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ULTRASONIC ASSESSMENT OF THE RADIAL CLEARANCE OF RIVETED JOINTS IN AIRCRAFT STRUCTURES

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ABSTRACT

In practice of airconstruction the riveted joints have wide application. It is known that the increase of their fatigue life is reached by making large radial (diametrical) clearance. the estimation of the efficiency of the large radial clearance application is hindered through an absence of non-destructive evaluation method. In production the radial clearance value is estimated indirectly basing on value of the hole expansion by destructive method.

In the report the results of the non-destructive investigations on the radial clearance testing in the riveted joints are presented. The investigations were based on high ultrasonic sensitivity to strength – strained state of the mating parts boundary. The echo amplitude-radial clearance relation is established by comparison of ultrasonic measurement results and measurement results of holes expansion after riveting (by destructive method). The investigations were carried out with specimens, modeling the joints of skin (material 1163) and stringer (material B95-T2). the specimens riveting carried out at the experimental facility realizing the riveting process by rod rivets similar to the process at the automatic machine "Gemcor".

The equation establishing the function between echo amplitude and radial clearance is presented. The estimate of ultrasonic measurements dispersion was made basing on random error value. the confidence boundary of calibrated curve was determinated for probability $P = 0.9$.

The reliability of proposed testing method was evaluated by comparison of ultrasonic measurement results and results of residual stresses measurement. The residual stresses were measured on specimens, which were cutted from longitudinal riveted seam of full-scale aircraft wing panel that had passed a fatigue test. The value of residual stresses was measured by radiographic method. The influence of surface cut mechanical treatment on estimation of residual stresses value was excluded. the obtained data and results of their processing has confirmed the high reliability of the ultrasonic testing results of riveted joints radial clearance in aircraft structures.

INTRODUCTION

The aircraft industry widely utilizes riveted joints. These may be source of fatigue damage, so their fatigue resistance should be improved – for example, by introducing large radial clearance.

With this, the tolerance interval for riveted joints in passenger-carrying airplanes should be 2.2% to 3.4%. By definition (as in paper$^{(1)}$), the clearance for a soft-collar rivet is

$$\delta = \frac{D_r - D_0}{D_0} \cdot 100\% ,$$

where D_r is the soft-collar rivet diameter at station 2 upon riveting (Fig. 1) and D_0 is the hole diameter prior to riveting.

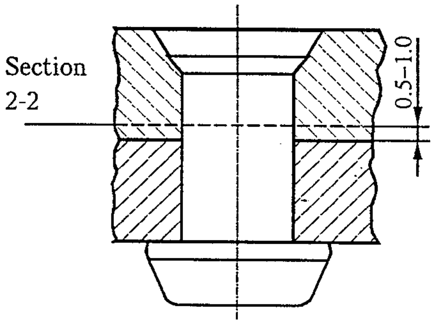

FIGURE 1 - The schematic of measuring the clearance in a joint with soft-collar rivet

Efficiency of resorting to large clearance values is notably reduced because there are no methods for nondestructive testing. In shop conditions the clearance is evaluated indirectly by destructive methods measuring the amount of hole expansion in a typical specimen upon riveting.

EXPERIMENTAL INVESTIGATIONS

Studies (see paper$^{(2)}$ for example) on ultrasonic evaluation of clearance in riveted joints were based on high sensitivity of ultrasound to stresses

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and strains at the interface of riveted parts. Inspection concepts were chosen so as to obtain echo signal from the in-plane section that governs fatigue resistance of a joint and is monitored in shops – the station 2 in Fig. 1. Dependence of the reflected signal amplitude on radial clearance was established by comparing the ultrasonic measurement data and hole expansion measurement with destruction of the joint. To validate the comparison of ultrasonic and destructive inspection data the diameters of holes and rivets were measured at the same locations in the joint as ultrasonic measurements were conducted, and in two mutually perpendicular directions – along and across the riveted joint. Figure 2 represents a schematic of clearance evaluation for a riveted joint.

