Press-fit joints study by multiangle ultrasonic sounding method

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Abstract. In the article the authors consider the problem and the way of press-fit joints quality quantitative estimation with an ultrasonic echo-impulse method. It is shown that the reflection coefficient is the general characteristics of press-fit joint quality rather its load carrying capacity defined by the maximum rotation moment transmitted by the press-fit joint, because it is bound with the normal stresses appearing on the joint surfaces. The equation for calculation of the coefficient of ultrasound reflection from the interference area of a joint by echo-impulse amplitudes measured from the quill cylinder and from a joint is received. Peculiarities of the research procedure are accentuated and described. The peculiarities allow receiving exact estimation of press-fit joints quality by a non-destructive method either on the localized areas of the interference or the estimation of an averaged value around the joint during multiangle study of the object on different directions in the definite ultrasonic sounding plane. Special attention is paid by the authors to the possibility and practicability of automation of the process of control on the basis of the multiangle ultrasonic sounding method in order to improve the joint quality studying process.

1. Introduction

During development of pressure couplings study methods it is necessary to solve either the problem of getting the reliable information about the fit-joint location and it’s strain-stress state character or the problem of fit-joint interference local and average value determination with the aim of estimation and reliable prognosis of the construction life cycle[1-3].

It is known [4-6] that the accuracy of the geometric parameters of pressure couplings comes from the accuracy of manufacturing, precision of shape and mutual arrangement of surfaces forming the coupling. Inaccuracies (deviation) of the form and arrangement of surfaces from the nominal values arise in the process of parts machining due to inaccuracies and deformation of the machine, tools and fixtures, deformation of the machined part, heterogeneity of the machined part material, etc. In connection with the distortion of a given geometric profile of the joint contact surface its strength decreases and the precision of centring is destroyed, operational and technological parameters of the coupling are reduced. With increasing loads, angular velocity, operating temperatures, typical for modern machines, the negative impact of these factors on the performance of the products based on pressure couplings increases. Thus, ensuring of the maximum precision of the form and arrangement
of surfaces during production, high accuracy of centring during assembly are the main factors of machines upgrading.

2. Main part

Considerable number of researches devoted to the problems of non-destructive testing of pressure couplings [7-9]. However, to forecast the service life of products based on pressure coupling only the methods of statistical analysis of accumulated data were used so far and, in case of ultrasonic methods application the possibility of "qualitative" assessment of the couplings was only talked about [10-12].

For example, in highly respected and sizeable reference manual on non-destructive testing, published under the editorship of academician V. V. Klyuev [10] it’s basically only mentioned of some test trials of solving this problem and there are references to just two or three works in this field.

In particular, in [11,12], which is the most "advanced" in this field and performed more than 20 years ago, authors examine a method of assessing the quality of press-fit joint of a cylindrical ring with a shaft (having a hole, thick-wall tube pipe), based on the detection of ultrasonic pulse-echo signal, when the coupling quality is estimated by the ratio of pulse-echo from the interference fit and the inner surface of the tube in grades:

1. Pulse-echo from the interference fit place is a lot less then the pulse-echo from the inner surface of the pipe: the pressure coupling is very good.
2. Pulse-echo from the interference fit place is less then the pulse-echo from the inner surface of the pipe: the pressure coupling is good.
3. Pulse-echo from the interference fit place is more then pulse-echo from the inner surface of the pipe: the pressure coupling is bad.
4. Pulse-echo from the interference fit place is a lot more then pulse-echo from the inner surface of the pipe: the pressure coupling is very poor.

The technique of pressure couplings quality estimation proposed by the authors of [11], in our opinion, is complex, unreliable and almost impossible, especially when the ring is placed on a solid shaft, since in these cases there is no pulse-echo from the inner surface of the pipe which is used by the authors of work [11] for comparison with the pulse-echo from the interference fit. In the work [11] it is also pointed out that quantitative assessment of pressure couplings quality is additionally hampered by the fact that the amplitudes of the compared echo-pulses depend on the radius of curvature of the ring, the radius of curvature of the shaft, on the path of ultrasound in the object of control, and a number of other factors which were not taken into account in the experiment described in the published work [11]. Other information about methods and means of pressure couplings non-destructive testing was not found in literature by the authors of this article, although the need of pressure couplings control is obvious, as well as inspection of welded and other junctions.

