DEVELOPMENT OF ULTRASONIC METHOD OF RADIAL CLEARANCE ASSESSMENT FOR BOLTED JOINTS AT RESTRICTED ACCESS

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Keywords: *bolted joint, clearance, quality, non-destructive testing*

Abstract

It is known, that the most weak place of a structure is the joint of elements. In a structure of an airframe quantity bolt and rivet joints may reach several hundred thousand. The creation of large radial clearance allows to increase the fatigue strength of such joints. In practice at assembly of airframes the part of joints, specially with restricted access, is made by hand. The human factor here can be exhibited. The joint without radial clearance can be a place of earlier beginnings of a fatigue crack. Therefore it is useful to have means permitting to make an assessment of quality of joins after assembly.

This paper considers the method of ultrasonic testing of radial clearance in bolt joints of elements, the design feature which one does not allow to apply the technique which has been given in paper [1]. The bolted joins of stringers with fittings in the cross-sectional joint of a wing of a passenger aircraft concern to such joints.

The research results of radial clearance influence on amplitude of echo-signal for different diameters of joints (6–12 mm) and materials of a fastening element (steel, titanium) are described. The dependencies between the value of radial clearance and the ultrasonic signal were determined on conical models of joints with clearance. The dependencies were obtained for echo-signal, reflected from first on a course of a ultrasonic beam of contact border and for echo-signal, passed in a material filling in a orifice and reflected from the second contact border. With the purpose of accuracy increase the assessment of joints quality is offered to execute on a difference of amplitudes of echo-signals obtained at reflection from both borders of a bolt join.

The results of inspection of specimens, modeling joints in the cross-sectional joint of a passenger aircraft wing are presented.

The scheme of application of the above-stated method is offered for service life tests of a passenger aeroplane and results of inspections are presented.

1 Introduction

It is known, that the most weak place of a structure is the joint of elements. Now at aircraft assembly bolted and riveted joints are predomonant and quantity of them may reach several hundred thousand. The creation of large radial clearance allows to increase the fatigue strength of such joints. There are some factors contributing to the increase of the service life of joints with clearance:

– with the increase of clearance in a ring-type zone, which directly adjoins the orifice contour, there comes a plastic condition (initial stresses). In operation the system of initial stresses is superimposed on the system of stresses caused by the external loading and there is a change of stresses that results in fatigue strength increase;

- strengthening the material around the orifice as a result a plastic deformation;
- reduction of joint motility and, as a result the decrease of fretting-corrosion.

In the paper [1] it was determined that the amplitude of ultrasonic echo-signal depends on value of the radial clearance in bolted joint and tends to decrease with the increase of the clearance. There was considered the ultrasonic testing scheme of a type of airframe joints which have rather good access and where the bolted joints with clearance are used. These are such joints as, for example, longitudinal junctions of wing panels. The ultrasonic echo-method was applied for estimating the quality of bolt joints in the full-scale panel of the passenger aircraft wing, delivered to TsAGI for service life tests and the reliability of the results of ultrasonic control was provided by the results of that fatigue strength tests.

In practice at assembly of airframes the part of joints, specially with restricted access, is made by hand and the human factor here can be exhibited. The joint without radial clearance can be a place of earlier beginnings of a fatigue crack. Therefore it is useful to have means permitting to make an assessment of quality of joins after assembly, specially joints with restricted access.

This paper presents the results of development research of non-destructive testing of radial clearance in bolted joints with restricted access.

2 Theoretical approuches

Analysis of testability of airframe junctions has allowed to select two main groups of joints with clearance. They are: "joint in panel" and "joint in stiffener (stringer)" (Fig. 1). Drawing a parallel with theory and practice of ultrasonic non-destructive testing, where the cylindrical defect models are widely used, the selected joint groups may be indicated as "vertical cylinder" ("joint in panel") and "horizontal cylinder" ("joint in stringer"). The possible schemes of ultrasonic testing of radial clearance in such joints are also shown in Fig. 1.

The first group of joints has been already investigated [1]. In this work the investigation of "joint in stringer" was carried out.

