Interpretation of the signal of acoustic emission in the thin plate as the consequence of the properties of Lamb's waves

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Abstract

The purpose of the present report consists in studying an opportunity of use of devices for registration of complex signals in thin-walled details of structures. Lamb's wave properties were used for explanation of dynamic reaction of thin plate surface when in some place there is some source of impulse loading. The experiment on the study of some parameters of propagation of elastic waves in the plate from the Al-Cu aluminum alloy was carried out. Using the Lamb's waves' dispersion property, the formal simulation of waves interference was carried out. It was shown that dynamic reaction of thin plate surface can be explained as effect of several waves' interference. More detailed researching of the structure and the parameters of signals, excited with the impact loading, composes the basis of this work.

Keywords: acoustic emission, Lamb's wave, dispersion.

Introduction

This research is implementing in frame of the 6FP project AISHA that main purpose is aircraft integrated health assessment. One of the most perspective methods of the continuous control of materials and structures is use of properties of Lamb's waves. Lamb waves are essentially ultrasonic waves, but they differ from classic bulk ultrasonic waves in their propagation properties. One important basic property of Lamb waves is their inherent dispersive nature: the velocity of propagation of a Lamb wave is dependent on its frequency or, to be more specific, on the product of frequency and plate thickness. The detection of material damage with Lamb waves is based on the fact that the propagation of these wave types is affected by the presence of phenomena like corrosion, cracking or delaminating. Lamb wave modes will partially reflect at defects, but part of their energy will also be transmitted, so both configurations can be used for detection.

Since the sample materials were typically of thin plate construction, we have concentrated exclusively on the propagation of ultrasonic Lamb's waves [1, 2] within the samples. Changes in the condition of the sample under test, affected parameters of the Lamb wave propagation characteristics, and in this fashion, by the application of suitable signal processing procedures, it was possible to infer the presence and position of structural damage within the sample plates.

Previous work [3, 4] has tended to focus on the echo discrimination of signals in a pitch-catch arrangement. This approach can be frustrated by the complexity of Lamb wave propagation; for in addition to problems of low signal amplitude and edge reflection effects, the propagation characteristics of ultrasonic Lamb waves can exhibit considerable pulse velocity dispersion and complications due to multiple mode propagation [5, 6]. Some novel approaches to addressing some of these problems have included processing to enhance defect visibility [7], system identification [8] and signal regeneration [9, 10, 11].

Lamb wave technology can be used in both an active and a passive manner:

- active: selected Lamb wave modes are injected into the structure, information about the damage state is deduced from observed reflected/propagated waves
- passive: Lamb waves are generated by the process of damage formation and are detected by suitable sensors; this technique is also known as modal acoustic emission.

The main contents of this article assumes research probably more common regularities of propagation of passive Lamb's waves at presence of a various kind of damages of materials, elements of structures and their joints.

As it is known, at use of a method of acoustic emission (AE) the main difficulty consists in adequate interpretation of results of measurement. The model "damage – signal" creation is base of successful application of AE method for NDI of structures [12-14].

Many devices for registration of signals AE use quantity of pulses which is proportional to quantity of fluctuations of a surface in a place of statement of the receiver of signals as parameter.

Earlier [15,16] there were published the results of an experimental research of ultrasonic signals, extending in the long strip from the aluminum alloy and excited from the source of impact loading. In the process of these experiments this was fixed the number of pulses of acoustic emission (AE). Certain no monotonic function between the number of pulses AE and the distance to the source of excitation is discovered. The attempt to explain the discovered effect was made with the aid of the formal procedure of the simulation of the propagation of Lamb's waves in thin sheet. In this case, however, the form of impact impulse and its spectral composition were selected arbitrarily. More detailed researching of the structure and the parameters of signals, excited with the impact loading, composes the basis of this work.

Experimental investigation

It is carried out the experiment on the study of some parameters of propagation of elastic signals in the plate from the Al-Cu aluminum alloy (analog of 2024-T4).The experiment was produced using the special device. Its scheme is shown on Figure 1. The plate is located on two supports. The distance between the supports was 50 cm. The length of the plate is 1 m. Cross-section width is 40 mm but the height (a thickness of the plate) is 5 mm. It was produced the free dropping of the fixed mass from fixed height on this plate. Thus the constancy of energy of impact was ensured; equal to 0.1 J. The elastic oscillations of surface were measured with piezoelectric gauge that was located at a distance of 5, 25 and 45 cm. There were conducted the multiple repetitions of the impacts for definition in each of them number of AE pulses. Some results are shown on the Fig. 2.

