Radar analysis of free oscillations of rail for diagnostics defects

To cite this article: G Y Shaydurov et al 2018 J. Phys.: Conf. Ser. 1015 032182

View the article online for updates and enhancements.
Radar analysis of free oscillations of rail for diagnostics defects

G Y Shaydurov, D S Kudinov, E A Kokhonkova, V S Potylitsyn

Military Engineering Institute, Siberian Federal University, 13a, Akademgorodok Ave., Krasnoyarsk, 660036, Russia

E-mail: kudinovdanil@yandex.ru

Abstract. One of the tasks of developing and implementing defectoscopy devices is the minimal influence of the human factor in their exploitation. At present, rail inspection systems do not have sufficient depth of rail research, and ultrasonic diagnostics systems need to contact the sensor with the surface being studied, which leads to low productivity. The article gives a comparative analysis of existing noncontact methods of flaw detection, offers a contactless method of diagnostics by excitation of acoustic waves and extraction of information about defects from the frequency of free rail oscillations using the radar method.

1. Introduction

Non-destructive testing (NDT) of railways is the most effective prevention of emergency situations. More than 5000 potentially dangerous parts are detected by means of NDT. Nevertheless, the current control systems do not meet the requirements for growth of speed parameters [1]. At present, defect detection systems for railroad applications are widely covered in various publications [2-6].

To date, electromagnetic and acoustic methods are used as the main methods of diagnostics on the railway and have some advantages and disadvantages. The advantages of acoustic methods are expressed in the detection of dangerous defects at any depth of the investigated object due to the high penetrating ability of ultrasound and high accuracy grade. Disadvantages are the strong influence of the human factor, the need for contact with the object, low productivity (speed no more than 20 km/h), fast wear of transmitters.

The electromagnetic method has the ability to control without physical contact with the object under study, which allows increasing the analysis speed (up to 80 km/h) and realizing it in real time. However, this method cannot detect defects located at a depth of more than 6-8 mm [7]. Thus, the problem of operational control of railway infrastructure objects, such as rails, nodes, contact network supports, bridges, etc., is reduced to providing non-destructive retrieval of information about defects of the monitored object at a device speed of up to 100 km/h [8].

2. Analysis of the methods of defectoscopy

Many methods of excitation and signal reception is used for contactless rail diagnostics for the presence of defects without direct contact. Methods of acoustic control can be based on a variety of methods.

The electromagnetic-acoustic method consists in creating eddy currents in the surface of the rail with depth of the skin layer much smaller than the sample size. However, only a small part of the
energy of electromagnetic oscillations is converted into the energy of acoustic vibrations. This method was used in the process of ultrasonic monitoring of parts and assemblies of rolling stock, but it was not widely used in the search for rail defects due to the complexity of implementation and application.

The laser method of generation uses the effect of a powerful optical radiation on the rail. This method allows monitoring at a distance of several meters and registers elastic waves of different frequencies, but has a high cost, complexity of implementation and a strong dependence on weather conditions.

Air acoustic coupling uses the effect of elastic waves on the rail through the air at a frequency of 10 kHz - 1 MHz, since attenuation in the air is minimal. Piezoelectric sensors with air coupling are used to receive elastic vibrations from the excited rail. The disadvantage is the strong attenuation of elastic waves of a given frequency at the air-metal interface, hence only the receiving part of the measuring system is used. The air shock wave method uses a horn to generate a powerful acoustic pulse with a spherical front to excite a large portion of the sample [9].

The electrostatic method of exciting acoustic waves uses a rail as one of the capacitor coatings. Elastic waves are caused by the interaction forces of charges in the capacitor coating. The registration of oscillations occurs due to the reverse effect - the change in charge on the capacitor coatings when the distance between the plates changes. This method is low cost and ease of implementation, but the least sensitive of all the presented methods. In the following chapters of the article, an alternative method for detecting defects will be considered by analyzing the frequencies of free oscillations (FFO) of the object under study.

