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# Lamb Wave Interaction with a Fatigue Crack in a Thin Sheet of Al2024-T3

S.Kuznetsov [1], E.Ozolinsh [1], I.Ozolinsh [1], I.Pavelko [1], V.Pavelko [1], Martine Wevers [2], Helge Pfeiffer [2,3]
[1] Aircraft Strength and Fatigue Durability Department, Riga Technical University, Riga, Latvia
Phone: +371 7089961, Fax: +371 7089990; e-mail: Vitalijs.Pavelko@rtu.lv
[2] KU Leuven - Materials performance and non-destructive evaluation, Leuven, Belgium
[3]METALogic nv, Technologielaan 11, 3000 Leuven

**Abstract.** The establishment of reliable correlations between the extend of damage and a sensor response using automated non destructive testing (structural health monitoring) is the first aim of the present paper. The second and its main aim is the estimation of the efficiency of different approaches of the fatigue crack prediction when scalar parameters are used to represent the signal-response. Investigation of ultrasonic Lamb wave interaction with a fatigue crack has been performed on thin sheets (1mm) of aluminum alloy (2024-T3). Three parameters of response were selected to compare efficiency and the standard deviation of a predicted fatigue crack was used for comparison. Quite definitely it is possible to conclude, that the proposed technology is capable of providing high stability and necessary accuracy at the continuous integrated SHM of thin-walled aluminum components of aircraft. It is also shown that the accuracy of damage prediction is one of the most significant parameter of SHM efficiency. It can be used as the main criterion at selection of diagnostic parameters for continuous integrated monitoring of structural elements of aircraft.

**Keywords**: damage, detection, fatigue crack, ultrasound wave, Lamb waves

## 1. Introduction

This article is result of the authors' participation in the European project Aircraft Integrated Structural Health Assessment (AISHA). This project aims at realizing a breakthrough in aircraft health monitoring technology by exploring the capabilities of ultrasonic Lamb waves as the basic sensing principle and by providing an integrated and multidisciplinary research path.

The safe use of complex engineering structures such as aircrafts can only be guaranteed when efficient means of damage assessment are in place. Whereas aircraft design is nowadays based on a damage tolerance approach and time based inspection cycles, it is envisaged that the large cost associated with this approach can be drastically reduced by switching to a condition based maintenance schedule. This does require continuous health monitoring capabilities using integrated sensing technology and autonomous damage assessment. Structural Health Monitoring (SHM) is becoming important for preventing catastrophic failures and also for the uninterrupted operation. Reducing the costs associated with inspection and maintenance will have a large impact on airline profitability and competitiveness. But the most important feature of SHM is reliable detection of all possible kinds of damage in structural elements of aircraft. For metallic components fatigue is one of the most dangerous damage mechanisms in aircraft structures. Multi-site fatigue damage, hidden cracks and corrosion, which, especially when combined, can lead to

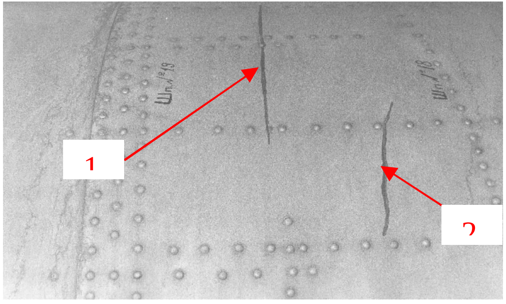


*Figure 1. The fatigue cracks in a skin are initialized by the stress concentration 1) near the most loaded fastening point in rivet-joint 2) on small hole in skin*

threatening damage states. Figure 1 shows two typical modes of fatigue crack in the skin of tail beam of helicopter MI-8 (at full scale fatigue test).

