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VALIDATION OF SELECTED PRESENTED METHOD MEASURED OF LENGTH FATIGUE GAP ON COMPRESSOR BLADES FORMING DURING RESONANT TESTS

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Abstract

In this work, the validation of selected presented method measured of length fatigue gap was shown. The article describes three methods of determining fatigue gaps. The object of the study was the first stage compressor blade from aircraft engine. Blades have defects on the leading edge. This defect on the blade (as a result of the resonance vibration) was the origin point of the fatigue gap. Two of the methods, fluorescent and thermovision, were optical. The fluorescent method was a direct measurement, whereas direct-indirect thermography. The last of the presented methods was an analytical method, showing an algorithm based on amplitude-frequency characteristics. The advantages and disadvantages of these methods were compared. As a result of the analysis performed by the algorithm, there were specified patterns defining the dependence of change in crack length depending on the asymmetry of AF characteristics. The accuracy of the following methods and the results obtained for chord length were determined. Thanks to such use, these results have a utilitarian meaning. Such a compilation allowed us to evaluate the usefulness of particular measurement methods. Proposed methods of measuring the length of fatigue crack are used in experimental studies. It is also possible to implement them for research conducted during the operation of an aircraft engine.

Keywords: *crack propagation, gap, thermovision, turbine engine, blades*

1. Introduction

There are many non-destructive and destructive methods used in the research of aircraft engine compressor blades. Compressor blades (Fig. 1a) are included to a group of critical components. This is due to the complexity of the operating loads (centrifugal force, vibration, the impact of the incoming air) and the possibility of damage by collision with a hard object (which falls into the engine). As a result of a collision with a hard object (FOD), on the leading edge, punctures (notches) and micro cracks are formed [4, 5, 7, 9-11] (Fig. 1b). These damages can be an origin of the fracture [5, 10, 11]. Most commonly, crack initiation occurs when the blade is working under resonance conditions. Flexural vibrations cause a concentration of stress in the top of the notch. Increase in local stresses, even if they do not exceed critical values, can cause fatigue. This phenomenon is seen as a crack propagation, where fracture propagates from a known damage point [10, 11].

Some studies assume that the appearance of damage will result in a change in the vibration frequency or a change in the amplitude of the vibration [3, 8, 13]. For this purpose, contactless measurement of the resonant frequency or the amplitude of the displacement of the vanes is required. In order to correctly verify the results obtained, it is necessary to properly transform and analyse the information collected. For this purpose, various methods of analysing these signals have been prepared [8, 12].

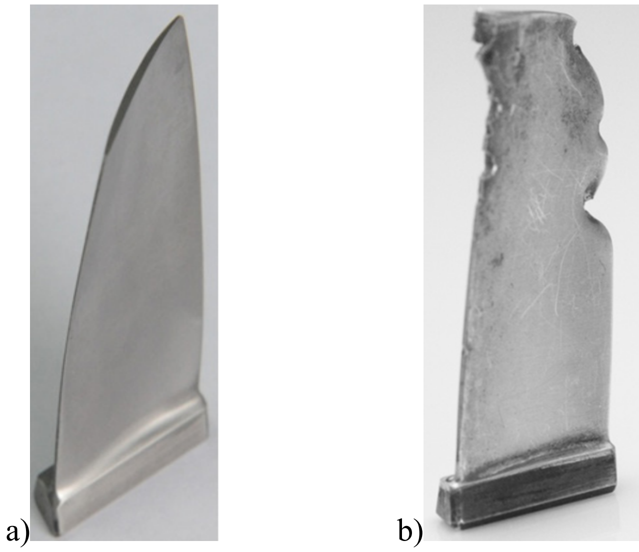


Fig. 1. Undamaged (a) and damaged (b) compressor blade

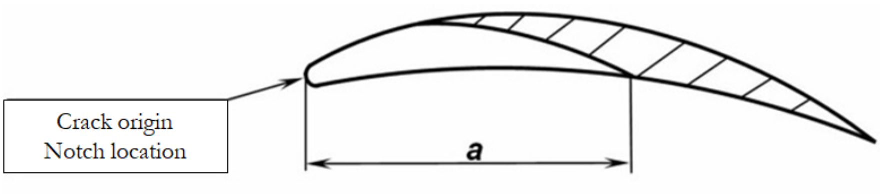


Fig. 2. Schematic of cross-section of the blade with definition of crack length

Most of mentioned and presented works concerned their research in resonance conditions. During these tests, the blade is attached to the vibration generators head and subjected to forced oscillation. The most important surveys measured during such tests are the number of load cycles, the blade tip displacement amplitude, the length of the fatigue crack (Fig. 2) and the frequency of vibration. To measure the length of the fatigue crack, fluorescent fluid (observed in UV light) is usually used. Unfortunately, this method has several disadvantages and problems. Another proposed method [1, 2] is a method based on observation of the heat released during vibration with using an infrared (thermography) camera. This method is also called as the thermovision method. This work presents a comparison of selected methods of measurement of fatigue crack length. These methods are the previously mentioned UV-based method; the thermovision method and the algorithm-based method (specify crack length based on amplitude-frequency characteristics).

