NON–DESTRUCTIVE ASSESSMENT OF THE RADIAL CLEARANCE OF THE BOLTED JOINTS IN AIRCRAFT STRUCTURES

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Abstract

Within the nearest ten years bolted and bolt-riveted joints will be still most often used in aluminium alloy airframes. One of the ways of increasing fatigue strength of bolted joints is the creation of large radial (diameter) clearance. Capability of estimating radial clearance in joints after assembly offers great practical prospects.

This paper considers the results of research on non-destructive control of clearance in standard bolted and bolt-riveted joints of airframes.

It describes the test facility, with the help of which dependencies between the value of radial clearance and the ultrasonic signal were determined for conical models of joints with clearance. Typical areas where there were revealed changes of ultrasonic signal that correspond to the areas of elastic, elasto-plastic and plastic deformation of materials. Contact pairs of materials typical for airframe joints (steel-aluminium, titanium-aluminium) were used for joint imitation.

The field of the method application was determined. There was introduced a concept of the limit value of clearance, which corresponds to the upper boundary of the area of unambiguous ultrasonic estimation of clearance.

Influence of axial clearance on the results of radial clearance estimation by ultrasonic waves is investigated. The required minimum of ultrasonic measurements for estimating clearance in bolted joint is determined.

The results of ultrasonic control of clearance in bolted joints of a full-scale panel of the passenger aircraft wing are given. The results of panel service life testing confirm the reliability of ultrasonic control of clearance in bolted joints of airframes.

1 Introduction

The problem of increasing the structures' service life is connected first of all with the safety of different air transportation, and also with the tendency to creating expensive aeronautical engineering (passenger airbuses, cargo superjumbos) as well as to increasing service and repair costs.

Within the next ten years bolted and the bolt-riveted joints will stay predominant in airframes from aluminium alloys. One of the ways of increasing fatigue strength of bolted joints is the creation of large radial (diametrical) clearance. clearance N for bolted joints is determined by the difference between diameters of bolt d_b and orifice d_{or} before the assembly:

$$N = d_b - d_{or} \qquad (1)$$

Or in percentage to the fastening element diameter:

$$\delta = \frac{(d_b - d_{or})}{d_b} \cdot 100\% \qquad (2)$$

At the installation of fasteners with clearance there will appear the initial stress field – tangential τ_q and radial τ_r in the sheet. The view of diagrams of these stresses‘ distribution depends on the material of the fastening element. Nowadays bolts from steel and titanium are used for airframe joints. With the increase of clearance in a ring-type zone, which directly adjoins the orifice contour, there comes a plastic condition, there is a clod hardening (strengthening) of the material. When loading such joint with external forces the system of initial stresses is superimposed on the system of stresses caused by the external loading and there is a change of tangential and radial stresses that results in considerable increase of fatigue strength. The second factor contributing to the increase of the service life of joints with clearance is strengthening the material around the orifice as a result of plastic deformation. The third factor is the reduction of joint motility and, as a result, the decrease of fretting-corrosion. Thus, using a guaranteed clearance comprehensively increases the fatigue strength of joints: by reduction of actual stresses and by partial elimination of fretting-corrosion.

Analysis of testability of airframe joints and of the available data on non-destructive examination of clearance in other branches of engineering has shown great prospects of applying ultrasonic echo – method for estimating the quality of bolted joints with clearance.

In the paper [1] when considering the elastic waves reflection we model the border of the coupling elements as a three-layer system, in which the reflection coefficient depends on the acoustic impedance of the joined elements, on the acoustic impedance and depth of the transient layer, as well as on the pitch angle of the ultrasonic wave.

