FAULTS DETECTION IN LAYERED COMPOSITE STRUCTURES USING WAVELET TRANSFORM

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Summary

In the paper the authors present their results concerning measurements of frequency responses of cantilever rectangular GFRP plates with intentionally inserted faults of three different types (fiber discontinuities, delaminations and notches for simulating cracks). The preliminary research shows that classical methods of signal conditioning (e.g. FFT or STFT) often do not project changes between damaged and undamaged structures, when faults are inconsiderable. In the experiment the frequency responses of the investigated samples with and without faults were obtained by means of the impact test carried out using LMS SCADAS and TestXPress software. For the approximation in wavelet transform (WT) Morlet and Db8 wavelet functions were applied. The shapes of these functions give the best imitation of the measured signal shape obtained from the impact test. The obtained results allow to assert that the proposed methodology of faults detection in layered structures based on WT can be useful for fault diagnosis even in early damage phase, when other methods are insensitive. In the further work the authors will develop the proposed method for faults identification and localization in layered structures and investigate laminate behavior with faults and self-heating in fatigue processes.

Key words: GFRP laminates, faults detection, wavelet transform.

DETEKCJA USZKODZEŃ W WARSTWOWYCH STRUKTURACH KOMPOZYTOWYCH Z ZASTOSOWANIEM TRANSFORMACJI FALKOWEJ

Streszczenie

W pracy autorzy przedstawiają wyniki pomiarów odpowiedzi częstotliwościowych jednostronnie utwierdzonych prostokątnych płyt z kompozytu polimerowego zbrojonego włóknem szklanym z celowo wprowadzonymi uszkodzeniami trzech typów (nieciągłości włókien, delaminacje i karby symulujące pęknięcia). Badania wstępne pokazują, że klasyczne metody obróbki sygnałów (jak FFT czy STFT) często nie obrazują zmian pomiędzy strukturą uszkodzoną i nieuszkodzoną, gdy uszkodzenia są nieznaczne. W eksperymencie z zastosowaniem testu impulsowego były otrzymane odpowiedzi częstotliwościowe badanych próbek przy pomocy LMS SCADAS i oprogramowania TestXPress. Do aproksymacji w transformacji falkowej użyto funkcji bazowych Morleta i Db8. Kształt tych funkcji daje najlepsze przybliżenie przebiegu wartości chwilowych zmierzonego sygnału otrzymanego z testu impulsowego. Otrzymane wyniki pozwalają stwierdzić, że zaproponowana metodologia detekcji uszkodzeń w strukturach warstwowych oparta na transformacji falkowej może być użyteczne przy diagnostyce uszkodzeń nawet we wczesnych stadiach degradacji, gdy inne metody są nieczułe. W przyszłych pracach autorzy będą rozwijać zaproponowaną metodę pod kątem identyfikacji i lokalizacji uszkodzeń w strukturach warstwowych oraz badać zachowanie laminatów z uszkodzeniami i temperaturą samowzbudną w procesach zmęczeniowych.

Słowa kluczowe: laminaty polimerowe, detekcja uszkodzeń, transformacja falkowa.

1. INTRODUCTION

Layered structures, such as composite laminates, are commonly used in many responsible engineering constructions (wind turbines, turbine blades, rotors, helicopter propellers etc). Behavior and mechanisms of faults initiation and their propagation completely differ from the corresponding phenomena that occur in homogeneous materials. Moreover, there are several additional properties that influence faults and their development, such as: structure properties, fiber orientation, self-heating etc [1]. Also, the behavior must be predictable in each mode of laminate usage. Therefore, methods of diagnosing and detecting faults must be adapted to the investigated structures. There are many methods of signal analysis for detecting and diagnosing faults (e.g. DFT, STFT, cepstrum analysis, signal demodulation etc.), but only several can be applied for high precise detection of faults in early damage phase. In many cases the standard procedure of signal analysis can be applied as well and evaluation of degradation of the structure can be carried out using Fourier Transform [2,3], but the methodology become useless when the structure condition is on early damage phase.