Elastic waves have been used for many years to analyze impact response problems, mechanical properties of various materials and structural damage. Various types of methods based on sound and ultrasound are applied for nondestructive testing (NDT). Modern NDT ultrasound equipment and technology allows hope that SHM problems can be successfully solved. Recent articles [1,2] present examples of calculation and experimental application of the implementation of structural health monitoring systems in aircraft fuselage structures using ultrasonic waves: the root mean square (RMS) values of calculated and measured signals showed good correlation between "healthy" and damaged structures. For the structural health monitoring of aging aircraft structures, two main detection strategies are considered: the E/M impedance method for near field damage detection, and wave propagation methods for far-field damage detection [3]. Two damage identification techniques are integrated in this paper, electromechanical impedance and Lamb wave propagation. Examples of successfully used PZT materials in the areas of active and local sensing Lamb wave propagations are given in [5,6] and of the impedance-based structural health monitoring methods can be found in [7].

A very important aspect of SHM is the reliable prediction of remaining strength and remaining life time. Two variants of models "signal - remaining lifetime" are essentially possible:

1) Direct model: "signal - remaining lifetime (remaining strength)". It may be established by results of direct tests on samples on structural elements in conditions completely conterminous with operating conditions of a structural element. In this case the model will represent a statistical connection between parameters of a signal and remaining lifetime.

2) Indirect model: "signal - damage - remaining lifetime (remaining strength)".

It is obvious that the first variant is preferable from the point of view of accuracy and reliability. In some situations such models may be constructed. However a variety of materials, structural forms of elements, variants of mechanical loading, aggressive influence of environment does not allow conditions for the application of direct models

Therefore in all other cases the second variant is really feasible: "signal - damage - remaining lifetime (remaining strength)". Analysis of damage phenomena, including its parameters and degradation conditions allows forming of main functions which are the basis of modeling "signal - remaining lifetime". For all damage phenomena there is some common scheme of remaining lifetime determination: after damage initialization its parameter grows. At some moment it is detected by the system of inspection. It is the initial parameter value. During damage development the remaining strength is decreasing. Durability at damage development to some parameter when the remaining strength has decreased to minimal level is defined as remaining lifetime???. A fatigue phenomenon is possible practically for all structural materials of aircrafts???. The main parameter of fatigue damage is the length and/or depth of a fatigue crack. Paris' law or similar regularities allows establishing of tight correlation between crack sizes and structural element remaining lifetime. So, in this case the basic point of remaining lifetime predicting is the correlation "signal – crack size" establishing and its features defining.

The establishment of reliable correlations between parameters of damage and a sensor response during automatic NDT is one of the most important conditions of successful establishment of the SHM system of aircraft. It is the first aim of present paper. The second, and its main aim is the estimation of the efficiency of different approaches (scalar parameters of a signal-response) for the fatigue crack prediction.

# 2. Experimental Investigation

## *2.1. Material, Samples, Equipment*

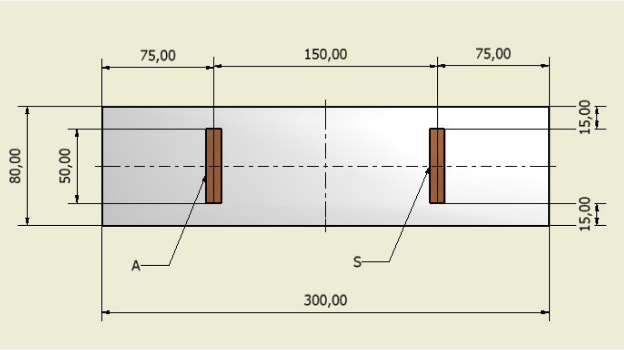


*Figure 2. Sketch of a sample with sensors in basic experiment*

Investigations of ultrasonic Lamb wave interaction with fatigue cracks have been performed on flat samples from aluminum alloy 2024-T3 with a thickness of 1 mm. The sketch of the base configuration with the size 80x300 mm is presented in Figure 2. For the initiation of a fatigue crack in the middle part of the sample the concentrator of stress was carried out??. In the experiment described here, a sample with a central circular hole with a diameter of 4mm was used. The sample was loaded using a servo-hydraulic test machine (Instron) working at a frequency of variable loading (10 Hz), the maximal stress in a cycle 150 MPa and cycle factor of 0.333.

