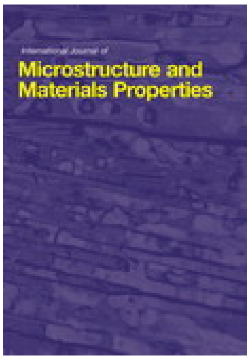
INDERSCIENCE PUBLISHERS
Linking academia, business and industry through research



International Journal of Microstructure and Materials Properties

ISSN online: 1741-8429 - ISSN print: 1741-8410
https://www.inderscience.com/ijmmp

Fatigue damage detection method of nano ceramic coating rail based on acoustic signal acquisition

Zhinan Li, Yafei Li, Chenyou Li

DOI: 10.1504/IJMMP.2024.10061245

Article History:

Received:	30 December 2022
Last revised:	10 February 2023
Accepted:	31 July 2023
Published online:	05 January 2024

Copyright © 2024 Inderscience Enterprises Ltd.

Fatigue damage detection method of nano ceramic coating rail based on acoustic signal acquisition

Zhinan Li*, Yafei Li and Chenyou Li

Department of Railway Locomotive and Rolling Stock,
Hebei Vocational College of Rail Transportation,
Shijiazhuang, 052160, China
Email: 471329163@qq.com
Email: yafei@mls.sinanet.com
Email: 287845610@qq.com
*Corresponding author

Abstract: In order to reduce the fatigue damage detection error and improve the recall rate of fatigue damage data, this paper proposes a detection method based on acoustic signal acquisition for fatigue damage of nano ceramic coated rail. Firstly, the long-term fatigue behaviour of nano ceramic coated rail is analysed, and the typical damage evolution state of coating cracking at each stage is obtained. Then, based on the ultrasonic theory, the one-dimensional nonlinear elastic wave equation of rail vibration signal propagation process is constructed, and the modulated sidelobe signal of high-frequency ultrasonic is obtained. Finally, modulation parameters of rail fatigue damage are calculated by Fourier transform to determine the extent of fatigue damage. The experiment shows that the maximum error of the method for fatigue damage detection is only 0.5 mm, and the damage recall rate can reach 99.9%, indicating that the method improves the detection effect for fatigue damage.

Keywords: nano ceramic coating; rail; Fourier transform; acoustic signal; fatigue damage detection; ultrasonic theory; sidelobe signal.

Reference to this paper should be made as follows: Li, Z., Li, Y. and Li, C. (2024) ‘Fatigue damage detection method of nano ceramic coating rail based on acoustic signal acquisition’, *Int. J. Microstructure and Materials Properties*, Vol. 17, No. 1, pp.69–83.

Biographical notes: Zhinan Li obtained his Master’s degree in Agricultural Engineering from the Agricultural University of Hebei School of Electrical and Mechanical Engineering in 2012. Currently, he is an Associate Professor at Hebei Vocational College of Rail Transportation. His research fields include automatic control, railway locomotive technology, locomotive braking technology and so on.

Yafei Li received her Master’s degree in Power Electronics and Power Transmission from the Faculty of Electrical and Control Engineering of Liaoning Technical University in 2015. Currently, she is a Lecturer at the College of Railway Rolling Stock System of Hebei Vocational College of Rail Transportation. Her research interests include electric locomotive control, electric locomotive electrics and electric locomotive overall.

Chenyou Li received his Master’s degree in Pedagogy from the School of Curriculum and Teaching Methodology of Hebei Normal University in 2015. Currently, he is a Lecturer at the College of Railway Rolling Stock System of

Copyright © 2024 Inderscience Enterprises Ltd.

Hebei Vocational College of Rail Transportation. His research interests include electric locomotive control, electric locomotive electrics and electric locomotive overall.

1 Introduction

According to the statistical bulletin data of the national railway department from 2016 to 2020, the railway industry is in a stage of rapid development. China's railway operating mileage increased from 121,000 km to 146,300 km, with an increase rate of 20.9% (Wang et al., 2021; Liu and Duan, 2022; Fang et al., 2022). Focusing on the current situation, the railway industry will implement the new development concept during the 'Fourteenth Five Year Plan' period, vigorously promote technological innovation in key areas such as intelligent construction, maintenance and repair, and play the role of 'the main artery' around the work route of 'strengthening the foundation to meet the standards, improving quality and increasing efficiency'. In this process, the health of the rail structure has always been the focus of the flaw detection personnel. Therefore, many rail fatigue damage detection technologies have also been designed (Zhou et al., 2020). The rail fatigue damage detection refers to the application of different technical means to analyse and detect the multiple fatigue cracks and micro defect damage on the rail surface and near surface, and effectively present the distribution, size, quantity and other information of the multi-crack fatigue damage existing in the rail through data. However, due to the variety of rail damage, the difficulty of rail fatigue crack diagnosis and structural health monitoring is greatly increased.