$$R=\frac{\left(\frac{z_2^2}{z_1^2}-1\right)\cos^2\varphi_3+\left(\frac{z_3^2}{z_1^2}-\frac{z_2^2}{z_3^2}\right)\sin^2\varphi_3}{\left(\frac{z_2}{z_1}+1\right)^2\cos^2\varphi_3+\left(\frac{z_3}{z_1}+\frac{z_2}{z_3}\right)^2\sin^2\varphi_3}-i\frac{\sin 2\varphi_3\left(\frac{z_3}{z_1}-\frac{z_2^2}{z_1 z_3}\right)}{\left(\frac{z_2}{z_1}+1\right)^2\cos^2\varphi_3+\left(\frac{z_3}{z_1}+\frac{z_2}{z_1}\right)^2\sin^2\varphi_3} \tag{3}$$

Where $z_1 = r_1 c_1$ – acoustic impedance of the first layer (for example the enclosing element); $z_2 = r_2 c_2$ – acoustic impedance of the second layer (for example the enclosed element); $z_3 = r_3 c_3$ – acoustic impedance of the transient layer; ρ_i – density of the i layer; C_i – speed of ultrasonic wave in the i layer; $\varphi_3 = 2\pi\cos\theta_3 d_3/\lambda_3$, where – θ_3 angle between the direction of the ultrasonic beam and the normal to the surface of the elements coupling; d_3 – depth of the transient layer; λ_3 – length of the ultrasonic wave in the transient layer.

The loads change the parameters of the transient layer and of the layers bordering on the joined materials. Therefore, when using the given model for estimating the quality of joints with clearance it is necessary to replace the transient and bordering layer parameters by the variables, which depend on physical and mechanical characteristics of the materials, on the type and class of mating surfaces processing, on the way of assembly, value of actual stresses and a number of other parameters. Such a great number of parameters are explained by high complexity of the process of forming the contact of random profiles, which ones the actual surfaces of elements are.

A microscope examination of the machined surfaces shows that they are not theoretically smooth and consist of set of peaks and cavities. 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 ($\Sigma Si = 0$) [2]. When applying load W pressure P calculated by the ratio $p = W/\Sigma Si$ fast increases up to the yield strength limit p_y, then the points of contact are plastically deformed in such a manner that the full contacting area becomes the final one. During the process of arising of plastic flow at the peaks of irregularities both profiles approach one another, other contact spots 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 rate of elastic waves propagation, which in its turn increases acoustic transparency of the contact border.

Conditions for random surfaces contact are rather complex of in themselves and there is also needed additional knowledge in the field of physical metallurgy, plasticity, chemistry, thermodynamics and acoustics in order to be able to receive analytical expressions which set the dependence of the transient layer variable parameters on the actual load value. Taking account of all this, we used the experiment as the basis for analysing the influence of clearance on the elastic waves reflection.

2 Experimental research of conical models

Experimental research were conducted on conical models of joints with clearance, which were made of materials widely used for airframe joints – aluminium, titanium, steel. The scheme of the test facility is shown in Fig. 1 (1 – indicator of moving (movement), 2 – hydraulic press, 3 – taper pin (steel, titanium), 4 – transducer of shear waves (MWB-60-N6), 5 – plate (aluminium)). By pressing cone (conicity 2°) made of steel (30HGSA) or titanium (WT-16) into the orifice in the aluminium plate (D16), the thickness of which is 10 mm, a radial clearance from 0 up to 2,4 % was created. The field of clearance was selected so that to cover the range typical for bolted and bolts-riveted joints of airframes. The value of relative clearance δ was determined by calculation under the formula

$$\delta = \frac{2l\,\mathrm{tg}\,\alpha}{2l\,\mathrm{tg}\,\alpha + d}100\% \qquad (4)$$

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 comparator (type IZA-2) 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 r 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 μm). Elastic waves were emitted and received with the help of the USIP-11 and USK-7 flow detectors and such transducers as MWB (Кrautkremer Corporation, Germany). Amplitude characteristics of shear waves were investigated. Acoustically transparent glue (implementation ИКХХВ А.В. Dumansky, Ukraine) was used as a contact medium in order to eliminate the influence of acoustic contact on the observed data.