With the aim of providing opportunities for getting joints with "guaranteed" interference, development of pressure couplings quality non-destructive testing, control automation, the authors of this work develop the new method for pressure couplings study with multi-angle ultrasonic sensing. The developed method of interference fit quality assessing provides the possibility to quantify the pressure couplings quality, since the measurement technique provides the account of all factors, which were not considered in the [11]. Due to the fact that for most of pressure couplings used in machine building, the ratio of joint length to the shaft diameter is recommended to be in the range of 0.5 to 2.0 [4] we studied pressure couplings received by fitting cylindrical steel rings to the solid shafts by thermal method [13,14] of the following dimensions: outer diameter of the covering part (the ring) – \(d_2 = 93\) mm; inner diameter of the covering part (the ring) – \(d_1 = 50\) mm; the diameter of the covered part (the shaft) – \(d_1' = 50 + \Delta,\) mm; joint length \(l = 50\) mm; ring and shaft material– steel 45. In accordance with GOST 24643-81 the surfaces of pressure couplings are executed with high precision by finish turning with the longitudinal feed. Roughness of mating surfaces in accordance with the regulations of GOST 9378-75 and GOST 2789-73 which are fully conformed to international standards (ISO), has a value of: the parameter \(Ra\) is in the range of 3.2 to 6.8 \(\mu m\), and the parameter \(Rz\) is in the range of 12.8 to 25.6 \(\mu m\), the offset of the shaft and the ring hole diameters are of \(8 \pm 10\)
µm. Tested objects: - steel bushing (the quill) and five samples of pressure coupling made by the method of thermal assembly with interferences: Δ=30 µm, 50 µm, 80 µm, 100 µm, 140 µm. In the experiment the ultrasonic flaw detector DUK-66 was used; the radiation and reception were provided at a frequency of f = 5 mHz using the piezoelectric transducer P111-5-KN [15].

During experiment it was taken into account that the oscillograph charts of the reflections of ultrasonic (US) signal from the quill surface on the metal-air boundary, and from the layer between two mating parts, represent a spectrum of multiple reflections. Therefore, the actual oscillograph charts obtained with the aid of the flaw detector DUK-66 look like in the figure 1 is shown.

![Figure 1. The oscillograph chartes of reflections of the ultrasonic signal.](image)

The weakening of the recording echo-pulse is influenced by the following factors: the quality of the fit joint (interference), divergence of the ultrasonic beam (radiation pattern), the attenuation, scattering and energy loss on the contact of sensor-detail [16-20]. However, given the fact that either the quill or the pressure couplings are made of the same material, and all other factors during the measurements are the same for all samples, the decrease of energy of the reflected echo-pulse (amplitude) can be considered depending only on the magnitude of the interference Δ of the coupling.

The pass of the ultrasonic impulse through the stress-strain layer is characterized by the coefficient of transparency D* of the joint

\[ D^* = 1 - R^* , \]  

and the reflection coefficient - R*. At that, the ratio of the energy (amplitude) of the reflected wave to the energy (amplitude) of the incident one is called the reflection coefficient by energy \( R^* \) (by amplitude \( R_{\text{a}}^* \)) and can be expressed in the form

\[ R^* = \frac{E}{E_i} = \frac{J}{J_i} ; \quad R_{\text{a}}^* = \frac{U}{U_i} . \]  

where: E – the energy; J - the sound intensity; U – the amplitude.

These rules are always executed, despite the fact that the specific acoustic impedance is a real value, equal to the environmental wave resistance, only for unlimited environments [8,21].