The aim of the study is to compare several proposed methods of determining the length of the fatigue crack, presenting the benefits and the inconvenience associated with them. Studies will be conducted for several cases of crack length. The reference point will be the crack length measured using fluorescent fluid and UV light.

2. Test in resonant condition

Fatigue tests of the blade were performed in the Laboratory of Rotary Machines Dynamics of the Rzeszow University of Technology. The basic of this test were resonant condition. These conditions were obtained by the Unholtz-Dickie UDCO TA-250 vibratory system. The blade was mounted in the handle of the moving vibration head in a horizontal position (Fig. 3). The first step on the analysis was to perform a modal analysis to determine the frequency of the vibration resonance of the blade. In second step of the study, the blade was subjected into resonance frequency corresponding to the first mode of vibration. Resonant vibrations (I mode) are purely flexural form. The amplitude of the blade tip displacement was monitored by a POLYTEC PSV H-

400S laser vibrometer. Object of the study is a blade from I stage compressor form PZL-10W engine. Blade has a notch located 3 mm above the foot of the blade. The depth of the notch is equal to 0.5 mm. Chord of this blade, in plane of notch is equal to 20 mm.

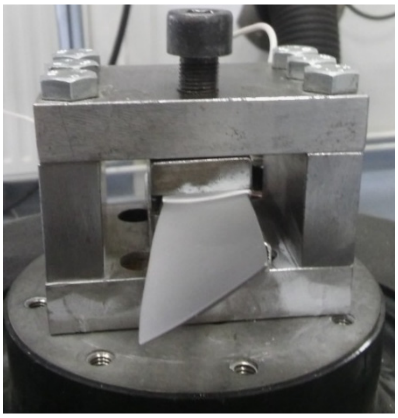
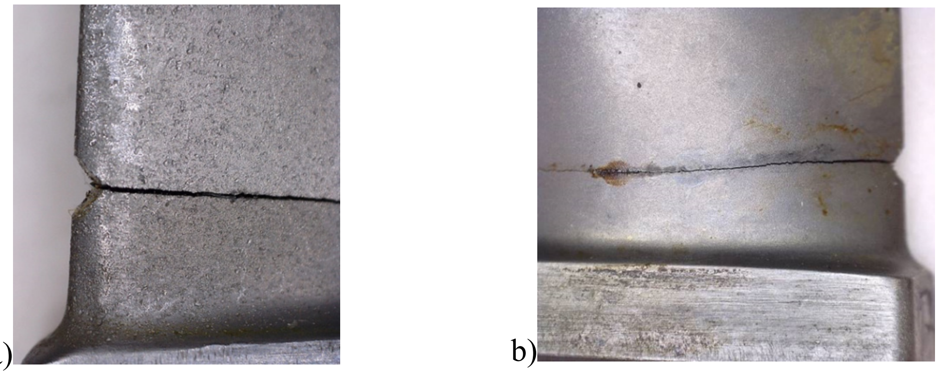


Fig. 3. Vibration head with mounted compressor blade



a) b)

Fig. 4. View of the fatigue crack on the internal-concave (a) and external-convex side (b) of the blade

Research was conducted while maintaining a constant amplitude of vibration. The blade was kept in resonance until the crack was appeared. The results [7, 8] show that for the PZL-10W compressor blades, the initiation of the crack occurs after observed decrease in the resonant frequency about 1%, which corresponds to about 8 [Hz]. Research on the determination of the resonance frequency of the blade (modal analysis) was performed for excitation equal to 1g (where 1g correspond to 9.81 [m/s^2]). Fatigue tests under resonance conditions were carried out with an excitation value of 15 g. The purpose of the resonance research was to create cracks (Fig. 4) and later to validate the methods used to measure the crack length.

The crack size (length – mentioned in chapter 1) was measured by three different methods. As the most accurate and primary method, the method of defectoscopy using fluorescent fluid was chosen. In the further part of the work, it will also be called the basic method. The other two methods were developed to remove the inconvenience and problems generated by the basic method.