The phenomenon of elastic wave reflection on cylinder is well studied. When considering the shear wave reflection on cylinder the potential of mirrored reflect wave Ψ_{mr} may be determined as [2]:

$$\Psi_{mr} = \frac{b}{2r}\cos\frac{\theta}{2}R_t\frac{\theta}{2}e^{ik_t\left(r-2b\cos\frac{\theta}{2}\right)} \tag{1}$$

Where b – cylinder (orifice) radius; r – distance between the cylinder surface and point of shear wave input in testing element; θ – pitch angle of the shear wave on surface of cylinder (angle between the direction of the ultrasonic beam and the normal to the surface of cylinder); R_t – reflection coefficient; k_t – angle wave number.

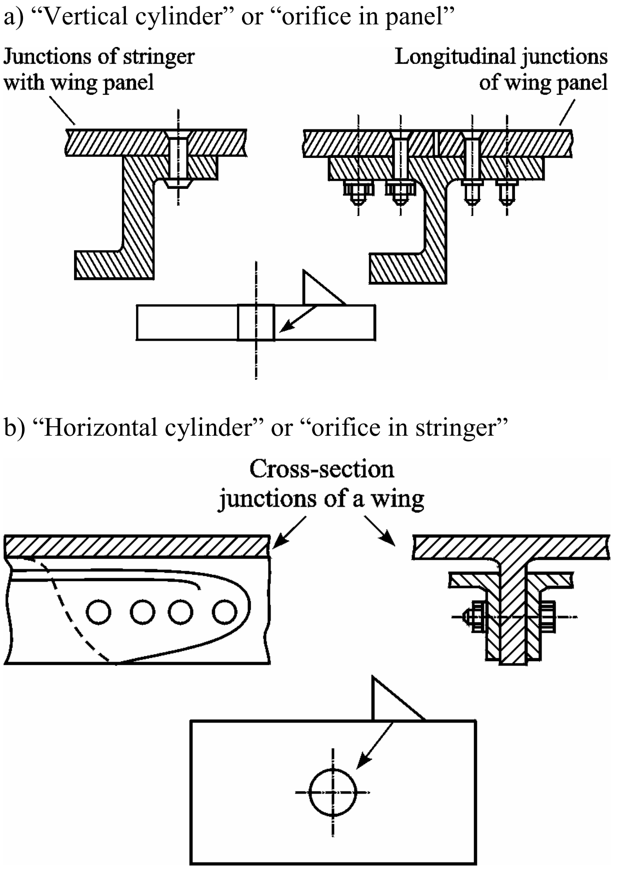

Fig. 1. Two groups of bolted joints with radial clearance and schemes of ultrasonic testing

The filling of cylinder (orifice) by any materials changes the reflection coefficient, as it depends on the acoustic impedance of the joined elements (materials) and depth of the transient layer. The filling of cylinder with loads (clearance) will change the parameters of the transient layer and of the layers bordering on the joined materials (bolt and panel). Therefore for this formula using it is necessary to replace the reflection coefficient by the variable, which depends on a number of parameters [1], including physical and mechanical characteristics of the materials, type and class of mating surfaces processing, way of assembly, value of actual stresses (radial clearance) and etc.

The process of large radial clearance creation in bolted joints is the process of forming the contact of random profiles, which ones the actual surfaces of elements are. Dependence of reflection coefficient on contact of random profiles is explained by the following phenomena.

When interaction between two bodies with similar hardness takes place the initial contact arises at three or more points with total area close to zero. When applying load, pressure on contact points fast increases up to the yield strength limit, then the points of contacts are plastically deformed. During the process of arising of plastic flow at the peaks of irregularities both profiles approach one another, other contact sports appearing. In plastic flow zones there occur a local welding together of the surfaces, due to which elastic waves pass through the contact layer. Thus, loading results in thinning-down of the transient layer, changing in its density and in the velocity of elastic waves propagation, which in its turn increases acoustic transparency of the contact border and influences on reflection coefficient.

Condition for random surfaces contact are rather complex of in themselves and there is also needed additional knowledge in various science fields (physical metallurgy, plasticity, chemistry, thermodynamics, acoustics and others) in order to be able to receive analytical expressions which set the dependence of the reflection coefficient on the actual load value (radial clearance).

In this research the experiment was used as basis for analyzing the influence of clearance on the ultrasonic shear wave reflection.

3 Experimental research of bolted joints models

Experimental investigations of the joints type of “horizontal cylinder” were conducted on conical models, which were made of materials widely used for airframes joints – aluminium, titanium, steel. The scheme of the test facility is shown in Fig. 2 (1 – indicator of movings, 2 – hydraulic press, 3 – taper pin (steel, titanium), 4 – transduser of shear waves, 5 – plate (aluminium).

