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Application of Fatigue Crack Open Effect for Aircraft Structural Health Monitoring

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Abstract
The phenomenon of the Lamb wave interaction with fatigue crack in Al2024-T3 sheet was investigated at cyclic loading. Mentioned effect is associated with the crack open/close that change acoustic impedance of a crack. Analytical simulation of fatigue crack opening using the generalized Dugdale's model of a crack in thin plate shows good accordance between the intensity of ultrasonic signal and a crack opening. The perspective of application for structural health monitoring (SHM) of aircraft

Keywords: Fatigue Crack, Lamb Wave, Aircraft, Structural Health Monitoring

1. Introduction

The guided Lamb wave technology (LWT) is one of the most effective means of structural damage detection in the thin-walled structural elements of aircraft. Its application for structural health monitoring (SHM) of aircraft is very perspective [1,2]. This technology is applicable as for Al alloy as composite structure and has many important advantages in comparison with others methods. The main of them is the ability to detect large surface of structure at distance about some meters. Therefore the LWT are intensively improved and the ways of it optimizing are investigated in view of practical use in the systems of SHM. In 7FP project AISHA II this technology is basic of SHM system of the MI-8 helicopter tail beam (Figure 1). This one is typical full-scale component of Al alloy aircraft thin-walled structure which contains a skin, stringers and frames. There are the rivet-joints and the point-welded-glued joints typical for these kinds of structure. The MI-8 helicopter is the world's most-produced helicopter and has 50-years history of application. The mechanical properties of structure (strength, fatigue lifetime and survival capability) are well investigated. Therefore a structure of this helicopter is very convenient as an object of SHM problems investigation of the aging aircraft.

For system of structural health monitoring of aircraft successful operation at least two requirements should be obeyed: 1) SHM system must be able reliably detect all possible structural damages, and 2) Own reliability of SHM system must be high.

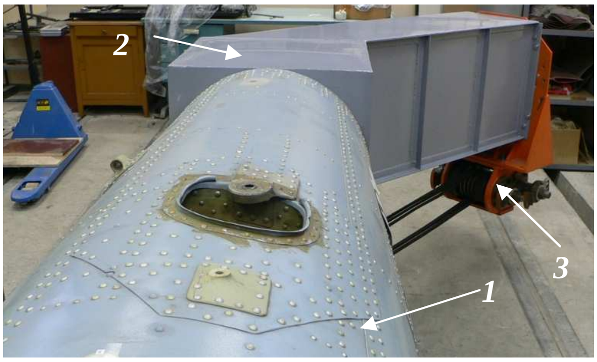


Figure 1. Test set-up of the Mi-8 helicopter tail beam: 1) the tail beam; 2) imitator of the tail propeller beam; 3) mechanical vibrator for exciting of vibration.

Usually two approaches are used for structural damage detection: ‚pitch-catch' and 'pulse-echo'. Both suppose that there is data of initial state of a structural element, so called 'baseline'. That is, as may say, the ultrasound portrait of undamaged structure. Its comparison with a current state with baseline defines the possibility of damage detection. But there is probability that the evolution of received ultrasound signal is associated also with degradation of some elements of the SHM system. The least vulnerable element of ultrasonic SHM system usually is a piezoceramics transducer integrated in structure. Conditions of aircraft operation are very complex: mechanical loading and vibration, environmental degradation, wide range of temperature and others. First of all the transducer is attached to the structural element. It means that is loaded by alternative operational load. It can induce static or fatigue destruction of transducer. For example, Figure 2 shows a piezoceramics 0.5x10x50mm PIC 151 transducer installed to an Al panel after about 60000 cycles of loading with the alternative stress 150/50 MPa [1]. The transducer was glued on a skin of panel in direction of load action. This level of stress is typical for Al alloy structure of aircraft. At least nine fatigue cracks on a surface of the transducer were detected by penetration. This effect associated with low tensile strength of piezoceramics that equal to 40-80 MPa [2,3]. It is much less than compressive strength (about 600MPa). The crack-resistance of piezoceramics is also low (the toughness about 1-3 MPa·$m^{0.5}$) [4]. There are some structural possibilities to protect piezoceramics from effect of mechanical loading. Pre-stressed transducer described in article [5] is good solution as from overloading as from corrosion. But it is no a complete guaranty of reliability of system. On other hand the hard constraining decreases sensitivity of damage detection.

