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Validity and informativity enhancement of ultrasonic testing of cast parts of railway rolling stock*

A. N. Kireev [1], Y. K. Sklifus [2], M. A. Kireeva[3]**
[1,3] Lugansk National University named after Vladimir Dahl, Lugansk, Ukraine
[2] Rostov State Transport University, Rostov-on-Don, Russian Federation

Повышение достоверности и информативности ультразвукового контроля литых деталей подвижного состава железных дорог***

А. Н. Киреев[1], Я. К. Склифус[2], М. А. Киреева[3]**
[1,3] Луганский национальный университет имени Владимира Даля, Луганск, Украина
[2] Ростовский государственный университет путей сообщения, Ростов-на-Дону, Российская Федерация

Introduction. Due to the process reasons, the structure of cast parts of the railway rolling stock (RRS) often has embedded flaws that affect drastically their strength. The degree of impact depends on many factors including the shape and location of defects in the product. The shape of the defect has the greatest effect under alternating loads. This often refers to dynamically loaded parts of the RRS underframe. The defect oriented perpendicularly to the direction of tensile loads reduces the component life to the maximum. To identify embedded flaws, the parts are subjected to ultrasonic testing by the classical pulse-echo technique. However, such methods require increased validity and informativity. For example, they do not provide the determination of the type and orientation of the defect.

Materials and Methods. Features, advantages and disadvantages of the classical pulse-echo technique of the ultrasonic non-destructive testing, which is based on the registration of the following echo signals, are considered:

- sent;
- reflected from the opposite surface (bottom) of the object;
- reflected from the defect (if any).

The pulse arrival time is proportional to the thickness of the part. If there is a defect, this time is proportional to the distance from the pulse input surface to the defect. This method can determine the presence of a defect, but it cannot determine its type.

Research Results. To determine the shape of a defect, a dual-frequency defectometry method is proposed. Its principle, algorithm and implemented analytical dependencies are described. When an echo signal from a defect is detected in the monitoring object, the amplitudes of the bottom signals and the amplitudes of the echo signals from the defect are measured at the ultrasonic wave frequencies of 2.5 MHz and

Введение. Структура литых деталей подвижного состава железных дорог (ПСЖД) по технологическим причинам часто имеет внутренние дефекты, которые существенно влияют на их прочность. Степень влияния зависит от множества факторов, включая форму и расположение дефектов в изделии. Форма дефекта оказывает наибольшее влияние при знакопеременных нагрузках. Это часто относиться к динамически нагруженным деталям экипажной части ПСЖД. Максимально снижает долговечность детали дефект, ориентированный перпендикулярно к направлению растягивающих нагрузок. Для выявления внутренних дефектов детали подвергаются ультразвуковому контролю классическим эхо-импульсным методом. Однако такие методики требуют повышения достоверности и информативности. Например, они не позволяют определить тип и ориентацию дефекта.

Материалы и методы. Рассмотрены особенности, преимущества и недостатки классического эхо-импульсного метода ультразвукового неразрушающего контроля, который основан на регистрации следующих эхо-сигналов:

- посланный;
- отраженный от противоположной поверхности (дна) объекта;
- отраженный от дефекта (при его наличии).

Время прихода импульсов пропорционально толщине детали. При наличии дефекта это время пропорционально расстоянию от поверхности ввода импульсов до дефекта. Этим методом можно определить наличие дефекта, однако нет возможности определить его тип.

Результаты исследования. Для определения формы дефекта предложен двухчастотный метод дефектометрии. Описана его сущность, алгоритм и реализуемые аналитические зависимости. При обнаружении в объекте контроля эхо-сигнала от дефекта измеряются амплитуды донных сигналов и амплитуды эхо-сигналов от дефекта на частотах ультразвуковой волны 2,5 МГц и 5,0 МГц. Рассчитывается коэффициент формы дефекта по аналитической зависимости

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**E-mail: lifter_23@mail.ru, keiser@i.ua, lifter_23@mail.ru
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5.0 MHz. The defect shape factor is calculated from the analytical dependence; and the type of defect is determined. It can be volume (pores, shells, non-metallic inclusions) or planar (cracks, segregations, etc.).
Discussion and Conclusions. A dual-frequency defectometry method to determine the type of defect under the manual ultrasonic testing of the RRS cast parts is proposed in the paper. For an express automated use of the proposed method, the software product NDTRT-07.04-L is developed, and its operation algorithm is described. The application of the technique can increase the validity and informativity of the test results.

