Integral Thickness Measuring

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***Abstract*–The method of integral thickness measuring has been developed. It is realizable on the basis of standard AE systems and AE sensors. On the object at a distance of several meters or tens of meters apart two AE sensors are placed. They are used as a transmitter and a receiver of the acoustic signals. On the spectrogram of received signal the dispersion curves are extracted. The arithmetic mean thickness, the thickness dispersion, and the estimation of the minimum thickness can be calculated.**

***Index Terms*—Thickness measuring, dispersion curves, Lamb waves, spectrogram.**

I. Introduction

MOST of the acoustic emission (AE) systems operate within the frequency range from 30 kHz to 500 kHz. This frequency range is used for AE testing, since only within this range the following two requirements are satisfied at the same time: first, the acoustic signal attenuation is so small that the useful signals can cover distances of several meters; and second, the noise level is low in comparison with the useful signals.

The unique properties of the above frequency range allow for fast and complete testing of the large areas of the object using a small number of sensors. It would be useful not only for the AE techniques, but also for the active acoustic testing [1]. The combination of two said techniques in a single device is particularly promising.

One of the most pressing problems of nondestructive testing (NDT) is detection of corrosion damage of the object and determination of its extent. Generally, values of residual wall thickness and areas of corrosion damage are used as a quantitative characteristic of the degree of damage. To determine these parameters, ultrasonic thickness gauges are commonly used which allow for making local measurements of the wall thickness.

The disadvantages of this method are the high labor content of testing of large-area objects, the necessity to remove insulation on the whole tested area, the impossibility to measure thickness of the object areas to which there is no physical access. These disadvantages lead to that the thickness is usually measured on a small part of area of the tested object as a result of which the degree of corrosion damage is determined with low accuracy; there is a probability of missing a corrosion defect, the degree of subjectivity of testing increases, and, in addition, the object parts of large area remain non tested at all. It should be also mentioned that arrangement of monitoring of the large-area objects by the methods of ultrasonic thickness measuring is a complicated problem.

Thus, the urgent problem is development of the method that permits to carry out an integral measuring of thickness, i.e. to receive data on the wall thickness between the sensors mounted on the object some distance apart.

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II. Integral Thickness Measuring

To solve the assigned task by the acoustic methods, it is necessary to transmit the signal through few meters of the object wall. This requires changing frequency range from the region of above 1 MHz that is typical for the conventional ultrasonic thickness gauges to the range from 30 kHz to 500 kHz that is typical for AE testing.

"INTERUNIS" company has developed the method of integral thickness measuring and monitoring, which is based on the phenomenon of dependence of group velocity of Lamb waves on the product of frequency and wall thickness, and realizable on the basis of standard AE systems and AE sensors [2].

The work scheme is as follows. On the object at a distance of several meters or tens of meters apart two AE sensors are placed (Fig. 1). They are used as a transmitter and a receiver of the acoustic signals. At the transmitter an electrical δ-pulse is fed with the result that this AE sensor radiates a wideband impulse with a length of about 1 μs.

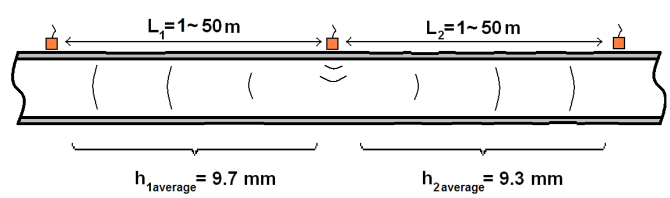

Fig. 1. Emitter and receivers arrangement on the testing object and the arithmetic mean thicknesses values between them.

The spectrogram of the received signal is calculated (Fig. 2). In this spectrogram we extract the dispersion curves of various Lamb waves [2]. Since the arrival times of different frequency components $t(f)$ in a complicated way depend on the plot of thickness $h(x)$ at the section between the sensors:

$$t(f) = t_{RAD} + \int_0^L \frac{dx}{v_i(f \cdot h(x))} , \tag{1}$$

analysis of the frequency dependence of the arrival times of Lamb waves enables to get information about the thickness values at the segment between sensors. Here, v_i is a group velocity of i-th mode of Lamb wave, t_{RAD} is a time point of radiation, L is a distance between sensors.

