Acoustic Non-Destructive Testing at Production of Liquid Jet Engines

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Abstract. Liquid jet engines are the basis of power-plants on modern space-rockets, that's why acoustic non-destructive testing is of great importance in production of engines' parts and units and at assembling of engines. Acoustic NDT is implemented for testing of half-finished products (such as rods, castings, sheet metals), weldings and connections. At that pulse-echo and mirror through transmission ultrasonic methods are used. For rods testing special equipment for mechanized ultrasonic testing was developed. This system provides detection of internal defects with double-crystal transducers and of external longitudinal-oriented defects with angle transducers at forward-back movement of rod.
The acoustic tensometry is implemented for strain measurements of bolts and studs of plug-type connections. Special system, realizing this method with calibrating stand and methodology of calibration and strain-stress testing was developed. The advantage of this method is an active character of testing, providing optimization of strain tightening of each thread pair and of the whole connection. The results of researches, made on the base of JSC "JSC «Glushko Scientific Industrial Association «Energomash»», are the base of industry standard "Strain tightening of thread connection testing with acoustic methods". As metrological support set of standard samples was developed.
The report is devoted to the questions of choice of acoustic NDT methods and means for welds testing, metrological support and technology of ultrasonic testing, gives the statistic data of detected defects, influence of flaw detector's sensitivity and acoustic tensometers' accuracy parameters on the operability of welding and plug-type connections. The tasks and perspectives for application of ultrasonic tomographic systems for complex geometry welds testing and ultrasonic tensometers with EMA transducers for plug-type connections are discussed.

JSC «NPO Energomash named after academician V.Glushko» is the leader in development and production of liquid propellant rocket engines (LPRE). Engines here were created, which one have put into orbit the maiden artificial satellite of the Earth and have ensured flight of first cosmonaut in the world. Overwhelming majority of the Russian spacecrafts are put into space with the help of engines, developed in NPO Energomash. They successfully work today in launch-vehicles (LV) "Soyuz", "Molnia", "Proton", "Cosmos", "Zenit" etc.
Russian RD-180 engine was installed on a first stage of "Atlas V" LV, which one has put New Horizons spacecraft on a way of interplanetary flight to a planet Pluto (fig. 1).

The liquid propellant rocket engines are the basis of power plants of modern space rockets, therefore serious attention is given to problems ensuring of reliability with use of the non-destructive check (NDC) during manufacturing of parts, units, at assembly, tests and operation of engines. The part blanks (bars, castings and sheet material), welded and detachable connections are subject NDC, thus echo - pulse and mirror - shaded methods of ultrasonic (US) check are applied. The technology of US check of weld joints of units and parts of the complicated shape envisions use of standard and original techniques with use of modern digital ultrasonic defectoscopes. The research of expensive units with the detected defects of weld joints is provided with use of US tomographs.

Fig. 1. Start of "Atlas V" LV to a planet Pluto

The device for mechanized US control with registration of results of the check was developed for the check of bars. This device ensures detection of internal defects with applying separately - mated converters and outside defects of longitudinal orientation by inclined converters at a rotationally – forward movement of a bar.

Acoustic strain measurement differs essentially from conventional methods of a non-destructive testing, a major task of which one is the check of a force of a tightening of bolts and studs of detachable connections. In modern designs of engines such connections average from 40 up to 70 % of total amount of connections. The task of the check of value of a tightening of threaded parts in detachable connections of LPRE is caused by necessity of reduction of quantity of engines allocated for development and tests because of their high price and increase of reliability in case of reusable flight operation.

