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THE STUDY ON ALGORITHM FOR IDENTIFICATION THE FATIGUE CRACK LENGTH OF COMPRESSOR BLADE BASED ON AMPLITUDE-FREQUENCY RESONANT CHARACTERISTICS

Daniel Lichoń, Arkadiusz Bednarz

Rzeszow University of Technology
Department of Aircraft and Aircraft Engines
Powstańców Warszawy Av, 8, 35-959 Rzeszow, Poland
tel.: +48 17 7432346, +48 17 7432348
e-mail: d_lichon@prz.edu.pl, abednarz@prz.edu.pl

Abstract

The article is focused on building the algorithm for identification the fatigue crack length in the first stage of compressor blade of the helicopter PZL-10W turbo-shaft engine. The fatigue wear of compressor blade is a process in which the fatigue crack begins at the structural notch of the working part. For compressor blade, the crack starts at the leading edge and progress along the blade chord. Due to working conditions, the compressor blades are referred to as critical components. The helicopter rotor downwash can easily lift particles form the ground that may cause damages in the compressor section. Aircraft engines are designed so that the rotational speed of impeller remains below the resonant frequency. However, the pulsation of working medium or mechanical vibrations may cause temporary increase of vibration frequency. The appearance of structural notch combined with temporary increase of vibrations may initiate the fatigue failure. The works undertaken at the Department of Aircraft and Aircraft Engines, Rzeszow University of Technology provided a wide spectrum of research data of amplitude-frequency (A-F) characteristics of 1st stage of compressor blade. For different crack lengths, the fatigue tests of resonant frequency and asymmetry of A-F characteristics were acquired. The crack lengths were measured by fluorescent or infrared mapping method. The aim of the article is to develop the numerical method for identification of crack length of compressor blade basing on A-F characteristics. The studies on A-F characteristics in order to find correlations between crack length, resonant frequency and characteristics asymmetry were performed. The next step was to build the algorithm for identification the crack length when only A-F characteristic is known. The article contains the description of researches background, A-F characteristics unique features, algorithm detailed methods of work and sample use of algorithm in identification the crack length.

Keywords: *fatigue failure, crack length, compressor blade, aircraft engine, failure identification algorithm*

1. Introduction

Airplane compressor blades are often referred to as critical components. Due to working conditions and loads that affect them, they failure may occur. The first stage compressor blades are particularly vulnerable to collisions with hard object. The suction force generated by the working rotor assembly can easily picks up fine particles from the zone in front of the engine. These particles, as a result of a collision with blades, can cause damage called notches. These notches can have different locations, geometry and shape. Consequently, there is no way clearly to assess the effect of a given notch on the fatigue life of the analysed item. The rotor assembly itself can rotate at speeds ranging from a dozen to several tens of thousands of revolutions per minute. It is dangerous when the rotational speed coincides with the blade's resonant frequency. Aircraft engines are designed so that the rotational speed of the impeller is below the resonance frequency. Unfortunately, the pulsation of the working medium or mechanical vibration of the shaft (or vane) can cause a temporary increase in vibration frequency. Such a phenomenon, combined with damage at the leading edge, can cause a failure of the blade as well as the entire engine.

Fatigue life, damage detection and assessment were the subject of many research papers and doctoral dissertations [3, 5, 6, 11-14]. Prof. Szczepanik in his dissertation [8-10] shows results about the influence of the particles sucked into the engine, on the geometry of obtained notches on the blades. In addition, his work on the vibration measurement system of the blades during engine operation allowed to obtainment vibration characteristics. Witoś in his works [15] focuses on the detection of damage in the compressor blades.

There are several methods for detecting defects [1, 2, 4, 7, 15]. Some of them are based on visual research. The main goal of research [1, 2] was prepared a method of detection and measuring a fatigue gap. This method based on the thermal image and the heat released during the friction between the spaced apart blade elements. Some of the other methods are used in the stationary overview of the engines or during fatigue tests. In addition to the classical measurement of slot length and counting of load cycles, the amplitude-frequency (A-F) characteristics are performed. The asymmetry on A-F characteristics indicates the appearance and further development of fatigue cracks. The works presented in the article focuses on development the numerical methods for identification the crack length of compressor blade. Basing on measured A-F characteristics, the unique features were studied in order to build A-F numerical processing method. In result, the resonant point and asymmetry coefficient are identified. Further, obtained numerical data are used to approximation the relation between crack and asymmetry of A-F characteristics. The final step is to use the algorithm in identification the crack length and discuss the results. The numerical implementation of algorithm was prepared in MATLAB environment.