Figure 2. The cracks in piezoceramics after cyclic loading

Therefore the research of any methods those are free from this disadvantage is very actual [2,3].
For example, the proposed in [3] non-destructive testing (NDT) procedure uses the polarization properties of the piezoceramics transducers attached on the both sides of the thin metallic sheet. Damage (crack, corrosion) formation induces the Lamb wave conversion due a local sudden change of the thickness of a sheet. This technique detects the damage appearance by extracting this mode conversion from the measured Lamb waves even at presence of changing operational end environmental conditions. There are others propositions used over Lamb wave modes conversion phenomena. The technique of ultrasonic time-of-flight diffraction [6] also can be used as a physic base of effective method of damage detection.
In article [7] it is shown that the known crack open/close effect also can be used for the same purpose. Some aspects of this effect and its application are discussed in this article.

2. Experimental study

2.1. Theoretical basis

Basic idea of proposed method is associated with the reflection/transmission properties of ultrasonic wave in the process of its interaction with some obstacle. It is well known, if wave falls normally to the boundary of the two media, then partly the wave is reflected and partly transmitted. The reflection factor (as a ratio of amplitude of reflected and incident wave), for example, on the boundary 'Al – air' is only a few less than 1. It means that the wave will be mainly reflected. Only a weak wave crosses boundary and propagates to air. In other case, if there are the two Al media compressed one to other, then the elastic wave crosses fully the boundary of media and the transmission factor is equal to 1. Therefore it can assume that the wave crossing via an open crack is closer to first case of mentioned ideal scheme, but a close crack with clamped sides more similar to the second case of ideal interaction.

Note that there are the results of ultrasonic measurements of specimens with fatigue crack in loaded and unloaded state [8]-[10]. The fatigue damage in a specimen notch was detected on earlier stage of fatigue initiation and short crack propagation by ultrasonic method at the 5 MHz frequency of excitation. Effect of crack open/close was reliably fixed. It is very important results that can have also application for SHM of near fields damages (initial fatigue damage and short crack). But the developed method is not effective for SHM of a large area of aircraft structure caused the intensive attenuation of ultrasonic signal at high frequency. Therefore for practice of SHM of aircraft structure the investigation of long fatigue crack open/close effect is very actual.

2.2. Material and Sample, Set-up, Fatigue Test, and Measurement

Some regularities of ultrasonic wave propagation in Al2024-T3 sheet with fatigue crack were investigated using a rectangular sample 80x300 mm of 1mm Al sheet (Fig.3). For fatigue crack initiation the 4 mm hole was drilled in center of a sample. Cyclic load 12/4 kN and 10 Hz was performed using 100kN hydraulic test machine 'Instron'. It means the maximal tensile stress was equal to 150 MPa, minimal 50MPa.

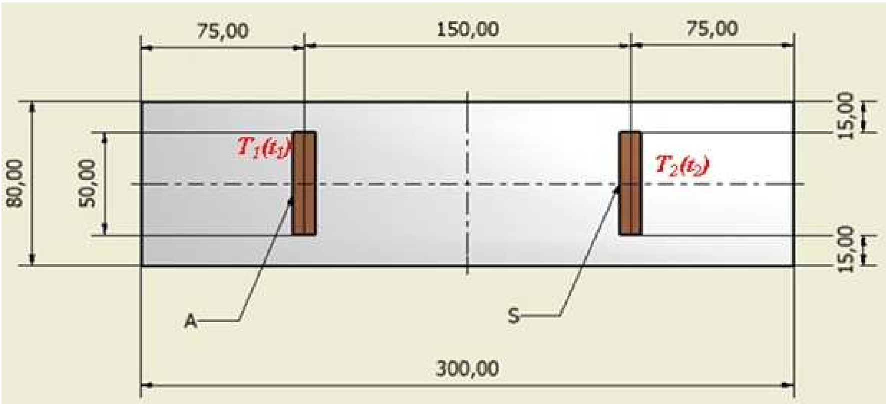


Figure 3. Test sample of Al2024-T3 1mm sheet

Two types of piezoceramics transducer were used. One is the PIC151 0.5x10x50mm (***T1*** and ***T2***) other transducer pz27 1x6.35x6.35mm (***t1*** and ***t2***). The ultrasound Lamb waves were excited by piezoceramics transducer (actuator) and received the same transducer (echo-signal) or other one (transmitted signal). Five sine burst with basic frequency in range 250-300 kHz was exciting. The excitation signal generated by transducer T_1 is shown in Figure 4.