For this reason, relevant scholars have studied the rail fatigue damage detection methods and made some progress. For example, Zhang and Liu (2021) applied machine vision technology to the process of rail fatigue damage detection, uses image sensors to collect rail surface image information, extracts rail surface image features according to the grey value integration method, and then obtains rail image gradient direction histogram according to normalisation. The unit area of the rail image is divided by machine vision method, and the rail fatigue damage is detected according to the gradient direction characteristics. Although this method can improve the detection accuracy, due to its division of a large number of rail fatigue damage images, this process is vulnerable to environmental impact, thus reducing the recall rate of fatigue damage. Fan et al. (2020) designed a fatigue damage detection method using electromagnetic detection technology. After the damage image is collected by the image acquisition sensor, the signal is filtered using wavelet technology. Then, the thermal mechanical coupling method is used to complete the qualitative analysis of fatigue damage, and then the electromagnetic non-destructive testing technology is used to realise the fatigue damage detection. Although this method can improve the detection accuracy of fatigue damage, it is difficult to classify the extent of fatigue damage. Wang et al. (2020) used cyclostationary theory to detect fatigue damage. Firstly, the machine vision technology is used to obtain the material image information, the contact stress analysis method is used to determine the surface stress of the material, the damage state is obtained according to the LAMMPS method, and the fatigue damage detection is completed according to the cyclostationary method. Although this method can complete the detection in a short time, its detection accuracy is poor.

Nano ceramic coating material is a kind of dense and high hardness ceramic coating formed by mixing nano ceramic powder and nano polymer binder, which has the function of anti-corrosion and wear resistance. It has been widely used in railway construction, such as nano ceramic coated rails. To solve the above problems, in order to improve the detection performance of fatigue damage of nano ceramic coated rail, reduce the fatigue damage detection error and improve the recall rate of fatigue damage data, a fatigue damage detection method based on acoustic signal acquisition is proposed in this paper. The specific research ideas are as follows:

1 According to the percentage of service life and the degree of damage, the damage evolution state of nano ceramic coating material was analysed.

2 The one-dimensional nonlinear elastic wave equation of the vibration signal propagation of the nano ceramic coated rail is constructed, and the evolution trend of the equation is combined. Combined with the evolution trend of the equation, the high-frequency ultrasonic wave in the nano ceramic coating rail structure is determined according to the perturbation theory, and the modulated side lobe signal of the rail in the fatigue damage state is obtained, so as to determine its modulation intensity.

3 After the acoustic signal of the rail is collected, Fourier transform is applied to each section of experimental data to obtain the corresponding frequency spectrum of each data, and the fatigue damage modulation parameters of the nano ceramic coated rail are accurately calculated to determine the fatigue damage degree of the nano ceramic coated rail.

4 The damage detection error, detection accuracy and fatigue damage data recall rate are used as indicators for experimental verification, and the effectiveness conclusion is drawn.

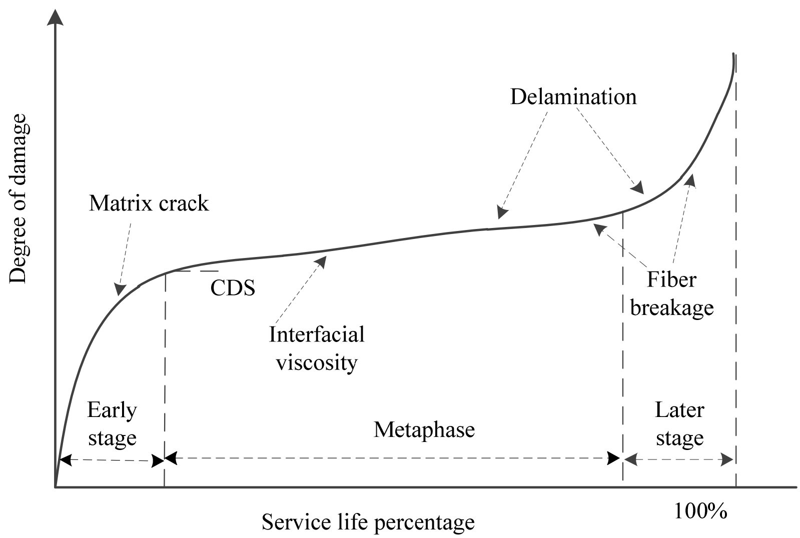
2 Long-term fatigue behaviour of nano ceramic coating materials

When subjected to cyclic loading, the properties of nano ceramic coating materials may vary depending on the load level defined by the cyclic strain amplitude. In the life of nano ceramic coating materials, the fatigue damage of nano ceramic coating materials under cyclic tensile load has experienced three damage evolution stages, as shown in Figure 1.

In the first stage (early stage), during the gradual loading process of the external force of the nano ceramic coating, the matrix cracks continue to develop and evolve until the crack density is saturated, which is called the ‘special damage state’ (CDS) (Kong et al., 2021; Zheng et al., 2021; Si et al., 2020). The nano ceramic coated rail provides the designed stiffness characteristics in the longitudinal and off-axis directions through the combination of on axis and off axis composite layers. The crack growth process of the nano ceramic coated rail is shown in Figure 2.

Initially (e.g., area I), cracking starts from matrix microcracks and quickly crosses the transverse thickness and width. When they are subjected to quasi-static load, the matrix is usually destroyed first, leading to the formation of microcracks. Because these microcracks are inherently unstable, they grow rapidly, spanning the thickness and width of the layer from the transverse direction to the loading direction. When the applied load is further increased (such as area II), more such cracks appear in the transverse layer, forming an array of nearly parallel (through the thickness and width of the laminates), the same size and equidistant crack surfaces (Huang et al., 2022). When there is sufficient crack density (such as area III), the stress fields of adjacent cracks interact to reduce the rate of crack density increase, and finally become saturated. This state is called 'special damage state' (CDS). On the other hand, the appearance of matrix cracks will lead to stress redistribution, and these redistributed stresses are uneven, but the overall residual strength of composite laminates does not decrease (Huo et al., 2020).

