A new feature for detecting defects in ultrasonic high-speed rail inspection

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Abstract. In high-speed testing of railway rails using ultrasonic transducers, there are significant deviations of the carrier frequency of echo signals from the frequency of filling the probing pulses. They are caused by the Doppler Effect. Since inclined ultrasonic transducers have a certain width of the directional diagram, the Doppler frequency of the echo signal from any reflector in the rail has a deviation that reaches 14-30% of the average value of the Doppler shift. Analysis of this frequency modulation of received signals allows detecting possible defects in rails with high noise immunity.

1. Introduction
Increasing the capacity of railway transport leaves less time to monitor the condition of the rails and eliminate defects detected in them. Therefore, the creation of reliable methods of high-speed (close to train speeds) testing of rails is an urgent task [1, 2]. For this purpose, many countries use flaw detection cars with ultrasonic equipment that implement testing speed of up to 80 km/h, and there are already applications to achieve working speeds of more than 100 km/h.

All over the world, the technology of registering high-speed testing signals with multi-channel ultrasonic flaw detectors in the form of a B-scan has been accepted [3]. It provides fixing only one or two informative parameters from the desired defects: the time \(t\) of the delay of the echo signal relative to the probing in pulse, and, for multi-level registration, the amplitude \(U\) of the signal (figure 1(b)). In this case, many informative parameters, such as the phase, duration, and shape of the echo pulse, are lost.

During rail scanning, groups (bundles) of signals from reflectors in the rails are formed. By analyzing these signals on the B-scan, you can detect internal defects in the metal of the rails against the background of interference (figure 1). However, as the scanning speed \(V\) increases, the number \(N\) of pulses from defects, defined as \(N = \Delta L / (VT)\), decreases noticeably. Given the significant level of electromagnetic and acoustic interference that increases with high-speed testing, the reliability of the testing is reduced. Consequently, there is a need to increase the information content of ultrasonic monitoring by adding additional signs of useful signals.
2. Demonstration of the Doppler Effect in acoustic diagnostics

Back in the early 1980s, the features of the acoustic Doppler Effect at significant scanning speeds were studied [4]. Due to the technical complexity of determining the instantaneous frequency of echo pulses at that time, which have only 10-12 periods of ultrasonic frequency, studies were conducted for continuous radiation mode.

The demonstration of the acoustic Doppler effect has been used successfully in different fields of science and technology. In particular, in medicine, while measuring the speed of blood flow in vessels [5], evaluating the parameters of vibration displacements [6], when processing diagnostic signals [7], etc.

Progresses in these areas inspire developers of flaw detection equipment to continue exploring the possibility of using the Doppler effect to increase the reliability of detecting defects in rails using ultrasonic methods at high scanning speeds.

The acoustic Doppler effect [8], when the frequency of the echo signal $f_e$ received from the defect differs from the frequency $f_0$ of the radiation of ultrasonic vibrations by the amount of the Doppler shift $F_D$, can be defined with sufficient accuracy for practice as:

$$f_e = f_0 \pm F_D,$$

where $F_D$, in relation to ultrasonic nondestructive testing, can be represented as [4].

$$F_D = 2f_0 \left(\frac{V}{c}\right) \sin \alpha,$$

where $c$ is the speed of spreading of ultrasonic vibrations; $\alpha$ is the angle of insertion of the ultrasonic beam into the testing object (figure 1).

The choice of the sign between the summands in (1) depends on the direction of movement: when the piezoelectric transducer and the defect approach each other (+) and when the defect is moved away from the transducer (−).
away (–). Further examples of using the Doppler effect will be given by the example of the direction of the transducer in the direction of approaching the defect (sign + in (1)).

By the Massachusetts Institute of technology a method of flaw detection using the Doppler effect, in which there is a relative motion between the radiating-receiving acoustic transducer and the testing product, was proposed [9]. The method is also aimed at promising non-contact input and receiving of ultrasonic vibrations during high-speed testing of products. The main idea of the known method is to select signals that have the Doppler frequency shift. In the process of relative motion of the acoustic transducer it emits into the testing product ultrasonic vibrations at a given frequency at a certain angle, at a known scanning speed, reflected signals are received, and echo signals from defects are isolated taking into account the Doppler frequency shift. Moreover, using the example of railway track monitoring, it is shown that an increase in the speed of scanning leads to a more expressed Doppler Effect and better efficiency.

However, in [9], it is not taken into account that the frequency of the echo signal in accordance with (2) depends not only on the scanning speed, but also on the variable (within the direction diagram) angle of input/output of ultrasonic vibrations, which changes in the process of sonic treatment of the defect.