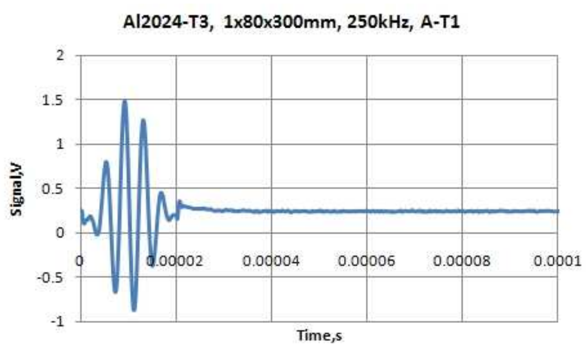


Figure 4. Typical excitation signal

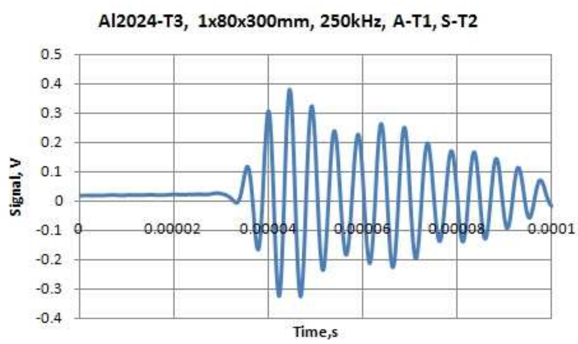


Figure 5. Received transmitted signal (initial range of time)

At first stage of testing the fatigue crack was initiated. The ultrasound signal generated by the transducer ***A*** (T_1) was received by the sensor ***S*** (T_2). Figure 5 shows received transmitted signal in the same range of time. In other serie the generating-sensing was opposite: ***A*** (T_2) - ***S*** (T_1). Similar measurement was performed using pz27 transducers.

After each 20000 cycles the cyclic loading was stopped and the serie of measurements was performed: the received transmitted signal at the static load 0, 6, and 12 kN was recorded and the impedance of all transducers was measured for estimation of their technical condition. Fatigue 5 mm crack (including a hole diameter 4 mm) was observed after 100000 cycles. At next stage of fatigue testing the same ultrasound and impedance measurements were performing after crack increment about 2 mm. The periodic ultrasound measurement was also done without of cyclic test stopping.

2.3. Procedure of signal processing

Received signal depends from excitation impulse. Therefore all imperfections (deviations from theoretical form) of the latter one induce some distortions of the received signal these are the main part of noise. Investigation shows that the statistical scatter of amplitude and a phase shift gives the most notable influence to noise of received signal. Effect of noise can be significantly reduced, if the received signal is constrained with excitation during its processing. This result can be achieved by using of special version of the continuous wavelet transform (WT).

Let the function $\Phi(\tau)$ is a transform of received signal $\varphi(t)$

$$\Phi(\tau)=\int_{-\infty}^{\infty}\varphi(t)f(t-\tau)dt, \tag{1}$$

where $f(t-\tau)$ is so called mother's function. Integral in right-hand-side of equation (1) is known as the convolution. If it is some special function, then $\Phi(\tau)$ is a version of wavelet transform with the shift parameter τ and some fixed parameter of scale.

For achievement of above mentioned effect as a mother's function at each response processing was used correspond excitation signal. In centered form it obeys to conditions of wavelet transform.

Finally the procedure of signal processing includes following steps:

1) Centering of signals;
2) Calculation of function $\Phi(\tau)$ for given couple of 'excitation-response';
3) Removing of basic frequency of signal (demodulating);
4) Smoothing digital vector that describes a demodulated function $\Phi(\tau)$ by a cubic spline;
5) Dividing the obtained function to the parameter of intensity of excitation signal (peak-to-peak amplitude).

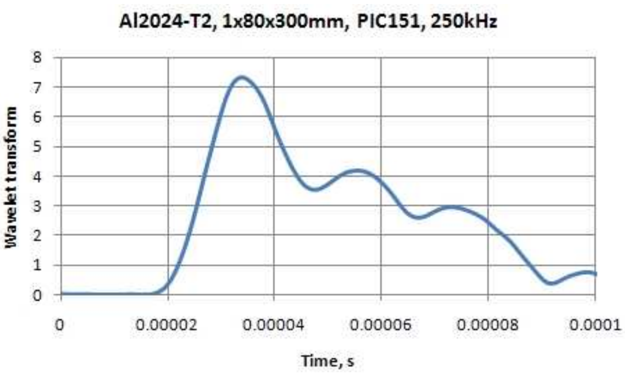


Figure 6. Wavelet transform of transmitted signal

The Figure 6 shows a result of this procedure realization for received signal presented by Figure 5. Note that the time as an argument of the WT is actually a of this function.