After reflection the ultrasonic wave propagates as if it comes from a point of the boundary surface, in which there is a reflection under the angle equal to the angle of incidence. If the reflective surface has curvature, the beam of ultrasonic waves starts to converge or diverge after reflection in the same way as in optics. In parts of cylindrical shape a divergent spherical wave is formed with a radiation pattern width of \( \sim 8\times10^5 \), so the ratio \( Ur/Ue \), and, consequently, \( D^* \) and \( R^* \) (both in the quill and pressure coupling), are affected not only by the wave divergence but also by the processes of attenuation and diffusion on the metal structure.
In contrast to qualitative assessments according to the method described in [11], the influence of these factors on the quality of the fit, in our experiment, is estimated by the ratio of measured amplitudes of falling \( U_1 \) and reflected \( U_2 \) ultrasonic waves from the examined region \( U_1/U_2 \) on the quill and by the ratio of the amplitudes of the falling \( U_1' \) and reflected \( U_2' \) ultrasonic waves from the interference fit-joint \( U_1'/U_2' \). The difference of \( U_1/U_2 \) from \( U_1'/U_2' \) characterizes the quality of the fit and can be quantified.

Measuring of \( U_1 \), \( U_2 \), \( U_1' \), \( U_2' \) values in decibels is carried out with flow detector. The developed technique intends the displaying of measured 1st echo-pulse \( U_1 \) taking 1/3-1/2 of the flow detector screen with the attenuator, recording the location of the attenuator in decibels (db), then the displaying of the amplitude of the 2nd echo-pulse to the same level using attenuator and recording its location in db. The difference between the recorded attenuator locations characterizes \( U_1/U_2 \) in db and, as a consequence, the ratio

\[
\frac{U_1}{U_2} = \frac{U_1'}{U_2'}\quad (3)
\]

For example, \( N_1 = 7 \) db is the characteristic of the \( U_1/U_2 \) ratio, and \( N_2 = 12 \) db is the characteristic of the \( U_1'/U_2' \) ratio. Then \( N_2 - N_1 = 5 \) db is the characteristic of the fit-joint quality and indirectly expresses the quantitative relationship between normal stresses in fit-joint areas and a reflection coefficient of ultrasonic waves in these areas. The figure shows the echograms obtained for the quill (Figure 2, a) and an interference fit (Figure 2, b).

![Oscillograph charts obtained with the use of the digital oscilloscope GDS-840C of echopulses at various values of interference Δ: a – the quill (Δ=0); b – a pressure coupling (Δ=50 µm)](image)

The sounding ultrasonic pulse was injected through the contact liquid into the outer lateral surface of a pressure coupling quill. On the quill surface a series of multiple "rereflections" of the sounding pulse is observed (Figure 2, a). In the case of a pressure coupling the ultrasonic wave emitting in the radial direction reflects from the fit-joint place (the mating surface) and reaching the contact plane of the test object with the piezoelectric transducer is recorded by the flow detector as the first echo-pulse. Further, "rereflecting" from the quill outer surface the first echo-pulse "goes" into the object along the same path (follows the sounding pulse), and then again reflects from the fit-joint place (the mating surface) and gives the second echo-pulse (see Figure 2, b), etc. When the thickness of the quill \( h = (d_2-d_1)/2 < d_1' \), where \( d_1' \) is the diameter of the shaft, we’ll see on the screen of the flaw detector series of damped echo-pulses containing not less than 3 "rereflections" from the fit-joint place.

To calculate the values of \( U_1 \) and \( U_2 \) is almost impossible, as they depend on many factors that were listed above. The technique of pressure couplings quality control is the measurement of the
amplitudes of two neighbouring echo-pulses from the quill, then from the tested fit-joint and calculation according to formula (3) of the reflection coefficient from the fit-joint place - R*. Note that for weak interference Δ→0 the R*→1, but when the interference is too much, when air gap in the place of interference tends to zero due to plastic deformation of the surface imperfection the R*→0. That is, limiting values of the reflection coefficient from the fit-joint place are 0<R*<1. Since for the flaw detector amplifier amplitude characteristics non-linearity the attenuator is commonly used, then the echo-pulse amplitudes ratios which are part of the (3) expression can be found experimentally with a sufficiently high accuracy. It seems to us that such connection allows to give an accurate enough valuation of the interference-fit quality by ultrasonic non-destructive method - both at the singular localized zones of the fit-joint, and the averaged value around the coupling circumference with multi-angle study of the object in various directions in a given zoning plane. Moreover, with the known interference fit surface area, the experimental data allow us to calculate the average normal pressure force acting in the coupling, and with the known radius of the fit-joint cylindrical surface and the friction coefficient also the allowable torque by which the coupling can be loaded [12]. The measurement of the local values of the normal pressure of the fit-joint will allow to evaluate the possible interruptions to the fit-joint manufacturing process and to correct the process, if it’s necessary.