3. Mathematical analysis of influence of defects on frequency of free rail vibrations

3.1 Mathematical model of the process of free oscillations of the spacing of the rail and the effect of its defects on the frequency of free oscillations

It is necessary to determine the frequency range of oscillations of the rail gap located between the sleepers with the help of the expression for the frequency spectrum of free oscillations of the elastic rod [10]:

\[ \nu = \frac{\pi}{2l^2} \sqrt{\frac{E}{S\rho}} \beta^2 \]  \( (1) \)

where \( l \) is the length of the rod; \( \beta \) is the root of the frequency equation; \( S \) is the cross section of the rod.

As can be seen from expression (1), the frequency of free oscillations of a rod fixed at both ends depends on its physical (modulus of elasticity, density) and geometric (length, moment of inertia, cross-sectional area) characteristics.

The main task in the development of the radar system for railway rail inspection is to select information criteria and evaluate the effectiveness of their use to detect defects.

To calculate the FFO, formula (1) is used; substituting in it the main parameters of the rail P65, let us obtain the following values of the fundamental frequency:

The plane axis 0Y axis:

\[ \nu_x = \frac{\pi}{2 \cdot 0.5^2} \sqrt{\frac{2.1 \cdot 10^{11} \cdot 3.6 \cdot 10^{-3}}{82.65 \cdot 10^{-4} \cdot 7830}} = 656 \text{ Hz} \cdot \]  \( (2) \)

The plane axis 0Y:

\[ \nu_y = \frac{\pi}{2 \cdot 0.5^2} \sqrt{\frac{2.1 \cdot 10^{11} \cdot 0.6 \cdot 10^{-3}}{82.65 \cdot 10^{-4} \cdot 7830}} = 213 \text{ Hz} \cdot \]  \( (3) \)
According to theoretical data, the presence of a defect is reflected, mainly, by a change in the integral density of the rod and the frequency shift is determined by the following expression:

$$
\Delta \nu = -\frac{\pi}{8l^2} \sqrt{\frac{E}{\rho}} \cdot \frac{V_d}{V}.
$$

Figure 1 shows the data obtained by modeling the frequency shift from the volume of the external defect. As can be seen even at a volume of the order of $1000 \, \text{mm}^3$, which is a defect of $10\times10\times10 \, \text{mm}$ in size. Modern equipment allows one to register frequencies with much greater accuracy.

**Figure 1.** The calculated frequency shift vs the volume of the external defect

### 3.2 Experimental evaluation of the influence of rail defects on the frequency of free oscillation

To conduct the experiment, the authors developed and created a Doppler locator at a frequency of 10 GHz and a power of 20 mW using a special parabolic antenna. The photos of the locator assembly are shown below in figure 2.

**Figure 2.** Experimental Doppler locator at 10 GHz

To obtain results that are close to the expected operating conditions, it is necessary to carry out an experiment in which the condition of the rail track multiplicity is considered, and also the distance between supports of 50 cm, corresponding to the gap between sleepers, is established. The radar is installed at a height of 50 cm from the irradiated surface above the center of the span. The scheme of realization of the experiment is shown in figure 3. The results of measurements of the FFO rail located on two supports are shown in figure 4.
Figure 3. Experimental set

Figure 4. Spectral characteristics of rails are combined FFO of vibrational mode of 1280 Hz with different depth of defect

The experiment includes the identification of information signs, as well as the determination of the dependence of the FFO on the size and nature of the defect. Information signs of defectiveness of the monitored rail section are determined by a comparative analysis of the spectral characteristics of defective and defect-free samples. The experiment is carried out as follows. At a distance point of 25 cm from the inter-spilled passage to be surveyed, a mechanical impulse is applied to the rail, resulting in free damped oscillations being excited in it. The measurement of the FFO of the surveyed span is made by irradiating the surface of the rail with radar in the vertical plane. Table 1 shows the data obtained in estimating the frequency shift for predetermined defect sizes.