2. Object and conditions of fatigue test

The object of the research was a compressor blade from the PZL-10W engine. This engine was used to propel the W-3 Falcon helicopter. This blade is made of EI-961 alloy steel (chrome-nickel). It is characterized by the following strength properties (at 20 degrees C): Modulus of elongation $E = 210$ GPa, Poisson's ratio $v = 0.3$, tensile strength $R_m = 1050$ MPa, Contractual elastic limit $R_{0.2} = 850$ MPa. Examined blades contain notches made by machining. The notches are located 3 mm above the foot of the blade and have depth equal to 0.5 mm. The radius of the rounding at the tip of the notch was 0.05 mm.

The compressor blades were subjected to a destructive high cycle fatigue test. During this test, the amplitude of the blade tip displacement was controlled and the number of load cycles was counted. Fatigue tests were carried out in the Laboratory of Rotary Machines Dynamics at the Rzeszow University of Technology. The blade was mounted in the head of the vibration inductor Unholtz-Dickie. The displacement of the blade was measured in two ways: using a laser vibrometer (which also performs amplitude-frequency characteristics) and using an optical microscope. Every tens of thousands of load cycles, the test was interrupted and the amplitude-frequency characteristic was performed at 1 g (g is a standard earth gravity, g = 9.81 m/s^2). Additionally, the length of the crack was measured using fluorescent fluid. The length of the crack was defined as the distance from the bottom of the notch to the end of the visible crack observed in ultraviolet light. The A-F characteristics with the information about crack length were used to prepare the learning data for the algorithm.

3. Algorithm construction

3.1. The amplitude-frequency characteristic features

Considering the steps in building the algorithm, it is essential to analyse the measured A-F characteristics to find common features of shape and potential irregularities of measured physical quantities, which need to be filtered. Fig. 1 presents the set of measured characteristics for 2 blades (named A and B) with different lengths of crack. The general tendency in A-F course is to decreasing the resonant frequency with crack length. Peak amplitude decreases when relative crack length (related to blade chord) not exceed $\overline{L} = 0.5$. When $\overline{L} > 0.5$ the plastic deformation occurs so that this state is not considered in the work. Asymmetry of A-F is the key importance in identification the identification of crack length. Starting with $\overline{L} = 0$ the characteristic is approximately symmetrical. With the increasing L ($\overline{L} < 0.7$) the characteristic has regular deviation directed to frequencies above the resonant (for $\overline{L} > 0.7$) the deviation is oppositely directed).