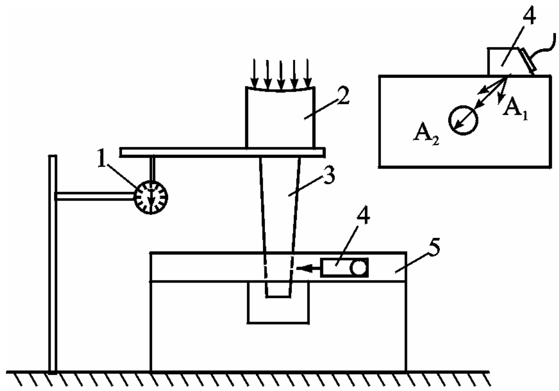

Fig. 2. The scheme of the test facility

A radial clearance was created by pressing cone (conicity 2°) made of steel (30ХГСА) or titanium (ВТ-16) into the orifice in the aluminium plate (Д16), the thickness of which is 10 mm. The range of created relative clearance was from 0 up to 2,4% and covered the typical range for bolted joints of airframes. The value of relative clearance δ was determined by calculation under the formula

$$\delta = \frac{2l\,\mathrm{tg}\,\alpha}{2l\,\mathrm{tg}\,\alpha + d}100\% \qquad (2)$$

Where l – movement of conical pin in the orifice; 2α – conicity of joint; d – nominal diameter of the orifice.

Movement of the pin l was measured with the help of the clock-type movement indicator. Orifice conicity was estimated by the results of ten-fold measurements of diameters on the ИЗА-2 comparator in two diametrically opposite directions with their subsequent average. It was determined that the orifices are made with a conicity of $1°40' < 2\alpha < 2°12'$. Conicity of pins was determined similarly by the results of diameter d measurements with the help of the micrometer МК-0-25 ($2\alpha = 2°$). Models with the diameter of 6÷12 mm were studied. The roughness of the mating surfaces complied with the requirements of production technology (R_z = 10÷20 microns).

The scheme of ultrasonic test of the bolted joint model was selected considering the testability and access to the "joint in stiffener". Investigations were carried out by the direct beam of share wave.

Elastic waves were emitted and received with the help of standard flow detectors and transducers. Acoustically transparent glue was used as a contact medium in order to eliminate the influence of acoustic contact on the observed data.

In the initial model state (without taper pin) there are several signals in the flow detector display: mirrored reflect signal, signals of non-homogeneous surface waves and signals reflected from geometry of plate.

The amplitude of mirrored reflect signal exceedes all another signals on 25–30 dB.

The character of the set experimental curves "echo amplitude – clearance value" changes depending on the stage of deformation of the joined materials (Fig. 3). The initial segment of dependence (decrease of echo amplitude) corresponds to the elastic deformation of

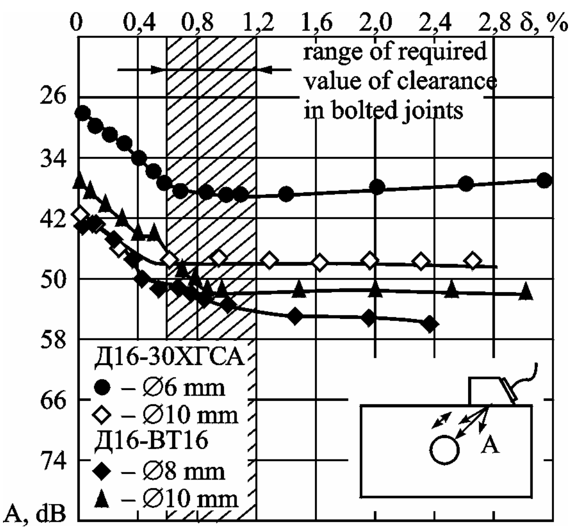

Fig. 3. Dependences of amplitude of an echo-signal of shear wave to value of relative clearance for contacts: Д16-30ХГСА (∅6 mm, ∅10 mm), Д16-ВТ16 (∅8 mm, ∅10 mm)

materials, at which the total contacting area of the joined elements increases and plastic flow appears at the peaks of main irregularities actually causing a spot welding due to which elastic vibrations (waves) go to the fastening element. The elasto-plastic deformation of materials is characterised by the development of plastic deformation from a microplasticity (in separate chips) to macroplasticity and is accompanied by formation of thin layers of materials with dislocations and other defects of grid (zone of a clod hardening) in the contact zone. It results in slowing down of the echo amplitude drop up to the minimal level. Further increase of the clearance invokes material yield, that shows, as a rule, by the horizontal area of amplitude dependence.