A very important result for us in this scheme of the pressure coupling studies is in contrast to the methodology outlined in [11] to enable quantitative quality evaluation of pressure couplings by the same ultrasonic echo-pulse method.

When planning the experiment, with the aim of identifying the dependence of the pressure joint stress-strain layer reflection coefficient R on the influencing factors (e.g., size, radiation pattern of piezoelectric transducer, roughness, unevenness, connections of contact surfaces, etc.) measuring is carried out with intervals of 22°30’ along the circumference of the coupling cross section. As it’s shown in the theory of measurements [22] this pitch allows to get the area of measured parameters optimal values with a high enough reliability. However, when analysing physical processes of echo-pulse method and possibilities of its use for study of pressure couplings it’s should also be taken into account the Abbe principle according to which the minimum measurement inaccuracies occur if controlled geometric element and the element of comparison are on the same line - the line of measurement [23]. When measuring we get the dependence of the reflection coefficient R from the interference. The data obtained in accordance with the scheme of measurements, are recorded in the form of a control sheet.

Instrumental inaccuracy of amplitude of damped reflected ultrasonic signals oscillations in decibels can be estimated to be about 5% while the statistic measurement inaccuracy which is characterized by average value (expectation function) and mean square deviation can be either considerably less or more than the instrumental one. It depends on the interference value and the value of impact of accidental factors influencing the measuring result.

The difference between the fixed attenuator situations characterises the ratio of the multireflected pulse amplitudes taken from the quill U1/U2 and from the pressure coupling U1'/U2' in db, and their ratio characterizes the dependence of the coefficient of reflection from the fit-joint place R*, in accordance with the formula (3). In this regard, for greater visualization, it seems to us to be useful to display the results in the form of round diagrams showing the weakening of the multireflected waves N* depending on the interference at different angular directions of input and propagation of ultrasonic waves while changing the angle of the measurement point on the test object surface with an interval of 22°30 (figure 3).

Due to the fact that studied pressure couplings were of the "quill-shaft" type, such form of the results representation illustrates not only the fact that the reflection coefficient varies around the part cross-section circumference due to technological deviations during coupling manufacture, but also indirectly illustrates the visibility and thus the effectiveness of echo-pulse method application to control interference fit joints.
Figure 3. Round diagrams describing the features of attenuation of a signal reflected from a region of contact at the connection area of the shaft and quill surfaces in the middle section of a pressure coupling depending on the interference.

You should pay attention to the fact that when the interference is 140 microns the graph cannot be approximated to a circle, and it is clearly shown in the figure 4. In accordance with the elasticity theory when the forces exceed the yield limit (in accordance with the calculations for the studied samples, the yield limit should correspond to the stresses arising when the interference is 112 µm) in the studied sample inevitably the local plastic deformations occur because of the breakdown of intergranular bonds. Therefore, with high enough probability, we can assume that if the sample has local plastic deformations, the reflection coefficient of such areas, to some extent, differs from the reflection coefficient of the surface regions staying in elastic-stress state.

3. Conclusions
The described method of multi-angle ultrasonic sounding combines safety, cheapness and efficiency with a high informativeness, reliability and accuracy of the results.

Automation of the pressure couplings quality control process with the use of multi-angle method of ultrasonic sounding is possible and relevant because it eliminates the influence on the control result of the human factor and significantly improves the control performance.

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