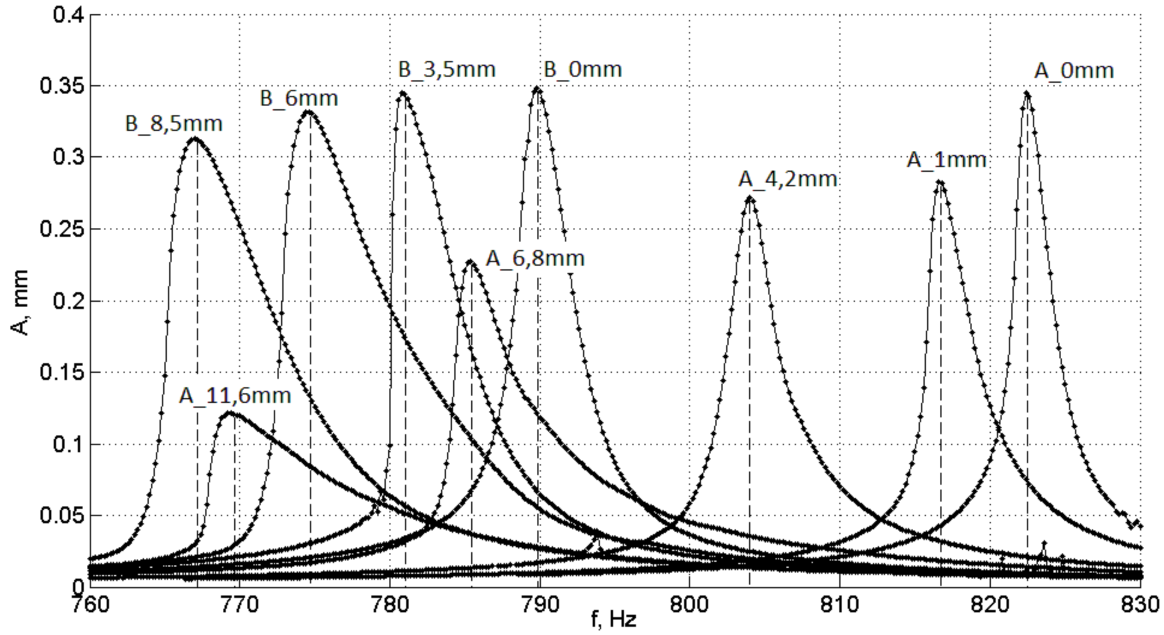

Fig. 1. Selected amplitude-frequency characteristics used in algorithm construction (blades A and B with crack length)

The irregularities of measured amplitude may occur in the neighbourhood of resonant point and on the characteristics slope as well. It is required to find the resonant frequency for each type of resonant neighbourhood (Fig 2). The practise have shown that slope irregularities have less importance since these appears when blades with crack length $\overline{L} > 0.7$ are investigated (Fig. 2c). The measurement-sampling step is 0.2 Hz. Nevertheless, it is still insufficient in analysing the asymmetry of A-F in the resonant area. Thus the intermediate values need to have linear approximation.

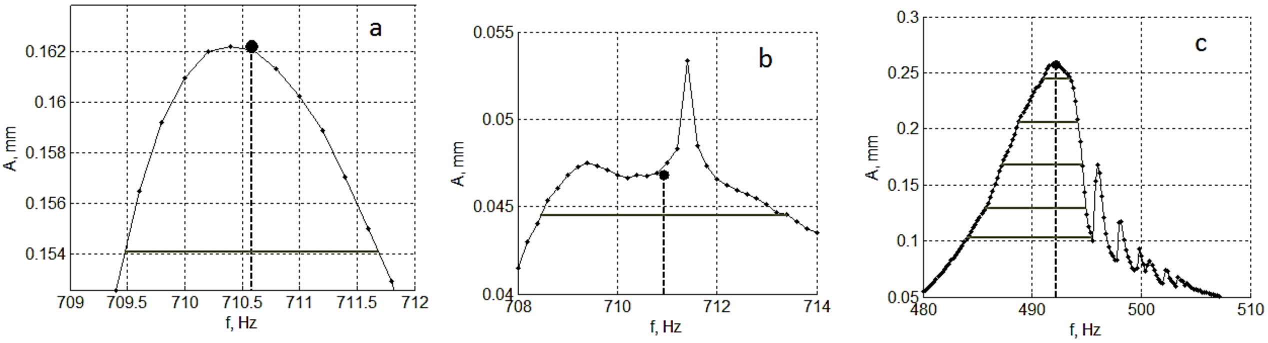

Fig. 2. A-F characteristics course cases, resonant point and asymmetries identification for a – regular peak neighbourhood, b – irregular peak neighbourhood, c – irregular peak slope

3.2. Algorithm method of work

The algorithm needs to solve the following issues:

a) Identification of resonant frequency independently form peak course.
b) Omitting the irregularities on the peak slope.

c) Identification of A-F course asymmetry coefficients.
d) Preparation the set of approximation data.
e) Identification the relationship between crack length and A-F asymmetry.
f) Identification of crack length based only on A-F characteristics.

The algorithm general sequence of work is divided on 4 modules (Fig. 3).

