APPLICATION OF THE FATIGUE CRACK OPENING/ CLOSING EFFECT FOR AIRCRAFT SHM

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Abstract. The effect of the Lamb wave interaction with fatigue crack in Al2024-T3 sheet at static and cyclic loading was investigated. Mentioned effect is associated with the crack opening/closing that change acoustic impedance of a crack. On-line and off-line measurement results are similar and very close one to other. The contrast between the behaviour of elastic waves at closed and opened crack enables to conduct online the reference-free SHM. Example of possible SHM system for monitoring of repaired skin of hermetic fuselage is proposed and its efficiency is demonstrated in a special test.

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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]. Usually two approaches are used for structural damage detection: 'pitch-catch' and 'pulse-echo'. Both suppose that there is known initial state of a structural element, so called 'baseline'. That is, as can say, the ultrasound portrait of undamaged structure. Comparison of a current state with baseline is the general principle of damage detection using LWT. But the mechanical load and environmental exposure leads to degradation both the monitored structural element, and the sensor of SHM system, embedded into the structure. It is known that the static and fatigue tensile strength of piezoceramics is very low, and if the transducer is loaded in parallel to monitored structure, then it can be partly or fully damaged.

Pic.1. Crack of the PZT after 60000 cycles of fatigue test

In the Pic.1 the piezoceramics 0.5x10x50mm PIC 151 transducer installed to an Al panel after about 60000 cycles of loading with the alternative stress 150/50MPa is shown [3-5]. The PZT was glued in direction of external tensile load. At least nine fatigue cracks on a surface of the transducer were detected by penetration. Environmental degradation of piezoceramics is other source defined evolution of some basic properties of transducer.
It means that the reliability of detection of structural damage can be substantially increased, if the rule of the structural health assessment is used the current measurement data only. It can be derived from some phenomena that enable to extract directly the contrast of structure behaviour in two different states of the structure. In particular, the effect of a fatigue crack opening/closing can be used as such phenomenon for effective examination of

the monitored structural component. It is caused by the difference in the features of ultrasonic waves at the closed fatigue crack (in the unloaded state) in comparison with an open crack (in the loaded state). Note that there are the results of ultrasonic measurements of specimens with fatigue crack in loaded and unloaded state [6-8]. 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. The same effect for a relatively long fatigue crack in a thin flat sample of aluminium alloy was investigated in the articles [9-11]. It is demonstrated that there is a stable correlation between the size of the crack and the amplitude of the transmitted or reflected signal. There is important that there is a perceptible difference of signals for opened and closed crack. Below the some results of these studies important for the purposes of this article are briefly reproduced.

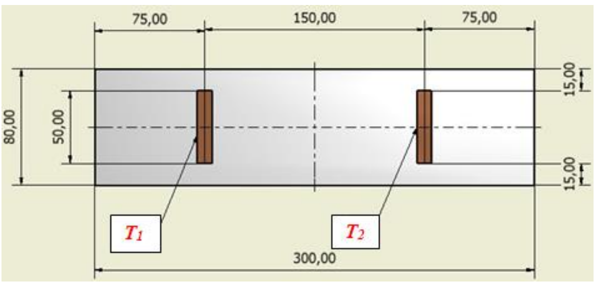
In Ref.12 new a reference-free NDT is proposed. This approach uses the Lamb wave mode conversion phenomena induced by crack/corrosion formation in a thin metallic structure. Other perspective approach was developed in [13, 14] It is based on the guided ultrasonic wave mode selective monitoring with high temporal resolution achieved by correlation techniques.

This technique application is considered for monitoring of aircraft components of aluminium and a fiber reinforced polymer composite. The methods developed in [15-17] have some perspective for a reference-free SHM.

In this article some aspects of the effect of a fatigue crack opening/ closing are investigated in more detail. Comparison of test and computer simulation of the guided ultrasonic waves propagation and they interaction with the fatigue crack was performed. The example of designing of the SHM system of aluminium skin of hermetic fuselage repaired by installing a doubler is done.

Some main regularities of the crack opening / closing to the lamb wave propagation

Here the overview of essential results of our research [9-11] important for the purposes of this article is reproduced. 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 (Pic.2). For fatigue crack initiation the 4 mm hole was drilled in centre of a sample. Cyclic load 12/4 kN and 10 Hz was performed using 100kN hydraulic test machine Instron 8801. It corresponds to the maximal tensile stress 150 MPa, minimal 50MPa. The sample were equipped by two piezoceramics transducers PIC151 0.5x10x50mm (***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 250 kHz was used for ultrasound wave excitation.