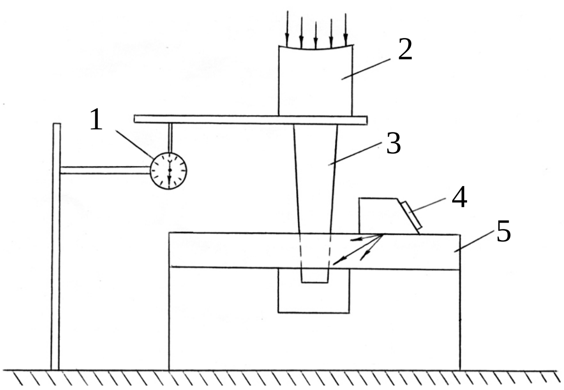


FIGURE 1. The scheme of the test facility

Research of radial clearance influencing the amplitude of an echo of the shear wave were carried out by a direct beam under the joint scheme. The scheme of the model insonification was selected considering the testability of airframe joints and the arrangement of the shear-section, which determined their fatigue strength.

For shear waves the character of the set experimental curves "echo amplitude – clearance value" qualitatively changes depending on the stage of deformation of the joined materials (Fig. 2). The initial segment of dependence described by a close-to-linear drop in the echo amplitude corresponds to the elastic deformation of 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 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 and in the subsequent slight growth of the amplitude. Further increase of the

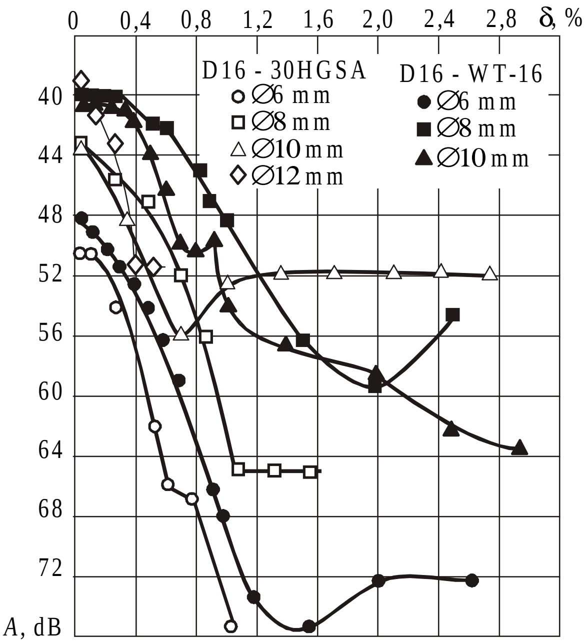


FIGURE 2. Dependence of amplitude of a echo of a shear wave to value of relative clearence

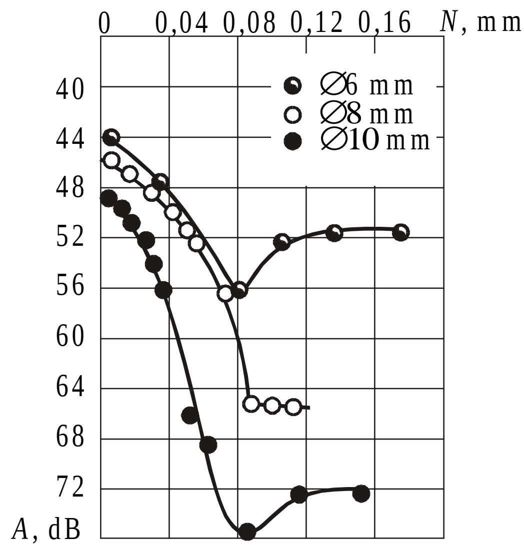


FIGURE 3. Dependence of amplitude of a echo of a shear wave to value of absolute clearence for a contact D16-30HGSA

interference 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.

As you can see from Fig. 2 amplitude characteristics have a minimum point and its position depends on the type of the joined materials and on the diameter of the joint. 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 minimum point location 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 clearance that results in changing the position of the minimum point.