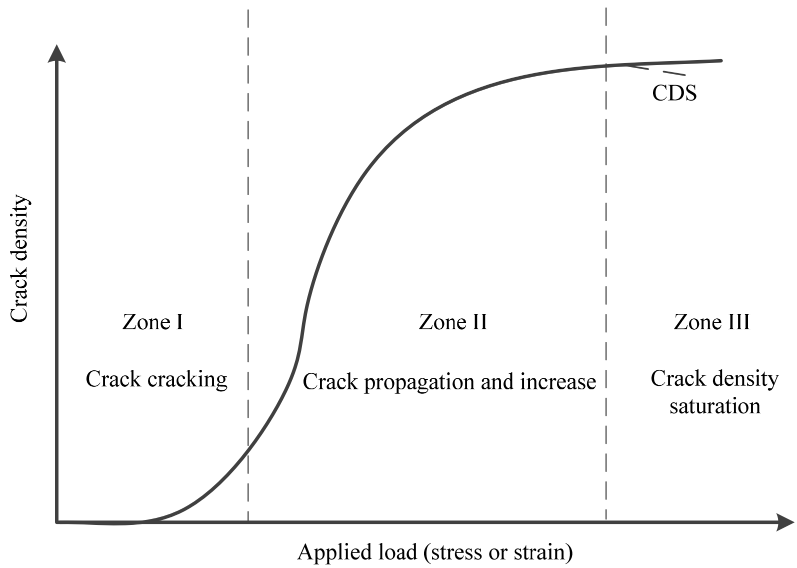
Figure 1 Sketch map of damage evolution of nano ceramic coating material



In the second stage (middle stage), the damage evolution curve is relatively flat, and the existing cracks will lead to interface debonding, a small amount of fibre fracture and local layer. When a transverse crack is formed in the nano ceramic coating of the rail, the interlaminar tensile normal stress will be generated. This stress tends to separate the plies, and the interlaminar shear stress tends to shear the plies along the interface near the crack. These interlaminar tensile and shear stresses provide the basic conditions for the interface debonding and delamination damage evolution of laminated plates (Cao and Liu, 2020).

In the third stage (later stage), large-scale delamination and large-area fibre fracture will occur, which are highly localised, leading to the failure of the laminate. The service life of the nano ceramic coating rail is approaching the end, at this time, the stiffness of the nano ceramic coating has a strong correlation with the fatigue damage. The change of stiffness is directly related to the redistribution of internal stress. For long-term fatigue behaviour with large strength reduction, the change of stiffness is also large (Cai et al., 2021). The fibre fracture of nano ceramic coating also occurred in the third stage. There are two modes of fibre failure, one is that there is a fibre failure sequence in the early stage of the initial life cycle near the edge of the sample; the other fibre failure mode is related to fibre fracture in the laminates. When matrix cracks intersect with adjacent plies under fatigue load, a series of local plies will be generated, and cracks will be generated along the fibres of adjacent plies. Once the crack is formed, the micro 'dendrites' separated from the interface will appear in a right angle to the direction of the matrix crack, and there is evidence that this damage mode is related to the fibre fracture.

Figure 2 Typical damage evolution curve of nano ceramic coating cracking on rail



In order to predict the residual fatigue life of composite plates by using the mechanism of fatigue damage evolution of composite materials, it is necessary to establish and obtain the physical information of laminated plates, and conduct fatigue damage detection of rail specimens.

3 Fatigue damage detection of nano ceramic coated rail based on acoustic signal acquisition results

In order to better analyse the fatigue damage status of nano ceramic coated rail, this paper collects the acoustic signal of Lamb wave to detect the fatigue damage of nano ceramic coated rail structure.

Lamb wave is the most commonly used guided wave in ultrasonic testing (Yang et al., 2021). When the ultrasonic wave propagates in the thin plate structure, the Lamb wave is formed by multiple reflections on the two free boundaries of the plate and superposition. The propagation diagram is shown in Figure 3.

According to the different vibration characteristics of medium particles, Lamb waves can be divided into two modes: symmetric (S type) and antisymmetric (A type) (Zhang et al., 2020). Formula (1) is the dispersion equation of symmetric mode, and formula (2) is the dispersion equation of antisymmetric mode:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2 pq}{\left(q^2 - k^2\right)^2} \tag{1}$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{q^2\left(k^2 - q^2\right)}{k^2 4pq} \tag{2}$$

where k is wave number, q is initial phase, h is period and p is frequency. According to the ultrasonic theory in solids, the one-dimensional nonlinear elastic wave equation of a free plate structure can be expressed by the following formula:

$$\frac{\partial^2 u(x,t)}{\partial t^2} - c^2\frac{\partial^2 u(x,t)}{\partial x^2} = c^2\beta\frac{\partial^2 u(x,t)}{\partial x}\frac{\partial^2 u(x,t)}{\partial x^2} \tag{3}$$

where u is the particle vibration displacement, c is the propagation velocity of ultrasonic wave in the measured medium, x is the propagation distance of ultrasonic wave, t is the propagation time of ultrasonic wave, and β is the nonlinear acoustic coefficient.