Therefore, the wavelet transform can be applied as well. Main advantages (in contrast of DWT or STFT) of WT (wavelet transform) are the possibility to avoid Heisenberg's indefiniteness principle and the possibility to manipulate with time-frequency window and more accurate signal approximation using different wavelet functions. Methods based on WT are widely used for analyses of non-stationary and transient signals like impacts. An additional advantage of using WT is Mallat theory, which gives an opportunity for multiresolution approximation analysis for analyzing the signal on approximation and detail part on each level of decomposition. Applications using WT were used for early detection of bearing failures [4], identifying structural defects in spindles [5], impact damages in laminates [6] and other.

2. PROBLEM DESCRIPTION

The subject of research is 24-layered GFRP laminate with epoxy matrix. Three types of faults were considered: fiber discontinuities, delaminations and notches for simulating cracks. In many situations traditional methods (e.g. DFT or STFT) do not give wide information about structure condition, especially when structure is on early damage phase. Therefore, the wavelet transform was used. Choosing the basic function for measured signal approximation it is necessary to take into consideration shape of the signal, for impact responses Morlet's and Daubechie's basic functions were applied.

The research problem, which the authors concern with is the development of sound methodology of faults detection in layered structures in an early damage phase, when other methods are insensitive. The early-stage detection has very essential meaning. Detecting faults as soon as possible is one of the most significant tasks for diagnosing laminate structures e.g. in airplanes. If some developing fault is detected early, it is very often possible to modify the schedule of usage or even the mission the airplane carries out. In the less severe cases it is possible to properly schedule the nearest repair and carefully plan its extent and duration.

Although owners and the maintenance personnel understands very well the importance of the incipient failure detection, methods and techniques used to-date quite frequently do not allow early detection of faults. This is due because of prevailing application of the symptom-based approach and employing symptoms that cannot provide any clear evidence of the incoming failure. Therefore there is the need to develop such a methodology and signal processing methods, which could help in detecting incipient faults of composite structures. To this end, patterns obtained by means of WT proved to be useful tool. The description of this approach is the main goal of the paper.

3. METHOD CONCEPTION

The research was carried out in two stages: in the first stage samples with fiber discontinuities, delaminations and undamaged samples were investigated, and in the second stage samples with notches for modeling cracks in different places were used.

The first stage concerned the preliminary analysis of faults detection in above-mentioned samples. Laminate plates with dimensions 400x50x5.28 mm were clamped on the one edge and tested in impact test using LMS SCADAS hardware with PC and TestXPress software. Measurements were processed in 2.56 seconds with sampling rate equaled to 6400 Hz. An impulse excitation was given by modal hammer PCB T086C01 and the response to the impact was measured by the shear accelerometer PCB T352C34. The number of averages was 10. The experimental stand is presented on Fig.1.

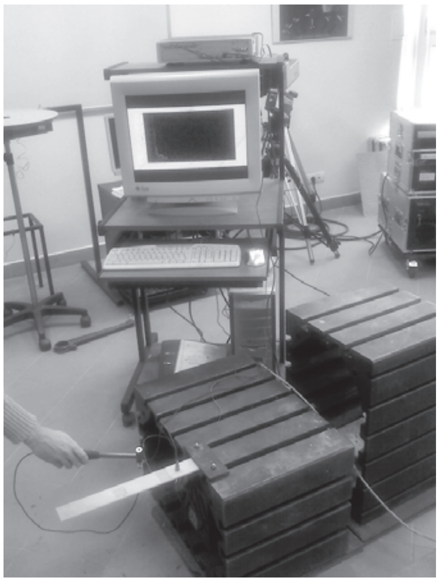

Fig. 1. Experimental stand

The collected measurements were exported to CSV format and then – to MATLAB data files (MAT). Then, signal processing was applied. Firstly, FFT analysis was processed and PSD charts were obtained, after that spectrograms of signals were made using STFT analysis and then CWT analysis was made using Morlet's basic function (Fig. 2) for obtaining scalograms. The scalograms were converted from scale representation to frequency representation using the formula (1):

$$f = \frac{5}{2\pi a}, \qquad (1)$$

where a is scale coefficient. The obtained results from all the analyzes were compared with taking into consideration the damage type of samples.