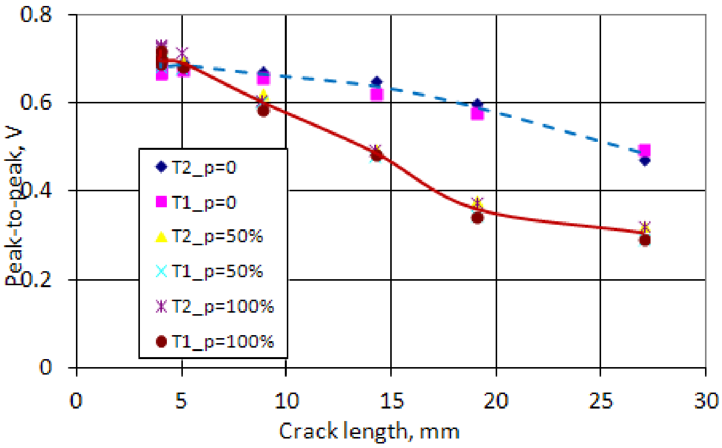


Pic. 2. Test sample of Al2024-T3 1mm sheet

The cyclic loading was periodically interrupted for ultrasound response and EMI measurements under static loading / unloading up to a maximum load of 12 kN. Below the most important final results are indicated:

1) Before the fatigue crack occurrence the intensity of a transmitted signal signal (expressed by peek-to-peek amplitude) remains practically is constant and independent from the number of cycles.

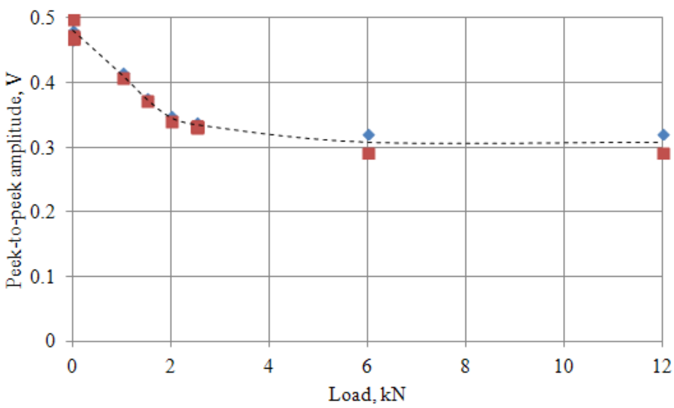
2) Since the fatigue crack occurrence and growing the transmitted signal significantly



Pic.3. PPA as a function of crack length

decreases. This effect was fixed at both variants of measurement: unloaded sample, and loaded by static tensile load. The maximum of transmitted as a function of crack length are presented in Pic.3. Dash line approximates results of measurement for unloaded state (crack is closed), but solid line corresponds to measurement for sample under load 6 kN (50% of maximal cyclic load) and 12 kN (100%). At both cases of load the fatigue crack is completely opened, and therefore measurement results are practically the same. In contrast the reflected signal increases but with a smaller rate.

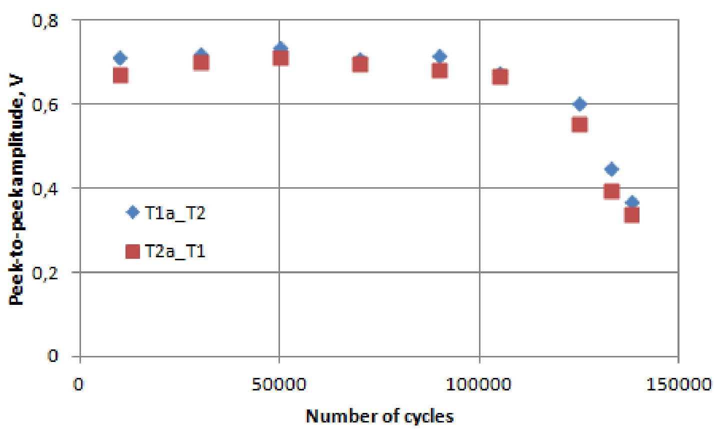
3) More detail investigation shows that the effect of crack opening affects only the initial stage of loading preceding the full opening of a crack. There is some threshold of load after which signal practically does not vary (Pic.4). Further increasing of load does not change both the transmitted and reflected signals. As it can be seen in the given test this threshold is in the range of 3.5-4 kN which is 30-33% of the maximum load under cyclic loading. It is close to the cyclic load ratio.