и определяется тип дефекта. Он может быть объемный (поры, раковины, неметаллические включения) или плоскостной (трещины, ликвации и др.).
Обсуждение и заключения. В работе предложен двухчастотный метод дефектометрии, позволяющий определить тип дефекта при ручном ультразвуковом контроле литых деталей ПСЖД. Для экспрессного автоматизированного использования предложенного метода разработан программный продукт NDTRT-07.04-L и описан алгоритм работы с ним. Применение данного метода позволяет повысить достоверность и информативность результатов контроля.

Keywords: ultrasonic testing, defectometry, defect form, dual-frequency method, software product, validity, informativity.

Ключевые слова: ультразвуковой контроль, дефектометрия, форма дефекта, двухчастотный метод, программный продукт, достоверность, информативность.

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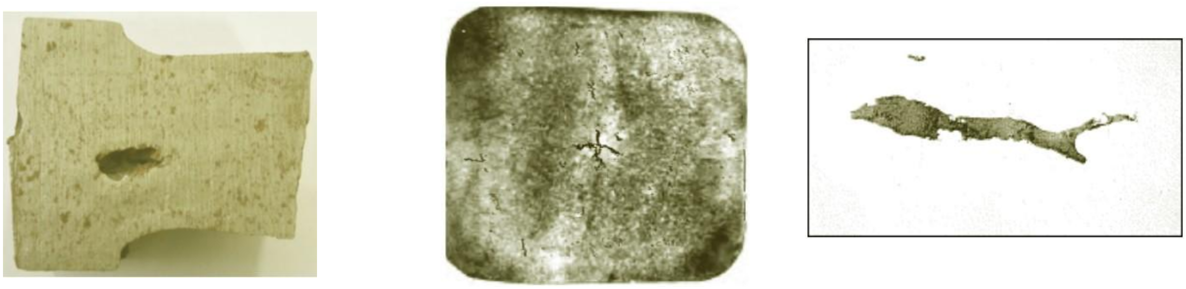
Introduction. Using casting technologies, many vital parts of the RRS underframe are manufactured, for example:

- disk wheel centres of diesel locomotives;
- spoke wheel centres of electric locomotives and electric trains;
- truck-side frames of freight wagons;
- bogie brackets of mainline locomotives.

The structure of cast parts often has defects due to process reasons. Fig. 1 shows some types of internal casting flaws in the parts of the RRS underframe.



a) *b*) *c*)

Fig. 1. Casting flaws in rolling stock parts: *a*) localized contraction cavity in cast wheel centre; *b*) internal longitudinal hot crack in wheelset axle workpiece; *c*) oxide non-metallic inclusions in casting wheel steel

The degree of impact of internal flaws on the structural strength of parts depends on a number of factors, such as:

- product operating conditions;
- product loading conditions;
- type and location of defects in the product

Internal flaws in the cast parts of RRS can have the character of both volume defect (pores, shells, non-metallic inclusions) (Fig. 1, *a, c*), and planar flaws (cracks, segregations, etc.) (Fig. 1, *b*). Volume defects reduce the cross-sectional area of the part, due to which its strength properties are lowered. Planar flaws breach the continuity of metal, concentrate stresses at the edges, and significantly reduce the strength. Moreover, the flatter shape of the defect, the greater its influence is. In this case, the decrease in strength can be significantly greater than from volume defects. The shape of the defect has the greatest impact at the alternate loads, which often refers to dynamically loaded parts of the RRS underframe.

The defect oriented perpendicularly to the direction of tensile loads reduces the component life to the maximum. The worst case is the location of the defect in the most loaded area of the part. If the direction of the planar flaw is close to or coincides with the direction of tensile forces, then the strength of the part practically does not decrease.