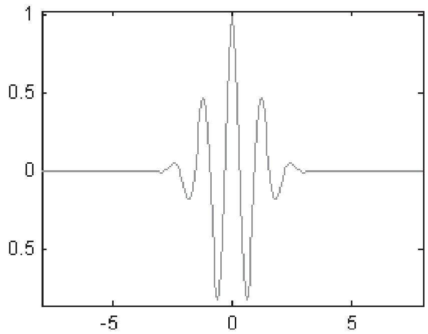

Fig. 2. Morlet basic function [7]

In the second stage samples with dimensions 250x25x5.28 mm and with intentionally inserted notches in different places were investigated. An algorithm of measurements was the same as in the first stage. After exporting measurements to MATLAB the CWT analysis was processed. The obtained scaleograms did not give clearly visible results, therefore the other approach was assumed. Each signal was approximated using Db8 (Daubechies 8) basic function (Fig.3) in DWT. Then, approximated signals were decomposed to approximate part and detail part on level of decomposition equaled to 5 with maximal decomposition level equaled to 15 (2).

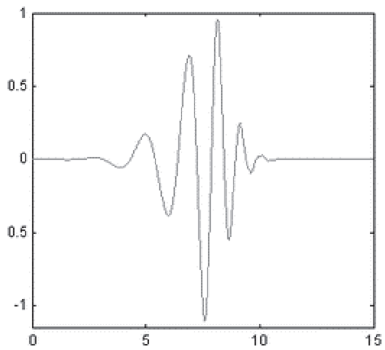

Fig. 3. Db8 basic function [7]

In theory the number of decomposition levels approaches infinity, but practically it is limited to one element of realization:

$$l = \log_2 N\,, \tag{2}$$

where N is the number of elements in the realization. Higher levels of decomposition were neglected because these realizations can be considered as noised ones. In the obtained results details parts of signal were taken into consideration. Here, the statistical approach was shown: the biased autocorrelation of details on decomposition levels of undamaged sample was compared with cross-correlation between damaged and undamaged samples. For evaluation of the difference as scalar the next metric was introduced: the mean value of difference between cross-correlation value of damaged and undamaged samples divided by the peak value of the autocorrelation (3):

$$CFV = \left(\sum_{i=1}^{N} \frac{\left(R_{xx} - R_{xy,i}\right)}{N} \right) \Big/ \max\left(R_{xx}\right), \tag{3}$$

Having done the analyzes the obtained results were compared: scalograms were compared with FFT and STFT results and finally statistical values of detail parts were confronted.

4. DETECTING THE DAMAGE TYPE

At the beginning, Fourier transform of the obtained signals took place. The results of the transform show that in cases of damaged samples the values of natural frequencies are growing, but this does not allow to clearly determine the fault occurrence and its type. The comparison of natural frequencies of the samples is presented in Table 1.

Table 1. Comparison of natural frequencies for undamaged and damaged samples

Mode number	Undamaged [Hz]	Fiber dis-cont. [Hz]	Delamina-tion [Hz]
1	18,36	18,75	18,75
2	114,5	116,4	116,8
3	314,8	319,1	321,5
4	598,8	616	619,5
5	991,4	1009	1017
6	2117	2172	2184

Then, STFT analysis was processed. Obtained spectrograms also do not show differences precisely (compare Fig. 4 – Fig. 6). Therefore, the CWT analysis was performed. In the algorithm, the researched frequency range was limited to 2560 Hz, because natural frequencies were excited with very low amplitudes and it did not allow to acquire any additional piece of information.