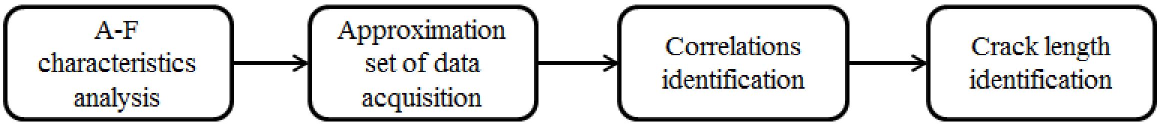

Fig. 3. General scope of algorithm work

The A-F characteristics analysis module reads the data. Next, the identification of resonant point is performed by searching the maximum of amplitude. The gradient of amplitude in the neighbourhood of maximal amplitude point is checked. If the gradient changes its sign the irregularities are detected and the middle measurement point of irregularity is assumed resonant point (Fig. 2b). In case of regular course of characteristics, maximal amplitude is assumed as a resonant point. However, this is the first approximation of resonant frequency and the correction of resonant point is applied after identification of asymmetry coefficients. The correction is based on practical assumption that in the close neighbourhood of resonant point the A-F characteristics are symmetrical. The correction is required since close to resonant point the measurement sampling is insufficient (Ch. 3.1). Asymmetry coefficients are calculated in five control points. The control points are placed relatively to resonant amplitude respectively [0.95 0.8 0.65 0.5 0.4]*A_{Resonant}. Further, at the control points the deviation of frequency form the resonant point is calculated (Fig. 2, horizontal lines inside A-F). Asymmetry coefficient is defined as a proportion between left and right deviation. Mentioned correction of resonant point is calculated by assume the asymmetry coefficient at the first control point is equal to 1 and next the resonant frequency and other asymmetry coefficients are recalculated. The effect of identification the resonant point and asymmetries were shown on Fig. 2.

The second module of algorithm is responsible for extract important data used in identification of crack length approximation. The module no. 1 is recalled several times in order to analyse set of A-F characteristics and finally the matrix of important data is created. The matrix contains the asymmetry coefficients, crack length, resonant frequency, relative crack length in single row and the number of rows is equal to inserted files. The test results of 4 blades (named A, B, C, D) were used to prepare set of approximation data (Tab. 1).

Module no. 3 refers to correlations identification thus the data form previous part were analysed in order to find regular relations between asymmetry coefficients and crack length. Since asymmetry coefficients are dimensionless, the relations were related to relative crack length (Ch. 3.1). The analyses have shown that the direct relation between relative crack length and asymmetry coefficients do not return regular tendency. Therefore, the new parameters named asymmetry downgrade (AD) were defined. The AD parameter, expressed in percentage, describes relative change between asymmetry coefficients for two selected control points. For instance AD52 refers to AD52 = (Asymmetry coeff. 5 / Asymmetry coeff. 2)*100%.

Several combinations of ADs were examined and finally for three ADs the regular relations has been found. These are AD42, AD52, AD53 (Fig. 4). The approximation equations for selected ADs were identified:

$$\overline{L}_{42} = -2\cdot 10^{-6}(\mathrm{AD42})^3 + 6\cdot 10^{-4}(\mathrm{AD42})^2 - 0.0712(\mathrm{AD42}) + 2.6193\,, \tag{1}$$

$$\overline{L}_{52} = 10^{-4}(\mathrm{AD52})^2 - 0.0275(\mathrm{AD52}) + 1.3681\,, \tag{2}$$

$$\overline{L}_{53} = -0.0123(\mathrm{AD53}) + 1.1976\,. \tag{3}$$

Tab. 1. Set of approximation data for crack length identification

Compressor blade index	Asymmerty coeff. 1	Asymmerty coeff. 2	Asymmerty coeff. 3	Asymmerty coeff. 4	Asymmerty coeff. 5	Crack length [mm]	Resonant fraquency [Hz]	Resonant Amplitude [mm]	Relative crack length
A	1	0.725	0.610	0.583	0.587	0	822.51	0.345	0
B	1	0.749	0.648	0.634	0.643	0	789.86	0.348	0
C	1	0.768	0.714	0.710	0.686	0	807.85	0.404	0
D	1	0.705	0.651	0.674	0.656	0	827.31	0.359	0
A	1	0.604	0.465	0.403	0.387	1	816.76	0.283	0.05
D	1	1.021	1.027	1.001	0.927	1.5	815.88	0.308	0.075
C	1	0.859	0.791	0.682	0.607	2	790.23	0.328	0.1
B	1	0.429	0.310	0.236	0.199	3.5	781.08	0.345	0.175
D	1	0.734	0.621	0.553	0.495	3.5	806.78	0.256	0.175
A	1	0.885	0.839	0.750	0.654	4.2	804.02	0.272	0.21
B	1	0.576	0.403	0.304	0.262	6	774.70	0.331	0.3
A	1	0.568	0.416	0.282	0.239	6.8	785.48	0.227	0.34
B	1	0.577	0.423	0.337	0.300	8.5	767.19	0.313	0.425
D	1	0.352	0.225	0.168	0.165	9.6	775.57	0.059	0.48
A	1	0.406	0.281	0.196	0.162	10	769.63	0.122	0.5
C	1	0.579	0.420	0.287	0.214	10.6	732.06	0.072	0.53
A	1	0.491	0.296	0.200	0.147	11.6	710.94	0.047	0.58
D	1	0.357	0.242	0.175	0.147	13	545.67	0.183	0.65
B	1	0.336	0.193	0.135	0.128	14	569.81	0.036	0.7