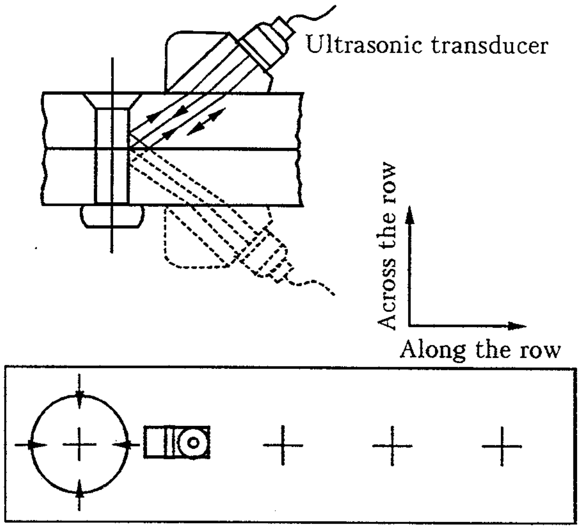

FIGURE 2 - Experiment geometry for ultrasonic measurement of radial clearance in riveted joints

Experiments were carried out on specimens modeling a joint of a skin (made out of 1163 alloy with thickness of 12 mm) and a stiffener (made out of V95-T2 with thickness of 12 mm) which is typical of wing structures. Specimens were riveted in a test facility which implements the soft-collar rivet installation process (with rivets made out of V65) similar to that in automata "Gemcor" or AK-16. A certain value of radial clearance was attained by selecting a head-forming force. Prior to riveting the specimens the hole diameters were determined; upon the riveting, amplitudes of echo signals from riveted joints were measured. Hole diameters and ultrasonic signals were measured for materials 1163 and V95-T2 separately. Ultrasonic waves were emitted and received (and amplitudes measured) by standard flaw-detectors and transducers (piezoelectric transducer diameter, 6.3 mm; prism inclination angle, 47°; ultrasonic oscillation frequency, 5 MHz). Thereafter, the joint was cut through, and rivet diameters were determined at the section corresponding to the ultrasonic inspection zone and the hole diameter measurement zone. Rivet diameters were established by using a special-purpose fixture. Clearance was determined on the basis of hole/rivet diameter measurements. The assumption adopted here is that both a hole and a rivet expand identically in the course of assembly. For each material for the riveted joint (1163 and V95-T2) we obtained four values of the echo amplitude and two clearance values. The amplitudes of reflected signals were averaged in accordance with clearance measurement directions.

MEASUREMENT RESULTS

These data have been the basis for establishing the "echo signal - clearance" correlation. Zero clearance was corresponded to by signal amplitude measurement results for a free hole. The experimental data were processed to derive the regression equation

$$\delta = 0.01e^{0{,}09A} - 0.03; \quad r = 0.97, \qquad (1)$$

where δ is the clearance amount, A is the mean value of ultrasonic signal amplitude, and r is the correlation coefficient.

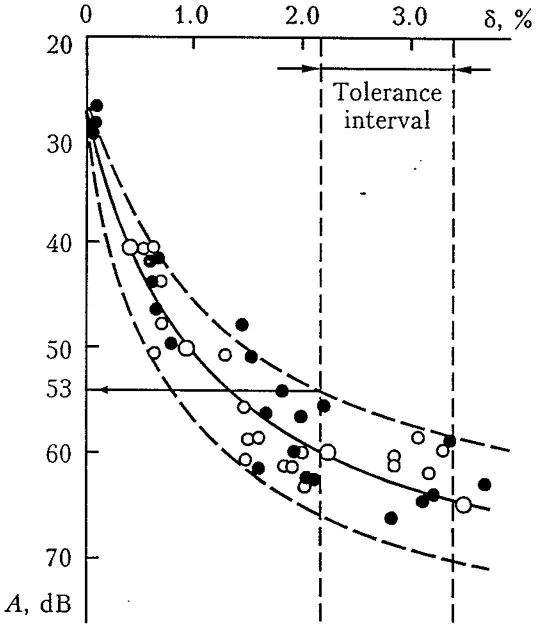

FIGURE 3 - Dependence of reflected signal amplitude on radial clearance in riveted joint. Flaw detector USK-7, transducer W60K5K (Krautkramer Company); ● – 1163, ○ – V95-T2; plates of 1163 and V95-T2, rivet of V65

Figure 3 represents measurement data and the processing result (the calibration curve). Scatter of ultrasonic measurements was estimated by utilizing random errors in the following way. One knows that mathematics makes it possible to use parameters of a random variable X in order to determine characteristics of distribution of the other random variable Y which is related functionally to X; refer to paper(3) for example. In the simplest way this problem is solved for a linear function $Y=f(X)$. By transforming equation (1) into a linear function,

$$\ln(\delta + 0.03) = 0.09A - 4.61,$$

we can write the following expressions:

$$S_{\ln(\delta + 0.03)} = S_{0.09A}, \quad S_{0.09A} = S_A$$

where S is the standard (root-mean-square) deviation.