According to the perturbation theory, formula (3) can be simplified as follows:

$$u(x,t) = u^{(0)}(x+t)\beta + u^{(1)}(c+t) \tag{4}$$

where $u^{(0)}$ and $u^{(1)}$ are linear and nonlinear displacements respectively, assuming that $u^{(1)}$ is proportional to wave propagation distance x, so:

$$u^{(1)}(x,t) = xf(\tau) \tag{5}$$

where $\tau = t - x/c$, $f(\tau)$ is a new function to be determined, assuming that the frequency of the input ultrasonic signal is f_1 and f_2, respectively, then:

$$u^{(0)}(x,t) = A_1\cos\left(f_1\tau\right) + A_2\cos\left(f_2\tau\right) \tag{6}$$

where A_1 and A_2 are the amplitudes of low-frequency vibration signals and high-frequency ultrasonic signals respectively. In order to determine function $f(\tau)$, k_i is defined as wave number, $f_i = k_i c$. Formulas (5) and (6) are introduced into formula (4), and finally into formula (3). Function $f(\tau)$ can be obtained as:

$$\begin{aligned} f(\tau) = &-\frac{A_1^2k_1^2}{8}\cos\left(2f_1\tau\right) - \frac{A_2^2k_2^2}{8}\cos\left(2f_2\tau\right) \\ &+\frac{A_1A_2k_1k_2}{4}\left[\cos\left(f_1 - f_2\right)\tau - \cos\left(f_1 + f_2\right)\tau\right] \end{aligned} \tag{7}$$

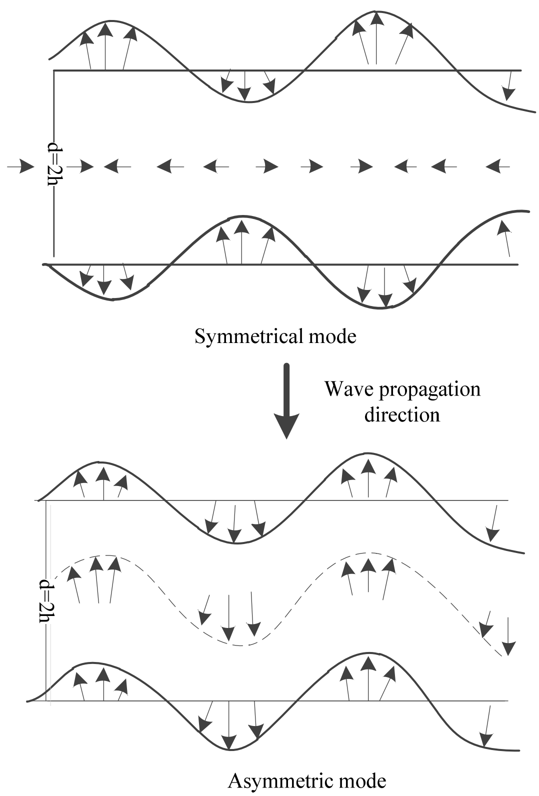
Finally, $u(x, t)$ can be expressed as:

$$u(x,t) = A_1\cos\left(f_1\right)\tau + A_2\cos\left(f_2\tau\right) + x\beta\left\{-\frac{A_1^2k_1^2}{8}\cos\left(2f_1\tau\right) - \frac{A_2^2k_2^2}{8}\cos\left(2f_2\tau\right)\right\} \tag{8}$$

where $k_1 = f_1/c$, $k_2 = f_2/c$.

It can be seen from formula (8) that the response function of the interaction between the input signal and the damage includes not only the fundamental frequencies f_1 and f_2, but also the harmonics with frequencies $2f_1$ and $2f_2$, as well as the side lobe nonlinear frequency components with frequencies $f_2 - f_1$ and $f_1 + f_2$, and the amplitudes of the harmonics and side lobes are proportional to the nonlinear acoustic coefficients β and the amplitudes A_1 and A_2 of the input signal.

Figure 3 Schematic diagram of Lamb wave propagation



It can be seen from the above analysis that when there is damage in the tested structure, the interaction of the applied low-frequency vibration, high-frequency ultrasonic and damage defects produces harmonic and modulated sidelobe, and the order of modulated sidelobe is related to the modulation intensity and the damage degree of the material structure. Therefore, this study determines the high-frequency ultrasonic wave in the nano ceramic coated rail structure according to the perturbation theory, and obtains the modulated sidelobe signal of the rail under the fatigue damage state, so as to determine its modulation intensity.

Modulation strength R is usually used to evaluate the damage degree of materials and structures, and its formula is defined as:

$$R = \frac{\sum_{i=1}^{n} \left(A_{LSB}^{i} + A_{RSB}^{i} \right)}{A_{HF}} \tag{9}$$

where A_{LSB}^{i} and A_{RSB}^{i} are the amplitude of the second order modulated sidelobe around the high-frequency ultrasonic frequency component, and A_{HF} are the amplitude of the high-frequency ultrasonic frequency component.

When the left and right first order side lobes are taken, that is, when $i = 1$, this parameter can better evaluate the damage degree in the structure. Therefore, the damage eigenvalue of vibro acoustic modulation can be selected as the modulation parameter *MI*:

$$MI = \frac{A_{L1} + A_{R1}}{A_{HF}} \tag{10}$$

where A_{L1} and A_{R1} are the amplitude of the left and right first order modulated sidelobe, respectively.