It is visible, that at ranges of frequencies 200-1000 number of AE pulses grow at increase of distance between AE source and the gauge. The confidential intervals with probability P=0.95 are shown also.

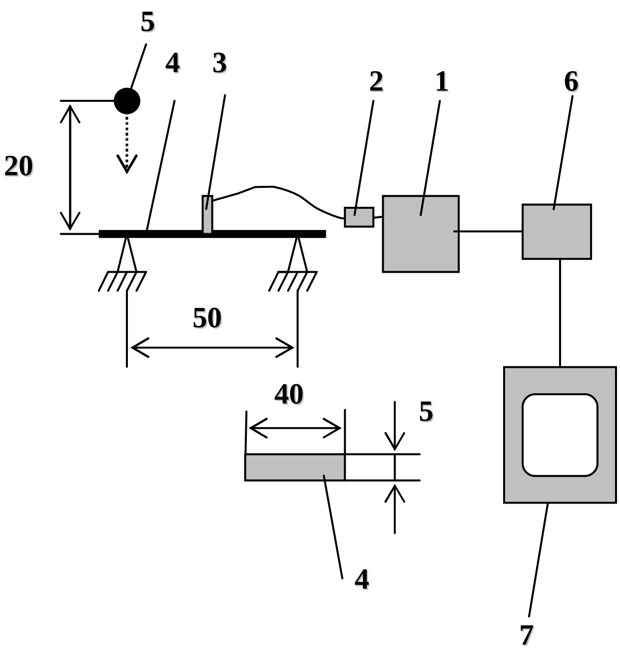


Fig. 1. **Experimental device: 1 - device for registration of AE signals (AΦ-15); 2 – amplifier of AE signals; 3 – piezoelectric gauge; 4 – thin-walled plate; 5 – fixed mass; 6 – USB HS4; 7 - PC**

Pulses of AE with different frequency are distributed with different speed and consequently at a great distance they are divided. Thus, the gauge on the greater distance fixes more pulses of AE.

Pulses of AE have different frequencies. It means that there are different speeds of distribution. At a great distance pulses with different frequencies are divided on a part. Thus, the gauge on the greater distance fixes more pulses of AE.

These dependences have more complex character. But at a range of frequencies of 200, 500 and 1000 hertz quantity of AE pulses in the beginning and in the end about identical. And here the level is less. Probably here level of AE is reduced because AE signals are imposed and thus extinguish each other. And here grows because of division of signals into parts.

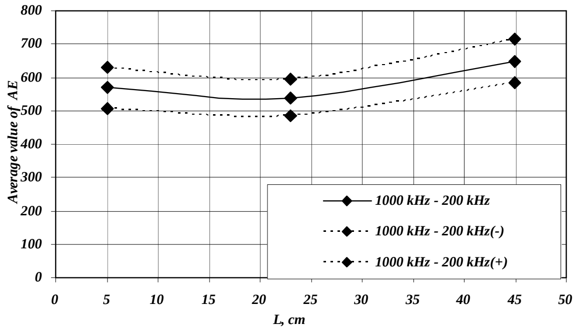


Fig. 2. **Number of AE pulses as a distance function**

It is visible that curves grow with increase of distance between source of AE and the piezoelectric gauge. It is visible that curves have the complex nature of a change.

A method of formal simulation for propagation of elastic waves after pulse excitation

Let the elastic, wide plate in length L and thickness δ at the initial moment of the time t=0 is exposed to bilateral pulse influence near a cross-section with distance a from one of the tips. In a result in this zone cross displacements which circuit of distribution is submitted on Fig. 3 have appeared. The parameter L_0 characterizes spatial extent of a pulse.

Initial function of displacements may be spread out on set of harmonious components. In case of a rectangular pulse this decomposition looks like

$$f(x) = A\frac{L_0}{L} + \sum_{n=1}^{\infty} B_n Cos k_n (x-a) \qquad (1)$$

where

$B_n = 2A\frac{L_0}{L}\frac{Sin\frac{\pi n L_0}{L}}{\frac{\pi n L_0}{L}}$, and $k_n = \frac{2\pi n}{L}$ is wave number of a harmonious component n.

