The acoustic waves propagation laws in the force-fit connections for test of the interference fit

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Abstract. Calibrated tuning samples of compression joints with an interference of 29, 72, 126 μm were developed and manufactured. The samples were tested by ultrasonic control with a pulse echo technique. The coefficients of reflection of longitudinal waves from the boundary of the parts of different values of interference are experimentally determined under real operating conditions at frequencies of 2.5, 5 and 10 MHz.

1. Introduction
One of the most common ways to install bearings on technical objects and vehicles includes stationary detachable joints created by interference fit. The violation of the manufacturing technology and operating modes, defects of the parts to be connected can reduce the values of interference fit (the difference between the diameter of the shaft and the hole before assembling). The weakening of the interference fit is one of the most common causes of the rotation of the inner ring of the bearing, and subsequently its jamming and destruction. According to the data of car repair companies, the failures of the axle blocks of rolling stock in operation are in the second place by the frequency of freight cars stopping (25%) and their subsequent repairing for 12 months of 2017 on railway transport. Malfunctions of the axle boxes due to the common causes of the occurrence are distributed as follows: heating (77%), defects (17%), axle shift (6%). Thus, the internal defects of the axle boxes (83%) are among the most common reasons for failure in operation, and the problem of checking the tightness of the bearing inner rings on the neck of the shaft is rather vivid. The task of monitoring joints planted with interference has been repeatedly considered in research papers [1–4], but the variety of such compounds requires a correction of the approach to it in each case.

2. Formulation of the problem
Currently, the interference fit bearing inner rings is determined indirectly by the difference in the results of measurements of the inner diameter of the ring and the outer diameter of the axis before mounting in a free state. The reliability of the measurements is influenced by: the difference in the temperature of the parts, the surface condition, the ovality and the conicity. Pressing the rings on the shaft leads to the occurrence of scoring of the neck of the axle, therefore, when repairing the axle boxes of wheel pairs, it is allowed not to remove the bearing inner rings of bearings provided that the interference is checked. Currently, the most common method of control is checking the density of interference fit on the rotation using specialized devices. The drawbacks of this method include the possibility of damaging the raceway of the bearing ring, leading to its rejection, and the low reliability of the method which is associated with the influence of the human factor. The railways use specialized measuring blocks for checking the tightness of the bearing rings on the neck of the axis: PS-219 (No. 22100-01 in the State Register of Measuring Instruments) [5] and
UDS1-SYN (No. 21975-09 in the State Register of Measuring Instruments). The principle of the UDS1-SIN device is to measure the amplitude-frequency characteristic, the decay time and the intensity of repeatedly reflected ultrasonic pulses. A special program sets the operating modes of the controller, collects, processes and displays the data of the interference fit [6]. The PS-219 is based on measuring the time interval, during which a pendulum colliding with a ring-mounted ring performs a predetermined number of oscillations. Planting (interference) is considered normal if the measured time interval is greater than the set limit value. These instruments were designed to be used together with the "hot" ring-to-axle interference fit technology, where the heated ring is freely mounted to the desired position on the axis, and the fixed connection is formed after the temperature of the parts to be connected is adjusted to an interference fit of 30 to 65 μm. At present, a cold press fit technology is applied in the rolling-stock sector, where the ring is mounted on the axle using a press with a difference in the diameters of the axis and rings from 45 to 130 microns. At the same time, the surfaces of the joined parts are rubbed, which, as experience of using devices in production shows, reduces the reliability of the results.

A separate line of research is related to the use of the influence of the landing density on the propagation velocity and amplitude of ultrasonic waves. Several methods are considered, in one of which [7] two types of waves come into action in the bearing ring and the value of the interference fit is judged by the difference in propagation times. Transverse waves propagate from the radiator to the receiver and are reflected from the cylindrical interface of the parts, and the inhomogeneous wave propagates along the outer cylindrical surface of the ring. However, fluctuations in temperature, chemical composition and structural state lead to the fact that the measurement error is comparable to the measured values of stresses arising in the rings, due to elastic deformation when planted on the axis.

The second method was carried in such a way that ultrasonic vibrations are excited by a combined ultrasonic transducer whose acoustic axis is oriented in the direction of the cylindrical aperture under the fastening element, signals reflected from the first and second contact paths along the beam are recorded. The value of the interference is determined by the difference in the amplitudes of the received signals. This method is aimed at controlling the quality of compact joints with interference with an air gap between parts, such as bolted and riveted joints.