There exist many independent occasional reasons for clearance δ to be recorded with fluctuations; so we may assume the ultrasonic measurement results to meet the normal distribution law; the compound criterion was used to validate this assumption. The standard deviation was estimated to obtain $S_A = 3.79$ dB. Thereafter, S_A was presumed to be constant throughout the A variation range. This assumption was validated by estimating S at four levels of clearance: 0.62, 1.51, 1.96, and 3.11%. In this case

$$S_{\ln(\delta + 0.03)} = 0.09 \cdot 3.79 = 0.34.$$

The standard deviation $\delta(S_\delta)$ may be established graphically or by computation. Five levels of clearance were used to compute S_δ; this activity revealed that the standard deviation is an asymmetric function and grows with δ. Error confidence boundaries are defined by the relation,

$$\Delta\delta = t \cdot S_\delta$$

where t is the Laplace function argument for the confidence level P.

For joints with soft-collar rivets the error in ultrasonic evaluation of clearance within the tolerance interval becomes considerable. We should take into account essential dependence of fatigue resistance on meeting the lower limit of the tolerance interval; with this, quality of a joint may be monitored by proceeding from the threshold level which is defined by the point where the clearance tolerance interval lower limit (2.2%) crosses the calibration curve confidence interval lower limit for the confidence level P.

Figure 3 demonstrates calibration curve confidence limits for the confidence level $P = 0.9$; as well, the echo signal amplitude threshold is indicated: $A_{\text{thr}} = 53$ dB.

VALIDITY OF THE ULTRASONIC METHOD

The present inspection method was validated by establishing the "measurement data – actual value" correlation function. In this case the "inspection validity" was mean to be the level of correspondence between measured and actual quantities, see paper(5).

As for riveted joints in aircraft structures, the actual quality figures include operational characteristics such as fatigue resistance. Upon ensuring clearance between a fastener and a metal sheet the latter features a field of initial (residual) stresses. in the case of very great clearance a ring around the hole gets into plastic state, and the material becomes hardened. If the joint is loaded with external forces, the system of initial stresses is added to the external stresses, and stress fields in the joint are changed; this improves fatigue resistance. Thus, residual stress is the most important quantity which defines fatigue resistance of a joint with clearance and is to be regarded as a reliable indicator of structural quality.

There exist a number of residual stress measurement methods: ultrasonic (based on variation in the ultrasonic wave speed), strain-gage, optical, X-ray, magnetic (based on Barkhausen noise), local-melting, semi-destructive (with hole drilling) etc. However, riveted joints have obvious features which do not allow these methods to be employed in order to determine residual stress without destruction.

When establishing the "echo signal amplitude – residual stress" correlation, residual stresses were measured by the X-ray method, including successive taking of roentgenograms at an angle during gradual removal of the material by milling (until the plane under question is reached). In this case the effect of rivet shear surface machining on residual stress should be eliminated; for this purpose an additional operation was introduced: a layer as thin as 0.1 or 0.2 mm was removed by a special milling cutter, and the surface was then subjected to electrolytic polishing. Residual stresses in the rivet rod were measured by using the X-ray stress analyzer (made in Japan); in so doing, the assumption was made of residual stresses in both the rivet and the female structural part being directly interrelated. The research area has the 8 by 4 mm size and was limited by dimensions of the beam emitted.

To establish the "echo signal amplitude – residual stress" correlation, we carried out tests on a specimen cut out of a longitudinal joint (where a stiffener had been riveted) in a full-scale panel of a passenger-carrying airplane wing that has been fatigue tested previously. The panel was manufactured from the 1163T7 alloy (a rolled plate), and the stiffener, from the V95ochT2 (a structural shape); the system was fastened by soft-collar rivets made of the V65 material. Appearance and dimensions of the specimen may be seen in Fig. 4.