3. Methods of crack length measurement

3.1. Optical method – fluorescence fluid observed in UV light

First (basic) method used to observation of the crack and measuring of its length based on fluorescence fluid (Fig. 5 and 6) applied on the blade. Fluid was penetrate crack and fulfil gap between separated pieces. Then the excess fluid was removed. Last step of this method was to observe crack in UV light and measure the crack length (Fig. 5). This application allows you to measure the length of the slot using a slider.

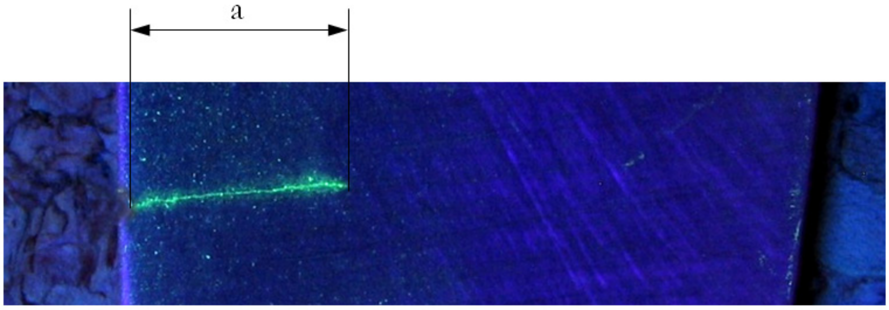


Fig. 5. Example of crack length measured by fluorescent defectoscopy method

The advantages of the fluorescent method were:

- good visualization of gap,
- accuracy of measurement at 0.2 mm,
- simplicity of measurement,
- time of measurement.

Disadvantages was:

- necessity interruption of researches, after every step of resonant test (to apply fluorescent fluid),
- no possibility of measurement during resonance testing,
- need to process results in each part of the test,
- problem with complete fulfilling of the gap by fluorescent fluid.

Based on advantages and disadvantages, a fluorescence method was enough to detecting and measuring the crack length after resonant test but was unpractical during exams. Because of the great versatility, accuracy and ease of measurement, the results of this method will serve as a benchmark.

3.2. Thermographic method

Another method used in test was thermovision method (Fig. 6a). The distribution of temperature around crack may show length of crack and also influence of crack length on speed of propagation. The phenomenon was caused by adhesive friction and pulsation of the stress around the top of the crack. Friction was existed between both part of newly established crack causes the release of energy around the gap (Fig. 6b). This energy was monitored as a local temperature gradient. This technic can be used to monitoring the crack during resonant test. This method is based on thermal imaging camera. In tests VarioCam system were used. Thermographic camera is characterized by the following parameters: sensitivity on level 0.3 K, resolution equal to 640x480 pixels and sampling frequency 30 fps.

a) b)

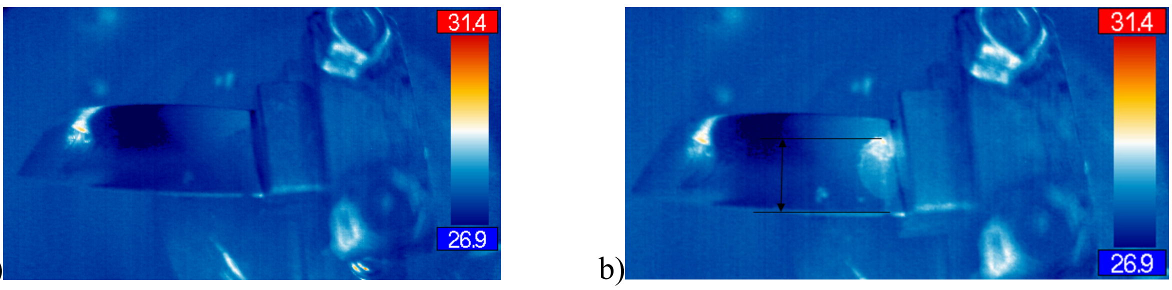


Fig. 6. Thermographic image of the blade: before (a) and during (b) resonant tests

Most benefits ensuing from this method is:
- possibility taken continuously measured (even during resonant test) – non contact method,
- accuracy of measurement at 1 mm.

This method has some disadvantages. The main are:
- complicated process of photos made,
- problem with positioning camera in right place,
- errors (reflections) in the pictures.

This method is useful for a crack length of 3 to 15 mm (15 to 75% of the relative chord of the blade).

