Estimation of energy ratios and selection of optimal wavelength for radar flaw detector

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Abstract. This article discusses the evaluation of energy relationships for the design of a radar flaw detector, the rationale for choosing its working frequency. The influence of oscillations of the reflecting surface of the rail head on the phase and frequency deviation is given. The article deals with the design of the circuit flaw detector implementation scheme.

1. Introduction

Currently, there are many different methods for monitoring defects in railroad tracks and rolling stock. Ultrasonic, laser and induction methods have been widely spread, but all of them have various disadvantages [1-3]. Ultrasonic methods do not allow high-speed operation [4]; induction methods have quite a small depth of penetration determined by the skin layer [5], and laser methods do not allow working under unfavorable weather conditions [6]. In this case, the problem arises of creating a new method that will eliminate the shortcomings of existing methods. In this article, it is proposed to use the radiolocation method for these purposes, which does not have the above-mentioned disadvantages.

To implement the radar system of the rail track defect detection system in the course of the convoy movement, it is necessary to solve the following tasks: to determine the optimum operating frequency of the radar, depending on the required antenna beamwidth and the amount of rail defect, and to evaluate the energy characteristics of the radio channel – to determine the energy relationships in the channel, the required transmitter power, taking into account external factors in the system, to make up the radar equation and investigate the main dependencies of the radar signals on the parameters of defects and motion parameters.

In this radar method, the effect of frequency shift of natural oscillations upon the occurrence of a defect is used as an information parameter, as well as the appearance of additional vibrational modes in the spectrum due to standing waves (Figure 1) [7].
Figure 1. The principle of revealing a defect by registering additional of vibrational modes in the spectrum of the natural oscillations rail

Below is an analysis of the energy relationships in the channel using the basic radar equation, i.e. mathematical relationship for the connection of the main parameters of the radio channel in different frequency bands with the attendant external factors and the observed information parameters.

2. Estimation of energy relationships for radar detection system

In order to estimate the energy in the required radar detection system as an object of irradiation, let us take a flat surface with an equal area, which is irradiated by a parabolic antenna at \( r \). This model is well described in the literature and the power on the receiving antenna will be described by the following expression [8]:

\[
P_R = \frac{P_t \cdot G_p \cdot S_A \cdot e^{-2\alpha \cdot r} \cdot \sigma}{4 \cdot \pi \cdot r^4 \cdot \lambda^2}
\]  \hspace{1cm} (1)

where \( P_R \) is the power of the reflected signal at the input of the receiver; \( r \) is the distance from the receiving and transmitting antennas to the rail (the height of the antenna suspension above the rail); \( \alpha \) is coefficient of absorption of radio waves by propagation medium; \( P_t \) is transmitter power; \( G_p \) is directivity factor of the antenna; \( \lambda \) is the wavelength; \( \sigma \) is the effective scattering area (ESA) of the rail; \( S_A \) is the effective area of the aperture of the transmitting or receiving antenna.

In this case, the propagation loss coefficient of the signal can be neglected, since the signal will propagate in the air. To calculate the ESA of the rail, let us consider it as a cylinder with a diameter corresponding to the width of the irradiated rail surface.

The effective scattering area of a flat spot on a rail head is determined by the following expression:

\[
\sigma = \frac{4 \cdot \pi \cdot S^2}{\lambda^2}
\]  \hspace{1cm} (2)

where \( S \) is area of the flat plate.

The directivity factor of a parabolic antenna is calculated by the following formula [9]:

\[
G = 0.65 \cdot \frac{4 \cdot \pi \cdot S_A}{\lambda^2}.
\]  \hspace{1cm} (3)
To estimate the output power on the radar antenna, let us restrict ourselves to the following parameters: $P_T = 20$ mW, effective antenna area - $S_A = 20 \cdot 10^{-6}$ m. Taking into account the (2) and (3), let us obtain the following curves of power dependencies at the receiver input for the 2.4 GHz and 10 GHz frequencies in figure 1.

As expected, the input power for the 10 GHz frequency is almost two orders of magnitude higher than that for the 2.4 GHz frequency. As a result, it reduces the antenna size and allows smaller dysfunctions to be detected.

Figure 2. Dependence of the power at the output of the receiving antenna on the distance to the object.

For the case under consideration, when the research object makes periodic oscillations, the distance $r$ will change periodically and accordingly the phase parameter in the expression (2) will change periodically and the reflected signal will have a Doppler frequency offset. In this case, this offset will be alternating, since its value depends on the oscillation phase at a given time and will be determined by the following expression:

$$U(t) = U_{pr} \sin \left( \left( \omega \pm 2\omega \frac{F\Delta r_{\text{max}} \sin(\Omega t)}{c} \right) t + \frac{2\pi \Delta r_{\text{max}} \sin(\Omega t)}{\lambda} + \phi_0 \right)$$  \hspace{1cm} (4)$$

$U_{pr}$ is amplitude of oscillations at the input of the receiver; $\Delta r_{\text{max}}$ is amplitude of vibrations; $\phi_0$ is stationary initial part of phase displacement; $c$ is the speed of light; $\omega$ is frequency of radar signal of the locator; $\Omega$ is frequency of oscillations of the object under study; $\lambda$ is the wavelength of the radio signal.

Consequently, the phase deviation will be determined as:

$$d_\phi = \frac{2 \cdot \pi \cdot \Delta r_{\text{max}}}{\lambda}$$  \hspace{1cm} (5)$$

All the above-mentioned descriptions present the evaluation phase deviation depending on the oscillation amplitude of the investigated object. Figure 2 shows the characteristics for frequencies 2.4 GHz and 10 GHz.
Figure 3. Dependence of phase deviation on the displacement of the reflecting surface

Considering [1] shows that when it concerns small vibrations in amplitude and relatively high frequency (above 1 kHz), the frequency sensitivity of the method is commensurate with a phase that leads to the feasibility of a simple circuitry solutions for detecting the desired signal. In another particular case, for example, when checking the strength of span structures of bridges having a low-mobility reflecting surface with a low vibration frequency, when the oscillating velocity tends to 0, the phase method is more suitable.

Thus, for creation, it was proposed to develop a radar at a frequency of 10 GHz. Below is a diagram of the Doppler locator, designed to register the frequency of natural oscillations of the rail. This scheme consists of high-frequency and low-frequency parts. The high-frequency circuit is a Doppler locator at a frequency of 10 GHz. The low-frequency part is a low-frequency amplifier with an amplification factor of $K_u = 10000$, with suppression of industrial interference of 50 Hz.

Figure 4. Flaw detector implementation scheme

The scheme of the radar defectoscope is implemented on the instrumental low-noise differential amplifiers INA128 and AD8675. Thus, this scheme allows one to record the oscillations of the head of
the rail under impact, both rolling stock, and with the help of various specialized drums. The selection of oscillations of the reflecting surface occurs in this case on the Doppler effect, which allows us to register the natural oscillations of the rails.

3. Conclusion
The method of radar parametric control analyzed in this article, according to the authors’ estimates, eliminates the shortcomings of the existing contactless control methods and will create on its basis a system of continuous remote monitoring of the technical condition of parts and components of rolling stock, as well as transport infrastructure.

This article shows that using the radar method will eliminate the shortcomings of existing flaw detection systems. In this case, the use of 10 GHz frequency avoids problems associated with weather conditions, and it has better energy characteristics compared to 2.4 GHz, which is most important when registering the frequency of natural oscillations of driveways and bridges, since this makes it possible to work at more distant distances.

The frequency of 10 GHz in comparison with the frequency of 2.4 GHz has a greater sensitivity to the amplitude of vibrations of the head of the rail.

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