There are some important properties of the WT function. If there is not dispersion of some mode of Lamb wave, then the shift parameter corresponding to maxima of WT function defines a time of this mode propagation from the point of excitation to a sensor. This feature can be used for estimation of phase velocity of non-dispersive wave-mode propagation. For example, a first maximum of WT in Figure 6 defines time of S_0 propagation that corresponds

to phase velocity 4438 m/s. It is a few less than theoretical velocity that associated with relatively small distance ‘actuator-sensor’.
If the wave-mode is dispersive, then the maximum of WT allows to estimate the group velocity. A third maximum of WT in Fig.6 defines time of A_0 propagation that corresponds to group velocity 2060 m/s.
Other advantage of WT is that the maximums are proportional to integral intensity of signal and it can be used for damage detection.

2.4. Test results

Before the fatigue crack occurrence the intensity of a transmitted signal remains practically independent from the number of cycles [7]. For example, WT first maximum (see Figure 6) as a function of number of cycles is shown in Figure 7 for a case when the T_1 transducer

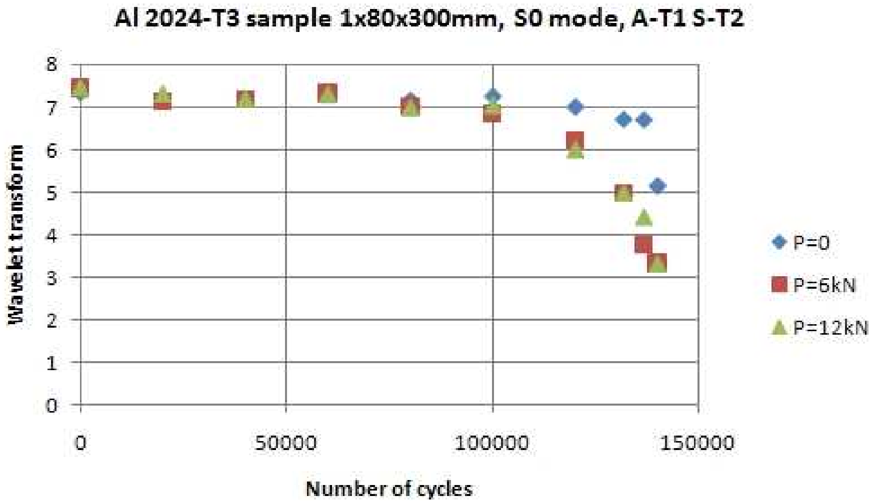


Figure 7. WT first maximum as a function of number of cycles

generates a wave and T_2 is sensor. It means the cyclic loading for about 100000 cycles does not induce any significant degradation of sensors and all system. Since the fatigue crack

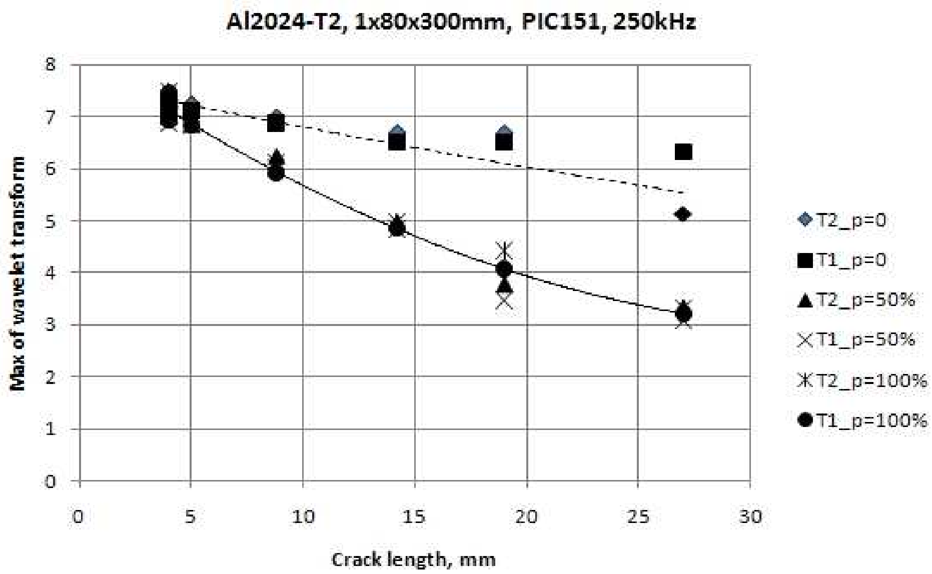


Figure 8. WT first maximum as a function of fatigue crack length

occurrence the significant decreasing of the received transmitted signal as a function of cycle number was observed. Similar effect of the crack growth was fixed in all variants of measurement: unloaded, loaded by 6 kN, and 12 kN. Easy see this effect is the same for both loaded states, and that is significantly more than for unloaded sample.
Results of measurement of signal intensity (the value of WT first maximum) as a function of crack length are presented in Figure 8. Note the direction of wave generating-sensing (***T_1***