3.3. Algorithm based on amplitude-frequency characteristics

The third method of crack length measurement is based on the asymmetry of the amplitude-frequency (AF) characteristic. Due to the development of the gap, this characteristic is no longer symmetrical. Studies have shown that when crack length increases then observed asymmetry is greater. The example of asymmetrical AF characteristic was shown at Fig. 7.

This method is based on the asymmetry coefficients. At different altitudes of AF, the distance travelled from the centre of this function was measured (Fig. 7). Then asymmetry coefficients are the ratio of the distance to the left of the function to the distance to the right of the function (denoted e.g. A2, A3, A4). In addition, the relationships successive coefficients (labelled A5 / A3 or A4 / A2) were calculated and are called coefficients of change rate. Fig. 8 shows the relationship between the given asymmetry coefficient and the relative crack length.

For a known data set, the functions approximating a given characteristic are defined. Given the AF characteristics of a given blade, it is possible to determine the asymmetry coefficients. Based on prepared approximation equations and asymmetry coefficients, the gap length can be determined.

Equations, which describe relations between asymmetry coefficients and crack length, were shown in Tab. 1. X is known coefficient and y is searched relative crack length.

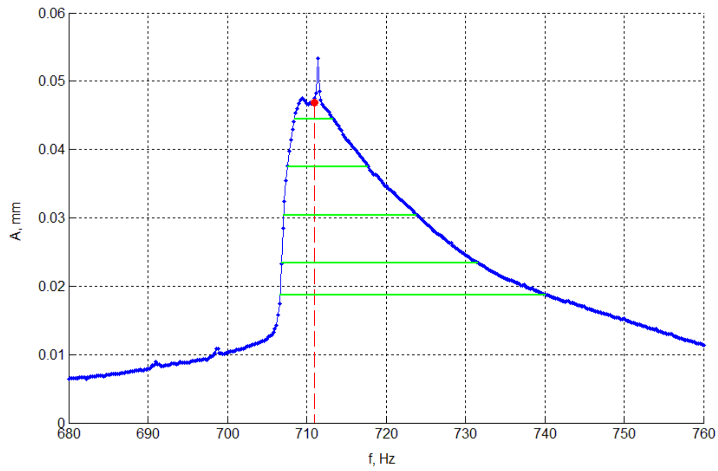


Fig. 7. Amplitude-frequency plot of the blade with marked measurement point used to calculation the asymmetry of the characteristic

Tab. 1. Example of equation, which represent crack length in function of asymmetry coefficient

Type of asymmetry coefficient	Equation
A4/A2	$y = -2 * 10^{-6} * x^3 + 0.0006 * x^2 - 0.0712 * x + 2.6193$
A5/A2	$y = -0.00001 * x^2 - 0.0275 * x + 1.3681$
A5/A3	$y = -0.0123 * x + 1.1976$

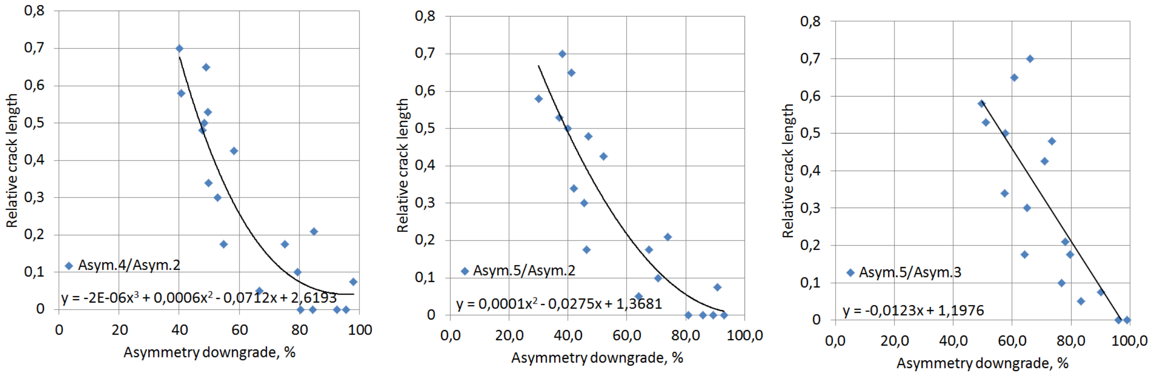


Fig. 8. Plots of relative crack length in function of asymmetry downgrade

In this method, crack was calculated from AF characteristics. This method is useful for detecting damage. Its range of applicability is from 0% to 50% of the relative length of the blade chord. The biggest advantage of this method is ease of use. In addition, this method allows for later evaluation of the results. The disadvantages of this method are:

- the need to determine equations for another case of damage and another blade,
- large scatter results at 30% of relative chord length (relative chord length correspond to relative crack length).

