NON-DESTRUCTIVE TESTING OF SURFACE DEFECTS BY RAYLEIGH WAVE

Abstract: Transit of surface waves through defects in steel surfaces has been viewed in this paper. The form of registered signal is changing as result of complex wave processes in the area of defects. The received signals are digitized and phase-spectral analyses are have been made. If there is a defect in the surface of the samples it shifts the phase of the Rayleigh wave. The phase shift depends on the size of defects. The results obtained can be used for the creation of innovative technologies with improved resolution for testing of surface and subsurface defects in the practice of non-destructive testing.

Keywords: NON-DESTRUCTIVE TESTING OF SURFACE DEFECTS, SURFACE WAVES, PHASE SIGNAL ANALYSIS

1. Introduction

A surface and subsurface discontinuity testing in elastic structures is a traditional problem in the practice of ultrasonic NDT. Usually, the method of reflection of a wave from defects has been used, because by using the method of transmission there is no significant alteration of the basic informative parameter – wave amplitude – it is in the range of 2 – 4%. The roughness after the mechanical processing further impedes interpretation of results [1, 2]. There is an admission in [1] issued on the base of experimental investigations that when the wave pass trough a cylindrical and spherical discontinuity, it disperses. The sources of dispersion are two: close to the surface and at the bottom of discontinuities.

Nowadays a digital transformation of signals is applied for creation innovative NDT technologies. Informative of NDT parameters increases in order to improve resolution and precision of measurement. The phase of wave is increasingly introduced as a parameter for evaluation of current situation of elastic structures when concrete problems are solved. [3].

Aim of this paper is to present theoretical and experimental investigation of Rayleigh wave signal change when pass trough surface and subsurface defects and to suggest additional diagnostic informative parameter for practical implementation in NDT.

2. Theoretical study of the problem and justification

The spreading of the surface wave in elastic body is presented in [1, 2]:

\[ 4k^2q_s - (k^2 + s^2) = 0 \] (1)

where \( q_s^2 = k^2 - k_i^2 \) and \( s^2 = k^2 - k_f^2 \). Here \( k, k_i \) and \( k_f \) are the wave numbers, respectively, on the surface, the longitudinal and transverse waves in the body. The energy density of the wave in the depth \( z \) is determined by the expression [1]:

\[ E = \frac{\lambda^2 \rho s^2 k^2}{2c^4} [A_1 \exp(-2qz) - A_1 \exp(-2s \cdot x) - A_3 \exp(-2sx)] \] (2)

where \( A_1 = 4 + \eta^2 - 4\eta^2 \frac{s^2}{\pi^2} \), \( A_2 = 2\sqrt{-1 + \eta^2} \frac{s^2}{\pi^2} (4\eta^2 - 1) + 2\sqrt{\eta^2 - \eta^4 - \eta^4 \frac{s^2}{\pi^2} (4\eta^2 - 1)) \), \( A_3 = 2\sqrt{\eta^2 - \eta^4} \frac{s^2}{\pi^2} (4\eta^2 - 1) - 2\sqrt{\eta^2 - \eta^4} \frac{s^2}{\pi^2} (4\eta^2 - 1)) \), \( \eta = k_1 / k = c_1 / c, \ \xi = k_1 / k_2 = c_1 / c_2 \). Here \( c, c_1 \) and \( c_2 \) are the speed of propagation, respectively, of the surface, longitudinal and transverse waves ( \( k = \omega / c, \ \omega \) is the angular frequency).

In fig. 1a) is shown a dependance, calculated by (2) for the average density of wave energy from the relative depth \( z / \lambda \) of spreading in a sample of low carbon steel. The energy is unevenly distributed in the depth of the layer. For example, 90% of wave energy passes trough a layer with relative thickness \( z / \lambda = 1 \). The entire wave energy is distributed in a layer with relative thickness \( z / \lambda = 1.6 \). In Fig. 1 b) numerical simulations are shown for the attenuation of the amplitude of the surface wave when cylindrical whole in the range 1 – 7 mm and depth 1 mm in the still sample is available. These results are obtained for wave width 10 mm. In the practice of non-destructive testing is accepted the uncertainty of attenuation of the probe-sample boundary is within 0 - 3 dB and that means the minimal detectable diameter of the cylindrical hole is 5 mm.

3. Experimental study

Experimental studies of the surface of the signal wave passing through a rough-milled steel samples having a thickness 8 mm were carried out (see Fig. 2 a). Artificially discontinuities in the shape of cylindrical openings and channel-shaped are produced in some of the samples. The holes have a depth 1mm and diameter 2 mm, and end with a right cone with a central angle 120° (depth 0.6 mm). The total length of such discontinues is 1.6 mm. They are formed perpendicularly to the surface in one or two rows (depending on the number of holes, the maximum number in a row is 3) with distance \( a = 4.5 \) mm. The ultrasonic sensors are positioned symetrically to the holes when experiments have been carried out. The channel has a width 3 mm and elliptic shape in cross-section, gradually changing depth from 0 to 0.3 mm and is disposed at an angle 30° in relation to the direction of wave propagation. A study in a section of a brake disc from a car with delaminated subsurface and visible cracks has been carried out. The defects are derived during normal operation of the part due to sudden temperature changes like heating and cooling. The surface deviations that were tested are described in Table. 1.