Pic.4. PPA as a function of static load

4) The process of fatigue crack opening / closing was also investigated analytically using so called the Dugdale's model, modified to the fatigue crack propagation under cyclic loading with constant amplitude. The analytical model predicts the existence of a threshold load at which a fatigue crack is fully opened. However, its value is lower than the observed in the test.

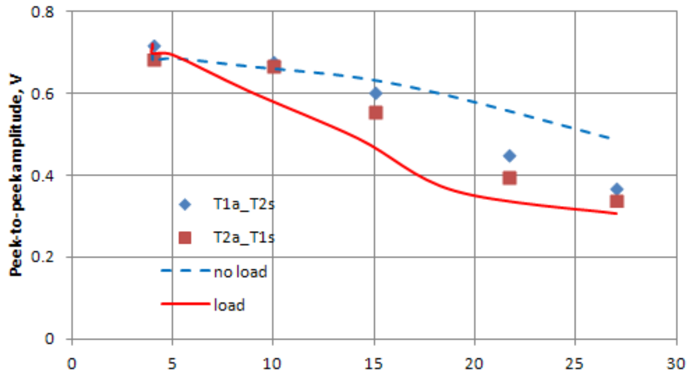
Experimental study: online fatigue crack detection



Pic.5. PPA as a function of the number of cycles

Fatigue test and online measurement for fatigue crack detecting were performed on the same samples. Conditions of cyclic loading were the same (12/4 kN). It is obvious that at this loading the crack remains completely open during the loading cycle. This means that the results of the online measurements should be close to those obtained in the offline measurements with interrupting of cyclic test and the subsequent static loading.

Some results of test are introduced below. Pic.5 demonstrates the peek-to-peek amplitude (PPA) evolution during cyclic test. The 1 mm initial crack was fixed at about 100000 cycles. Before this the PPA variation is relatively small and is associated with others secondary (for this test) effects. In Pic.6 the test results of online measurement are showed as a function of crack length (points).

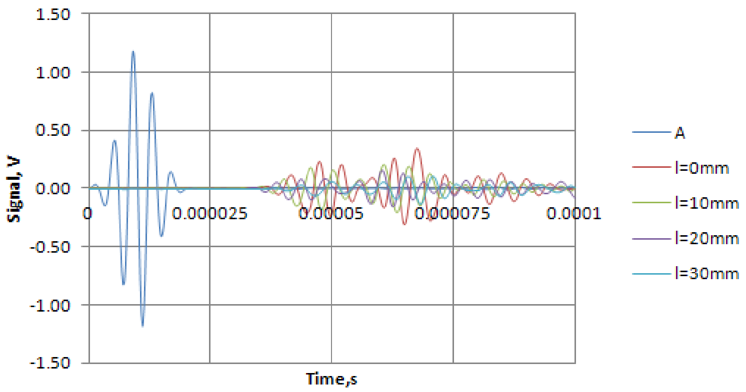


Pic.6. PPA as a function of crack length (points for online measurement). Lines indicate the same functions for offline measurement statically loaded and non-loaded sample

The lines corresponded to offline measurement reproduced by the blue dash line (closed crack at unloaded sample) and the red solid line (fully opened crack at loaded sample). It can be seen that at the online measurement the effect of crack opening is smaller than at the static, particularly for crack lengths up to 15 mm. However, similarly to offline measurement the response of transmitted signal to opened crack is much more than for unloaded sample (with the closed crack).