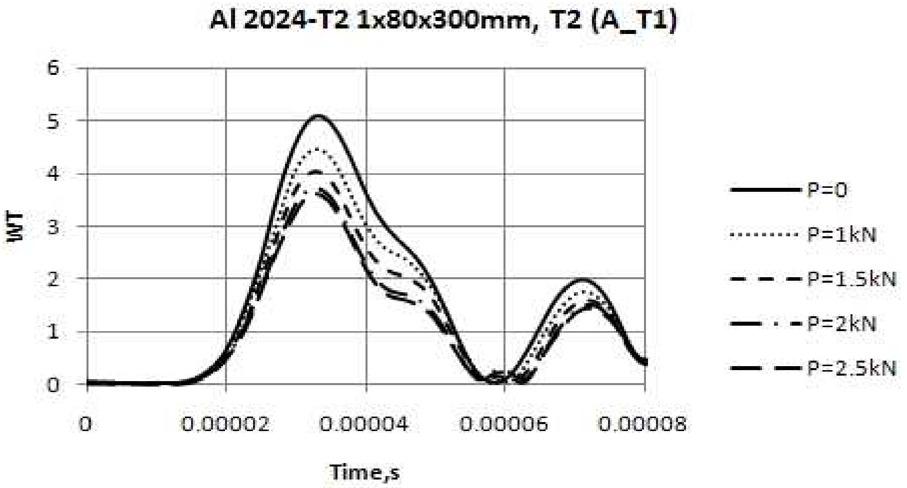


Figure 9. Evolution of WT function during static loading

→***T_2***, ***T_2*** →***T_1***) does not noticeably affect the measurement result.
Easy to suppose the effect of loading is connected with crack opening which decreases the acoustic permeability of a crack. But as it was mentioned above the loading effect is the same for both load 6 and 12kN. Therefore logically suppose that there is some threshold of load of the beginning of the crack closing at unloading. It can also suppose it can be defined by ultrasound detection.

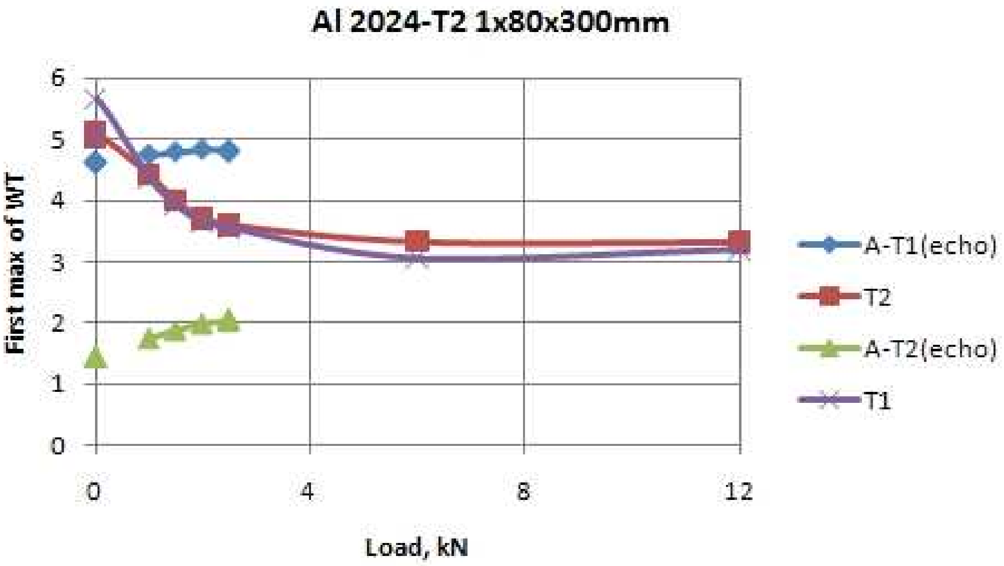


Figure 10. First maximum of WT as a function of load at crack length 27 mm

Special test shows that these suppositions are substantiated. After 133990 cycles of loading the crack reached a 27mm length, and the static test with 0.5 kN load increment was performed. The Figure 9 shows evolution of WT function during static loading.
Joined result of all tests is presented in Figure 10. It can see the load increasing induces decreasing of transmitted ultrasound signal intensity to about 3 kN load, and at the larger load remains constant. For initial stage of loading the reflected signals (pulse-echo) were also obtained (the curves A-T_1 and A-T_2). The intensity of both reflected signals is shown. This result can be easy predicted because crack opening increases acoustic impedance of a sample.