To identify internal flaws, vital cast parts of RRS are subjected to ultrasonic pulse-echo control when releasing from production. However, classical methods based on comparing the working value of the amplitude of the echo signal to the standard value of this parameter make it possible to determine whether the defect is admissible or not; but they do provide the type and orientation of the defect in the part. Therefore, an increase in the validity and informativity of such a control is required.

Materials and Methods. The pulse-echo technique [1–7] of the ultrasonic non-destructive testing is based on the registration of echo signals from defects in the part volume. In this case, the sent (probing) pulse *I* and pulse *III* reflected from the opposite surface (bottom) of the product (bottom signal) are observed on the screen of the ultrasonic flaw detector. If any defect in the body of the product, pulse *II* (an echo signal reflected from the defect) is observed (Fig. 2.). The arrival time of pulses *III* and *II* is proportional to the thickness of the part and to the distance from the input surface of the ultrasonic wave to the defect. If the control circuit is compatible (Fig. 2), the transmitter and receiver are operated by a single converter. If the circuit is independent, two different converters are used.

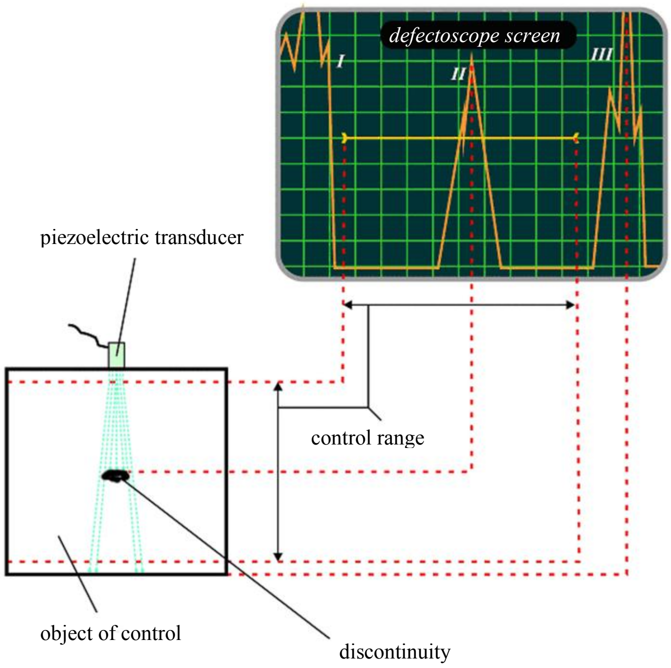


Fig. 2. Ultrasonic testing circuit by pulse-echo technique

The admissibility of discontinuities is evaluated through comparing the amplitude of the echo signal from the defect to the amplitude of the echo signal from the standard reflector in the shop reference sample (equivalent sensitivity), or to the reference sensitivity level tuned on the standard sample (measure) CO-2 (Fig. 3) [8] with the addition of a gain factor (conditional sensitivity) [9].

Fig. 3. CO-2 measure

The shop reference sample is made from a product identical to the object of control in terms of material, acoustic properties and geometry. Various types of artificial reflectors imitating real defects are used as standard reflectors. A flat-bottomed cylindrical reflector got the most widespread use under the control of RRS parts. This is a standard reflector in the form of a flat bottom of a cylindrical hole oriented perpendicularly to the cylinder axis.

Research Results. To determine the defect shape under the manual ultrasonic testing of RRS cast parts, a two-frequency defectometry method was proposed [10–13]. Its essence is as follows:

1. When an echo signal from a defect is detected in the monitoring object, the following characteristics are measured at the ultrasonic wave frequencies of 2.5 MHz and 5.0 MHz:

- amplitude of bottom signals;
- amplitude of the echo signals from the defect;
- distance from the wave input surface to the reflective surface of the defect.