In this paper, we investigate the influence of the interference fit of the bearing inner rings on the shaft (axis) after press fit on the pattern of propagation of acoustic waves through the joint boundary to assess the possibility of controlling the detachable fixed cylindrical joints manufactured by the press fit method.

3. Theoretical aspects
The connection with the interference is the interface between the three media (figure 1): the material of the ring - the gap between the ring and the shaft - the material of the shaft. A gap of thickness h between the ring and the shaft is completely or partially filled with lubricant. For acoustic control methods, the thickness of the gap serves as the informative parameter, which determines the acoustic properties of the medium interface and characterizes the tightness of the controlled connection.
Figure 1. The scheme of interaction of the ultrasonic wave pulse with the ring-shaft boundary and the outer boundary of the ring

In the case of pulsed emission of acoustic waves $A_0$, a series of acoustic pulses ($A_1, A_2, \ldots, A_n$) as shown in Figure 1 which are repeatedly reflected from the interface and the ring insertion surface by the receiving transducer is captured. In the plane model, the amplitude of the $n$th pulse is proportional to the amplitude of the $(n-1)$th pulse and depends on the damping ratio and the reflection ratios from the input surface $R_c$ and the media interface $R_g$ according to the law [9]:

$$A_n = A_0 \cdot (R_c \cdot R_g \cdot e^{-\gamma \cdot 2 \cdot l})^n$$

where $A_n$ is the amplitude of the signal reflected $n$ times from the interface, rel. units; $A_0$ is the amplitude of the emitted signal, rel. units; $\gamma$ is the attenuation coefficient, $m^{-1}$; $R_c$ is the reflection coefficient from the input-boundary surface – the ring-air material; $R_g$ is the reflection coefficient from the ring-gap-shaft boundary; $l$ is the thickness of the ring, m.

In relative logarithmic units, dB, expression (1) takes the form:

$$N = 20 \cdot \log \frac{A_n}{A_0} = \alpha \cdot n$$

where $\alpha$ is a ratio of proportionality, which depends on the damping ratio, the path length of the ultrasonic wave in the ring, and the reflection rate from the input surface:

$$\alpha = 20 \cdot \log(R_g) + 20 \cdot \log(R_c \cdot e^{-\delta / \lambda_2})$$

Expression (2) relates the coefficient of proportionality of the amplitude and the number of the pulse with the reflection coefficient from the interface of media, which in turn depends on the thickness of the layer $h$ [10]:

$$R_g = \frac{(z_1 - z_2)^2}{4 \cdot \text{ctg}(\frac{2 \pi h}{\lambda_2}) \cdot \text{ctg}(\frac{z_1 + z_2}{z_1})}$$

where $z_1$ is the acoustic resistance of the material of the ring, equal to steel 46 MPa·s/m; $z_2$ is the acoustic resistance of the material of the gap medium, taken for an oil equal to 1.3 MPa·s/m, the acoustic resistance of the air – 0.00043 MPa·s/m; $\delta$ is the width of the gap, m; $\lambda_2$ is the wavelength of the acoustic wave in the second material, m.

Thus, the experimentally determined proportionality factor $20 \cdot \log (R_g)$ of the dependence of the amplitude of the echo pulse $N$ on the momentum number $n$ in expression (2) with the help of expression (4) makes it possible to estimate the thickness of the contact layer of the gap, which, in other words, characterizes mechanical stress in the parts to be connected.

4. Experimental results

The experiments were carried out on specially designed samples with a known interference fit. Samples were made from a shaft and a bearing ring 36-42726E2M in accordance with GOST 18572-
2014. Calibration is performed before the rings are placed on shafts in FGUP SNIIM with an error of no more than 1.5 μm (Certificate of calibration No. 10-1291 dated August 1, 2017). The conicity of shafts and axes does not exceed 2.0 microns, ovality doesn’t exceed 0.5 microns. The roughness of the landing surfaces of the bearing and shaft rings did not exceed the standard value \( R_a = 1.25 \mu m \). The rings and shafts were selected in such a way as to provide minimum, maximum and medium tension with a difference in the diameters of the axis and bearing inner rings: 29, 72 and 126 μm.

In the manufacture of tuning samples, they tried to implement the technology used in car repair depots if it was possible. Inside, the rings were preliminarily worn on the shafts by the method of thermal fit for 20% of the length. For this purpose, the EMPI-1 grease was applied to the mating surfaces of the parts. The inner rings were heated to a temperature of 120 °C, and the shafts were cooled to -15 °C. At the last stage, the joints (figure 2) were formed on the press with a force of 400, 800, 1500 kN, respectively.