The theoretical and experimental researches of acoustic-elastic effect are made by author's team [3, 4]. A fundamentals of the linear theory of acoustic elasticity are developed on the basis of matrix methodology. Its essence consists of the introducing of matrixes of speeds, relative measurement of speed and time of propagation of ultrasonic waves, in establishment of relations against values describing external actions (mechanical stresses σ_{ln}, temperature T, magnetic H_j and electrical E_j fields), in definition of a kind of factors linking required values. The suggested methodology has a number of advantages, among which ones it is necessary to mark a standard method of setting of the task, capability of obtaining of principally new results, relative simplicity of computational relationships. The obtained relationships allow to decide as a straight line task of acoustic elasticity (definition of the elastic characteristics of the medium at known stresses), and return one - check of mechanical stresses by results of acoustic measurements. The ideally elastic originally isotropic boundless medium (in which one the anisotropy can be induced as a result of any external actions) and harmonic monochromatic waves are used as initial models. The major task consists in determination of non-linear on deformation corrections to speed and polarization of elastic waves.

The computational relationships of an acoustic strain measurement are obtained in the form of:

$$\delta v_{ik} = \beta_{ik}\sigma_{\ln} \; ; \quad \delta\tau_{ik} = \alpha_{ik}\sigma_{\ln} , \qquad (1)$$

where δv_{ik}, $\delta\tau_{ik}$ - matrixes of relative change of speed and time of propagation of US waves under action of stresses $\sigma_{\ln}$;

$\beta ik, \alpha_{ik}$ - matrixes of acoustic-elastic factors of speed and time of propagation of US waves, accordingly. The relation between α_{ik} and βik looks like:

$$\alpha_{ik} = A_{ik} - \beta_{ik} \qquad (2)$$

where A_{ik} - the function of a Young's modulus E and Poisson's constant V is written in form of matrix.

The obtaining of computational relationships (1), (2) has allowed to work out the common approach at development of a serial production equipment, its metrological and methodological maintenance.

The expressions of acoustic-elastic factors $\beta_{ik\ln}$ and $\alpha_{ik\ln}$ through members of matrixes of acoustic-elastic factors of single-axially stressed state β_{ik}^{Z} and α_{ik}^{Z} were found.

The structure and signs of acoustic-elastic factors are studied, their calculation for a number of structural materials is made, the expressions for acoustic-elastic factors of longitudinal and shift waves for a case of hydrostatic pressure are found:

$$\beta_p^l = \beta_{33} + 2\beta_{11}, \quad \beta_p^t = \beta_{12} + \beta_{13} + \beta_{31}, \quad \alpha_p^l = \alpha_{33} + 2\alpha_{11}, \quad \alpha_p^t = \alpha_{12} + 2\alpha_{13}.$$

As the time of propagation of elastic waves is directly monitored parameter in an acoustic strain measurement, then in the practical purposes it is convenient to use a matrix of acoustic-elastic factors of time of propagation α_{ikln}. The results, obtained for volume waves, were widespread on surface waves of the Rayleigh, and it was revealed, that in case of effect of principal stresses the relative change of speed $\delta\upsilon^R$ is determined by expression:

$$\delta\upsilon_{ik}^R = r_{ikln}\sigma_{ln} \qquad (3)$$

In case of flat stresses (for example $\sigma_{33} = 0$) the main equations become simpler:

$$\delta\upsilon_{13}^R = \beta_{31}\sigma_{11} + \beta_{12}\sigma_{22}\,; \delta\upsilon_{23}^R = \beta_{12}\sigma_{11} + \beta_{31}\sigma_{22} \qquad (4)$$

Some features of propagation of elastic waves in actual conditions, in particular, difference of acoustic-elastic factors for phase and group speeds of ultrasound are reviewed. The experimental researches of features of propagation of elastic waves in a solid body at external actions are made. First of all it is concerned research of change of time (speed) of propagation of US oscillations at single-axis loads with the purpose of research of acoustic-elastic factors of a single-axial - stressed state β_{ik}. The results of experiments confirm reliability of expressions (1) and (2). Such relations are confirmed up to values σ_T for all structural metals.

For an example it is presented in a fig. 2 the relation $\delta\upsilon_{ik} = f(\sigma_{ln})$ within the limits of change σ_{ln} up to 200 MPa. The measurements were conducted with the help of US instrumentation having relative error 10^{-4}. Maximum change of values $\delta\upsilon_{ik}$ for the most metals within the limits of elastic area does not exceed (1-2) 10^{-2}, that is (1-2) %.