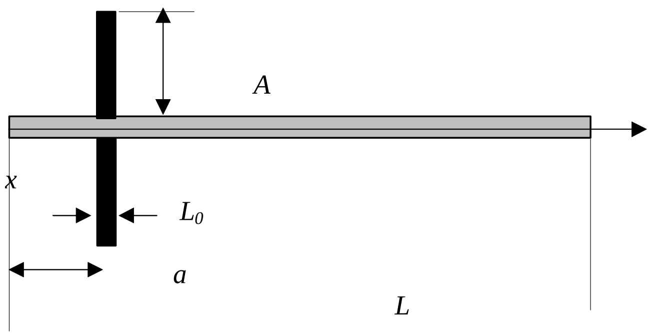


Fig. 3**. Scheme of a plate and its dynamic initial loading**

After the initial moment of time excitation begins to be propagated, breaking up to direct and return waves. Each of them, reaching the tip of a plate, is reflected and goes in an opposite direction. As against volumetric waves or surface waves Raleigh elastic surface waves in thin plates have property of dispersion (Lamb's waves). In this connection everyone harmonious component of a compound signal will be distributed with the phase speed dependent on product of wave number on thickness of a plate. The harmonious component n will have phase speed c_n. At absence of attenuation the oscillations raised in a point of a surface with coordinate x by a harmonious component n, have the period $2T_n=2\pi/(k_n c_n)$. In connection with various speed of propagation of separate components the form of a total signal at each moment of time will differ from initial. In particular, at the initial stage (at small t) for points of a surface with coordinate x, a little distinguished from coordinate of section of initial excitation the current form of a signal is described with expression

$$F(x) = A\frac{L_0}{L} + \frac{1}{2}\sum_{n=1}^{\infty} B_n \left[Cosk_n(x - c_n t - a) + Cosk_n(x + c_n t - a)\right], \qquad (2)$$

It is easy to define the contribution of each component to moving a surface to a point with coordinate x at the moment of time t. It is defined differently on number of a half-cycle of movement of direct and return waves.

Let the following designations are entered:

1) In an odd half-cycle harmonious component n

- The direct wave

$$F_n^+(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(x - c_n t - a), & \text{if} \quad x \geq c_n t_1 \\ 0, & \text{if} \quad x \leq c_n t_1 \end{cases} \qquad (3)$$

- The reflected direct wave

$$F_{no}^+(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(2L - c_n t - x - a), & \text{if} \quad x \geq L - c_n t_1 \\ 0, & \text{if} \quad x \leq L - c_n t_1 \end{cases} \qquad (4)$$

- The return wave

$$F_n^-(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(x + c_n t - a), & \text{if} \quad x \leq L - c_n t_1 \\ 0, & \text{if} \quad x \geq L - c_n t_1 \end{cases} \qquad (5)$$

- The reflected return wave

$$F_{no}^-(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(c_n t - x - a), & \text{if} \quad x \leq c_n t_1 \\ 0, & \text{if} \quad x \geq c_n t_1 \end{cases} \qquad (6)$$

2) In an even half-cycle harmonious component n

- The direct wave

$$F_n^+(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(c_n t - x - a), & \text{if} \quad x \leq c_n t_1 \\ 0, & \text{if} \quad x \geq c_n t_1 \end{cases} \qquad (7)$$

- The reflected direct wave

$$F_{no}^+(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(x + c_n t - a), & \text{if} \quad x \leq L - c_n t_1 \\ 0, & \text{if} \quad x \geq L - c_n t_1 \end{cases} \qquad (8)$$

- The return wave

$$F_n^-(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(x - c_n t - a), & \text{if} \quad x \geq c_n t_1 \\ 0, & \text{if} \quad x \leq c_n t_1 \end{cases} \qquad (9)$$

- The reflected return wave

$$F_{no}^-(x,t) = \begin{cases} \frac{1}{2} B_n Cosk_n(2L - c_n t - x - a), & \text{if} \quad x \leq L - c_n t_1 \\ 0, & \text{if} \quad x \geq L - c_n t_1 \end{cases} \qquad (10)$$

Number of a half-cycle is defined under the formula

$$N = fix\left(\frac{c_n t}{L}\right) + 1, \qquad (11)$$

Where function fix () represents the whole part of the fraction worth in brackets.

Time t_1 characterizes duration of process in the current half-cycle and is defined under the formula

$$t_1 = t - (N-1)T_n \qquad (12)$$

where $\mathbf{c_n}$ is phase speed of a harmonious component $\boldsymbol{n}$.

