Development and experimental testing of the technique of ultrasonic control of brazed joints of heat exchangers

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Abstract. High reliability requirements are imposed on the quality of the soldered joints. Typical defects in the soldered joints of heat exchangers are non-soldered. The minimum size of the non-penetration area that must be detected is about 1 square millimeter. The existing assessment of the quality of soldering is reduced to destructive tests. These tests include hydraulic and pneumatic tests. There are control technologies that use non-destructive methods. For example, the applicability of the ultrasonic echo method based on thermo-optical (laser) excitation of ultrasonic waves has been proven. However, continuous inspection of the liquid-propellant engine chamber using the traditional echo method is not rational, since the inspection speed is limited by the size of detected defects (1 square millimeter) and amounts to a few millimeters per minute. In order to increase the scanning speed without losing the ability to reliably detect defects such as "non-soldered", it is proposed to use phased array antennas (PA) as a means of implementing the ultrasonic echo method. The paper considers the issues related to the interpretation of the information obtained when scanning the soldered joint, as well as issues related to modeling the acoustic field in the model of the soldered joint of the heat exchanger.

1. Introduction

High reliability requirements are imposed on the quality of the soldered joints. This is due to the high-temperature modes of operation of double-walled finned brazed structures and the corresponding high loads, at which the presence of a defect in the joint structure can lead to the destruction of the entire product. Typical defects in solder joints of finned double-walled brazed structures are non-soldered. The magnitude of the opening of the non-soldered is not precisely established, however, according to preliminary estimates, it can be of the order of several micrometers. As practice shows, the minimum size of the non-soldered area, which must be detected, is about 1 mm².

The existing assessment of the quality of soldering is regulated by OST 92-1190 and in practice, in most cases, is reduced to carrying out destructive tests. These tests include hydraulic and fire tests. There are control technologies that use non-destructive methods [1]. For example, the applicability of the ultrasonic echo method based on thermo-optical excitation of ultrasonic waves has been proven [2–4].

However, continuous inspection of the product in the soldering area using the traditional echo method is not rational, since the surface scanning speed is limited by the size of detected defects and amounts to a few millimeters per minute. In addition, the control results are presented in the form of A and B-scans that are difficult to interpret.
In order to increase the scanning speed without losing the ability to reliably detect non-propay defects, it is proposed to use phased array antennas (PA) as a means of implementing the ultrasonic echo method. The method of displaying information on the flaw detector screen (S-scan) allows visualizing the internal structure of the soldered joint. A set of operations for adjusting the sensitivity and setting the laws of focusing of the PA will make it possible to achieve the concentration of the ultrasonic field in the soldering plane, which increases the likelihood of detecting defects in the soldered joint. The confirmation of the results of the PA control was carried out using an optical-acoustic transducer, which also implements the ultrasonic echo control method. The contact laser-ultrasonic method is based on laser excitation of broadband acoustic signals in a specially developed optical-acoustic transducer.

2. Finite element modeling
To assess the possibility of using the PAA technology to control soldered joints, the acoustic field was simulated using the Comsol Multyphysics software of the Elastic Waves, Time Explicit module. This module allows you to solve equations of the theory of elasticity using the finite element method.

The simulation was carried out in order to determine the amplitude of the reflected signal from the model of the section of the soldered joint with a complete loss (defect-free connection) and with a defect of the “non-solder” type. For this, the acoustic field of a phased antenna array was simulated and the focal law was calculated, at which the maximum field intensity falls on the section with soldering.

The phase shift of the generation of each element of the PAR was calculated by the formula:

$$\varphi_n = \frac{x_n}{c} = \frac{\sqrt{f^2 + l_n^2 - f}}{c},$$  \hspace{1cm} (1)$$

where \(\varphi_n\) – phase shift of the PA element, \(x_n\) – the difference between the focal length and the distance from the center of the PA element to the focal point, \(f\) – focal length, \(l_n\) – distance between the center of the PA element and the center of the PA, \(c\) – the speed of propagation of longitudinal ultrasonic waves in the test object.

Explanations for formula (1) are shown in figure 1.

![Figure 1. Scheme for calculating the phase shift of the generation of PA elements.](image)

To reduce the amount of calculated data, modeling was carried out for 4 active elements of the phased array. This approach does not contradict the real algorithm of the PAR operation, since the instrumental implementation makes it possible to initiate the operation of various groups of lattice elements. For example, each sequential array of elements can be focused to a specific depth to achieve better resolution than focusing all array elements to a single focal point.

Figure 2(a) shows the results of modeling the acoustic field of a PA in a defect-free joint. Figure 2(b) shows a model of the propagation of ultrasound in a defective soldered joint (a “non-soldered” defect).

3. Approbation of PA technology on samples of complex soldered joints
The existing method of soldering control based on thermooptical excitation of elastic vibrations in the material of the object has a significant drawback, which consists in a low scanning speed. This is due to the narrow directivity of the acoustic field of a single-element laser-ultrasonic transducer. In addition, due to the complex internal structure of typical soldered joints of double-walled finned structures, an ambiguous interpretation of the results obtained, presented in the form of A or B-scans, is possible.
Deciphering the control results seems, in practice, extremely difficult. The disadvantages described above lead to a decrease in the reliability of the obtained control results.