It seems more reasonable to use absolute clearance characteristic *N* for estimating the quality of joints with clearance. In doing so for

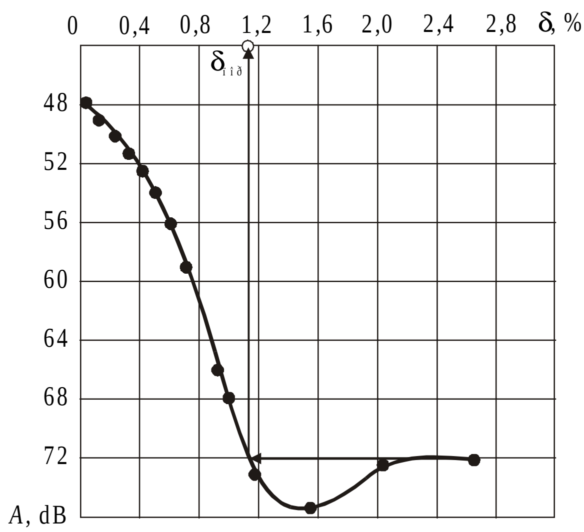


FIGURE 4. The scheme of definition of the upper limit of range of a unambiguous estimation of interference on amplitude characteristic (D16-HGSA ∅6 mm)

one type of contact, for example for aluminium-steel, there is practically no influencing of the joint‘s diameter on the position of the amplitude characteristic extreme (Fig. 3).

The availability of a minimum point in the amplitude characteristics makes the estimation of radial clearance value ambiguous. The field of application of the ultrasonic method is limited by the range of one-valued change of clearance, the upper limit of which δ_{lim} is offered to be determined as the point of intersection of the initial segment of the amplitude dependence with the extension of the horizontal area in the field of plastic deformation (Fig. 4.).

As it is obvious from the expression (3) the echo amplitude depends on the angle of incidence on the border of elements coupling. The reasonability of using the results obtained on conical models for cylindrical joints control is proved by the data [4], according to which the change of the echo amplitude within the limits of the model conicity is insignificant and can be easily neglected for transducers with prism slant angle of 30°÷50°.

3 Analysis of echo-method estimation of joints‘ quality

The established relations of echo amplitude to stress-strained state of the controlled surface are obtained for the case of unilateral insonification of the controlled orifice.

Analysis of the acoustic channel was conducted in order to determine the size of this segment. The analysis was carried out using radiate geometrical acoustics, which ensures good visualisation when considering phenomena of elastic waves passing through and reflection. According to the geometrical acoustics the sound field is represented simplistically as a system of rays, which diverge from the radiator in parallel or as a fan. The beam dropped on a curved element of the surface (with radius of curvature much more than the wave length), is reflected in the same way as from the plane tangent to the surface at the point of beam drop. We used this assumption when constructing the path of rays, as the basic joints of airframes have the orifice radiuses (2,5-8 mm) much superior than the length of a lateral wave in aluminium (for frequencies 2,5÷5 MHz a wave length is accordingly 1,2÷0,6 mm).

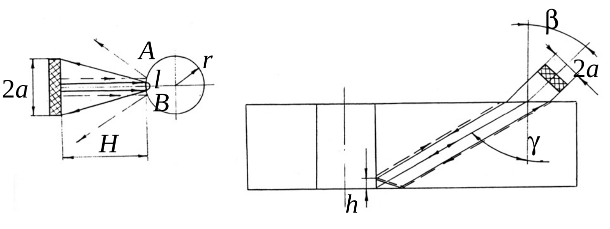


FIGURE 5. Scheme of determining the size of the controlled segment

The size of the controlled segment was estimated by the orifice generatrix (altitude of the joint) and by its circumference, the signal amplitude not being considered. Fig. 5 shows the scheme of determining the size of the controlled segment by the orifice circumference. Elastic waves generated by a piezoelectric transducer with diameter 2*a* drop on the cylindrical surface of the orifice with radius r, which lies at depth *H*. High curvilinearity of the surface results in a strong divergence of ultrasonic beams. The length of the arc 2∪*AB*, which corresponds to the length of the controlled segment as extended along the circumference of orifice *L*, is determined as

$$L = \frac{\pi r}{90°} \operatorname{arctg} \frac{a}{\sqrt{a^2 + (H + r)^2} + H} \tag{5}$$

The size of the controled segment as to the joint‘s altitude was also determined for the zone nearest to the transducer

$$h = \frac{a}{\cos\beta \, \mathrm{tg}\, \gamma} \tag{6}$$

Where 2*a* – diameter of the transducer, β, γ – wave angles of ultrasonic oscillations accordingly in the transducer prism and in the controlled item.