Example of simulation and the basic results

Simulation of the interference making the polyharmonious signal extending in a plate after pulse excitation of oscillations is executed by a technique stated in item 2. If the top limit of the sum in the Eq. 1 to limit, the form of a pulse will differ from rectangular, but this signal will consist of the limited number of harmonious components with the lowest wave numbers. Such approach allows to limit consideration by a the signal, making which lay in a range of the wave numbers appropriate to symmetric style S_0 of Lamb's waves.

At simulation the following parameters are accepted: δ/L=0.005, a/L=0.25; L_0/L=0.02. They are corresponded to similar parameters in experiment.

If number of harmonious components m in (1) to limit (m=100), it corresponds to the top border of product of wave number on thickness of a plate (at its thickness of 5 mm) which is approximately equal 3. In this range from symmetric styles there is only zero style S_0. Curve of the spectrum of amplitudes as functions of wave number is submitted on Fig. 4.

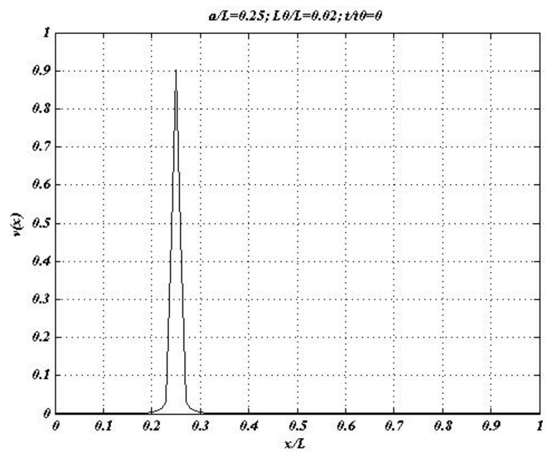


Fig. 4. **The form of an initial pulse**

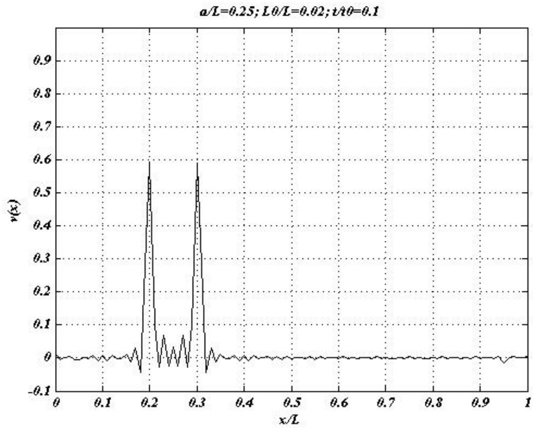
At simulation the curve of change of phase speed as functions of product of wave number on thickness of a plate can be approximately expressed as a formula

$$\frac{c_n}{c_R} = 1 + \frac{0.6}{1 + 0.2(k_n \delta)^2}, \qquad (13)$$

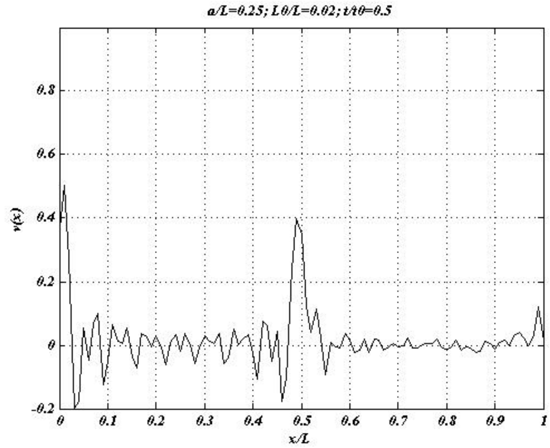
where c_R is speed of surface Raleigh's waves.

On Fig. 4 the form of an initial pulse, and on Fig. 5a,b view of distribution of displacements of a surface is submitted at the moment of time t/t_o=0.1, 0.5, 1, where $t_o=L/c$ is time of passage of distance L by an longitudinal elastic wave with speed c.