4. Comparative analysis of investigate methods of crack length identifications

To comparative analysis a 8 cases of crack length (in 2 different blade) were used. The crack length was measured in three different ways. First, basic method was a fluorescent penetrant (optical) method. A measurement was taken during stops in the resonant test. Second method used in comparative analysis was thermovision method. Thermal images were taken when AF characteristics were made. Last method based on analytical calculation which basics were an asymmetry in AF characteristics.

Tab. 2. Results of comparative analysis

Test number	Optical method	Thermovision method			Algorithm based on AF characteristics		
	Reference crack length [mm]	Identified crack length [mm]	Absolute discrepancy [mm]	Relative discrepancy [%]	Identified crack length [mm]	Absolute discrepancy [mm]	Relative discrepancy [%]
1	0	0	0	0	0.31	0.31	1.55
2	1	0	1	5	1.77	0.77	3.85
3	3.6	4	0.4	2	4.67	1.07	5.35
4	6.5	7	0.5	2.5	5.97	0.53	2.65
5	9.4	9	0.4	2	4.76	4.64	23.2
6	0	0	0	0	0.66	0.66	3.3
7	4.8	5	0.2	1	3.34	1.46	7.3
8	8.5	9	0.5	2.5	5.88	2.62	13.1

Results of comparative analysis were shown in Tab. 2. In first column information about examined blade were placed (Test number). In second column a crack length measured with fluorescent (optical) method were written. In next 3 columns, results from thermovision method were shown (identified crack length, absolute discrepancy and relative discrepancy). In last 3 columns, results from algorithm (based on AF characteristics) were written. Absolute discrepancy was calculated as the difference between result from optical (basic) method and other method (thermovision or algorithm). Relative discrepancy was calculated as absolute discrepancy divided by chord length.

As mentioned earlier, the results obtained by the optical (fluorescent) method were used as the reference point. The highest inaccuracy for the thermovision method, at 5%, was observed in case of crack initiation. The length of the gap (1 mm – 5% of chord length) was too small to produce significant friction between the pieces of blade, and the heat released during crack propagation process was too small. A further increase in crack length cause increase in the accuracy of the observed results. The maximum error (relative crack length) observed in this method (for a range of 1 to 15 mm length of the crack) is 2.5%. The advantage of this method is that the measurement process was executed in real-time (without interruptions in the test). The disadvantage is the need to individually evaluate each image and manually determine the length of the gap. Also, remember that thermal imaging may display errors and reflections from the environment. In the case of small lengths of fatigue gap, it is necessary to pre-determine the location of the failure.

Much higher scatter in the results (up to 25% of the blade chord) is observed for the algorithm method. The biggest advantage from this method is a detection of the damage correlated to crack initiation. In comparison to thermovision method, in algorithm method was possible to determine crack in early stage of size (less than 1 mm). This method is useful roughly to 50% of the length of the blade chord. For low values of crack, length (up to about 25% of chord) is high accuracy in the results, about 5-7%. This result is satisfied. The crack length measurement method can be used for fault detection. Another advantage of this method is the ability automatically to determine the gap length (based on amplitude-frequency characteristics). Scatter in the results of this method is related to the permissible operating deviations for a given blade.

5. Conclusions

The following work show results of investigation concerned on validation the method to crack length measurement. The first method was an optical (fluorescent) method. The results of this method served as a benchmark for the other methods. This method was characterized by superior accuracy. Unfortunately, this method is a contact method and it was necessary to break the fatigue test in order to measure the crack length.

Another method studied was the thermovision method. The results from the thermographic studies were similar to the reference points. For crack lengths from 1 to 15 mm, the maximum error was 2.5%. This method is not useful for crack length less than 1 mm. Because of the nature of the measurement (no contact with the examined object), there was no need for breaks during resonance studies. The main limitation of this method is the need to predefine the location of the damage and to reject the reflections appearing in the thermal image.

The last test method was an algorithm based on an asymmetry of amplitude-frequency characteristics. This method allowed the detection of cracks length less than 1 mm (such damage was not detected by optical methods). Its disadvantage was the large difference in results (rows of 25-30%) for gap lengths higher than 10 mm. This is related to the permissible deviation of the blades.

The presented methods can be used simultaneously or alternately. Each of them has some errors and limitations. Choosing the right method depends on test conditions and test assumptions. With the appropriate modification of the thermal method and the algorithm, it is possible to implement these methods for used the maintenance of aircraft engines.

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