3. The deviation frequency of the echo signals during the scanning

For any method of excitation of acoustic vibrations (non-contact laser, electromagnetic acoustic (EMAT) radiation, contact piezoelectric transducer), when receiving echoes reflected from an internal defect, a certain resulting directional diagram is formed in the testing object with a central input angle of \( \alpha_0 \) and an opening angle of \( 2\phi \) (figure 1 (a)). In the process of continuous scanning of the testing object at speed \( V \), when approaching a local internal defect at the initial moment of time, the defect is sonicated by the edge of the directional diagram at an angle of \( \alpha_s = (\alpha_0 + \phi) \). Herewith, in accordance with (1) and (2), where \( \alpha = \alpha_s = (\alpha_0 + \phi) \), the echo signal has a frequency that is equal to

\[
F_{es} = f_0 + 2 f_0 \left( \frac{V}{c} \right) \sin(\alpha_0 + \phi). \tag{3}
\]

As the acoustic transducer moves in the area of the defect location \( \Delta L \), progressive “run over” of the directional diagram towards the defect occurs, while the pre-property sonication of the defect occurs at an angle \( \alpha_0 \), and the instantaneous frequency of the echo signal is determined by the expressions (1 and 2), where \( \alpha = \alpha_0 \).

In the future, the “slope” of the ultrasonic beam from the plane of the reflector begins and the defect is sonicated at an angle \( \alpha_e = (\alpha_0 - \phi) \),

\[
F_{ee} = f_0 + 2 f_0 \left( \frac{V}{c} \right) \sin(\alpha_0 - \phi). \tag{4}
\]

As a result, the frequency of filling in the echo signals during scanning changes by the amount

\[
\Delta f_e = 2 f_0 \left( \frac{V}{c} \right) \left[ \sin(\alpha_0 + \phi) - \sin(\alpha_0 - \phi) \right] = 4 f_0 \left( \frac{V}{c} \right) \sin \phi \cos \alpha_0. \tag{5}
\]

This leads to the conclusion that the wider directional diagram (the greater \( \phi \)) of the acoustic transducer is the greater the deviation \( \Delta f_e \) of the frequency of the echo signal is in the process of locating the defect.

Registration and accounting of changes in the frequency of the echo signal (figure 2) within the main petal of the directional diagram is one of the characteristic features that allows us to distinguish useful signals from defects in the process of processing against the background of various interferences.

Deviation of the frequency of filling of echo signals from defects in the scanning process is typical for both specific and very rare continuous radiation in nondestructive testing [4] and traditional pulsed (figure 2) radiation of ultrasonic vibrations.

Thus, both continuous and pulsed ultrasonic radiation in the zone of defect location receives echo signals with a variable frequency of filling.
With continuous radiation as one long pulse with the duration $\Delta t = \Delta L / V$, and a filling frequency, defined by the expressions (1) and (2) where the angle $\alpha$ changes from $\alpha_s = (\alpha_0 + \varphi)$ to $\alpha_e = (\alpha_0 - \varphi)$. In this case, the change in the filling frequency occurs almost linearly [4].

With pulsed radiation emitted in the same location zone $\Delta L$ (figure 1a), a group of echo pulses is received from the defect during scanning (figure 2) [3]. These pulses are formed sequentially in the process of sonic treatment of the reflector. This way, in the defect sonication with the scanning speed $V$, the resulting group of signals has the following features:

- approaching the defect, the first ultrasonic echoes (figure 2(b) impulse No 1) in the bundle has a filling frequency found by the expression (3);
- echo signals with the maximum amplitude (figure 2(b) position No 3), formed by the axis of the directional diagram, have a frequency in accordance with expressions (1) and (2), where $\alpha = \alpha_0$;
- moving away from the defect, the filling frequency of the ultrasonic echo pulse (figure 2(b) No 5) becomes the minimum and can be found by the expression (4).

**Figure 2.** Changing the filling frequency of echo signals (radio pulses) in the signal burst from the reflector as the piezoelectric transducer moves.

For the value of the ultrasound input angle $\alpha_0 = 60^\circ$, the radiation frequency $f_0 = 2.5$ MHz and the half-width of the directional diagram $\varphi = 7^\circ$ of the contact acoustic transducer, at scanning speeds of $V = 25$ m/s = 90 km/h and the length of the local defect location zone in the product being tested $\Delta L = 32$ mm (figure 1) during the scanning process, only five echo pulses will be sent to the acoustic transducer ($N = 5$):

$$N = \Delta t / T,$$
where $\Delta t = \Delta L / V$ is the travel time of the acoustic transducer (figure 1c) in the defect location zone $\Delta L$ (figure 1); $T$ is the period of sending probing pulses ($T = 250$ ms).

At the speed of distribution of transverse ultrasonic vibrations in the object being tested ($c = 3260$ m/s), first echo signals (figure 2(b), impulse No 1) have a filling frequency determined by the term (3), and differ from the value of the radiation frequency $f_0 = 2500$ kHz by the value $F_D$ at the angle $(\alpha_0 + \varphi)$ i.e. $f_{ce} = 2535.294$ kHz (figure 3). The last echo pulse of the bundle (figure 2 position No 5), obtained during moving away from the defect, in accordance with (4): $f_{ce} = 2530.620$ kHz. As a result, the instantaneous frequencies of the echo pulses (figure 2(b)) received from the defect during scanning change by almost $\Delta f_e = 5.0$ kHz (more exactly 4.674 kHz) (figure 3). The deviation of the pulse filling frequency in the packet in accordance with the term (5) is about 14% of the average value of the Doppler shift $F_D$, which is quite sufficient for practical accounting of it in order to increase the reliability of testing [10].