For any complex signal, in the time domain, the relationship between signal amplitude and time can be expressed as:

$$v(t) = \int_{-\infty}^{+\infty} v(f)\exp(2\pi ift)df \tag{11}$$

According to Fourier transform, the signal can be decomposed into a combination of sinusoidal signals in multiple frequency domains, and the relationship between amplitude and frequency of each sub signal is as follows:

$$v(f) = \int_{-\infty}^{+\infty} v(t)\exp(2\pi ift)dt \tag{12}$$

where $v(t)$ and $v(t)$ are the amplitude of the signal in the time domain and frequency domain respectively, t is the time, and f is the signal frequency.

The principle of FFT is to use the odd, even, virtual and real properties of Fourier transform to decompose a sequence with a length of N into a discrete Fourier transform of a shorter sequence. When the sampling point is N, the discrete Fourier transform function is expressed as:

$$v_p(t_k) = \frac{1}{T}\sum_{n=0}^{N-1} V_p(f_n)\exp(-2\pi ikn/N) \tag{13}$$

$$V_p(V_n) = \frac{T}{N}\sum_{j=0}^{N-1} v_p(t_j)\exp(2\pi ijn/N) \tag{14}$$

where $T = N\Delta t$, Δt is the sampling time interval, the corresponding signal frequency is $f_n = n\Delta f = n/N\Delta t$, and the corresponding time is $t_j = j\Delta t$.

After the signals are collected, each section of experimental data is processed by FFT signal processing, and the corresponding frequency spectrum of each data is obtained. The corresponding modulation parameter MI is calculated by formula (10), so as to obtain the fatigue damage degree of nano ceramic coating rail.

Fatigue damage evolution mechanism is one of the main concerns in studying the fatigue behaviour of materials and structures, and is also the basis for predicting the residual fatigue life of materials and structures. Generally, under the action of cyclic stress and strain or tensile load, the material will undergo microscopic and local irreversible structural changes, resulting in fatigue damage of the material. With the gradual increase of the number of loading cycles, this change will increase, and fatigue damage will accumulate synchronously, and will germinate and expand in different positions and directions, resulting in changes in the overall mechanical properties of the material, such as the degradation of material strength or stiffness.

In material damage mechanics, fatigue damage variable D is usually used to describe the continuous development process of micro damage in material structures. This variable can be derived from the degradation of material elastic modulus, namely:

$$D = 1 - \frac{E}{E_0} \tag{15}$$

where E and E_0 are the elastic modulus of damaged and undamaged material structures respectively. For the corresponding fatigue damage model, the expression of fatigue damage variable D is:

$$D = 1 - \frac{E}{E_0} = D_0 + (1 - D_0)\left(\frac{N}{N_f}\right)^b \tag{16}$$

where N is the number of impact fatigue, N_f is the total number of impact fatigue corresponding to material failure, the ratio of N to N_f is the impact fatigue life, b is the fitting parameter, and D_0 is the initial fatigue damage variable, that is, the fatigue damage variable of the material when the number of impact fatigue is $N = 0$.

At this time, the fatigue damage variable in formula (16) is the fatigue damage detection result of nano ceramic coating rail.

In conclusion, fatigue damage detection of nano ceramic coated rail based on acoustic signal acquisition is realised. In the detection process, firstly, by analysing the long-term fatigue behaviour of the nano ceramic coated rail, the typical damage evolution state of coating cracking at each stage was obtained, which laid an effective foundation for the subsequent damage detection. Then, according to the ultrasonic theory, the one-dimensional nonlinear elastic wave equation of the rail vibration signal propagation process is constructed, and the modulated sidelobe signal of high-frequency ultrasonic in the fatigue damage state is obtained, so as to determine the modulation intensity of the rail, which fundamentally reduces the subsequent damage detection error.

4 Experimental results and correlation analysis

In order to verify the application effect of nano ceramic coating rail fatigue damage detection method based on acoustic signal acquisition in practical work, the following experimental process is designed and the results are analysed.

4.1 Experimental design

The nano ceramic coated rail with a nonlinear crack of 5 mm in length and 1 mm in coating depth at the centre was selected for the experiment. The length and depth of the crack were kept unchanged. The width of the nonlinear crack was set to 0.1, 0.2, 0.3, 0.4, 0.5 mm one by one. The proposed fatigue damage detection method was used to detect the nano ceramic coated rail with nonlinear cracks of different widths using the same operation. In this section, two groups of control methods are designed to verify the effectiveness of method of Zhang and Liu (2021) and method of Fan et al. (2020) respectively.

4.2 Result display

4.2.1 Fatigue damage detection results of nano ceramic coating rail

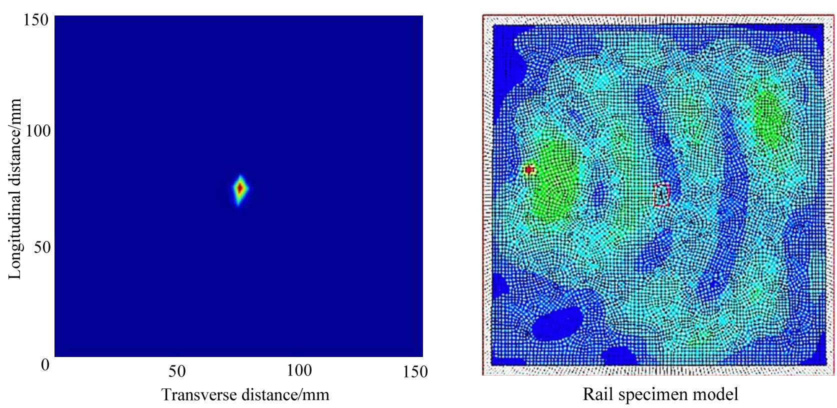
With the location of nonlinear microcracks as a single variable, three experiments were designed for mutual comparison to verify the effectiveness of the proposed fatigue damage detection method for nano ceramic coated rails when the damage is located in the direct wave propagation path, above the direct wave propagation path and below the direct wave propagation path respectively.