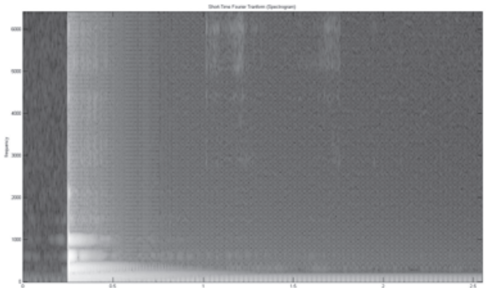

Fig. 4. STFT spectrogram of undamaged sample

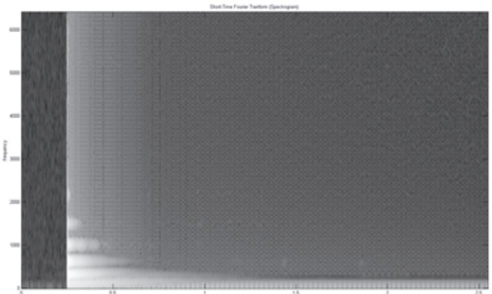

Fig. 5. STFT spectrogram of sample with fiber discontinuity

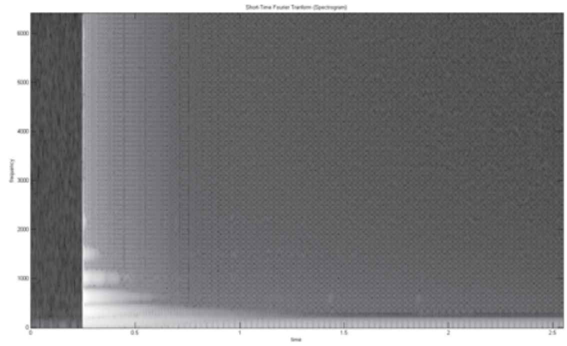

Fig. 6. STFT spectrogram of sample with delaminations

The scaleograms (Fig. 7 – Fig. 9) were prepared in direct visualization mode and transformed from scale representation to frequency representation using the formula (1). In the scaleograms the differences between undamaged and damaged samples are clearly visible. It shows that the excited natural frequencies of the damaged samples are damped lower than undamaged sample. Also, the differences can be observed in the frequency range 1000-1500 Hz. In case of the undamaged sample, frequencies in this range were excited also after impact impulse and shows alternate behavior, but in case of fiber discontinuity damage frequencies in this range were excited after pause and in case of delamination it is mostly damped.

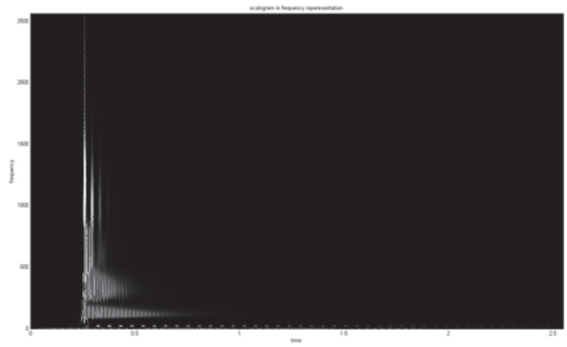

Fig. 7. CWT scalogram of undamaged sample

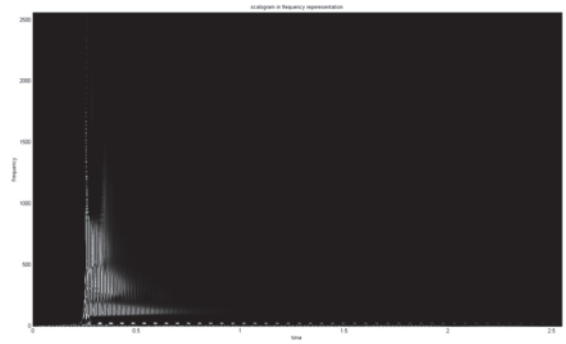

Fig. 8. CWT scaleogram of sample with fiber discontinuity

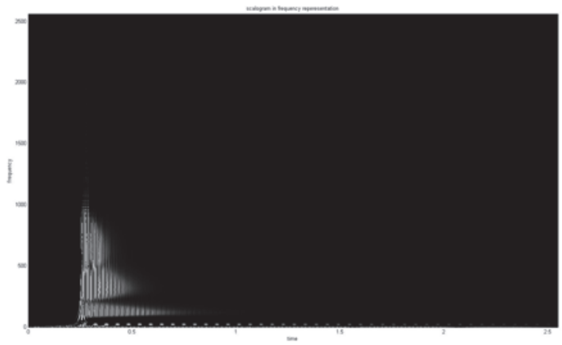

Fig. 9. CWT scaleogram of sample with delaminations

Basing on the scaleograms shown one can conclude about high sensitivity of the method and to assume the usability of the method for faults identification of the above-mentioned types. The quantitative evaluation can be calculated using degree of scaleogram concentration factor [1].

5. USABILITY OF THE METHOD FOR LIGHT-DAMAGED STRUCTURES

If the structure is on early damage phase, the scaleograms often do not show differences clearly as well. Therefore, the multilevel decomposition analysis was performed. The main idea of the analysis was presented in Fig. 10. and formula (4).