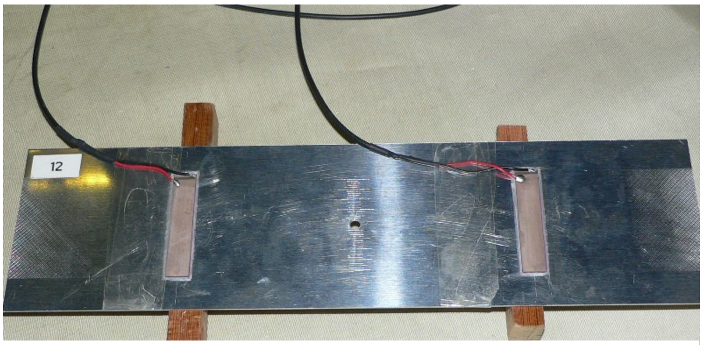


*Figure 3. Experimental sample: Al 2024-T3, 1x80x300mm, 4mm central hole*

At the first stage of tests the initial crack at the edges of a hole with a size up to 1 mm was initiated.

Before the beginning of the second stage of tests, the PZT transducers were installed according to the scheme shown in Figure 2. As transducers the Piezoceramic PIC 151, 0.5x10x50mm (PI Piezoceramic) were used**.** PZT transducers were pasted directly to the sample surface by means of Hysol adhesive (Hysol EA 9309.3NA). The preliminary tests executed in a laboratory of the K.U. Leuven (Katholieke Universiteit Leuven) have shown that the performance of the adhesive was sufficient so that the connection PZT-Al 2024 kept its strength and working performance up to a high number of cycles. The picture of a sample prepared for the tests is shown in Figure 3.

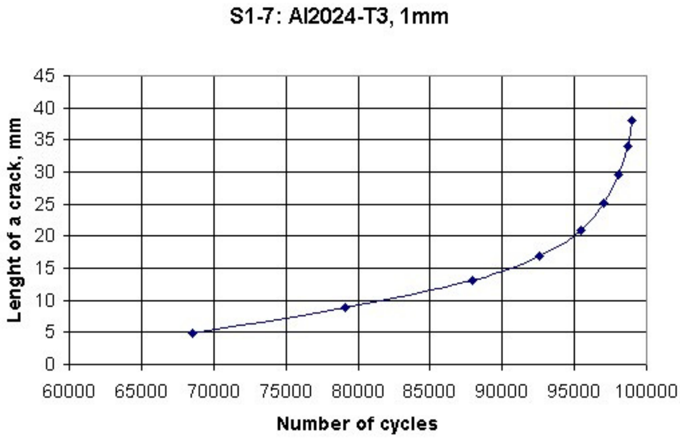
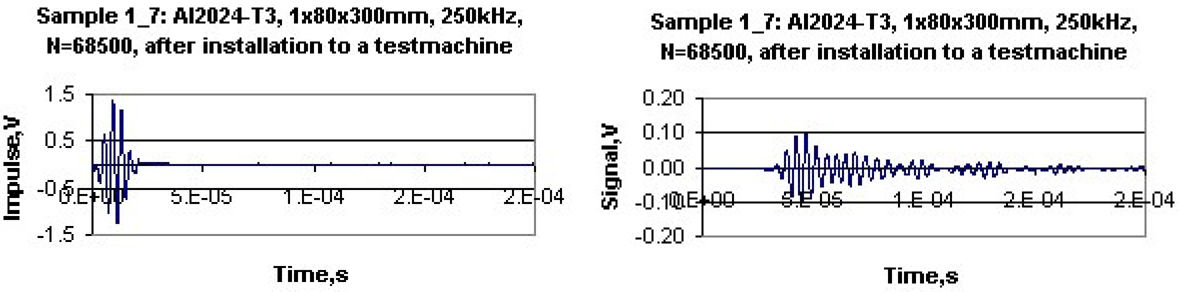