During the verification experiment, keep the length and width of the nonlinear crack in the nano ceramic coated rail unchanged at 5 mm and 0.2 mm, and place the location of the nonlinear crack in the centre of the signboard, the upper left side of the rail and the lower right side of the rail.

The same operation is used to detect the steel rail specimens with nonlinear cracks at different positions. First, a row of high-frequency Rim wave signals is separately excited to the steel rail specimens, and then a row of low-frequency vibration signals are separately excited to the steel rail specimens. After a stable sound field is formed in the plate, the low-frequency vibration is continuously input. Then, a series of high-frequency Lamb wave signals are superimposed on the receiving sensor array, and each array element receives two columns of received signals. After the time-frequency spectrum subtraction of the signals received successively by each array element through ultrasonic theory, the time when the nonlinear side frequency modulation component (i.e., damage signal) arrives at each array element is extracted, and the results are calculated by the rail fatigue damage detection method proposed in this section, as shown in Figure 4.

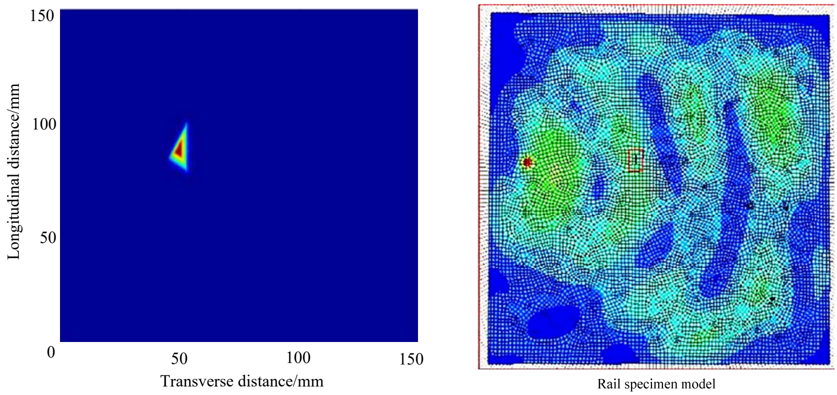
The coordinates of the maximum damage probability point in the three groups of microcrack location results are counted and compared with the actual location coordinates of the microcrack centre. The specific results are shown in Table 1.

Figure 4 Microcrack detection algorithm results, (a) position 1: the microcrack is located in the centre of the rail specimen (b) position 2: the microcrack is located at the upper left of the rail test piece (c) position 3: the microcrack is located at the lower right of the rail test piece (see online version for colours)

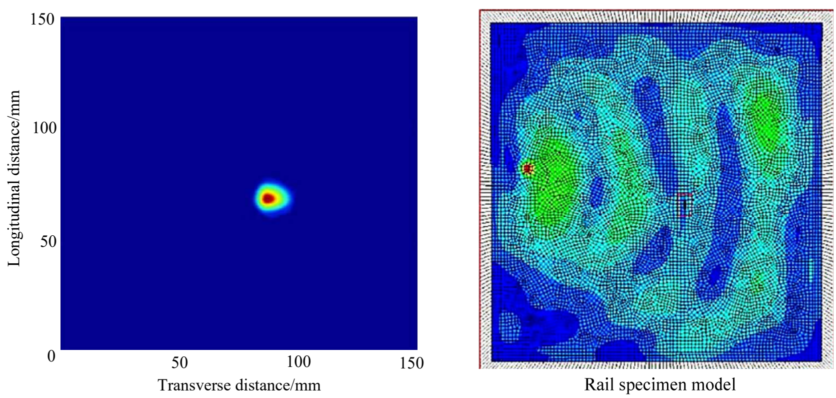


(a)

Figure 4 Microcrack detection algorithm results, (a) position 1: the microcrack is located in the centre of the rail specimen (b) position 2: the microcrack is located at the upper left of the rail test piece (c) position 3: the microcrack is located at the lower right of the rail test piece (continued) (see online version for colours)



(b)



(c)

Table 1 Comparison between damage location results of rail specimen and actual crack location (unit: mm)