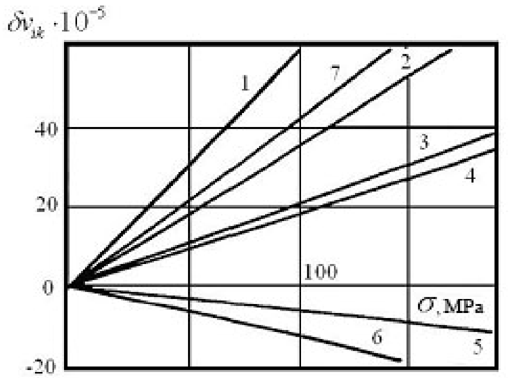

Fig. 2. Relation of relative change of speed of US waves for Д16Т alloy against value of stresses:
1 - $\delta\upsilon_{zz}$, 2 - $\delta\upsilon_{xz}$, 3 - $\delta\upsilon_{zx}^R$, 4 - $\delta\upsilon_{zx}$, 5 - $\delta\upsilon_{xy}$, 6 - $\delta\upsilon_{xx}$, 7 - $|\delta\upsilon_{xz}| + |\delta\upsilon_{xy}|$

The physical-mechanical characteristics and numerical values β_{ik} are presented in the tables 2 and 3 for materials with a broad range σ_T, however with small difference of the elastic characteristic.

It is shown, what values β_{ik} depend on the elastic-plastic characteristics of a material. It is necessary to pay attention on following. Those acoustic-elastic factors are greatest ones on an absolute value, for which the vector of oscillating speed coincides with vector of action of applied force. At development of methods of an acoustic strain measurement an absolute values β_{ik} determine sensitivity of acoustic measurements to monitored value of stresses.

Table 2

Material	ρ_i, g/cm^3	ν	σ_T, MPa	Elastic modules, GPa				
				λ	μ	-l	-m	-n
60С2Н2А	7,744	0,290	1600	112	82	314	639	840
35ХГСА	7,748	0,289	1300	110	80	325	632	804
Ст. 3	7,800	0,288	250	112	83	360	690	820
ЛС59-1	8,380	0,352	150	91	38	410	414	488
Д16	2,772	0,339	120	60	28	275	394	368

In practice, when the control is necessary to make directly in process of operation, temperature of monitored object, as a rule, is unstable one. Consequently the temperature relation of modules of elasticity μ, l, m, n was investigated. The results are obtained with the help of research of change of speed of propagation of US oscillation and definition of value of acoustic-elastic factors depending on the external factors. The obtained results have proved a used linearization.

Thus, the common overview about behavior of elastic oscillations of a different type at single-axis homogeneous stress in metals is obtained as a whole. It has allowed to establish expediency of use (in some cases) simultaneously of several types of US waves (for example, two ones). At realization of real experiments on the control of connections assembled with tightness, shift and surface US waves were used.

The comparison of computational and experimental values has shown their coincidence within the limits of 10 %. It is determined, that the acoustic strain measurement allows to understand a state of stress both in elastic, and in plastic area of deforming. Theoretical calculations and the results of experiments demonstrate, that it is necessary to conduct the acoustic measurements with relative error no more than 10^{-5}. The hardware implementation envisions use of piezo-electric converters and electromagnet - acoustic converters, and also their combination.

Table 3

##	Material	Acoustic-elastic factors of speed β_{ik}, 10^{-12}, Pa^{-1}					Acoustic-elastic factors of time of propagation α_{ik}, 10^{-12}, Pa^{-1}			
		$-\beta_{zz}$	β_{xx}	β_{xz}	$-\beta_{xz}$	$-\beta_{xy}$	α_{zz}	$-\alpha_{xx}$	$-\alpha_{xy}$	$\alpha_{xz}=\alpha_{zx}$
1	60С2Н2А	12,1	1,2	1,6	7,9	1,8	16,8	2,6	3,0	6,5
2	35ХГСА	13,6	1,3	1,3	8,2	1,9	18,5	2,7	2,7	6,8
3	Ст. 3	14,6	1,4	1,6	8,3	2,3	19,3	2,7	1,9	7,0
4	ЛС59-1	32,8	3,1	8,8	18,7	5,5	42,6	6,5	12,2	15,3
5	Д16	71,4	11,7	4,9	36,0	18,1	84,7	16,7	9,5	31,4