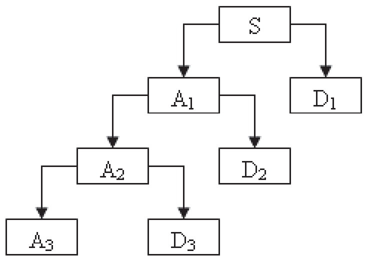

Fig. 10. Idea of multilevel decomposition [8]

$$S = A_n + \sum_{i=1}^{n} D_i \, , \qquad (4)$$

In the proposed approach the detail parts of decomposition were analyzed. Five cases of faults location and two cases of notch depth were observed. In the first and second case the notch with 0,25 mm and 1 mm depth was located on XY surface at the distance 150 mm by Y, in third and fourth case notches were placed at the distance 220 mm by Y and in fifth and sixth case they were oriented angularly (60^0) starting from 207 mm to 215 mm. In other cases the notches with depths 0,5 mm and 3 mm were placed on XZ surface on distance 200 mm by X and on YZ surface on distance 12,5 mm by Y.

After decomposition of the signal of the undamaged sample the biased autocorrelation of detail parts was processed. Then, detail parts of signals wavelet spectrum of damaged samples were cross-correlated with the undamaged sample. Results were grouped by notches location. As an example the results concerning the last two cases were shown in Fig. 11 and its detail in Fig. 12.

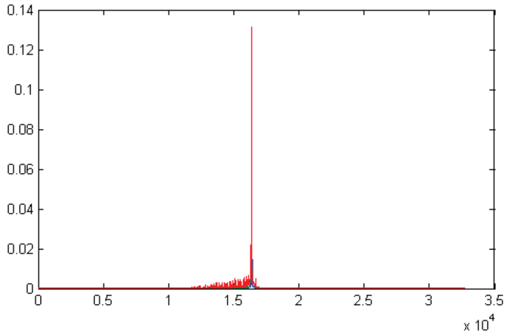

Fig. 11. Details cross-correlation of damaged and undamaged samples

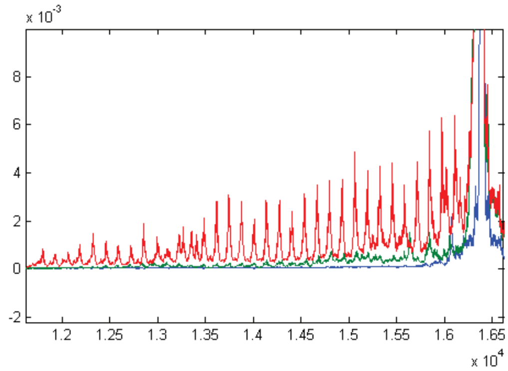

Fig. 12. Fragment of details cross-correlation from Fig.11

As the research shows, the detail parts of WT spectra damage samples have higher correlation factor, local maxima (Fig.12) near the main peak (Fig.11) and higher peak value. This regularity was confirmed in all the considered cases. For quantitative scalar evaluation CFV (correlation fault values) given by (3) were calculated and presented in Table 2. On higher levels of decomposition the CFV is quite different. Therefore the statistical normalization must be included into the algorithm.

Table 2. Correlation fault values.

Case No.	Sur-face	Fault localization [mm]	Notch depth [mm]	CFVs
1.	-	-	-	0
2.	XY	X: 150, Y: 0	0,25	$4{,}8\cdot10^{-3}$
3.	XY	X: 150, Y: 0	1	$6{,}1\cdot10^{-3}$
4.	XY	X: 220, Y: 0	0,25	$2{,}5\cdot10^{-3}$
5.	XY	X: 220, Y: 0	1	$2{,}6\cdot10^{-3}$
6.	XY	X: 207, α: 60^0	0,25	$2{,}4\cdot10^{-3}$
7.	XY	X: 207, α: 60^0	1	$7{,}6\cdot10^{-3}$
8.	XZ	X: 200, Z: 0	0,5	$7{,}8\cdot10^{-4}$
9.	XZ	X: 200, Z: 0	3	$8{,}0\cdot10^{-4}$
10.	YZ	X:250,Y:12,5	0,5	$1{,}8\cdot10^{-3}$
11.	YZ	X:250,Y:12,5	3	$3{,}2\cdot10^{-3}$

The results were presented for the first level of decomposition. On the higher levels the regularity of correlation differences was confirmed. In Figs. 13 – 16 the results of cross-correlation for higher levels of decomposition are presented.