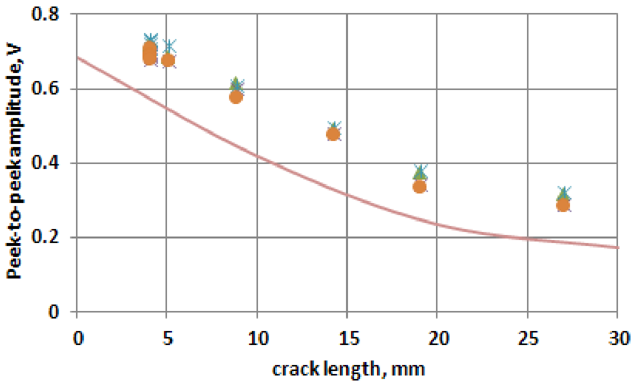
Simulation results

Propagation of elastic ultrasonic waves and their interaction with the opened fatigue crack was simulated using the piezoelectric device module of the COMSOL Multiphysics software. Geometric shape, boundary conditions, mechanical and piezoelectric properties of the sample and transducer materials, as well as conditions of the ultrasonic waves excitation were exactly corresponded to the test. In Pic.7 primer results of simulating are showed: excitation (A) is five sine burst, and the sensor responses at four crack lengths. Firstly, this figure can easily see the structure of the response: Package symmetric (C0) wave reaches the sensor first with the phase velocity of the order of 5000 m / s, with followed by a package of asymmetric (A0) waves with a phase velocity of 2000 m / s. Secondly, the maximum of amplitude A0 mode is greater than the amplitude of C0 mode. Third, it is clearly visible reduction of the peak-to-peak amplitude of the two modes with increasing crack length. Pre-processing results of simulation are demonstrated in Pic.8. The monotonic reduction of the peak-to-peak amplitude of the response as a function of the fatigue crack length is observed. Here are represented also the test data. We see that the general trend the transmitted signal amplitude of reducing is also retained in the simulation. But there is a quantitative difference between test and simulation. Reasons for a systematic shift of the curve relative to the data of the test are one of the objects of the discussion below and in our other paper [18].



Pic.7. Excitation signal and response of a sensor for different length of a crack

Example of SHM system using the fatigue crack opening/closing effect



Pic.8. Comparison of simulation (curve) and test (points): The PPA of the response as a function of the fatigue crack length

As a possible useful application of fatigue crack opening/closing is a local SHM system for a skin of Al hermetic fuselage monitoring.

Skin is a thin-walled component of structure that on the flight altitude is high-stressed by action of the air pressure into hermetic part of fuselage. High level of the flight-to-flight cyclic stress and additional dynamic stress induced by the aircraft control and atmospheric turbulence can cause the fatigue damage appearance and its development in operation. For Al-alloys skin the crack stress corrosion is also typical kind of material degradation.

The usual way to repair a skin for restore of its strength is installation on the damaged skin a doubler that is one or two sheets metal plate riveted in the damaged area. However, the concentration of efforts on the extreme rows of rivets at a operation loading can cause the appearance and growth of secondary fatigue cracks. For monitoring repaired structure can be effectively used local SHM using the effect of the opening/closing of a fatigue crack. Two online measurements should be done: one at high altitude where the air pressure into hermetic fuselage is sufficient for a crack full opening, but second at small altitude or after aircraft landing when tension stress decreases to level caused fatigue crack closing.

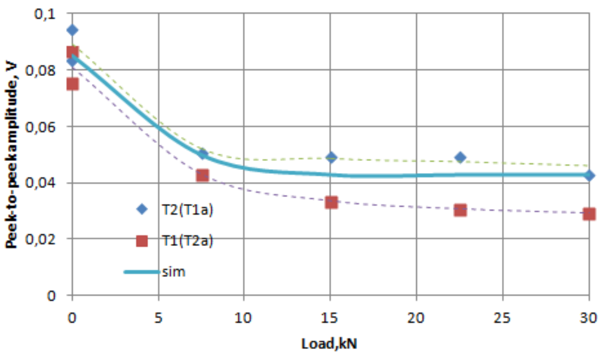
a)

b)

Pic.9. Simulation of a some plate of a hermetic fuselage skin (a) and the picture of the Al2024-T3sheet with a doubler (b)

Below the results of experimental investigation of such kind of SHM system is briefly described. Some plate of Al2024-T3 1.15 mm thickness skin was equipped by three piezoceramics transducers PIC-151 0.5x10x50 mm (Pic.9, a). The distance between axes of T_1 and T2 – T_3 transducers is equal to 280 mm, but width of a plate 200 mm. Series of tests with pseudo-damage simulation was done for damage presence detection into monitored area. Lamb wave electronics LWDS45 (Cedrat Technology) was used for ultrasound wave Excitation at basic frequency is equal to 250 kHz . National Instrument PXI oscilloscope was used for sensor signal measurement and transforming to digital form.

Fatigue test at cyclic load 30/10 kN and frequency 10 Hz was performed in two stages. In the center of a plate the 3.5 mm hole was drilled for fatigue crack initiation. At the first stage of cyclic loading fatigue crack was obtained at about 100000 cycles and this crack growth was observed till 173000 cycles with periodic measurement of transmitted signal at the different actuator – sensors combinations (A: T_1 , S: T_2 , T_3; A: T_2 , S: T_1 , T_3; A: T_3, S: T_1 , T_2). First stage was stopped when the crack length reaches 42 mm (including a diameter of the central hole). After finish of first stage of fatigue test the static stepped loading was performed in the load range 0 – 30 kN by step 7.5 kN. At the each level of load the ultrasound signals of transducers were measured for crack opening/closing effect investigation. Final results are similar to described above. In the Pic.10 the peek-to-peek amplitudes of T_2 (at excitation by T_1) and T_1 (at excitation by T_2) are presented as the functions of static load.