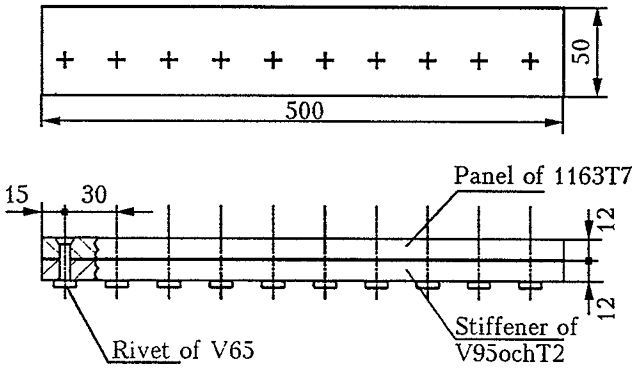

FIGURE 4 - Specimen with riveted joint

Figure 5 demonstrates measured data on echo signal distribution around holes in the panel and stiffener. Figure 6 represents profiles of mean echo signal amplitudes along the riveted joint. On the basis of ultrasonic measurement results we have selected the joints with minimum, maximum, and middle values of echo amplitude. To these joints the X-ray method has been applied in order to obtain residual stress profiles along the rivet axis. Figure 7 provides residual stress profiles along the axis of the joint, as well as the results of ultrasonic measurements. In general the pattern of the echo signal amplitude mean value is agreed with residual stress variation. Typical of all rivets are almost identical residual stresses at both rivet ends. Along the rivet axis the stress varies from 0 to 20 kg/sq.mm. At the same time the residual stress profile of the joint featuring the maximum value of the mean echo amplitude (that is, the minimum clearance) has a notable drop (to 0 kg/sq.mm) in the area where the panel and the stiffener are connected (in the ultrasonic inspection zone). The joint with the middle value of the mean echo amplitude has a similar kind of residual stress profile, but the stress drops to -10 kg/sq.mm. The joint with the minimum echo amplitude (that is, with the maximum clearance) does not have such drops.

The ultrasonic and X-ray measurement results were processed by the least-square method. In doing so, the echo signal mean amplitude was corresponded to by a mean residual stress obtained by measurement in two diametrically opposed areas along the row.

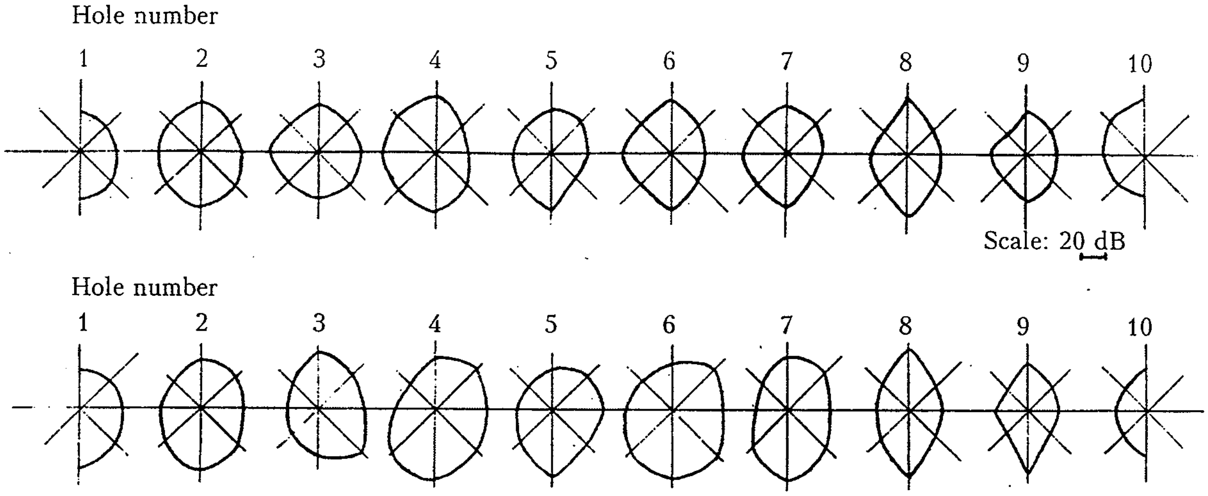

FIGURE 5 - Reflected signal amplitude profiles around rivets: *a* – panel, *b* – stiffener