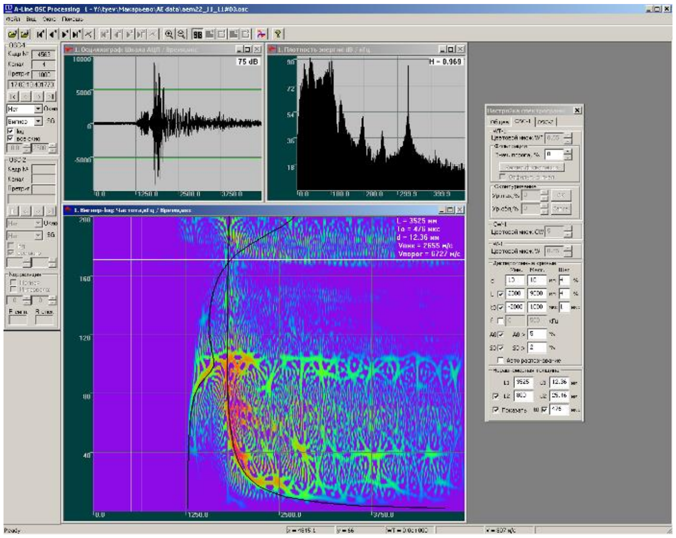

Fig. 2. A waveform, spectrum and spectrogram calculated using a specialized software “A-Line OSC Processing”.

III. Experiments on Objects with Uniform-thickness Wall

To test the method operation, at first we have conducted a series of experiments on pipelines with a uniform-thickness wall. In such cases the equation (1) is simplified to

$$t(f) = t_{RAD} + \frac{L}{v_i(f \cdot h)}. \quad (2)$$

Fig. 3. An experiment on the section of pipeline of length 56 m.

It has been found that the accuracy of thickness measuring can reach 1%. It has been also found that this method is operable at least within the thickness range from 4 mm to 40 mm. It has been revealed, that the present method is operative only when the distances between AE sensors are more than 1 m, because in this case the different portions of dispersion curves are sufficiently separated from each other along the time axis. Furthermore, it has been revealed that the maximum distance can amount up to 12 m on pipes with the insulation and up to 56 m on pipelines with the insulation removed (Fig. 3). The experiments have shown that welded seams have no effect on measurements.

To automate the process of extraction of dispersion curves from the spectrogram and determining the wall thickness in cases when the thickness is uniform, a modification of the Hough transform has been developed. This extraction method has been added to the specialized software “A-Line OSC Processing” developed by “INTERUNIS” company, which is applied for manual and automatic processing of waveforms and spectrograms of AE signals [3].

Since the group velocity of Lamb waves depends on the product of frequency and thickness, the plots of dispersion curves on spectrograms (2) corresponding to any distances between sensors and to any objects of the same material with uniform thicknesses are related to one another by an affine transformation (Fig. 4). Therefore, theoretically any Lamb mode and any frequency range can be used for extraction on such objects – the result is supposed to be the same. However, the most preferred selection is an operation using zero-order Lamb waves, S_0 and A_0, because only waves of this type can propagate at any frequencies that enables to select frequencies rather low to ensure low signal attenuation. In this situation an emitted signal can cover the sufficiently great distances between sensors. Furthermore, for decreasing errors of determination of thickness, the frequency regions are preferable, within which the derivative of the group velocity with respect to frequency is sufficiently high.

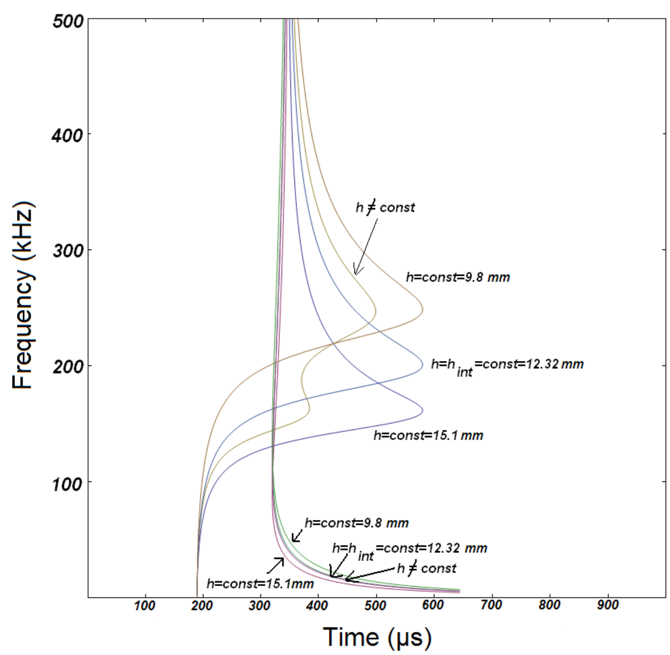

Fig. 4. The plots of dispersion curves on spectrograms corresponding to objects with uniform thicknesses and to objects with thickness variations.