If we consider the representation of the frequency spectra of signals on the frequency axis, we can see that the signals from internal defects (zone S in figure 3) have a Doppler shift and the corresponding frequency modulation within the signal bundle. A band pass filter covering frequencies from $f_{ce}$ to $f_{es}$ (i.e. a bandwidth equal to $\Delta f_e$ defined by expression (5)) can be used to isolate all expected signals from potential defects.

The numerical values of the frequencies of expected echo signals on (figure 3) are given for a non-contact electromagnetic acoustic transducer (EMAT) with the most typical parameters of the directional diagram: the beam input angle $\alpha_0 = 30^\circ$, the half-width of the radiation pattern $\alpha_0 = 10^\circ$ [11]. All other conditions ($f_0$, $c$ and $V$) are identical to the case of exhilaration and reception of ultrasonic vibrations by contact method using piezoelectric transducers. It can be seen that the $\Delta f_e / F_D$ ratio is noticeably higher here than in the case of contact input and represents almost 30% of the average value of the Doppler shift $F_D$ which is caused by a wider directional diagram and a smaller input angle of ultrasonic vibrations.

According to the law of change (deviation) of instantaneous signal frequencies, it is possible to isolate echo signals from internal defects against the background of possible interference. An example of such interference is false reflections from surface microcracks on the rail head (figure 1).
It is known that any directional diagram of an ultrasonic transducer has side petals. Possible reflections from minor damage on the scanning surface will also generate ultrasonic signals. However, since the sound angle does not change relative to the normal and will be close to $\alpha = 90^\circ$, the signals from them, although they have a Doppler shift (moreover at the maximum value), will not have a frequency deviation during scanning (zone A in figure 3).

Similarly, possible reflections from the opposite surface of the tested item (rail) taken at an angle close to $\alpha = 0^\circ$, they will be concentrated near the radiation frequency $f_0$ on the frequency axis, and there also will be no Doppler shift or frequency deviation (zone B in figure 3) as well. Only signals from internal defects, sonicated by the main petal of the directional diagram with a certain opening angle ($2\phi$) will form ultrasonic echo signals (figure 2), the frequency of which will change depending on the current sound angle (zone S in figure 3). This way, by tracking the frequency deviation of ultrasonic echo signals, it is possible to distinguish signals of internal defects from the background of various kinds of interference. It is also unlikely that the electromagnetic interference unavoidable in the practice of testing that affect the acoustic transducer and get on the receiver input will have a Doppler shift and frequency deviation $\Delta f_e$.

4. Implementation of ultrasonic vibrations in pulsed radiation

With pulsed ultrasonic vibrations emitted the selection of frequency deviation of echo signals in a group requires additional manipulations, because traditionally, the duration of a single echo pulse is only units of the ISS, which is significantly less than one period of the Doppler frequency. Therefore, the frequency deviation caused by the change in the angle of location of the defect as it is scanned is proposed to evaluate by the results of determining the instantaneous frequencies of echo pulses.

Various methods for determining the effective (instantaneous) frequency of an undetected radio frequency echo signal are known. In accordance with [12], the effective frequency is determined by the maximum frequency spectrum of the echo signal or using Fourier window conversion. However, these methods have low noise immunity. The most practical determination of the effective frequency of an undetected radio frequency echo signal can be performed using the method [13], which offers an algorithm for estimating the instantaneous frequency based on the application of a wavelet conversion. In this connection, within the duration of the radio pulse (echo signal), a certain time window is selected with a width comparable to the period of the carrier frequency. It is advisable to select a time window in the echo pulse zone corresponding to the maximum amplitude.

While determining the instantaneous frequencies of all echo signals included in the signal bundle from the target defect 3 (figure 1), it is possible to trace the frequency deviation (figure 2(b)) during the scanning process. A comparison of the characteristics of changes in the time positions $t_i$ of the echo signals relative to the probing pulses during scanning of the defect zone (figure 1(c)), and changes of the carrier frequency $f_c$ of the same signals (figure 2(b)), due to the Doppler effect, shows their complete identity.

The sampling frequency of echo pulses in a bundle of signals with impulsive radiation of ultrasonic vibrations is assessed in a natural way – the discreteness corresponds to the frequency of sending probing pulses (in the given example with the frequency of sending probing pulses of 4 kHz, the instantaneous frequency is counted every 250 ms).

5. Conclusion

The considered feature of the behavior of echo signals on the frequency axis during rail scanning and the comparison of the dynamics of changes in time parameters on the V-scan confirm the relationship between the frequency and time characteristics of signals. The considered informative feature of the defect is not correlated with the amplitude and provides greater noise immunity of the parameter. This is particularly valuable at high scanning speeds, where maintaining a stable acoustic contact with the changing state of the scanning surface is quite problematic.
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