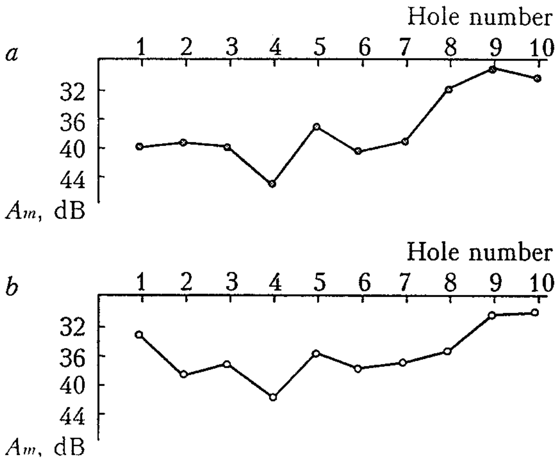

FIGURE 6 – Reflected signal amplitude distribution along rivets

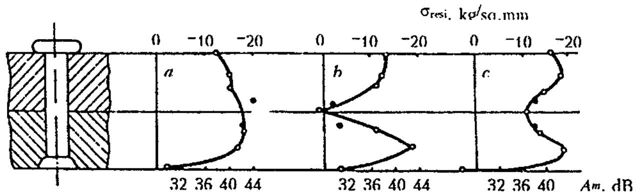

FIGURE 7 – Residual stresses in riveted joints: *a* – joint #4, the maximal clearance; *b* – joint #9, the minimal clearance; *c* – joint #2, intermediate clearance

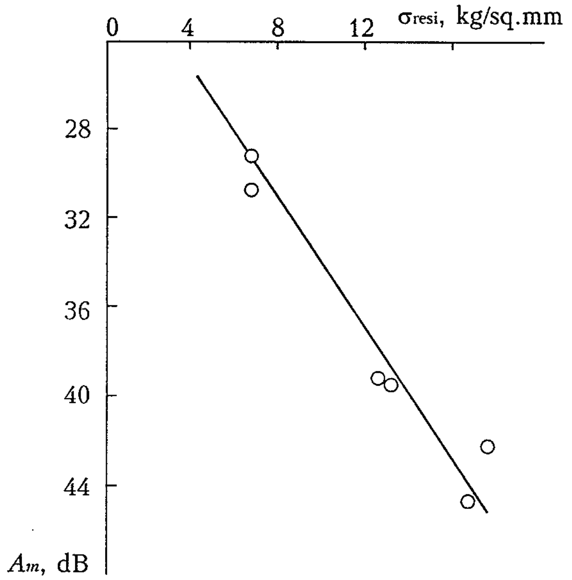

FIGURE 8 - Dependence of the ultrasonic signal amplitude on residual stress

Figure 8 shows the results of measurements and processing. The ultrasonic signal amplitude depends on the residual stress as,

$$A = 19.3 + 1.5\sigma_{resi}$$

with the correlation coefficient $r = 0.95$. As assessed on the basis of the maximum deviation, the ultrasonic measurement error is 12% of the quantity measured.

The high value of the correlation coefficient evidences a close relation of the ultrasonic amplitude to residual stresses and confirms validity of the ultrasonic method for determining clearance in riveted joints.

It is known that introduction of large clearance causes plastic deformation of the parts joined; therefore, the results on deformation zones in joints with clearance may also validate the ultrasonic inspection method.

Note, however, that deformation zones in joints with aluminum structures are impossible to study by the traditional microsection metallographic analysis because no indication of deformation might be found. This is due to the fact that microscopic plastic deformation in a face-centered lattice is implemented through sliding. The track of sliding is a line where the sliding plane intersects with the microsection metallographic specimen, and vanishes in the course of preparing the microsection metallographic specimen. Hardness measurement methods widely utilized in laboratories are also ineffective because of their considerable data scatter when used for evaluating the surface hardening in deformed aluminum structures.

For estimating the deformation zones the present work relies upon the aluminum alloy hardening evaluation method based on recrystallization-type annealing; the method has been developed by Mrs. Ye.S.Kosyakina, a NIAT employee. The concept is as follows. Dislocations and other defects in the lattice that appear during plastic deformation, become recrystallization centers during the subsequent annealing; therefore, recrystallization in the course of a deformed metal would initiate at worked areas. By selecting a proper temperature-time variation law, one could make the hardened layer appear as a fine-grain zone on the non-crystallized material background. The recrystallization zone size is an indicator of deformation amount – and clearance severity.

The quality of a joint with clearance was estimated by applying the ultrasonic method and the recrystallization annealing method to five specimens with riveted joints. The test specimens were cut out of a longitudinal joint (where a stiffener had been riveted) in a passenger-carrying airplane wing panel that has previously been fatigue tested. The first stage was the ultrasonic measurement of echo amplitude. A mean amplitude was determined on the basis of nine readings at various locations around the hole.