It was found, that the pipe curvature had no significant effect on the values of group velocity and this made it possible to use the model of Lamb waves instead of the more complicated Pochhammer-Chree model [4]. However, when analyzing the spectrograms, the substantial problem was in signals arriving not by the shortest routes, but by helixes, once or several times rounding the pipe. Existence of such signals resulted in occurrence of one or several additional curves on the spectrogram which in contrast to electromagnetic interferences or other noises, are not always distinguishable in their shape from the true dispersion curves (Fig. 5).

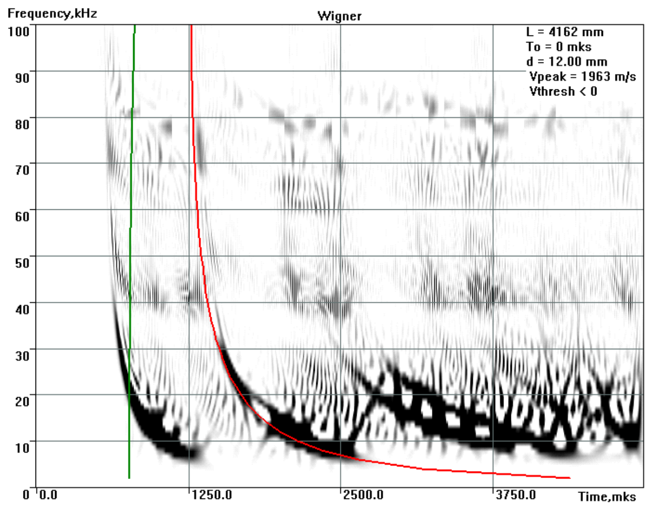

Fig. 5. Signals propagating by the helixes are indistinguishable from signals propagating by the shortest routes.

IV. Experiments on Objects with Wall Thickness Variations

Later, a series of experiments was conducted on the objects with wall thickness variations.

Fig. 6. A pipeline whose thickness was reduced up to 50% of its original value aside of the segment between the sensors.

First experiment was set up in which on a pipeline which firstly had a uniform-thickness wall, the thickness was reduced up to 50% of its original value by means of an angle grinder aside of the segment between the sensors (Fig. 6). As a result, it has been found that the region, wherein the thickness values affect the measurement results, is a narrow elongated area with a width of no more than 6% of the distance between the sensors along the segment connecting the sensors.

In another experiment, on a pipeline which firstly had a uniform-thickness wall, a thickness profile in the form of the step-function was made. To do this, using an angle grinder the thickness was reduced up to 50% of its original value at the portion of the segment between the sensors (Fig. 7). The dispersion curves obtained by experiment (Fig. 2) coincided with the curves calculated for the corresponding geometry of the object by (1).

Fig. 7. A pipeline with the thickness profile in the form of the step-function.

It should be noted that plots of dispersion curves on the objects with significant variations of wall thickness are no longer related to one another by an affine transformation, and differ from the previously discussed case of the objects with the uniform thickness (Fig. 4). As the first approximation, it is possible to consider, that the time of arrival at any frequency is equal to the time of arrival, which would be observed on some object with thickness being anywhere equal to the arithmetic mean value $M[h]$ of thickness on a real object, summarized with an correction, which depends on product of the variation σ^2 of thickness values on a real object, and the second derivative of reciprocal of the group velocity with respect to the product of thickness and frequency:

$$t_i(f) = t_{RAD} + \frac{L}{v_i\left(f \cdot M[h]\right)} + \frac{1}{2}\left(\left. \frac{\partial^2\left(v_i^{-1}(f \cdot h)\right)}{\partial (f \cdot h)^2} \right|_{f \cdot M[h]} \right) f^2 \cdot L \cdot \sigma^2 \cdot$$

For this reason, when applying the extraction method developed for the simpler geometry of objects, a mismatch appears among the results obtained using different frequency ranges and different Lamb modes. For example, when using the portion of mode S_0, corresponding to the low-frequency part of the slope of the group velocity plot, the obtained effective values of thickness falls in the range between the arithmetic mean value and the maximum value of thickness. When using the portion of mode S_0, corresponding to the essentially linear part of the group velocity plot, the obtained effective values of thickness coincide with the arithmetic mean value of thickness. At the same time, when using the low-frequency portion of mode A_0, corresponding to the rapid growth of the group velocity with increasing frequency, the obtained effective values of thickness fall in the range between the minimum value and the arithmetic mean value of thickness.