For models with a titanium pin there were captured oscillations of amplitude dependence, similar to the oscillations of "pressure-deformation" curves for titanium alloys. Such oscillations are a consequent of abnormal phenomenon known as a "discontinuous flow" [3]. The observed oscillations of amplitude dependence are an extra evidence of the fact that the amplitude of echo follows the changes in the stress-strained state of a joint with clearance.

The horizontal area of the amplitude dependence makes the estimation of clearance value in that range ambiguous. It is offered to determine the upper limit of the field of ultrasonic method application as the point of intersection of the initial segment of the amlitude dependence (zone of elastic deformation of materials) with the extension of the horizontal area (zone of plastic deformation).

For investigated models the upper limits are: aluminium-steel pair (Д16-30ХГСА) δ_{limit} = 0,8% (∅=6 mm), δ_{limit} = 0,6% (∅=10 mm), aluminium-titanium pair (Д16-ВТ16) δ_{limit} = 1,4% (∅=8mm), δ_{limit} = 1,0% (∅=10mm).

Physical and mechanical characteristics of the joined materials determine the nature of deformation and the load, at which a transition into the plastic condition takes place. It explains the dependence of the upper limit value on the type of the material. The influencing of the diameter of the joint is explained by the fact that the value of relative clearance does not characterise directly the stress-strained state of the joint. Stress-strained states of the joints of different diameters differ at the same value of relative interference that results in changing the upper limit value.

At models research it was stated that besides mirrored reflect signal another one dependes on clearance value. The results of time calculation and testing have shown that the signal corresponds to echo-signal, passed in a material filling in a orifice and reflected from the second contact border. In process of clearance growth the amplitude of this signal grows, coming nearer to amplitude of mirrored reflect signal. The minimal difference between amplitudes of signals is about 0–2 dB. Character of change of amplitude of the second signal in mirror repeats the first echo – signal change.

The obtained dependencies for echo-signal, reflected from first on a course of a ultrasonic beam of contact border (A_1) and for echo-signal,

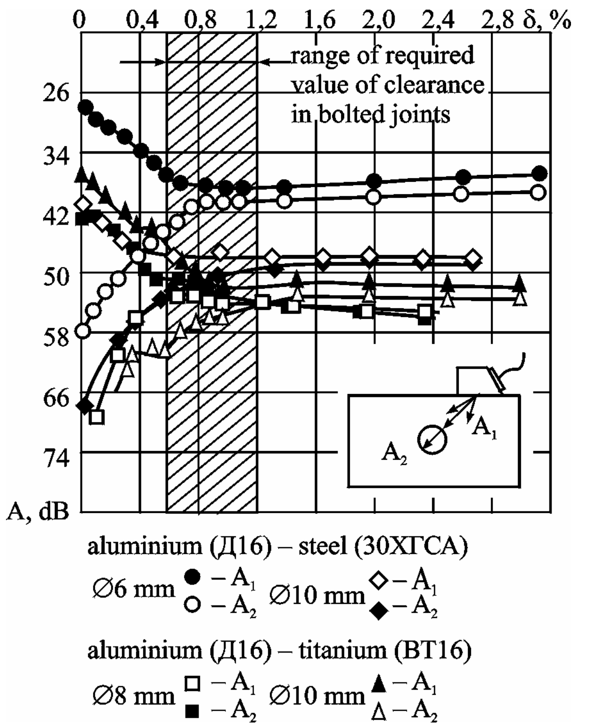

Fig. 4. Dependences of amplitude of echo-signals reflected from first (A_1) and second (A_2) contact borders of bolt joint model to value of relative clearance: for contacts aluminium (Д16) – steel (30ХГСА): ∅6 mm (A_1, A_2), ∅10 mm (A_1, A_2), aluminium (Д16) – titanium (ВТ16): ∅8 mm (A_1, A_2), ∅10 mm (A_1, A_2)