It is visible, that the form of surface waves significantly varies eventually. Thus it is possible to note the tendency: peak values of a total signal decrease, but the number of cycles with rather big amplitude is increased.



a



b

Fig. 5. **a - Distribution of displacements at the moment of time *t/to*=0.1; b - distribution of displacements at the moment of time t/to= 0.5**

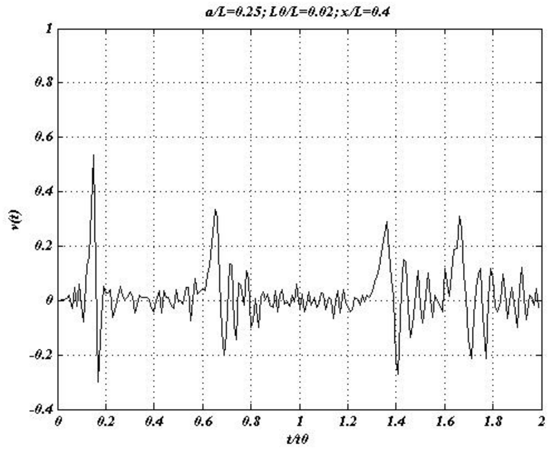
On Fig. 6 a, c the process of oscillations are shown at some cross-sections along the longer side of plate. Structure of this process is significantly dependent from a coordinate of section.

AE signal recording and analysis method

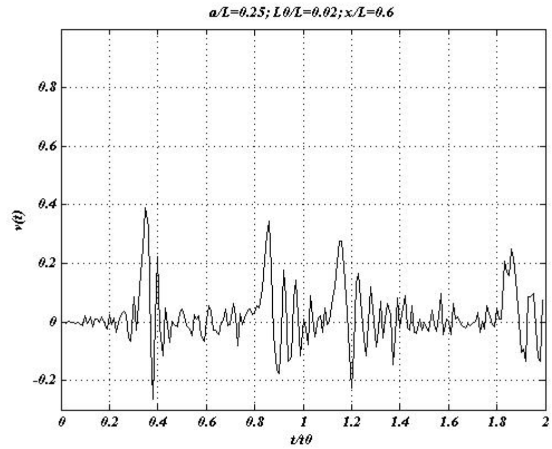
Modernization of measurement system allows making AE signal recording and analysis. There were carried out multiple number of signal records for different conditions of impact loads. The energy of impact was various 0.1-0.2J. Typical record of signal is showed on Fig. 8, but it spectrum is on Fig. 9. This kind experimental information allows more completely interpret AE signal and its transformation caused by structural damage.

Conclusion

For both active and passive Lamb wave technology, one of the main problems that has been encountered in the past lies in the fact that a multitude of modes can propagate at the same time in a structure. The modes have to be separated in order to deduce usable information. On the other hand, the use of multiple modes will provide more



a



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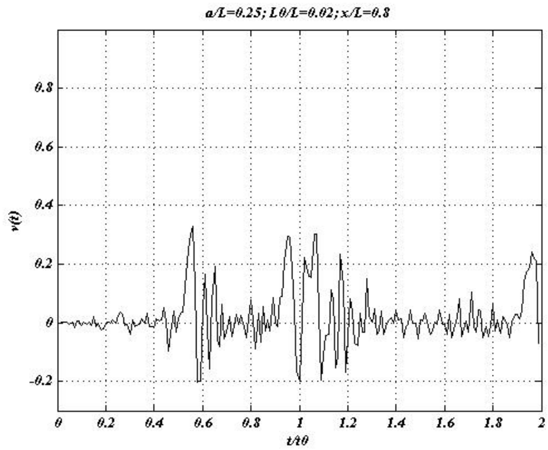

c

Fig. 6. **The process of oscillations at cross-sections: a - x/L=0.4; b - x/L=0.6; c - x/L=0.8**

information about the damage state than a single mode technique could.

The proposed method of formal simulation makes it possible to more deeply understand nature of the acoustic reaction of the thin-walled elements of structure to the local release of energy from the active or passive source. It is possible to assert with the high portion of confidence, that the number of pulses AE with the impulse excitation is

Fig. 8. **Direct and reflected signal after impact**

explained mainly by the special features of the interference of the harmonic components of serrated signal, the caused by property of Lamb's wave dispersion.

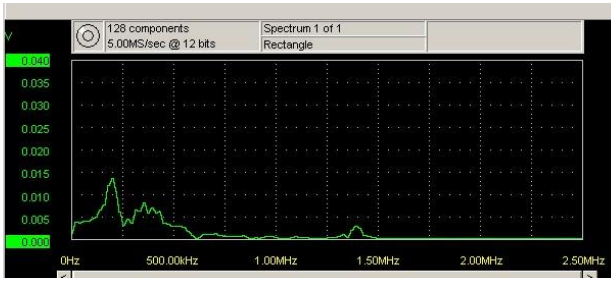

Fig. 9. **Spectrum of AE signal shown on Fig.8**.

Using the Lamb's waves' dispersion property, the formal simulation of waves interference was carried out. It was shown that dynamic reaction of thin plate surface can be explained as effect of several waves' interference.

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