2. The defect shape factor is calculated using the following dependence:

$$v = N_{\text{деф}2.5} - N_{\text{деф}5.0} + N_{\text{д}5.0} - N_{\text{д}2.5},$$

where $N_{\text{деф}2.5}$ is the amplitude of the echo signal from the defect at the frequency of the ultrasonic wave 2.5 MHz, dB; $N_{\text{деф}5.0}$ is the amplitude of the echo signal from the defect at the frequency of the ultrasonic wave 2.5 MHz, dB; $N_{\text{д}2.5}$ is the amplitude of the echo signal from the defect at the frequency of the ultrasonic wave 5.0 MHz, dB; $N_{\text{д}5.0}$ is the amplitude of the bottom signal at a frequency of an ultrasonic wave of 5.0 MHz, dB.

3. The boundary value of the shape factor of an ideal planar point defect is calculated from the formula:

$$v_{\text{пл.т.}} = 20\lg\left(\frac{\lambda_{5.0}^2 \cdot S_{a2.5}}{\lambda_{2.5}^2 \cdot S_{a5.0}} \cdot \left(\frac{\lambda_{2.5} \cdot S_{a5.0}}{\lambda_{5.0} \cdot S_{a2.5}}\right)^{\frac{x}{x_{\text{д}}}}\right),$$

where: $\lambda_{2,5}$, $\lambda_{5,0}$ is the ultrasonic wavelength at a frequency of 2.5 MHz, mm, and 5.0 MHz, mm, respectively; $S_{a2,5}$, $S_{a5,0}$ is the area of the piezoelectric transducer at a frequency of 2.5 MHz, mm^2, and 5.0 MHz, mm^2, respectively; x is the distance from the surface of the input wave to the reflective surface of the defect, mm; $x_{\text{д}}$ is the distance from the wave input surface to the bottom surface, mm.

4. The boundary value of the shape factor of an ideal volume point defect is calculated from the formula:

$$v_{\text{об.т.}} = 20\lg\left(\frac{\lambda_{5,0} \cdot S_{a2.5}}{\lambda_{2.5} \cdot S_{a5.0}} \cdot \left(\frac{\lambda_{2.5} \cdot S_{a5.0}}{\lambda_{5,0} \cdot S_{a2.5}}\right)^{\frac{x}{x_{\text{д}}}}\right).$$

5. The boundary value of the shape factor of an ideal planar extended defect is calculated from the formula:

$$v_{\text{пл.пр.}} = 20\lg\left(\frac{\sqrt{\lambda_{5.0}^3} \cdot S_{a2,5}}{\sqrt{\lambda_{2.5}^3} \cdot S_{a5,0}} \cdot \left(\frac{\lambda_{2.5} \cdot S_{a5.0}}{\lambda_{5,0} \cdot S_{a2.5}}\right)^{\frac{x}{x_{\text{д}}}}\right).$$

6. The boundary value of the shape factor of an ideal volume extended defect is calculated from the formula:

$$v_{\text{об.пр.}} = 20\lg\left(\frac{\lambda_{5,0} \cdot S_{a2.5}}{\lambda_{2.5} \cdot S_{a5.0}} \cdot \left(\frac{\lambda_{2.5} \cdot S_{a5.0}}{\lambda_{5.0} \cdot S_{a2.5}}\right)^{\frac{x}{x_{\text{д}}}}\right).$$

7. The type of point defect is determined as follows:

a) the defect is considered planar if the following condition is satisfied:

$$\nu \le v_{\text{пл.т}} + 0.3\left|v_{\text{об.т}} - v_{\text{пл.т}}\right|;$$

b) the defect is considered volume if the following condition is satisfied:

$$\nu \ge v_{\text{об.т}} - 0.3\left|v_{\text{об.т}} - v_{\text{пл.т}}\right|.$$

If both conditions are not satisfied, the point defect is not planar, however, it is not ideally volume either.