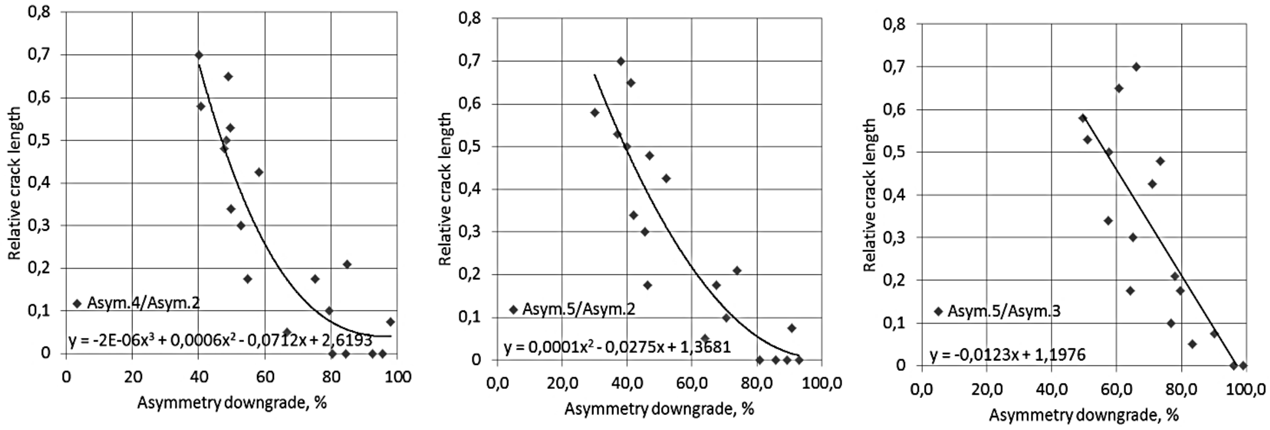

Fig. 4. Correlations of asymmetry downgrade parameters and relative crack lengths

The crack length identification realized in module no. 4 uses approximation equations listed above (1)-(3). The new A-F characteristics were not used in module no. 3 are inserted into the algorithm processed with the following way:

- for the inserted A-F characteristics the where resonant point and asymmetry coefficients are identified,
- the asymmetry downgrade parameters are calculated AD42, AD52 and AD53,
- using equations (1)-(3) the relative crack lengths $\overline{L}_{42}$, $\overline{L}_{52}$, $\overline{L}_{53}$ are calculated.

To identify relative crack length the arithmetic average is calculated:

$$\bar{L} = \frac{1}{3}(\bar{L}_{42} + \bar{L}_{52} + \bar{L}_{53}) . \tag{4}$$

The crack length is obtained by using the blade local chord c in the location of crack:

$$L = \bar{L} \cdot c . \tag{5}$$

Additionally, using the $\bar{L}_{53} = f(\mathrm{AD53})$ characteristic (Fig. 4) the neighbourhood of $\bar{L} = 0$ is supported by additional linear equation, which approximates the characteristics for $\bar{L} < 0.2$. This allows to more accurate crack length identification in the beginning phase of fatigue crack.

4. Fatigue crack length identification

The identification of crack length was performed on A-F characteristics, which were not used for algorithm construction. Tab. 2 presents results of identification where the calculated crack length is compared with crack length obtained by reference fluorescent fluid method.