<table>
<thead>
<tr>
<th>Deviation №</th>
<th>Type of discontinuity</th>
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<tbody>
<tr>
<td>1</td>
<td>A cylindrical hole, 1 pc.</td>
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<tr>
<td>2</td>
<td>A cylindrical hole, 3 pc.</td>
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<tr>
<td>3</td>
<td>A cylindrical hole, 6 pc.</td>
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<tr>
<td>4</td>
<td>Channel with variable depth</td>
</tr>
<tr>
<td>5</td>
<td>Brake disc with delaminated subsurface and visible cracks</td>
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The experimental results were recorded by digital flaw detector of LECOEUR ELECTRONIQUE SARL, working with a PC via USB interface. The surface wave is excited and registered by
sensors with rectangular plate with width 10 mm, nominal frequency of 4 MHz and a real resonance frequency 3.81 MHz, determined by spectrum analysis of recorded signals by flaw. The velocity of the surface wave is measured 2923 m/s, which determines $\lambda = 0.77$ mm and layer thickness for distribution within 1.23 mm.

Some results of the comparison of the signals obtained when the waves propagate on surfaces without and with deviations № 1, 2 and 3 are shown in Fig. 3 a) – d). The signals were recorded at different distances between the probes and the deviations. There is no significant dispersion of signals from studies of identical discontinuities. The existing deviation is likely due to imperfections in the machining and different positioning. A comparison of the signals in the above is shown in Fig. 3 e). Here there is a significant deviation between signals recorded under different conditions. Here 1 refers to the wave without surface deviation and with 2, 3 and 4 - the deviations №, respectively, 1, 2 and 3. There is coincidence at the beginning of all the signals, however at the end of the signal there is some dissipation. This fact can be explained by interference of two waves: the first (main) passed through the discontinuity, it has a major share of the signal amplitude; and second: the scattered wave from the surface of discontinuity. When there is a deviation, then the signal is longer. This is an indication of an increase in the propagation path of the second wave as a result of the geometrical characteristics of the deviation. A comparison between the spectra of the signal from the sample without defect and signal from the sample with deviation № 1 is shown in Fig. 3 f). The spectra were obtained using the built-in flaw detector software after digital filtering and maintaining a constant level of amplitude. There is a shift of the spectrum. A clear deviation in the resonant frequency of the wave can not be taken into account visually. Similar results were obtained by comparing the spectrum with other deviations.

A comparing the test result with deviation № 5 is shown in Fig. 4 a). There is increasing of duration for wave propagation trough the deviation within a 0.088 $\mu$s . Therefore, there is an increased equivalent length of the wave path (the calculated increase of the length is in the range 0.26 mm). In the Fig. 3 b) the images of the signals are superposed on each other by shifting, so to obtain complete coincidence of the beginning of the signal. Similar to the previous results, an increase of the duration of the signal is remarked (an increase in the duration of 0.037 $\mu$s is noticed, which corresponds to the extension of the path of the dispersed wave 0.109 mm). These facts can be explained again with dispersion of the surface wave from the wall of the discontinuity and interfering with the base wave.

A study of surface and subsurface stratifications in the brake disc is shown in Fig. 5. Some rough unevenness in the surface are cleaned in advance. A significant dissipation of the waveform due to the influence of the roughness has been found. The measurements were carried out in reference distance between the probes 17 mm. A significant compensation (about 60 dB) of losses in the layer between surface and probes (in comparison with measurements with laboratory samples) has been made. There is good agreement in the beginning and some deviation at the end of the signals. There is some deviation in the signal spectrum because of surface cracks and stratifications.

It is appropriate an additional informative parameter for testing of discontinuity to be formulated on the base of experimental results obtained by study of signal change when the surface wave pass through artificial and natural discontinuities. The discontinuity causes partial wave dispersion. The scattered wave and the passed wave have equal speed. The both waves interfere and it changes the signal form. The registered signal carries information for both waves, including for the passed length of the scattered wave by its phase shift. Therefore, it is appropriate that the phase shift of the...
surface wave after the discontinuities to be used as a further data parameter for testing.

4. Modification of the phase of the wave if there is discontinuities

The obtained experimental data on wave signals are digitized using software. The number of points of sampling is within 126-256. In Fig. 6 a) is shown an example for the digitization of the registered signal wave. The digitized signals are processed by an algorithm, as shown in [3], in order to obtain the phase of the waves by means built-in the software MathCAD functions spectral analysis as directed in [4]. The specters are compared by superimposing of images by samples without and with surface deviations.

Fig. 5. Experimental results comparison in the study of unventilated car brake disc.

There is a correlation between the phase difference and shape / size of the discontinuity. Therefore, it is appropriate to introduce phase shift as a further informative parameter for characterizing the size of discontinuities.

5. Conclusion

Spread of the Rayleigh surface wave in samples with artificial and natural discontinuities has been studied in this paper. Waveforms are analyzed and obtained the spectrum and phase of the recorded signals. Existence of discontinuities in the sample surfaces is a reason for phase shift of the signals. It has been found by experimental way that the phase shift depends on the overall size of discontinuities. Phase shift measurement of the signal ensures testing defects with smaller dimensions. Phase as an additional parameter to allow abnormal with smaller sizes. These results can be used for creating innovative non-destructive technologies with improved resolution for testing of surface and subsurface defects by surface waves.

References

1. Викторов. И. А. Злуковые поверхностные волны в твёрдых телах. М. Наука, 1981.

2. Бре́ховских Л. М. Волны в сло́йских средах. М. Наука, 1974.