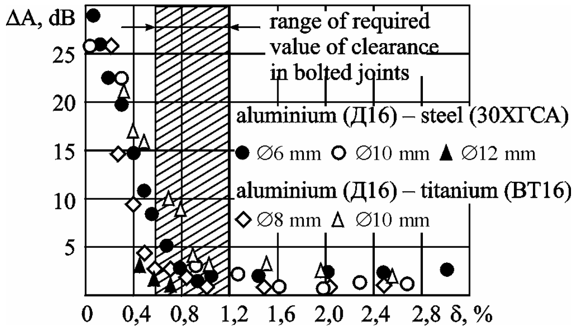

Fig. 5. Dependences of difference of amplitude of echo-signals obtained at reflection from both borders of bolt joint model for contacts aluminium (Д16) – steel (30ХГСА): ∅6 mm, ∅10 mm, ∅12 mm, aluminium (Д16) – titanium (ВТ16): ∅8 mm, ∅10 mm

passed in a material filling in a orifice and reflected from the second contact border (A_2) are presented in Fig. 4.

With the purpose of accuracy increase the assessment of joints quality is offered to execute on a difference of amplitudes of echo-signals ($\Delta = A_2 - A_1$) obtained at reflection from both borders of a bolt joint (Fig. 5). This allows to eliminate the influence of acoustic contact on the observed data and as a result to increase the accuracity clearance estimation.

The estiation of the size of the controlled segment has shown that for both groups of real joints of airframe this area is 1÷5% from the whole contact surface that allows to consider the ultrasonic estimation to be local one. It is determined [1] that the required minimum of measurements made around the joint is four – two measurements lengthways and two shearwise of the junctions. The proposed scheme allows to decrease the required minimum of measurements for estimation of quality of joining in two times.

4 Experimental research of specimens and a panel of passenger wing aircraft

The ultrasonic testing of specimens modelling bolted joints of panel and stringer were carried out. The specimens were assembled in the facility which implements the bolt installation process similar to that in aircraft production. By specimens testing there was determined the limit level of the echo amplitude needed for testing of the panel of the passenger aircraft wing.

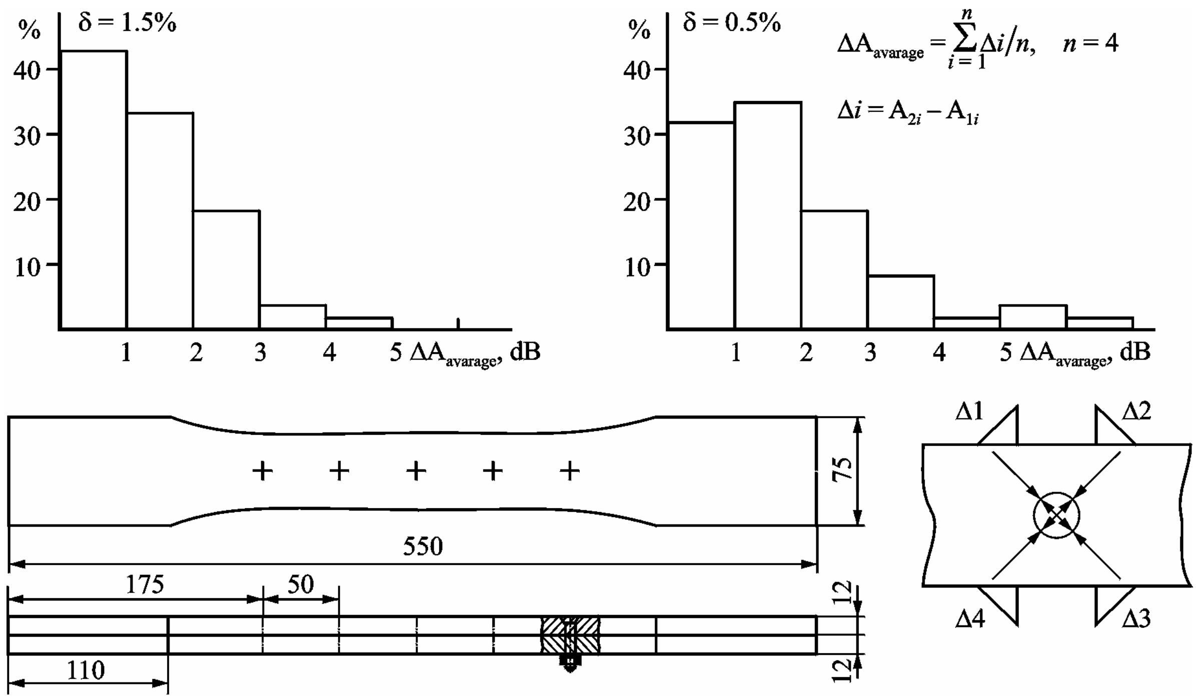

Fig. 6. Histograms of difference of echo amplitudes distribution (number of bolted joints = 120)