Tab. 2. Algorithm identification of fatigue crack length with relation to reference method

Compressor blade index	Reference crack length [mm]	Identified crack length [mm]	Absolute discrepansy [mm]	Relative discrepancy [%]	Compressor blade index	Reference crack length [mm]	Identified crack length [mm]	Absolute discrepansy [mm]	Relative discrepancy [%]
E	0.0	0.31	0.31	1.6	F	4.8	3.34	1.46	7.3
F	0.0	0.66	0.66	3.3	E	6.5	5.97	0.53	2.7
G	0.0	1.04	1.04	5.2	G	6.6	10.08	3.48	17.4
I	0.5	0.78	0.28	1.4	I	7.0	3.87	3.13	15.7
E	1.0	1.77	0.77	3.9	I	8.0	3.93	4.07	20.4
H	1.5	2.30	0.80	4.0	F	8.5	5.88	2.62	13.1
E	3.6	4.67	1.07	5.4	E	9.4	4.76	4.64	23.2

The absolute difference between identified and reference crack length was included. The parameter of relative discrepancy is defined as the absolute crack length difference with relation to compressor blade chord.

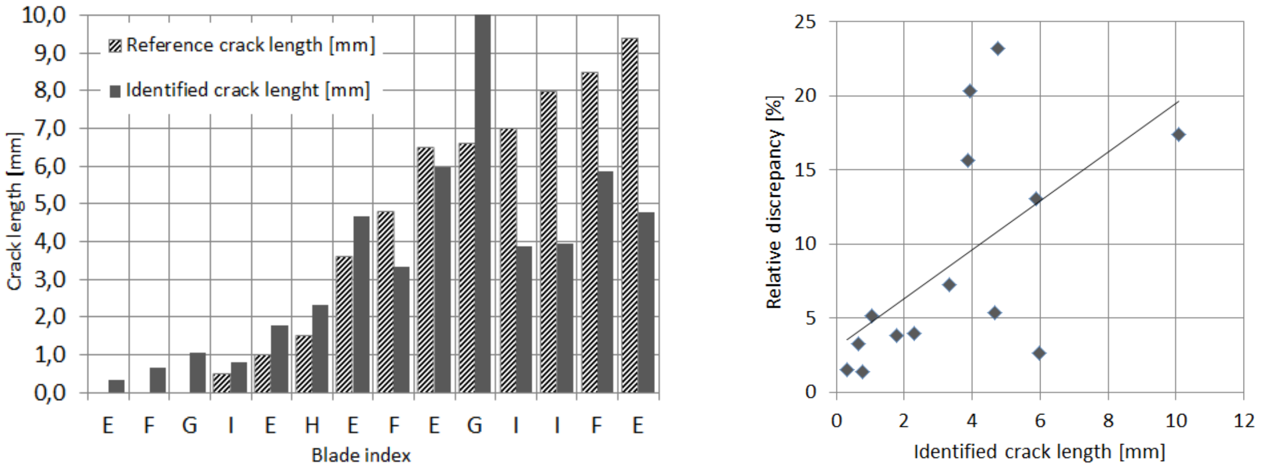

Fig. 5. Comparison of reference and crack length algorithm identification (left); relative discrepancy if identified crack length (right)

The identified crack lengths have high accuracy for relative crack lengths $\overline{L} < 0.25$. In this range, the defined relative discrepancy is below 10% and absolute crack length difference not exceeds 1.5 mm. For $\overline{L} > 0.25$ the accuracy is on acceptable level and mentioned parameters are suitably below 25% and not exceed 5 mm (Fig. 5, left). The relation of identified crack length and relative discrepancy is increasing with crack length, which is shown by trend line on Fig. 5 (left).

5. Summary

The wide scope of work was performed in building the algorithm for numerical identification of fatigue crack length of compressor blade. The building of algorithm is based on the Amplitude-Frequency characteristics obtained by destructive high cycle fatigue tests (Ch. 2). The objective of the work was to supplement the methods for crack length identification with algorithm-based method.

Considering above the first step was to analyse the measured A-F characteristics in order to find unique features, which enabled to read and determine basic parameters of A-F course (Ch. 3.1). The dependency between crack length and A-F asymmetry was written in form of non-dimensional asymmetry coefficients, which are crucial in algorithm identification of crack length. In the next step, several A-F characteristics with known crack length have been numerically processed and the asymmetry coefficients were calculated. The composed set of data was used in approximation process. Finally, the approximation method for identification the crack length was implemented (Ch. 3.2). The A-F characteristics not used in algorithm construction were processed. The algorithm possibilities in identification of crack length were verified (Ch. 4).

Further works shall focus on examination the wider range of approximation method and improve the algorithm accuracy.

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