For practical application of loading effect the statistical estimation is significantly important. Special statistical extracts were obtained. Analysis shows that statistical scatter of signal intensity changing is relatively small. For example the first maximum of WT as a function of static load for echo signal of transducer T_2 together with 99% confidence interval. It can see if even the length of a crack is small (7-10 mm), the effect of loading can be reliably extracted and used for crack detection.

3. Analytical study of a crack open/close effect

The crack in the plate is an obstacle at the way of crack propagation. It is known the properties those define the wave reflection-transmission features. At the crack-close configuration the contact of crack sides decreases the acoustic resistance of a crack and transmitted signal intensity increases. At the crack-open configuration the acoustic resistance of a crack increases and transmitted signal intensity decreases.

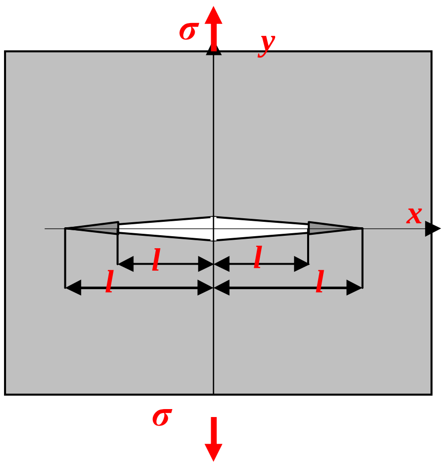


Figure 12. The crack opening and a zone of plastic deformation

In contrast the reflected signal will be more in the crack-open configuration. The level of crack opening should define the degree of crack effect.
Analytical simulation of fatigue crack opening using the generalized Dugdale's model of a crack in thin plate was performed. This model principal advantage is defined by a possibility to obtain an exact elastic solution of elastic-plastic problem of the infinite thin plate with a crack. Of course the actual strain distribution in plastic zone cannot be obtained. But displacements of crack sides in plastic zone are precise estimates of the integral effect of plastic deformation.
In basic configuration there is $2l_0$ length crack in infinite elastic plate (Figure 12). In Dugdale's model the crack length is artificially extended to size $2l$. It is supposed the crack sides in extended zone are loaded by normal stresses equal to yield stress of material σ_Y. The crack side displacements is distributed in accordance to following expression:

$$\bar{v}(\bar{x}) = \frac{v(\bar{x})}{\frac{\sigma_Y}{E} l_0} = (\bar{x} - 1)\Gamma(\bar{x}, \bar{l}) - (\bar{x} + 1)\Gamma(-\bar{x}, \bar{l}) \qquad (2)$$

where $\bar{x} = \frac{x}{l_0}$, $\bar{l} = \frac{l}{l_0}$, E is the elasticity modulus, and

$$\Gamma(\bar{x},\bar{l}) = ln\frac{\bar{l}^2 - \bar{x} - \sqrt{(\bar{l}^2 - 1)(\bar{l}^2 - \bar{x}^2)}}{\bar{l}^2 - \bar{x} + \sqrt{(\bar{l}^2 - 1)(\bar{l}^2 - \bar{x}^2)}} \qquad (3)$$

Obviously the normal displacement of crack side in extended zone is integral measure of plastic strain in direction perpendicular to surface of a crack.
If a crack grows at cyclic loading, then in each half-cycle of load increasing is possible crack extension (fatigue crack rate). As a result the crack tip moves into plastic zone, but the layer of residual plastic strain is formed behind crack tip. It is so called the plastic wake of a crack. In each half-cycle of unloading there is reversible plastic deformation.
Using known theorem about plastic deformation at cyclic loading and supposing that material is cyclic ideal the shape of a crack during unloading was investigated.
Unloading with range of stress $\Delta\sigma$ induces the reverse plastic deformation. In particular, the range of displacement $\Delta\bar{v}(\bar{x})$ of crack sides can be defined by the formula (2), if instead the yields stress to use $2\sigma_Y$. As a result the crack side displacement after unloading $\bar{v}_1(\bar{x})$ can be defined by formula:

$$\bar{v}_1(\bar{x}) = \bar{v}(\bar{x}) - \Delta\bar{v}(\bar{x}) \qquad (4)$$

Remaining plastic displacement $\bar{v}_{rem\,0}$ in tip of a crack corresponds to $\bar{x} = 1$ and

$$\bar{v}_{rem\,0} = \bar{v}_1(1) = \bar{v}(1) - \Delta\bar{v}(1) \qquad (5)$$

It can suppose that at cyclic loading with the constant amplitude of stress and fixed cycle ratio this plastic displacement remains during next loading. As a result, the plastic stripe at each side of the crack. Its thickness can be estimated by following method.
The formula (2) at $\bar{x} = 1$ give:

$$\bar{v}(1) = -\frac{4}{\pi} ln\left(Cos\frac{\pi\sigma}{2\sigma_Y}\right), \qquad (6)$$

$$\Delta\bar{v}(1) = -\frac{8}{\pi} ln\left(Cos\frac{\pi\Delta\sigma}{4\sigma_Y}\right), \qquad (7)$$

and

$$\bar{v}_{rem0} = \frac{4}{\pi} ln\left(\frac{Cos\frac{\pi\sigma_{max}}{2\sigma_Y}}{\left(Cos\frac{\pi\Delta\sigma}{4\sigma_Y}\right)^2}\right) \qquad (8)$$

At cyclic loading with constant amplitude the equation of thickness of one layer of crack wake is very simple:

$$\bar{v}_{rem}(\bar{x}) = \bar{x} \cdot \bar{v}_{rem0} \qquad (9)$$

The numerical analysis of the shape of fatigue crack under cyclic loading with the cycle ratio 0.333 was done and its results are presented by Figures 13-17. This case completely corresponds to fatigue test described above.

Figure 13 presents a fatigue crack shape under maximal and minimal load of cycle with ratio 0.333. Here is shown the ¼ part of a crack shape. Relative coordinate that is equal to 1 corresponds to the crack tip, but the inside region between a curve and abscissa at $\bar{x} > 1$

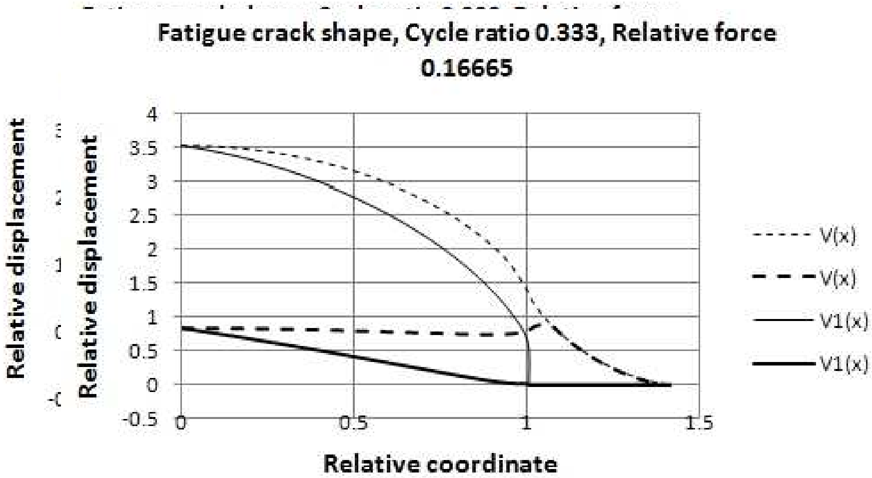
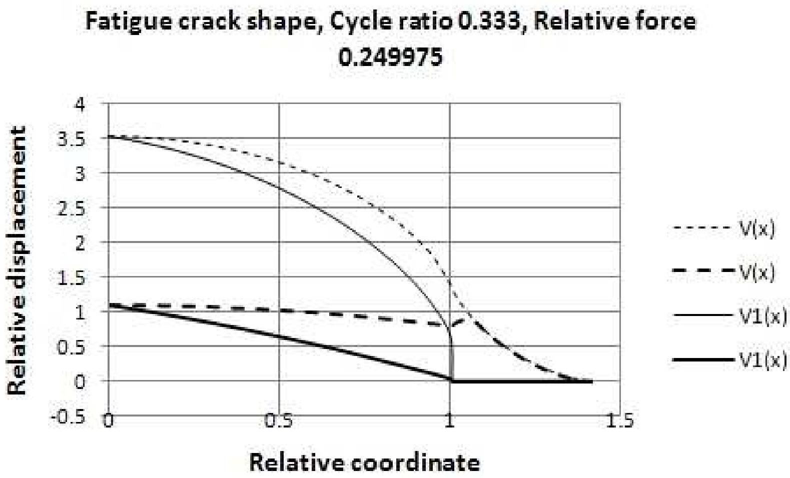


Fig. 13. Fatigue crack shape under maximal and minimal load of cycle

Fig. 15. Fatigue crack shape under maximal load and at further unloading to relative force about 0.167

defines integral plastic displacement into active plastic zone. Couple of the lines with the same thickness shows the ‘plastic’ displacement into a crack wake. Thin lines correspond to maximal load, but thick lines to minimal load. It can see that a crack is open under minimal load of cycle. Others figures show the process of the gradual crack closing at further unloading. The same assignments were used there.Figure 14 corresponds to unloading to relative force about 0.25. The crack remains open at this level of load.