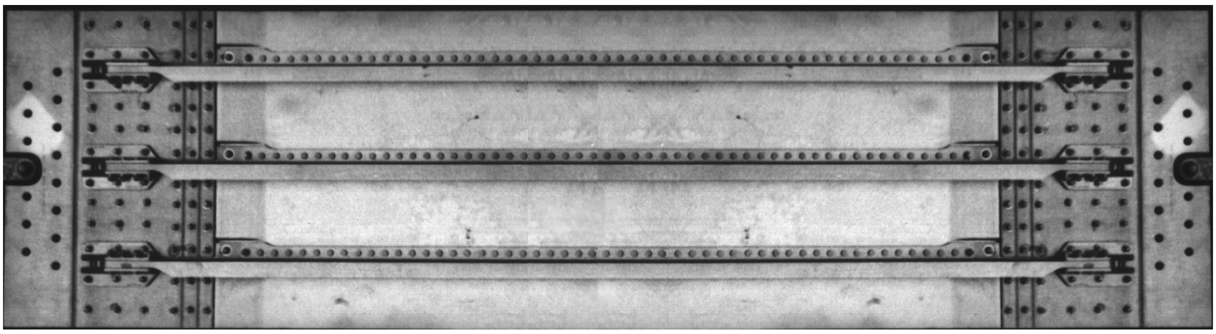

Fig. 7. Panel of the passenger aircraft wing

Fig. 6 provides the appearance and dimensions of the specimens. There were investigated 12 specimens (60 joints) with average clearance equal 0,55% (6 specimens) and 1,5% (6 specimens). The average value of clearance was determined on the basis of orifice/bolt diameter measurements before assembly.

The results of ultrasonic testing are represented in Fig. 6 as histograms of distribution of the average difference of amplitudes of echo-signals ($\Delta = A_2 - A_1$). The scheme of amplitudes measurement may be seen in Fig. 6.

For investigated joints (aluminium–steel pair, ∅=10mm), the field of ultrasonic method application is restricted by the upper limit of the clearance equal $\delta_{limit} = 0{,}6\%$. The difference of amplitudes of echo-signals ($\Delta = A_2 - A_1$) equal 3 dB corresponds to this value of clearance (0,6%).

There was determined the quantity of bolted joints for which the difference of amplitudes of echo-signals ($\Delta = A_2 - A_1$) not exeed 3 dB, namely for specimens with average clearance equal:

– 1,5% about 95% of joints,
– 0,55% about 85% of joints.

Taking account of all the obtained results the difference of amplitudes of echo-signals $\Delta = 3$ dB was used as the limit level for research of a panel of passenger aircraft wing, delivered to TsAGI for service life tests (Fig. 7).

Ultrasonic control of the joints was carried out both in panel and stringers. The quantity of the tested joints in stringers was equal 92 ones.

According to the results of the ultrasonic measurements there were determined joints for which the difference of amplitudes of echo-signals exceeds 3 dB (17 joints, 18%).

For today the fotigue strength testing of the panel is not completed and there is no any fatigue crack in the joints.

5 Conclusion

1. It is determined two main groups of bolted joints with clearance:"joint in panel" and "joint in stiffener (stringer)".
2. For "joint in stiffener (stringer)" it is proposed the scheme of ultrasonic evaluation of the clearance.
3. It is determined by the experiment that the amplitude of ultrasonic echo signal tends to decrease with the increase of the clearance.
4. Three typical areas of changing in the echo-signal amplitude were determined: a close to linear drop in the segment of elastic deformation, slow-down of the drop up to the minimum point in the transient area from the elastic deformation to the plastic one and horizontal area in the segment of plastic deformation.
5. With the purpose of accuracy increase the assessment of joints quality is offered to execute on a difference of amplitudes of echo-signals ($\Delta = A_2 - A_1$) obtained at reflection from both borders of a bolt joint.

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