Figure 2. The result of modeling the field of a straight 8-element phased antenna array in the Comsol Multyphysics program, (a) – a defect-free connection, (b) – non-soldered connection.

To search for defects of the "non-soldered " type in soldered joints with the ability to visualize the controlled section, it is proposed to use the ultrasonic echo method based on the PA. This method will significantly increase the scanning speed due to the larger aperture of the sensor, in comparison with the control of a single-element transducer. To implement the selected method, an Olympus OmniScanMX2 flaw detector with a 16-element phased antenna array was used.10 MHz (figure 3).

Figure 3. Olympus OmniScanMX2 flaw detector.

To confirm the presence of a soldering defect detected during continuous inspection of the PA, it was proposed to use the UDL-2M laser-ultrasonic flaw detector developed at the International Laser Center of Moscow State University, as an additional inspection method complete with a combined broadband optical-acoustic transducer (OAT) (figure 4). The advantages of the laser-ultrasonic method for generating ultrasonic waves are as follows:

- high resolution of the measurements in the time domain due to powerful and short aperiodic ultrasonic signals generated by laser excitation;
- high accuracy of measurements of the speed of ultrasonic waves (relative error no more than 1%, repeatability 1–2 m/s) due to the broadband and short duration (70–80 ns) of thermo-optically excited acoustic pulses.

The diagram of the propagation of ultrasound in a soldered joint of a double-walled finned structure in the presence of non-soldered sections in it, as well as a typical B-scan of a defective joint, is shown in figure 5. Blue arrows indicate the recorded acoustic signals from the cavities between the ribs, red arrows – reflections from non-soldered or structural grooves, green circles – areas in which signals should be recorded in the presence of a loose or torn edge.
4. Main results and their discussion

In order to confirm the possibility of detecting non-propay defects in complex soldered joints using a PA, the following sequence of studies was developed:

- production of a control sample (CS) from a cutout of a soldered joint with an imitation of a “non-propay” defect;
- adjustment of a flaw detector with a PA (Olympus OmniScanMX2) on the CS, taking into account the data obtained during the modeling of the acoustic field of the PA in the soldered joint;
- revealing of a defect model of the “non-flash” type in the CS using the PA;
- confirmation of the detectability of the detected reflector using the UDL-2M flaw detector;
- carrying out complex ultrasonic testing (phased array and laser ultrasonic testing) with localization of non-solder points in prototypes of soldered joints;
- metallographic confirmation of the presence of detected defects in prototypes.

For the manufacture of CS, a cut from a product with a double-walled ribbed structure was used. From this cut, 2 CS were made (figure 6):

- defect-free CS (sample № 1);
- KO with a flat-bottomed hole with a diameter of 1.1 mm for the entire width of the rib, imitating "non-soldered" (sample № 2).
Figure 6. Photo of defect-free sample № 1 and sample № 2 with an artificial defect.

Figure 7 shows the interpretation of the control results obtained by the PA on the CS. The red circle shows the echo from the flat-bottomed hole (non-drip model).

As can be seen from the results presented above, the "non-soldered" defect model is reliably detected against the background of noise during the PA control.

The result of confirmation of the echo method detected during the PA control, implemented on the basis of the UDL-2M laser-ultrasonic flaw detector, is shown in figure 8.

Figure 8. B-scan of the reflector in the control sample.

To substantiate the applicability of the proposed method, samples of cutouts from a product with a double-walled ribbed structure were inspected. The sensitivity adjustment of Olympus OmniScanMX2...
and UDL-2M flaw detectors was carried out on sample № 2. Section scans with detected echo-signals are shown in figure 9.

![Section scans with detected echo-signals](image)

**Figure 9.** Acoustic image of detected defects in a cut from a product with a double-walled ribbed structure.

The detected cross-section with a rejection level echo was examined using metallographic analysis tools. Figure 10 shows a photograph of a microsection with a "non-soldered" defect.

![Photograph of a microsection with a "non-soldered" defect](image)

**Figure 10.** Results of metallographic studies of the revealed defects.

Thus, the possibility of using PA for monitoring complex soldered joints and searching for a “non-soldered” defect in them was proved.

5. Conclusion

As a result of studies of the possibility of using the technology of complex ultrasonic testing of soldered joints, the following results were achieved:

- a computer simulation of the acoustic field of a phased antenna array in a soldered joint in the presence and absence of a “non-soldered” model was carried out;
- the sensitivity of the control (flat bottom hole \( d = 1.1 \) mm) was confirmed on the manufactured control sample. The control results were confirmed using the echo method, realized by the thermo-optical method of ultrasound excitation, as well as metallography;
- it has been shown that the proposed inspection method using a PA makes it possible to detect real defects in complex soldered joints.

References

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