The area of the controlled segment of the investigated models and actual airframe joints is 1÷1,5% from the whole contact surface

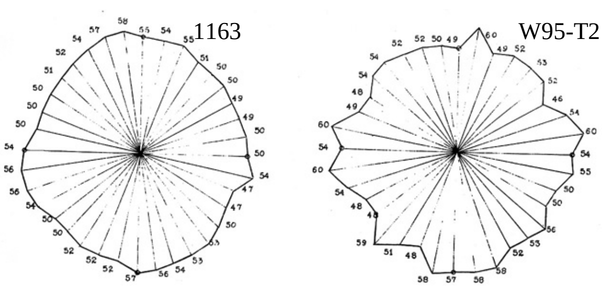
(L = 0,6÷1,0 mm, h = 2-3 mm). At such ratio of the areas it is possible to consider the estimation of joints‘ quality by the echo amplitude to be local. The local character of the estimation is that advantage of the ultrasonic method, which enables drawing circular charts for the joints‘ quality, which can be presented in values of clearance, deformation or residual stresses. A widely used on practice integral estimation of quality of joints can be obtained by averaging the results of discrete measurements around the orifice.

For full scope of joint contact surface along the circumference it is necessary to make $n = 2\pi r/L$ of ultrasonic measurements.

4 Influencing of the number of measurements on accuracy of A_{aver} estimation

The influence of the quantity of measurements on the accuracy of A_{aver} estimation as investigated on rivet joint models, which imitated a skin-stringer joint of the passenger aircraft wing. Models were made at the Moscow Aviation Institute by technology, which corresponds to the production assembly.

In the investigated models the controlled orifice was fully covered at n = 36. Therefore the value obtained by results of 36 measurements was adopted for true value of A_{aver}. Fig. 6 shows circular charts for echo amplitude distribution, which were made for one joint in the panel (material 1163) and in the stringer (material B95-T2) separately.



n = 36, A_{aver} = 52,3 dB, n = 4, A_{aver} = 54,3 dB

n = 36, A_{aver} = 53,3 dB, n = 4, A_{aver} = 53,7 dB

FIGURE 6. Circular charts for echo amplitude distribution

When determining the required number of measurements around the orifice there were considered different factors influencing the clearance distribution around the joint, such as:

– Irregularity of orifice extension in different directions,
– Influence of the adjacent joints’ stress-strained state,
– Fatigue damage of airframe joints.

The irregularity of orifice extension is a result of material anisotropy. Technological processing is one of the factors increasing material anisotropy. Rolled slabs (sheets) are widely used for airframe manufacturing. The structure of such materials has peculiar orientation along the direction of roll, the greatest difference in properties being observed lengthways and shearwise the direction of roll.

The influence of stress-strained state of the adjacent joints is most probable along the juncture and, in case with the element edge or when there is a second raw of joints, also shearwise of the juncture.

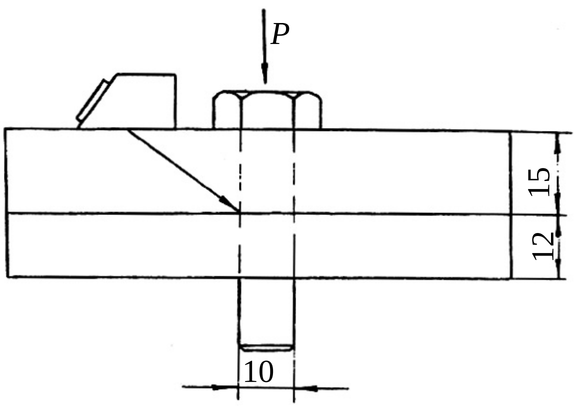
The analysis of fatigue damage of airframe joints has shown that shear-sectional distractions are typical for longitudinal junctures, and longitudinal ones – for shear-sectional joints of panels. While under other equal conditions the joint fatigue life is defined by the value of clearance, in case with bolt and rivet joints it is necessary to control quality lengthways and shearwise of the juncture.