*Figure 4. Curve of a fatigue crack propagation*

At the second stage of the tests the fatigue crack was growing

from the central hole in the sample during cyclic loading. The size of a crack on a surface of the sample was determined by means of a microscope with a tenfold magnification. The crack developed practically symmetrically with respect to the center of the hole. The crack growth history is shown in Figure 4. The growth of a crack is well described by Paris' law with an exponent =3.78 and a constant =1.69·10-8, if growth rate to measure in mm/cycle, and stress intensity factor in MPa·m$^{0.5}$.
The loading was interrupted and the non-destructive testing of the sample was performed by means of the built-in monitoring system described above after a crack had grown until approximately in steps of 2mm.
Dedicated electronics (LWDS45) of Cedrat Technologies with controlling software developed at the K.U. Leuven was used for the excitation of the ultrasonic signals.
A 5-cycle sine burst signal at 250 kHz was used to excite the actuators at their approximate resonance frequency. The time window of every burst was 20 μcs, and the amplitude did not exceed 1.5 V (Figure 4a). The Lamb waves excited by the actuators propagated along the plate and were received by the sensor. The response was amplified and transferred to a digital oscilloscope PXI-5105 (National Instrument**)**.
The typical response is presented on Figure 4b. The complex signal is composed of interfering echoes mainly originating from reflections at the side edges of the sample. Thus, the intensity of a burst, i.e. the form of the direct and reflected impulses can vary. During the fatigue experiment the essential change of signal propagation is connected with the growing of a crack. Therefore, the analysis of features of the response and detection the most essential of them which are caused by propagation of a crack is the key problem of processing of ultrasonic NDT results.



a) b)

*Figure 4. Form of an impulse of excitation (a) and Sensor response (b) in Al sample with the 4mm central hole and initial crack*

### *2.2. Signal Processing and Features Extraction*

There are a number of simple time domain measures in structural damage detection [7]. These include response maximum and minimum and peak-to-peak of a response (a difference between the maximum and minimum), arrival time - absolute time when the signal first crosses the threshold level and others simple parameters of a response. The Root Mean Square (RMS), statistical moments are more complex signal parameters.

Three parameters of response were chosen for comparing their efficiency:

- Peak of amplitude - maximum amplitude of the signal (half of a peak-to-peak of a response);
- Maximum of the ***RMS(t)*** on time interval $[0,t]$, $t<T$, where $T$ is the duration of a

record;

- Global maximum of the smoothed function ***S(t)*** on time interval $\left[t-\Delta t, t+\Delta t\right]$, $\Delta t < t < T - \Delta t$, where $2\Delta t$ is the trimmed interval of a record.

The first parameter can be easily defined using of a response record (Figure 4).

The second parameter, maximum of the ***RMS(t)*** on time interval $\left[0,t\right]$, can be defined by the following way. First of all, the ***RMS(t)*** on time interval $\left[0,t\right]$ must be calculated by the formula:

$$RMS(t)=\sqrt{\frac{\sum_{i=1}^{n(t)}(s_i-\bar{s})^2}{n(t)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where ***n(t)*** is the number of samples in a response record, $s_i$ is the value ***i*** of digital record, $\bar{s}$ is the mean value.

Then

$$RMS_{max}=\max_{t\in[0,T]}\left[RMS(t)\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

An example of ***RMS(t)*** as the time function is shown in Figure 5. Usually this function has one peak and in all cases first peak is maximal.

The third parameter, the global maximum of the smoothed function ***S(t)*** on time interval $2\Delta t$ is defined by similar way.

$$S(t)=\sqrt{\frac{\sum_{i=n-\Delta n}^{n+\Delta n}(s_i-\bar{s})^2}{2\Delta n}}\ , \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where $\Delta n$ is the number of samples in the time interval $\Delta t$.

An example of this function ***S(t)*** is shown in Figure 6. In contrast to the previous case this function usually has several peaks and the maximum peak is not ever the first peak. The largest peak is named global peak.