8. The type of extended defect is determined:

a) the defect is considered planar if the following condition is satisfied:

$$\nu \le v_{\text{пл.пр}} + 0.3\left|v_{\text{об.пр}} - v_{\text{пл.пр}}\right|;$$

b) the defect is considered volume if the following condition is satisfied:

$$\nu \geq v_{\text{об.пр}} - 0.3\left|v_{\text{об.пр}} - v_{\text{пл.пр}}\right|.$$

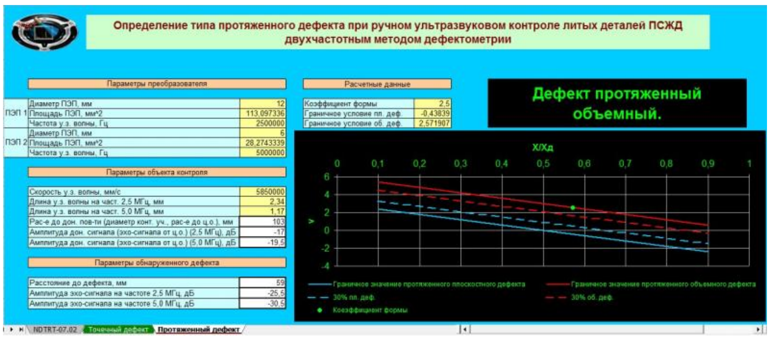
If both conditions are not satisfied, the extended defect is not planar, however, it is not ideally volume either.

In the methodology for determining the type of both point and extended defects, a confidence interval of 30% is assigned for the discrepancy between the actual and boundary values of the shape factor of volume and planar discontinuities. This interval is obtained empirically as a result of the experimental studies; it considers the methodological and instrumental measurement errors.

A special software product NDTRT-07.04-L is developed for fast automated use of the dual-frequency defectometry method for the ultrasonic testing of cast parts of RRS. Fig. 4 shows its work windows.

a)

b)



c)

Fig. 4. Software product NDTRT-07.04-L windows:
a) start screen; *b*) “Planar defect” window; c) “Volume defect” window

Work with the software product NDTRT-07.04-L is carried out as follows:

1. Input the following data at wave frequencies of 2.5 MHz and 5.0 MHz in the relative window:

• amplitudes of bottom signals;
• distance from the wave input surface to the defect;
• amplitude of the echo signals from the defect;
• distance to the bottom surface.

2. Input the type of defect and the diagram of the dependences of the boundary conditions and the confidence interval on the ratio of the distance to the defect to the distance to the bottom surface in the relative window.

Discussion and Conclusions. Using manual ultrasonic testing, the acceptability of internal defects of cast parts of RRS is determined; however, it is not possible to determine the type of defect: volume or planar. At the same time, the type of defect significantly affects the structural strength of the product. Planar defects are more dangerous than volume ones, especially under the dynamic loads during RRS movement. Thus, a different approach is required to evaluate the acceptability of different types of defects.

The authors have proposed a dual-frequency method of defectometry, which provides the determination of the defect type under the manual ultrasonic testing of cast parts, as well as an increase in the validity and informativity of the control results. High reliability of the dual-frequency defectometry method was confirmed by the results of experimental studies [14].

For an express automated use of the dual-frequency defectometry method, the software product NDTRT-07.04-L was developed.

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Authors:

Kireev, Andrey N.,
associate professor of the Railway Transport Department, Lugansk National University named after Vladimir Dahl (20a, Molodezhny bl., Lugansk, 91000, Ukraine), Cand.Sci. (Eng.), associate professor,
ORCID: https://orcid.org/0000-0002-7548-3348
lifter_23@mail.ru

Sklifus, Yaroslav K.,
associate professor of the Traction Rolling Stock Department, Rostov State Transport University (2, Rostovskogo Strelkovogo Polka Narodnogo Opolcheniya sq., Rostov-on-Don, 344038, RF), Cand.Sci. (Eng.), associate professor,
ORCID: https://orcid.org/0000-0002-8471-4697
yaroslav.sklifus@mail.ru

Kireeva, Margarita A.,
teaching assistant of the Railway Transport Department, Lugansk National University named after Vladimir Dahl (20a, Molodezhny bl., Lugansk, 91000, Ukraine),
ORCID: https://orcid.org/0000-0001-7463-2682
lifter_23@mail.ru