Thus, the required minimum of measure-ments made around the joint is four – two measurements lengthways and two shearwise of the juncture. The difference in A_{aver} estimation by 36 and by 4 measurements is 2÷3 dB, that lays within the limits of accuracy of the verification method. Similar results were obtained for three more joints. It allowed drawing a conclusion that four echo amplitude measurements around the orifice are sufficient for estimating the quality of joints with clearance.

5 Influence of axial tie on the clearance estimation by the echo – method

Echo amplitude provides information on reflectivity of the surfaces of the dihedral angle, one edge of that is the lateral surface of the orifice for a fastening element, the other being the surface of the controlled element coupling with the second element of the package. Information on reflectivity of the lateral surface of the orifice is useful for estimation of radial clearance. Changes in reflectivity of the second edge of the dihedral angle will introduce a variation of the mean error to the estimation of radial clearance value.

Estimation of package axial tie influence on echo amplitude was fulfilled on the model of bolted joint of two laminas (Fig. 7). To eliminate the influence of possible changes in reflectivity of the orifice lateral surface, the bolt was set with a gap. The strength of the package tie was changed with the help of a hydraulic press. The range for varying the pressure on the bolt head was selected so that to cover the tie efforts in airframe joints. The research was carried out with joint loading from 0 up to $7{\cdot}10^3$ kg and with subsequent joint unloading two times.



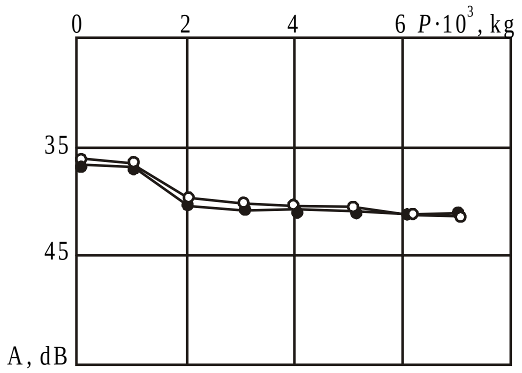


FIGURE 7. Axial tie influence on echo amplitude

The value of the created contact pressure in the test zone was calculated under the well-known formulas:

$$P = P/S, \quad S = S_b - S_{orifice}$$

Where P – effort created by press; S_b , $S_{orifice}$ – area of shear-section of the bolt head and of the orifice accordingly.

Echo amplitude changing was measured with the help of the USK-7 flaw detector and the W60K5K transducer. In order to eliminate the influence of the acoustic contact on the observed data, the transducer was sticked to the lamina with the help of acoustically transparent glue.

As a result of the conducted experiment it is established, that a noticeable change of the echo amplitude (by 4dB) occurs when press power increases from 0 up to $2{\cdot}10^3$ kg. Further increase in the package compression up to $7{\cdot}10^3$ kg results in slight alteration of the echo amplitude (by 0.5÷1 dB). Thus, the range of the echo amplitude sensitivity to the changes in contact pressure on the surface of the package joined elements coupling is 0÷11 kg/mm^2 that is 2÷2.5 times less than the range of sensitivity to the radial clearance. It can be assumed that high sensitivity of the echo amplitude is determined not only by the value of actual stresses but also by their direction and by the complexity of the contact boundary stress-strained state.

The realised tie efforts for real airframe joints are more than $2{\cdot}10^3$ kg, that is why the influence of axial interference on echo amplitude can be considered a systematic error. As the calibration charts for estimation of the radial clearance value were obtained at the effect of axial tie, there is no need to introduce the correction in order to avoid this systematic error.