Table 1. The calculated values of the dependence of the frequency shift on size of the defect

| V (mm³) | f (Hz)   |
|---------|----------|
| 0       | 853      |
| 562     | 852.95   |
| 1125    | 852.89   |
The experiment is carried out consistently in several stages. At the first stage, a defect in the form of a transverse cut on a rail head 3 mm wide was created on the rolling surface of the rail head. Thus, a defect of the following size was obtained: the defect length corresponds to the width of the rail head; width is 3 mm; depth is 5 mm.

The device for simulating the interaction of a wheel with a rail mechanically affects the rail head at a point 30 cm from the surveyed span, resulting in free damped oscillations in the rail (figure 4). Then using Doppler locator sensor extracted parameter information and process the vibrational spectrum allocated FFO rail.

4. Conclusion
The subsequent steps are carried out in the same order with a gradual increase in the depth of the defect by 2.5 mm. As a result of the experiment on measuring, the change in the spectrum of the CSF, depending on the size of the defect, spectral characteristics for defects with a depth of \( \delta_1 = 5 \) mm, \( \delta_2 = 7.5 \) mm, \( \delta_2 = 10 \) mm, \( \delta_2 = 12.5 \) mm, \( \delta_3 = 15 \) mm were obtained. The spectral characteristics of the CSF of defect-free and defective rail specimens are shown in figure 4 where each characteristic line of the spectrum has a frequency shift corresponding to the size of the defect.

5. Acknowledgments
This work was supported by the Russian Foundation for Basic Research (RFBR) No. 16-07-00426.

References

[1] Tian H B, Xu C G, Lin L P, Wang J F and Song J F 2017 Nondestructive testing and control of the residual stress of rail in service. 2016 IEEE International Wheelset Congress (Chengdu: China) 141–145

[2] Alemi A, Corman F and Lodewijks G 2017 Condition monitoring approaches for the detection of railway wheel defects. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, vol 231 (Netherlands: Delft University of Technology) 8961–981

[3] Boronahin A M, Larionov D Y, Podgornaya L N, Shalymov R V, Filatov Y V and Bokhman E D 2016 Specialized navigation system for rail track diagnostics. 2016 IEEE North West Russia Section Young Researchers in Electrical and Electronic Engineering Conference. (Russian Federation: St. Petersburg State Electrotechnical University) 401–403

[4] Ma C and Hui J 2016 Research of diagnosis of high-pressure common rail system based on real-time model. Conference on Society of Automotive Engineers of China (Jiangsu: FAW Wuxi Fuel Injection Equipment Research Institute) 621–630

[5] Boronahin A M, Filatov Y V, Yu Larionov D, Podgornaya L N and Shalymov R V 2014 Fusion of heterogeneous sensor information for railway track diagnostics. 2014 Workshop on Sensor Data Fusion: Trends, Solutions, Applications (Russian Federation: St. Petersburg State Electrotechnical University) 6

[6] Khabarov V N and Demidov V N 2003 Monitoring and diagnostics of the bearing units of track-laying machines. Tyazheloe Mashinostroenie (Russian Federation) 1(10) 33–35
[7] Liu Z, Li W, Xue F, Xiafang J, Bu B and Yi Z 2015 Electromagnetic Tomography Rail Defect Inspection. *IEEE* (Shenzhen: Transactions on Magnetics National Supercomputing Center in Shenzhen) *51*(10)

[8] Meixedo A, Goncalves A, Calcada, R, Gabriel J, Fonseca H and Martins R 2015 On-line monitoring system for tracks. *Exp.at 2015 - 3rd Experiment International Conference: Online Experimentation* (Portugal: University of the Azores Ponta Delgada) 1 133–134

[9] Wang K Y and Liu P F 2012 Characteristics of dynamic interaction between wheel and rail due to the hunting motion on heavy-haul railway. *Gongcheng Lixue. Engineering Mechanics* (China: Chengdu) *11*(29) 235–239

[10] Kudinov D S and Shaïdurov G Y 2009 Non-contact nondestructive rail testing. *International Siberian Conference on Control and Communications, SIBCON-2009* (Russian Federation: Tomsk) 1 290–295