![Figure 2. Appearance of adjusting sample of connection with interference fit](image)

![Figure 3. Scheme of test of stationary detachable connection of a ring with an axis by an pulse echo technique](image)

The studies of the density of rings on the neck of the axis were carried out by pulse echo technique. Direct combined converters with an operating frequency of 2.5, 5.0 and 10 MHz were used for the excitation and reception of ultrasonic waves. (figure 3). The converters were connected to the universal echo-pulse flaw detector USD-50 (No. 52657-13 in the State Register). The connection of the ring to the axle was radially observed from the rolling surface of the bearing ring. A series of echo pulses, re-reflected from the inner and outer cylindrical surfaces of the bearing rings, were registered. The smallest uncertainty in the amplitude of the re-reflected pulses at various points on the ring surface was observed when monitoring direct PES with an operating frequency of 5 MHz. All the results of further measurements are given for a PET operating at a frequency of 5 MHz. Dependences of the amplitudes of echo pulses, expressed in dB, on their ordinal number (figure 4) are satisfactorily described by a linear relationship with a correlation ratio greater than 0.95. The method of least squares is used to calculate the proportionality ratios for different values of the interference (figure 5, item 1). The lowest slope of the dependence is observed for the free bearing ring - 1.9 dB.

5. Discussion

The oscillation damping, the input surface deviation from planeness, the ultrasonic beam divergence are characterized by a polar pattern which has an influence on the slope of the dependence between the echo amplitudes and their serial number for the free ring (0 mm). The difference between the proportionality factor for joints with interference and for a free ring is directly proportionally to the logarithm of the reflectance for the ring-gap boundary \( R_g \):

\[
\text{Lg}(R_g) = \frac{\sigma_2 - \sigma_0}{20}
\]
where $\alpha_\Delta$ and $\alpha_0$ are proportionality factors (slope) of the dependence between the echo amplitudes and their serial number for the reference blocks with an interference fit $\Delta$ and for a free ring, respectively.

The reflectance from the boundaries in the reference blocks is determined by the expression (5):

$$R_g(29 \mu m) = 0.66, \quad R_g(72 \mu m) = 0.58, \quad R_g(126 \mu m) = 0.62$$

The average design thickness of the gap, filled with industrial oil, in the reference blocks based on (4) and (5) is:

$$h(29 \mu m) = 0.27, \quad h(72 \mu m) = 0.19, \quad h(126 \mu m) = 0.23$$

Figure 4. The chart of the dependence between the echo amplitudes and their serial numbers:

1 – free ring, 2 – interference fit is 29 $\mu$m, 3 – 126 $\mu$m, 4 – 72 $\mu$m

The obtained values of the thickness of the gap with the ointment correspond to their roughened surface for the ring which is less than $Ra = 1.25 \mu m$, and for the shaft - $Ra = 0.8 \mu m$. The estimated thickness of the gap when it is filled with air is less than $10^{-6} \mu m$, which significantly exceeds the surface roughness.

The main change of the proportionality factor (3) and, respectively, of the reflection coefficients (6) occurs in the range of the interference fit range from 0 to 30 $\mu$m (see figure 5). The test results of real connections of rings with axles with a weak interference by the ultrasonic method in the car repair depot conditions are shown in figure 5, pos. 2. The part of the connections has a proportionality factor close to the proportionality factor for the free ring, which may be due to the difference between the shape of the axis and the cylindrical: out-of-roundness and taper. An indirect confirmation of this fact is the standard deviation in a series of connections’ measurements. This deviation is always higher with a weak interference fit than the standard deviation for the connections with a strong interference fit.
Figure 5. The chart of the dependence between the proportionality factor and the interference fit: 1 – reference blocks, 2 – real objects

6. Conclusions
A technique for measuring the reflectance from the force-fit connection boundary based on a comparison of the proportionality factor between the echo amplitude and the serial number on the controlled connection and the free bearing ring has been proposed and implemented. The reflectance of 0.66, 0.58 and 0.62 on reference blocks with the interference fit of 29, 72 and 126 μm was experimentally established. The calculated oil contact layer thickness of the connection is 0.27, 0.19 and 0.23 mm, which corresponds to 20-30% of the surface roughness. The greatest gradient of the reflection coefficient on the reference blocks corresponds to the interference fit range from 0 to 30 μm.

In actual service conditions, the deflection of the axis surface from the cylindrical shape has a significant effect on the connection gap thickness and on the acoustic characteristics of the connection. Consequently, the ultrasonic method can be used to assess the closeness of parts to be fit and detect the out-of-roundness and taper.

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