Basing on the obtained results (Table 2.), tone can conclude about different sensitivity of the proposed fault detection algorithm with respect to the fault placement and its size. The sensitivity is good enough when the fault is placed on XY surface (compare CFV for cases 2-7 in Table 2.) and on surface YZ (cases 10, 11 in Table 2.), but poor enough when the fault is placed on XZ surface (cases 8, 9 in Table 2). In the case 8 and case 9 the algorithm is less sensitive and gives underestimated evaluation. The phenomenon can be interpreted by natural frequency shifting in frequency response of the investigated structure.

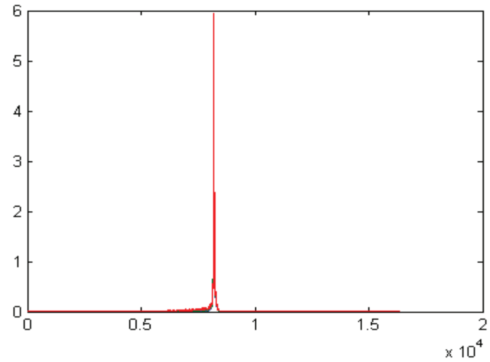

Fig. 13. Details cross-correlation of damaged and undamaged samples on 2nd decomposition level

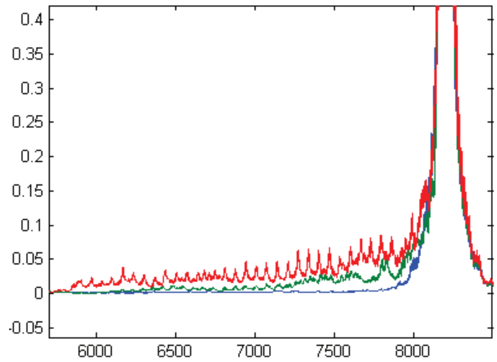

Fig. 14. Fragment of details cross-correlation on 2nd decomposition level

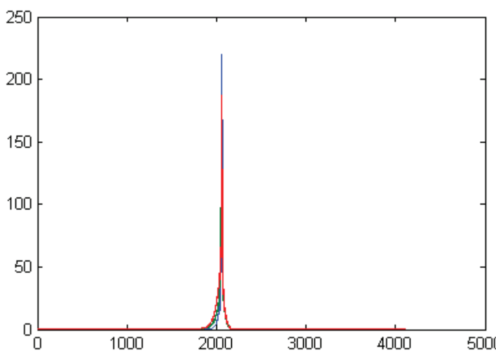

Fig. 15. Details cross-correlation of damaged and undamaged samples on 4th decomposition level

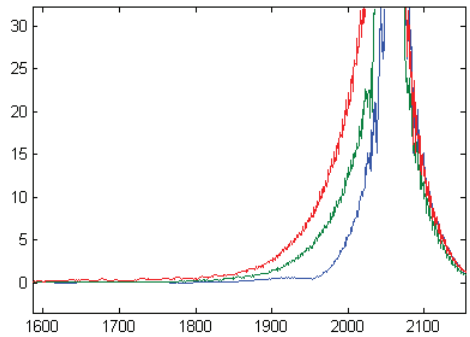

Fig. 16. Fragment of details cross-correlation on 4th decomposition level

On higher levels of the decomposition the regularity of obtained CFVs were similar. In few cases on higher levels of decomposition the CFVs for smaller faults were shown lower sensitivity of the method. After carrying out the investigation tone can conclude that the first level of decomposition gives best results for CFVs calculation. In higher levels there is a decreasing tendency of set length in detail parts and, according to this, set length in cross-correlation; the accuracy of CFVs were lower than in first level of the decomposition.

6. CONCLUSIONS AND REMARKS

The research presented in this paper proves the possibility of incipient fault detection in composite layered structures. As the results show, the proposed algorithm can be used for detection of even smallest faults, when the structure is on early damage phase in contrast to known and applied methods of signal processing. On the cross-correlation charts the faulty specimens can be recognized. For evaluating scalar values that are symptoms of faults the new metrics was introduced. The value of this metrics allows detecting faults not less than 10^{-3} CFV, so that it can be used as the lower threshold limit for faults detection.

Our next research will be targeted on the other types of faults as described in the Chapter 5. This research concerned only the surface faults, while in the future research the internal faults will be detected. Moreover, the temperature influence and structure behavior with different types of faults during fatigue processes will be detected.

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