The mathematical simulation shows that in case when the arithmetic mean value of thickness is determined with the use of the linear portion of the plot of the dispersion curve of mode S_0, it becomes also possible to determine the variation. For this purpose, used is the mismatching value between the arithmetic mean value of thickness and the effective thickness values obtained with the use of the low-frequency portion of mode A_0. For example, we have applied the following formula:

$$\sigma^2 = \frac{t(f) - L \cdot v_{\mathrm{i}}^{-1}\left(f \cdot M[h]\right) - t_{RAD}}{\left(\frac{1}{2}\frac{\partial^2\left(v_{\mathrm{i}}^{-1}(f \cdot h)\right)}{\partial(f \cdot h)^2}\bigg|_{f \cdot M[h]}\right) f^2 L}.$$

In turn, the arithmetic mean value of thickness and the value of variation of the thickness allow estimating of the minimum thickness of the object, for example, by the formula:

$$h_{\min} = M[h] - k\sigma,$$

where k is a safety factor within the range from 0.5 to 3.

Now, work is underway on experimental estimate of determination accuracy of the arithmetic mean thickness value and the minimum thickness value between the sensors. It should be mentioned that this 2 parameters are widely used for NDT of objects exposed to corrosion and erosion [5].

Fig. 8. Portable universal device “UNISCOPE”.

The procedure of data acquisition for the integral thickness measuring has been added to capabilities of the portable universal device “UNISCOPE” (Fig. 8), intended for AE testing, leak detection and vibration control [6]. It has enabled to combine the benefits of active and passive methods of acoustic testing in a single device.

V. Conclusions

1. The method of integral thickness measuring and monitoring is developed. It allows us to measure thickness values in the area between two AE sensors installed on an object some distance apart.

2. The experiments show that the method is operable within the thickness range from 4 to 40 mm and within distances from 1 to 56 m.

3. The region, wherein the thickness values affect the measurement results, is a narrow elongated area with a width of no more than 6% of the distance between the sensors.

4. The use of the portion of mode S_0, corresponding to the essentially linear part of the group velocity plot, makes it possible to determine the arithmetic mean value of the thickness between two sensors.

5. Work is underway on experimental estimate of determination accuracy of the arithmetic mean thickness value and the minimum thickness value between two sensors.

6. The procedure of data acquisition for the integral thickness measuring is realized on the basis of the portable universal device “UNISCOPE” manufactured by "INTERUNIS" company.

References

[1] *Advanced ultrasonic methods for material and structure inspection / edited by Tribikram Kundu*. ISTE, 2007, 393 pp.

[2] S. Elizarov, A. Bukatin, M. Rostovtsev and D. Terentyev. “New developments of software for A-Line family AE Systems”, *Journal of Acoustic Emission*, vol. 26, pp. 311-317, 2008.

[3] D. A. Terentyev, V. A. Barat and K. A. Bulygin, “The extraction method for dispersion curves from spectrograms using Hough transform”, *Journal of Acoustic Emission*, vol. 29, pp. 232-242, 2011.

[4] F. Seco and A. R. Jiménez, "Modelling the generation and propagation of ultrasonic signals in cylindrical waveguides", in *Ultrasonic waves*, ch. 1, pp. 1-28, Intech Open Access Publisher, 2012.

[5] *ASME standard API 579-1/ASME FFS-1*, June 5, 2007, 1128 pp.

[6] S. V. Elizarov, A. L. Alyakritskiy, V. G. Koltsov, V. A. Barat, P. N. Trofimov, “Portable NDT instrument UNISCOPE”, *Proceedings of the 30th European Conference on Acoustic Emission Testing & 7th International Conference on Acoustic Emission EWGAE 30 / ICAE 7*, Granada, 12-15 September 2012.