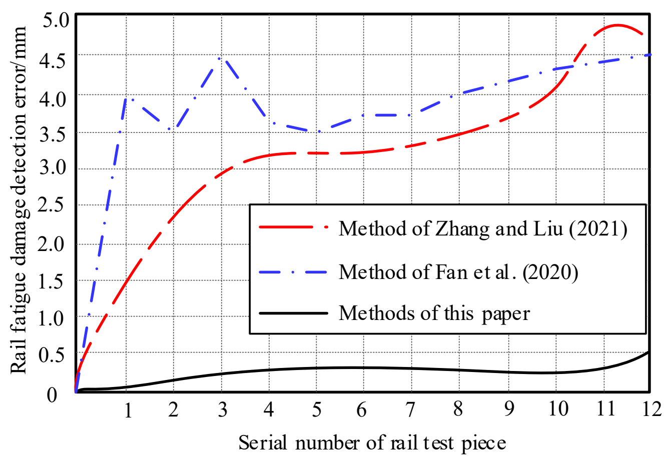
Crack location	*1*	*2*	*3*
Where the maximum damage probability is calculated	(75.02, 75.01)	(49.32, 85.33)	(86.77, 71.01)
Actual crack centre position	(75.00, 75.00)	(50.00, 85.00)	(85.00, 70.00)
Positioning result error	(0.02, 0.01)	(–0.68, 0.33)	(1.77, 2.01)

For the case where the crack at position 1 is located in the centre of the nano ceramic coated rail specimen, the damage detection method proposed in this chapter has high accuracy. When the crack at position 2 is located at the upper left of the aluminium plate, the calculation error of the damage detection method is within 1 mm. When the crack at position 3 is located at the lower right corner of the aluminium plate, the calculation error of the damage detection method is relatively large, which may be caused by the close distance between the crack at position 3 and the receiving sensor array, and the small time difference of the damage signal received by each array element, resulting in the large positioning error of the damage detection method, but the distance error between the calculated result and the actual position of the crack centre can still be controlled within 3 mm. The above results can show that the method of this paper is feasible, with high positioning accuracy, large detection coverage, low calculation cost and significant advantages.

4.2.2 Comparison of detection errors

The fatigue damage detection errors of different methods are tested, and the results are shown in Figure 5.

Figure 5 Fatigue damage detection error of nano ceramic coating rail (see online version for colours)



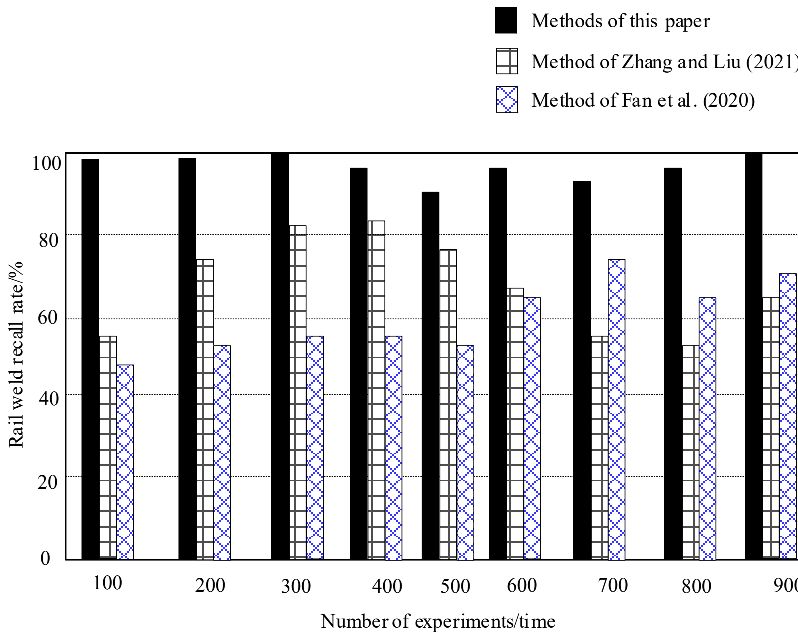
It can be seen from the analysis of Figure 5 that for the test piece sequence of rail no. 1, the detection error of method of Zhang and Liu (2021) is 1.5 mm, the detection error of method of reference Fan et al. (2020) is 4.0 mm, and the detection error of method of this paper is 0.01 mm; For the rail no. 8's test piece sequence, the detection error of method of Zhang and Liu (2021) is 3.5 mm, the detection error of method of Fan et al. (2020) is 4.0 mm, and the detection error of method of this paper is 0.25 mm; For the test piece sequence of rail no. 12, the detection error of method of Zhang and Liu (2021) is 4.7 mm, that of method of Fan et al. (2020) is 4.5 mm, and that of method of this paper is 0.5 mm.

To sum up, the method of this paper always has a low detection error for the fatigue damage of nano ceramic coated rails. The reason for this result is that after collecting the acoustic signal of the rail, the method of this paper implements Fourier transform processing on each section of experimental data, and accurately calculates the fatigue damage modulation parameters according to the data frequency spectrum, thus effectively reducing the detection error.

4.2.3 Comparison of recall

The recall ratio of fatigue damage data of nano ceramic coated rails by different methods is compared, and the results are shown in Figure 6.

Figure 6 Inspection recall rate of rail fatigue damage (see online version for colours)



According to the analysis of Figure 6, when the number of experiments is 100, the recall ratio of method of Zhang and Liu (2021) to the fatigue damage data is 57%, that of method of Fan et al. (2020) to the fatigue damage data is 50%, and that of method of this paper to the fatigue damage data is 99.2%; When the number of experiments is 500, the recall rates of method of Zhang and Liu (2021), method of Fan et al. (2020) and method of this paper on fatigue damage data are 83.2%, 56.9% and 98.0% respectively; When the number of experiments is 900, the recall rates of method of Zhang and Liu (2021), method of Fan et al. (2020) and method of this paper on fatigue damage data are 68.9%, 70.3% and 99.8% respectively.