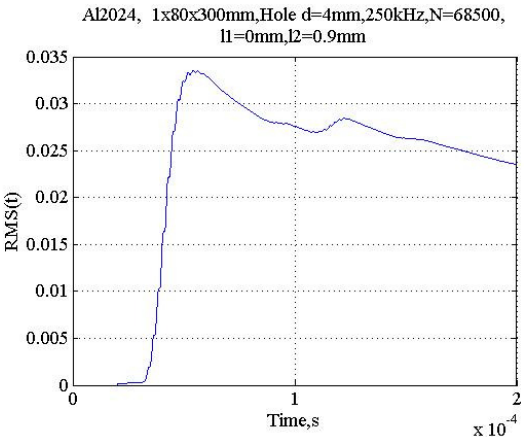


*Figure 5. The **RMS(t)** as a function of the time*

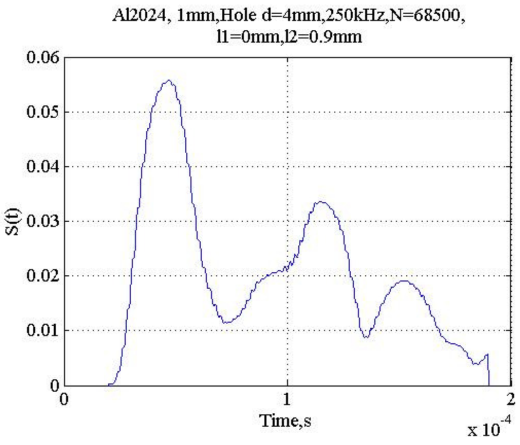


*Figure 6. The **S(t)** as a function of the time*

After processing experimental data, the functions “parameter of signal vs. length of the crack” were obtained (Figures 7, 8, 9) for each of three kind’s parameters.

It is visible, that the obtained functions have a similar shape. Parameters of a signal noticeably decrease, if the length of a crack increases. It can essentially be explained by the shading effect of a crack. Because the crack is oriented (down on a way of direct distribution of an elastic wave???) perpendicular to the ultrasonic wave front moving from actuator to a sensor, there is partial reflection from the crack surface. The degree of reflection increases with increasing crack size which causes both a change of the shape, and the signal intensity received at the sensor. Because all of three parameters characterize signal intensity its reduction during growth of the crack is to expect.

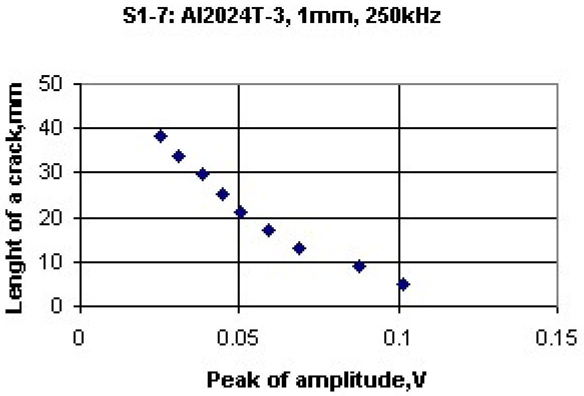


*Figure 7. Correlation function for the first parameter of response*

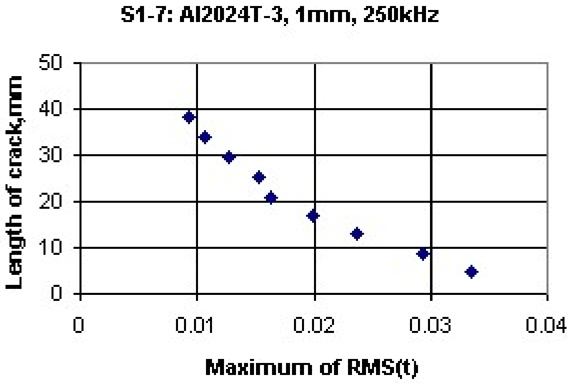


*Figure 8. Correlation function for the second parameter of response*

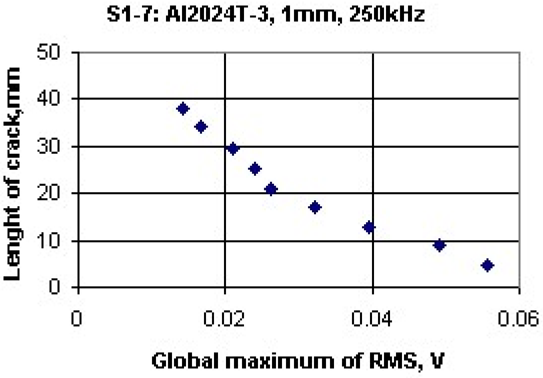


*Figure 9. Correlation function for the third parameter of response*

### *2.3. Comparison of Efficiency of Different Parameters of a Response*

One of the main tasks of the present paper is the comparison of the efficiency of the use of different scalar parameters of a signal-response at the predicting of the size of a fatigue crack. A natural criterion is the prediction error of the length of a crack as a result of the natural scattering of measured values of parameter. So, the variance and the standard deviation may be used as the measure of natural scattering. The variance is the second central statistical moment. The variance describes the variability of a signal from its mean value. The standard deviation from the mean value is widely used in statistics to indicate the degree of scattering.

