.

| Case No | 1   | 2   | 3   | 4   | 5   |
|--------|-----|-----|-----|-----|-----|
| Crack length | -   | 1 mm | 3 mm | 5 mm | 7 mm |

Figure 4(a) and (b) shows the signals in time-domain diagram received by the receiving sensor, in which figure 4(a) is the time-domain signal for the rail without crack, and figure 4(b) is the one for the rail with a 3mm-in-length crack at the bolt hole edge. By comparing them, the results show that there are also multiple wave packets in addition to the incident wave packet for the rail crack. However, it is difficult to explain which wave packet is generated by the crack. In order to further analyzing the influence of the presence of cracks on the test signal, we will carry out Fourier transform on the signal in the following section. The higher harmonic will be discussed to identify the crack.
3. Analysis and discussion

Fig. 5 (a)-(d) respectively show the spectral analysis results when 1, 3, 5, 7mm cracks exist in the bolt hole edge with no crack case as a reference. As can be seen from the figures, there are high harmonic frequencies such as $2f_c$ and $3f_c$ are also occur in the frequency-domain for all cracked cases in addition to the frequency component of the excitation signal ($f_c = 0.5\text{MHz}$). However, only 0.5MHz frequency component will be observed for the case without crack. This indicates that the high harmonics are generated in the cracked rail specimen. High harmonics is a typical feature of nonlinear ultrasonic propagation [10]. As can be seen from the figure, the $3f_c$ frequency is more significant than the $2f_c$ frequency. In this paper, the $3f_c$ frequency is used to indicate the crack.

Breazeal[11] and Cantrell[12] et al. studied the propagation of one-dimensional nonlinear ultrasonic waves in solid media, and defined a nonlinear parameter based on the frequency peak value of the third harmonic wave to the one of the fundamental wave as:

$$\beta = \frac{24A_3}{k^3A_1x}.$$  

Here, $k$ is the wave number and $k = \omega/c$, and $c$ is the wave speed; $A_1$ represents the frequency peak value of the fundamental wave, and $A_3$ represents the frequency peak value of the third harmonic wave. $x$ is the distance that the ultrasound travels. In this experiment, $x$ is a constant because of the excitation at the top of the rail and the receiving of the top of the rail. The nonlinear parameter $\beta$ is proportional to $A_1/A_3^3$. 

Fig. 5 Frequency spectrum for all cases
According to Eq. (2), the nonlinear parameter of cases 2-5 is calculated. The relationship between the nonlinear parameter parameters and the crack length can be obtained as shown in Figure 6. Obviously, the nonlinear parameter approximately meet the linear relationship with the increase of the crack length, which indicates that the nonlinear parameter can be used as the damage index for detecting the crack at the bolt hole edge for the rail joint.

Fig. 6 Relationship between nonlinear coefficient and crack length

4. Conclusion
This paper verified the feasibility of the hole edge crack detection method for rail joint using the third harmonic wave. A single frequency ultrasonic signal was stimulated at the railhead, and the second harmonic and the third harmonic could be found in the received signal for all cracked rail. Comparing the two harmonic, the third harmonic was more suitable for crack detection. For this reason, the third harmonic had been further studied. Finally, the nonlinear parameter $\beta$ was defined by the ratio of third harmonic to the fundamental wave. An approximately linear relationship between the nonlinear parameter and the crack length can be found. This makes it possible to evaluate the size of the crack at the edge of the bolt hole.

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