As many as 60 riveted joints have been inspected to chose joints with the maximum and minimum values of the mean amplitude:

Joint #	14	23	38	39	54
Material	V-95	1163	V-95	V-95	1163
A_m, dB	49.4	46.9	36.1	34.8	34.9

At the second stage the joints have passed recrystallization annealing. For the alloys of interest the recrystallization conditions were tuned thoroughly. In order for the residual stress not to be eliminated, all joints were first heated to a certain temperature, and then the specimens were cut out in the necessary direction, and microsection metallographic specimens were manufactured, etched (in the Keller agent) and studied visually (in the Neophot microscope).

In the specimen # 14 along the rivet rod on the V-95 alloy the recrystallized layer has the thickness of one grain and the width of 0.03 mm.

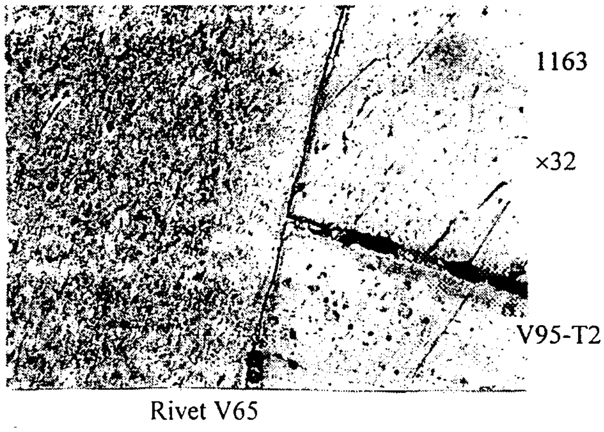

FIGURE 9 – Microstructure of materials upon annealing around joint #38

In specimens # 38 and # 39, no recrystallization has been revealed in the maximum-stress area (at the point of the rivet) and the area where the skin is joined with the stiffener (in the ultrasonic inspection area). Results of analyzing the microsection metallographic specimen is represented in Fig. 9.

In specimen #54 (made of 1163) recrystallization was local. Depth of some "isles" was 0.08 mm. There exist area where no recrystallization is seen at all.

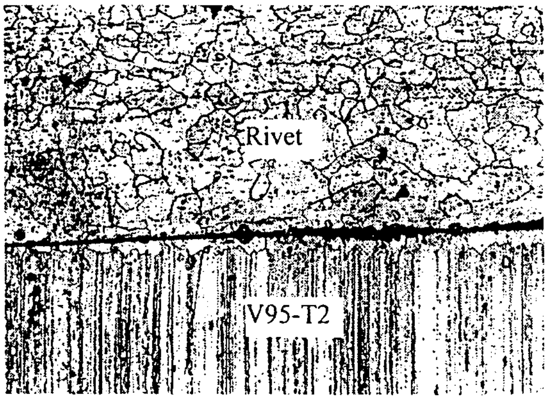

FIGURE 10 – Microstructure of materials 1163 and V95-T2 around joint #23 upon annealing

In specimen #23 (made of 1163) recrystallization was more uniform than in the previously mentioned specimen. The maximum recrystallization layer depth was 0.1 mm (Fig. 10).

The metallographic analyses after recrystallization annealing were compared with ultrasonic measurement data; this demonstrated that joints with the maximum echo amplitude feature the minimum deformation amount Joints with a greater deformation show a lower amplitude of echo signal. Thus, deformation in a joint with clearance is definitely related to ultrasonic readings. A quantitative description of the "deformation – signal amplitude" correlation has not been derived because there were limited arrays of data obtained. Nevertheless, the results validate the ultrasonic methods for evaluating joints with clearance.

CONCLUSION

1. Established has been the relation between the ultrasonic echo signal amplitude and the radial clearance amount in riveted joints with soft-collar rivet; the equation is nonlinear.

2. Errors in evaluating clearance by the ultrasonic method are variable asymmetric quantities, growing with clearance amount.

3. High reliability of the ultrasonic inspection is evidenced by the high correlation coefficient ($r = 0.95$) for ultrasonic measurements and residual stress X-ray-based measurements.

4. The echo amplitude is unambiguously related to stresses in a joint with clearance; this is

confirmed by the analysis based on recrystallization annealing method.

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