It is supposed that $\boldsymbol{X}$ is a simple scalar parameter of a response. It is a random value and follows some distribution law $\boldsymbol{F_X(x)}$. Let the length of a crack be the parameter of a signal function $y = f(X)$. It is obvious, that in this case the predicted length of crack $Y$ is also a random value with the law of distribution $F_Y(y)$. If the function $y= f(x)$ is relatively smooth, then

$$(y - y_0) \approx \left.\frac{\partial f}{\partial x}\right|_{x=x_0} (x - x_0) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4)$$

If for some fixed $x_0$ is the mean of random $X$, then the variance $D(Y)$ of random $Y$ and its standard deviation $\sigma(Y)$ can be expressed using

$$D(Y, y_0) = \left( \left.\frac{\partial f}{\partial x}\right|_{x=x_0} \right)^2 D(X, x_0), \qquad \sigma(Y, y_0) = \left.\frac{\partial f}{\partial x}\right|_{x=x_0} \sigma(X, x_0), \ldots\ldots\ldots..(5)$$

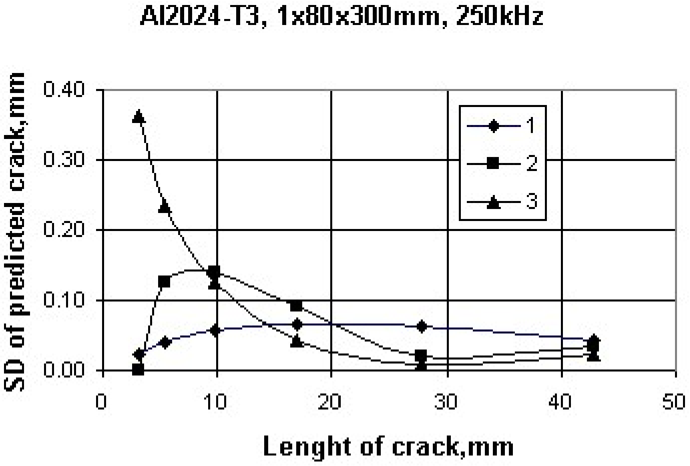


*Figure 10. Standard deviation of the crack length, predicted at the use of three parameters of a response: 1- peak of amplitude, 2- maximum of the **RMS(t)** , 3 - global maximum of the **S(t)** .*

If there are experimental data of the random $X$ for different means $x_0$, then the variance $D(Y)$ of random $Y$ and its standard deviation $\sigma(Y)$ can be estimated.

The statistical data obtained in the experiment are sufficient for such an estimation. Final results of statistical analysis are presented in Figure 10.

## 3. Conclusions

It can be sees that any of the three parameters of response shows a relatively small scattering. Thus, (the length of a crack predicting with their use???), the accuracy of predicting the crack size, especially for a crack length of more than 10mm, is acceptable for SHM. A comparison of the three parameters shows:

1) The peak of the amplitude is a stable criterion in a large interval of the length of a crack and preferred for small cracks.
2) Integral criterions 2 and 3 are preferred for large cracks.
3) The criterion 3 for small cracks can give sufficient difference in predicted crack length .

It is necessary to notice, that the received estimations are based on limited experimental data. With increasing volume of statistical data, certain changes of the results are possible. However, quite definitely it is possible to conclude, that the given technology is capable of providing high stability and necessary accuracy at the continuous integrated SHM of thin-walled aluminum components of aircraft. Result of this research shows that the multi-parametric criterion can be used.

It is also shown that the accuracy of damage prediction is one of the most significant parameter to assess the SHM efficiency.

## Acknowledgement

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