In conclusion, the method of this paper has a higher recall rate for rail fatigue damage data. The reason for this result is that the method of this paper has analysed the complete damage evolution state of nano ceramic coating materials according to the percentage of service life and the degree of damage before testing, and has implemented Fourier transform processing on each section of acoustic signal in the later stage, effectively avoiding data omission.

5 Conclusions

In this paper, a fatigue damage detection method of nano ceramic coated rail based on acoustic signal acquisition is proposed. After analysing the long-term fatigue behaviour of nano ceramic coating materials, the one-dimensional nonlinear elastic wave equation of nano ceramic coated rail is constructed, and the modulation signal strength of nano ceramic coated rail is determined according to the acoustic signal acquisition. Then, after the acoustic signal is collected, Fourier transform signal processing is performed on each section of experimental data to obtain the corresponding frequency spectrum of each data, so as to accurately calculate the fatigue damage modulation parameters of the nano ceramic coated rail, and then obtain the fatigue damage degree of the nano ceramic coated rail.

The experimental results show that:

1 this method always has a low fatigue damage detection error of the nano ceramic coating rail, and the detection error is controlled within 0.5 mm

2 the recall rate of the fatigue damage data of this method is high, up to 99.8%, indicating that this method effectively realises the design expectation.

Acknowledgements

This work was supported by the scientific research and Development Center of the Ministry of Education. The project is called 'Research on the construction of a platform for virtual simulation teaching management and resources sharing of railway locomotives'. The project number is ZJXF2022072.

References

Cai, Z., Chen, L., Li, H., Qin, T. and Shen, M. (2021) 'Wear detection method of CL60 wheel and U75V rail based on nonlinear ultrasound', *Journal of Transport Engineering*, Vol. 21, No. 6, pp.136–146.

Cao, Y. and Liu, L. (2020) 'Background difference rail surface defect detection method based on defect proportion limitation', *Computer Application*, Vol. 40, No. 10, pp.3066–3074.

Fan, W., Li, B., Chen, B. and Ren, S. (2020) 'Analysis of electromagnetic nondestructive testing technology for stress concentration and fatigue damage of wire ropes', *Electromechanical Information*, Vol. 19, No. 12, pp.144–147, 149.

Fang, X., Zhang, H. and Ma, D. (2022) 'Effect of wheel rail profile matching on rail subsurface fatigue crack growth', *Journal of Central South University (Natural Science Edition)*, Vol. 53, No. 5, pp.1824–1833.

Huang, G., Fan, Y. and Jiang, Y. (2022) 'Wind induced fatigue damage analysis of high-rise buildings based on improved T-B spectrum method', *Vibration and Impact*, Vol. 41, No. 5, pp.243–250.

Huo, J., Liu, Z., Wang, C. and Wang, Y. (2020) 'Mixed frequency electromagnetic rail flaw detection method based on amplitude feature extraction', *Electronic Measurement Technology*, Vol. 43, No. 13, pp.105–110.

Kong, Q., Ye, B., Deng, W., Chen, C. and Wang, D. (2021) 'Probabilistic imaging method for fatigue damage of carbon fiber composites based on ToF damage factor', *Progress in Laser and Optoelectronics*, Vol. 58, No. 16, pp.171–179.

Liu, Y. and Duan, Z. (2022) 'Effect of rail bottom slope on fatigue crack initiation life of heavy haul railway rails', *Journal of Railway Science and Engineering*, Vol. 19, No. 5, pp.1250–1259.

Si, G., Li, W., Xu, H. and Xu, Z. (2020) 'Fatigue damage condition monitoring method of TC4 alloy based on DIC and acoustic emission', *Journal of Northeast Petroleum University*, Vol. 44, No. 3, pp.119–126, 12.

Wang, J., Zhou, Y. and Shen, G. (2021) 'Effect of rail hardness on fatigue crack initiation and rail wear', *Journal of Southwest Jiaotong University*, Vol. 56, No. 3, pp.611–618.

Wang, M., Zhang, E. and Li, D. (2020) 'Fatigue damage detection method based on cycle stability', *Mechanical Design and Manufacturing*, Vol. 15, No. 3, pp.181–184.

Yang, Z., Wang, P., Jia, Y., Ji, K. and Shi, Y. (2021) 'A rail damage determination and counting method based on magnetic flux leakage detection', *Measurement and Control Technology*, Vol. 40, No. 4, pp.65–69.

Zhang, B. and Liu, X. (2021) 'Machine vision based rail contact fatigue crack detection method', *Railway Architecture*, Vol. 61, No. 11, pp.116–119.

Zhang, B., Yu, D., Zheng, J., Qu, W., Zhang, Z. and Li, N. (2020) 'The influence of rail corrugation on the fatigue life of high-speed EMU frame', *Railway Vehicles*, Vol. 58, No. 1, pp.1–3, 31, 34.

Zheng, R., Zhang, K. and Tian, J. (2021) 'Research on fatigue damage assessment method of ship structures based on rain flow counting method', *Electromechanical Equipment*, Vol. 38, No. 3, pp.112–116.

Zhou, Y., Li, J. and Si, D. (2020) 'Research and inspection on rolling contact fatigue crack initiation of ordinary speed railway rails', *Railway Architecture*, Vol. 60, No. 5, pp.107–111.