For a number of years control of a force of a tightening of detachable connections in assembly shops of aerospace companies is provided with serially production ultrasonic strain gauges of domestic production such as УП-31Э (Akon-4), УП-31ЭМ (Akon-4M). The metrological maintenance of hardware for measurements is realized with the help specially designed complete set of standard samples КМВР-01, representing the certificated samples on time of propagation of a ultrasound with accuracy 0,006 microseconds.

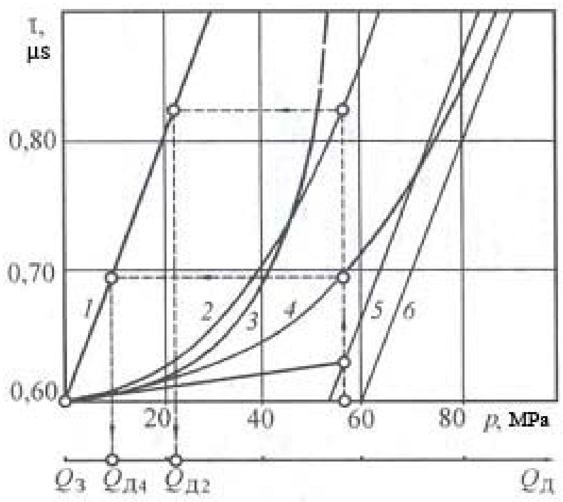

Fig. 3. A graphic method of definition of a factor of the main load by results of acoustic strain measurement

Before use of acoustic strain measurement frequently at development of the connection it "was uncovered", and the behavior of a curve of additional load, in particular, value of a factor of the main load χ was differed from values obtained by a classic computational method.

But only US method has allowed to study actual objects during assembly and hydrotests, and the visual picture of operation of connection as a whole was obtained. It has appeared specially important, as was found out, that the local rigidity of separate segments of the actual connection is unequal. It was offered to account for such differences of rigidity with the help of a factor of the main load χ, determined by an acoustic method:

$$\chi = \frac{\tau_Д - \tau_З}{KQ_Д} \qquad (5)$$

where,τЗ , τД - time of propagation of a ultrasound after the applying main load Qз and additional load QД, accordingly; K – constant of proportionality. The upper segment of the calibration characteristic of bolts of the connection is shown in a fig. 3. The beginning of coordinate axes is placed in point, corresponding to a nominal value Qз. The curves 2-4 illustrate (for connections of different rigidity) additional changes of time of propagation of ultrasound in the tightened bolts due an operation pressure p in an internal volume of a design. The values of pressure, at which ones connections are uncovered, are determined by points, where tangents to curves 2-4 are parallel to the line of uncovering 5, counted on the classic theory. For calculation of current values of additional load QД the auxiliary abscissa axis, being prolongation of the corresponding axis of

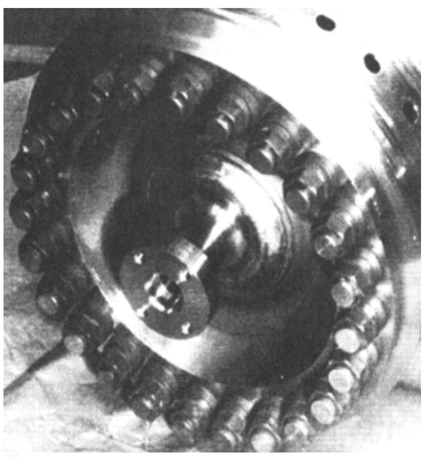
Fig. 4. A general view of a detachable connection of the gas generator of one LPRE, made in NPO Energomash