6 Experimental research of a full-scale panel of the passenger aircraft wing

The ultrasonic echo-method was applied for estimating the quality of bolt joints in the lower panel of the passenger aircraft wing, delivered to TsAGI for service life tests (Fig. 8). Ultrasonic control of the joints was carried out for the zones with the higher level of actual stresses – at the inspection hatches. Opposite

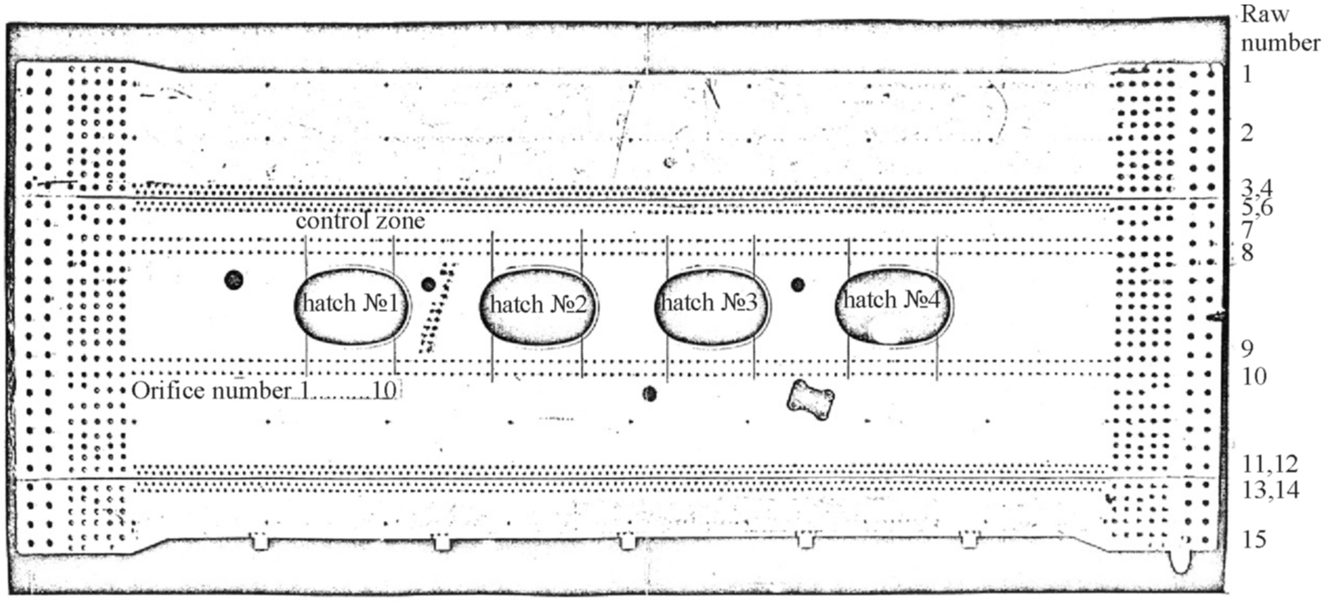


FIGURE 8. Lower panel of the passenger aircraft wing

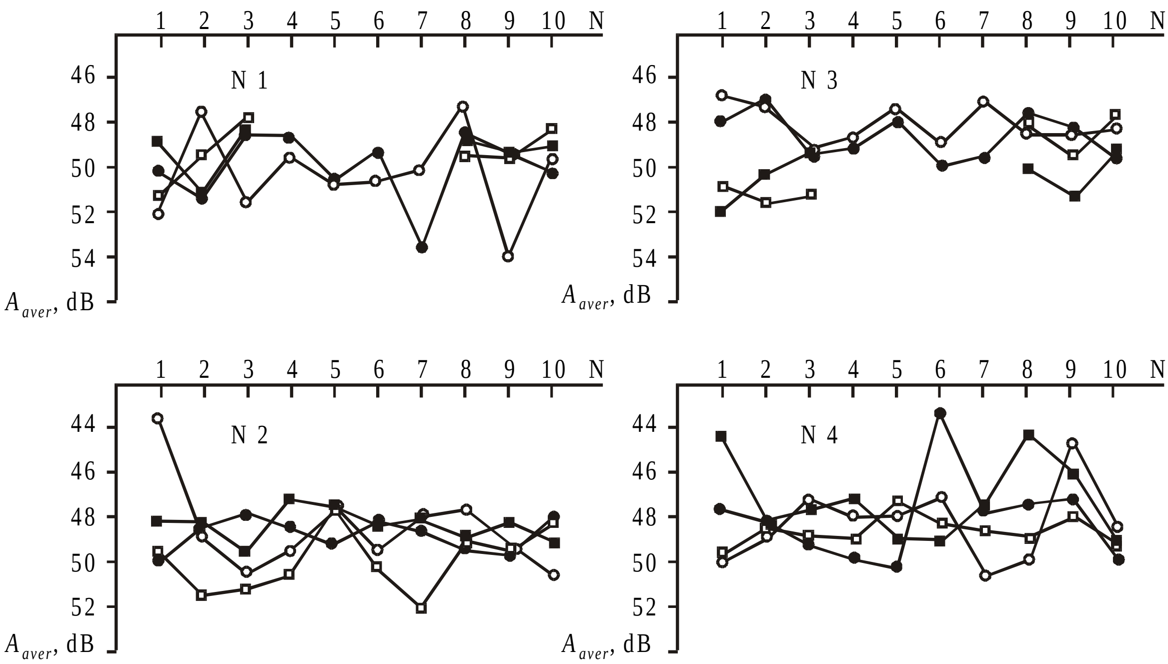


FIGURE 9. The charts of distribution of echo-signal amplitude average values in each raw for four hatches

each inspection hatch there were determined segments of two-layer longitudinal junctions – with 10 bolt joints in each raw (total 160 joints). The quality of joining was estimated by the average value of amplitude of the echo-signal emerged from the orifice. Ultrasonic measurements were carried out with the help of the USK-7 flaw detector and the MWB-45-N4 transducer.

According to the results of the ultrasonic control there were determined joints for which the increase in the echo-signal amplitude appear to be by 5÷6 dB less than 49 dB. Four from the five “weaken” joints were located at hatch N4, and one joint – at hatch N2. The obtained data enable defining the hatch-N4-zone as one required a special attention when inspecting during tests.

After fatigue strength testing of the panel there were found two fatigue cracks in the hatch-N4-zone, one of which appeared in a weaken orifice (Orifice N6, Raw 9).

Thus, the results of service life tests of the passenger aircraft wing panel have proved the reliability of ultrasonic testing of the quality of the joints with clearance and the reasonability of carrying out such type of control for full-scale structures before their testing.

7 Conclusion

1. It is determined by the experiment that the amplitude of ultrasonic echo-signal tends to decrease with the increase of the clearance.
2. 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 and the afterwards increase in the transient area from the elastic deformation to the plastic one , horisontal area of „saturation“ in the segment of plastic deformation.
3. The notion of a limit value of clearance, which corresponds to the boundary of the area of unambiguous ultrasonic estimation of clearance, is introduced.
4. It is suggested that the absolute clearance should be used when estimating the quality of joining, the limit value of which for one type of contact does not depend on the diameter of the joint.
5. It is determined that for real joints of airframe the area of the controlled segment is 1÷5% from the whole contact surface that allows to consider the ultrasonic estimation to be the local one.
6. It is suggested that the quality of joining should be estimated by the average value of echo-signal amplitude obtained by four measurements carried out around the orifice in the zones of the greatest influence of design and technological characteristics on the stress-strained state distribution (lengthwise and shear-wise of the junction).
7. It is determined by the experiment that axial tie of the package influences the echo-signal amplitude. The error of the tie‘s efforts realised in full-scale airframes is constant and systematic.
8. The reliability of the results of ultrasonic control of quality of joints with clearance is proved by the results of fatigue strength tests of a full-scale panel of the passenger aircraft wing.

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