Fig, 14. Fatigue crack shape under maximal load and at further unloading to relative force about 0.25

The crack closing start is seen at unloading to relative force about 0.167 (Figure 15). The contact of opposite sides of a crack (about 6-7%) is seen there.

In Figure 16 the negative displacement of significant part of crack upper surface is seen at unloading to relative force 0.083. Of course it is physically impossible, but allows to conclude that at least 30% of crack is closed there. The intensive crack closing is observed at full unloading of a sample (Figure 17).

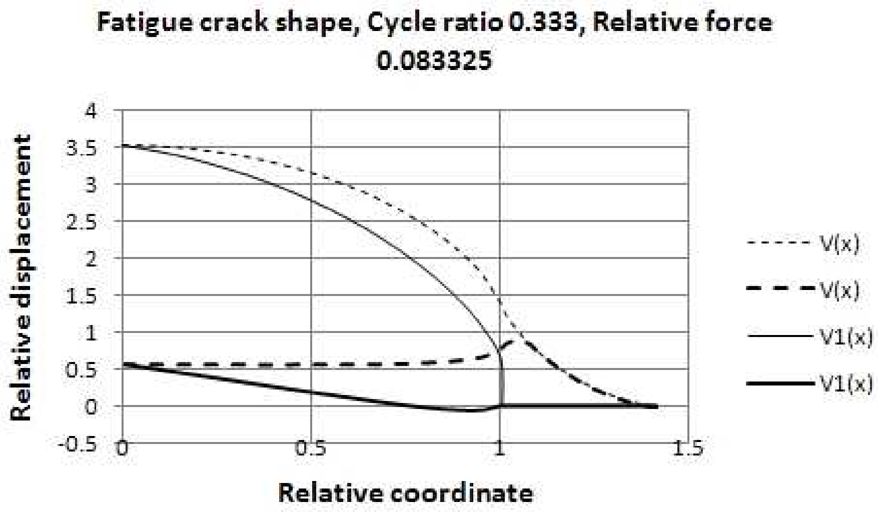
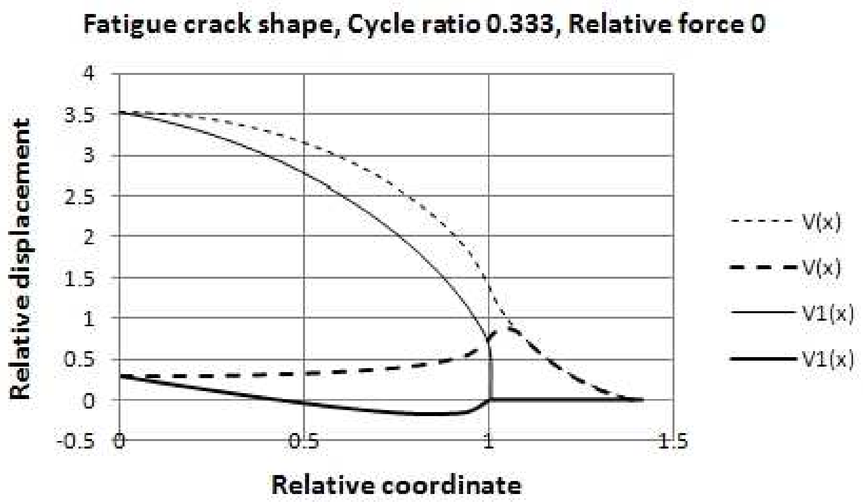


Fig. 16. Fatigue crack shape under maximal load and at further unloading to relative force about 0.083



Fig, 17. Fatigue crack shape under maximal load and at full unloading

4. Discussion and Conclusions

Results of fatigue test shows that there is stable load effect to the ultrasonic signal in Al alloy sheet with fatigue crack. Intensity both transmitted and reflected waves those are result of interaction with a crack is different in loaded and unloaded state of a sample. It is nonlinear effect: increment of signal intensity is not proportional to load increment.

Moreover there is the upper level of a load more which the effect of further increment of load does not induce any increment of ultrasonic signal intensity. Naturally to suppose that the mentioned effect is associated with the crack open/close effect during loading/unloading of a sample.

Results of analytical study of a fatigue crack open/close correspond to conclusions of experimental study. Similar properties were used for building so called the strip-yield model of fatigue crack, for example [11]-[13].

Fatigue crack open/close effect allows developing the technology of a fatigue crack detection without using prior baseline data. On other side the Lamb wave technology can be useful for investigation of fatigue crack growth.

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