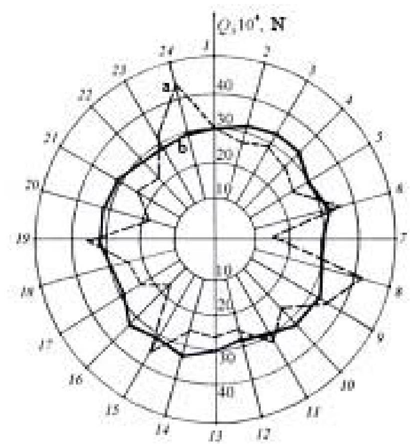
Fig. 5. Distribution of forces in studs at the check:
a - by a torquemeter wrench,
б - by a US method

the calibration characteristic, is drawn. The simple geometrical constructions allow to proceed from current values p to values QД. Obviously, that the additional load on a bolt in the rigid connection is much less at the same values of an operation pressure, and the load curve passes closer to a calculated curve 5.

The important advantage of a developed method before other ones, which don't use an ultrasound, is the active nature of a procedure of the check. It means, that the given technique allows not only to evaluate quantitatively, as each threaded pair is tightened, but also gives run-time and reliable information that it is necessary to change for approaching an effort of a tightening to a best value.

Results of researches held on the basis JSC «NPO Energomash named after academician V.Glushko», have allowed to create a technique, which one underlay in the basis of the branch standard "Check of a force of a tightening of threaded connections by an acoustic method".

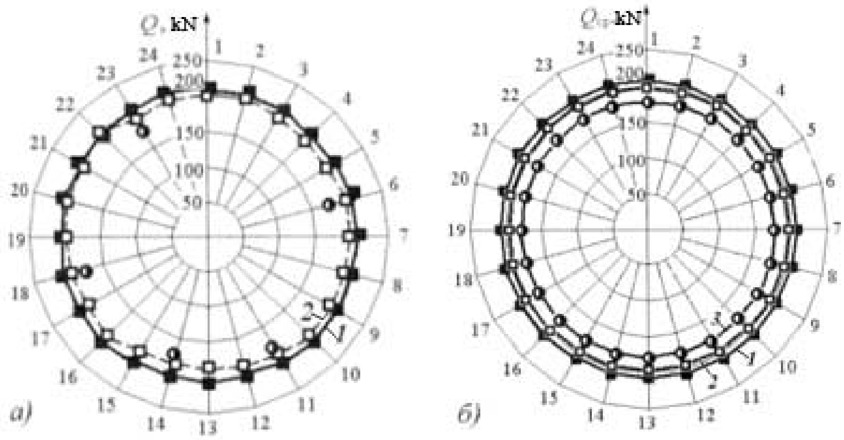

Fig. 6. Results of acoustic strain measurement: distribution of forces Q in studs (a) and mean forces Qcp in connection (б) at different phases: 1 - assembly, 2 - recheck after hydro-pneumatic tests, 3 – torque retention loss (actual forces) (1 … 24 - numbers of studs)

Besides a technique of realization of graduation and check of a force of a tightening the standard sets a requirements to design of used parts and check samples, regulates the order of processing of measurement results, rule of paper work with design and manufacturing documentation. The requirements of personnel safety are taken into account also. The technical conditions on the check are developed, in which ones the requirements of realization of acoustic strain measurement in relation to particular items are defined concretely, the lists of connections, being a subject to the check are presented. As an example a general view and comparative results of different methods of strain measurement of a detachable connection of the injector head and case of the gas generator of one LPRE of NPO Energomash development are shown in a fig. 4-6.

For metrological maintenance of devices the set of standard samples is designed.

The development of the scientific-technical, metrological and methodological fundamentals of an acoustic strain measurement has allowed to conduct 100 % manufacturing check of design parts directly in the production and operation conditions.

With the purpose of further increase of accuracy and the run-time capability of the check of detachable connections the researches of a feasibility of electromagnet - acoustic converters are made.

Literature

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