Pic.10. PPA as the functions of static load: test (points) and simulation (curve)

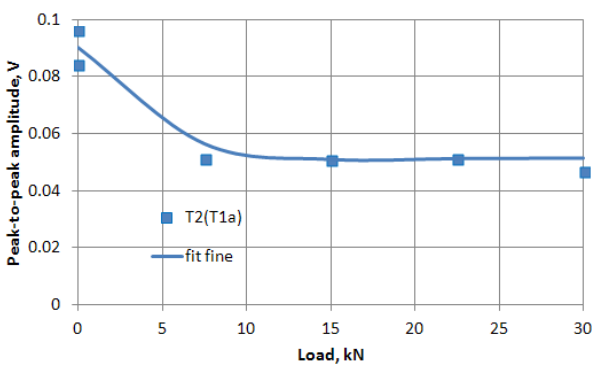
Before second stage of testing the repair of the skin was performed by installation of a doubler. The Al2024-T3 1.15x80x80 mm doubler is riveted by 3.5 mm rivets. For more reliable bracing of fatigue crack the 1.5 mm holes in the skin at the end of a fatigue crack were drilled and additionally the material in this neighbourhood was plastically deformed to create a retarding residual stresses.

In the picture (Pic.9, b) the repaired sample with clamps are showed.

Second stage of fatigue test was performed in the same loading regime. The secondary fatigue crack of the initial length 3 mm was seen after about 100000 cycles and continued to grow until the termination of test at 191750 cycles. Final crack length is equal to 22.5 mm. In the Pic.11 the doubler front and back views are showed.

Pic.11. The doubler front and back views. Primer (1) and secondary (2) fatigue cracks

At the final stage of test the load effect of crack opening/closing was investigated for sample with a doubler at static stepped loading. Pic.12 demonstrates that secondary crack can be reliably detected by a couple of transducers T_1 (actuator) T_2 (sensor). Note that a couple of transducers T_1 (actuator) T_3 (sensor) does not detect secondary fatigue crack because it is out of direct way of wave propagation from T_1 to T_3.



Pic.12. Effect of fatigue crack opening/closing: PPA as a function of load

Discussion and conclusions

The process of fatigue crack growth takes its periodic opening at the maximum load of a cycle and partial of full closure at the minimum load. At the full closure the opposite surfaces of fatigue crack are contacted. If there is an ideal contact, then the crack does not affect the process of wave propagation. However, in actual contact the surfaces of crack are not ideal. This is caused by the roughness of fracture surface and its local plastic deformation. Therefore, the actual fatigue crack is an obstacle for the elastic wave propagation. The crack causes a partial reflection of and decreasing of the transmitted wave energy. When the load increases the contact area of crack surfaces gradually decreases, and the acoustic impedance increases. It reaches a maximum at the full opening of crack and remains constant during further increasing of the load. Described behaviour is completely supported by the test data obtained in this paper. On-line and off-line measurement results are similar and very close one to other. The contrast between the behaviour of elastic waves with closed and opened crack enables to conduct online the reference-free SHM.

As noted above, the difference between the opening and closing loads is relatively small. This means that at designing of the SHM system the regimes of operational loading for measurements must be carefully defined.

Computational simulation of the wave interaction with a crack is an important tool for the design and optimization of the SHM system. The results presented here show similar trends of predicted and measured signals. However, there is a systematic deviation between the simulation and test. At least, it is due to two factors:

1) Change of the electric capacitance of piezoceramics transducer embedded into structural component. (For example, the electric capacitance of used here transducer is reduced to about 15% after its installation into the aluminium alloy sheet).

2) Change of the piezoelectric constants of piezoceramics under load.

The further analysis of these effects and the development of methods for taking them into account in the simulation are needed.

Note also that the full opening load values obtained here experimentally and using the modified Dugdale's model is substantially less than given by the Elber's theory of the fatigue crack growth [19]. For example, the load of crack opening in given test is approximately equal to load ratio of cycle (i.e. 33% of the maximum duty cycle), the modified Dugdale's model gives about 20% [10], but for the Elber's the crack opening load is equal to 57.7% of cycle maximal load [19].

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