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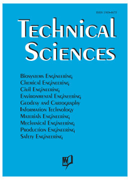

FATIGUE CRACK DETECTION METHOD USING ANALYSIS OF VIBRATION SIGNAL

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Abstract

This paper discusses the method used to identify the process involving fatigue cracking of samples on the basis of selected vibration signal characteristics. Acceleration of vibrations has been chosen as a diagnostic signal in the analysis of sample cross section. Signal characteristics in form of change in vibration amplitudes and corresponding changes in FFT spectrum have been indicated for the acceleration. The tests were performed on a designed setup, where destruction process was caused by the force of inertia of the sample. Based on the conducted tests, it was found that the demonstrated sample structure change identification method may be applied to identify the technical condition of the structure in the aspect of loss of its continuity and its properties (e.g.: mechanical and fatigue cracks). The vibration analysis results have been verified by penetration and visual methods, using a scanning electron microscope.

Introduction

Brackets are among the most frequently used structural elements in engineering. They are commonly used, from simple structures like pressure gauge connections in pipelines, to more sophisticated components, such as aircraft wings or airscrew vanes. Methods applied to monitor these objects in order to identify and forecast their technical condition have now become an important area of research. It is possible to prevent the damage to structures

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and machine components by early detection of fatigue cracks, carried out using various non-destructive testing methods. The following conventional non-destructive test methods: penetrant testing, magnetic methods, ultrasonic testing, etc., have their constraints and are often expensive and ambiguous in evaluation of the condition. Alternative methods based on identification of the form and parameters of vibrations may constitute an effective, quick and convenient diagnostic tool for the detection of fatigue cracks in machine components and structural systems.

In the literature, structure cracks are identified in two ways: linearly and non-linearly. In the linear method, vibrations are examined in the objects, where changes of modal parameters in relation to the initial model are taken into account, whereas in the non-linear model, a crack is identified through the analysis of frequency characteristics (ANDREAUS, BARAGATTI 2011, ANDREAUS 2012, ANDREAUS, CASINI 2016, ANDREAUS et al. 2005, ANDREAUS et al. 2007, ANDREAUS, BARAGATTI 2012, BRODA et.al. 2014b, LIU et al. 2015, MENDROK 2014, PREIBISCH et al. 2009, RADKOWSKI, SZCZUROWSKI 2012, SUDINTAS 2015).

In the linear approach, a crack is always considered as open, and it is modelled as a local flexibility (GUDMUNSON 1998). Crack size and location are examined and characterised through changes of modal parameters including: natural frequency (OSTACHOWICZ, KRAWCZUK 1991), damping factor (PANTELIOU et al. 2001) or modulus of rigidity (GIBSON 2000, KAŹMIERCZAK et al. 2013). However, this approach has two primary constraints. First, a change in natural frequency is significant only for large crack sizes (CHENG et al. 1996), and second, a measured natural frequency shift cannot be unequivocally attributed to cracking itself, since it may be also generated by other factors, as wear, relaxation, etc. (ANDREAUS, BARAGATTI 2009, ANDREAUS et al. 2016, BIAŁKOWSKI, KRĘŻEL 2015).

In the non-linear model it is generally recognised that vibration theory is correlated with modal parameters of a system, that is: natural frequency, damping, and forms of vibrations. In other words, it is a physical system consisting of physical structure properties (mass, rigidity and damping). These model parameters are homogeneous systems described by differential equations of the model physical motion expressed with reference to its mass, damping and rigidity, acceleration, speed and displacement. As a result of this, all changes in modal parameters are directly proportional to the change in physical property of the modelled object due to damage (ANDREAUS, CASINI 2016).

The problem of identifying structural damage on the basis of vibrations was raised by numerous authors (BRODA et al. 2014a, OH et al. 2015, JASSIM et al. 2013, KLEPKA et al. 2014, TAO et al. 2014, TROCHIDIS et al. 2014, TROJNIAR et al. 2014, XU 2014, ZHOU 2006). Object vibration parameters are defined in this approach, and structural damage identification is the function of change in object structural properties, such as rigidity and mass. The presence of damage affects both vibration signal response and dynamic properties of a given structure. Dynamic properties of the structure include: natural frequencies, shapes and damping mode indicators. These properties are used as indicators of damage in the structure being tested. Early detection of structural damage allows for timely maintenance and repairs, extending the system service life.

In order to ensure safety and structural reliability it is necessary to perform long-term, medium-term and short-term monitoring of the structure technical condition in the operating process. One of the basic dynamic properties is rigidity, which may lead to changes in the shape and frequency reduction mode, and to damping coefficient increase.

The paper presents an attempt to use vibration signal analysis to detect the loss in sample structure continuity.

Measurement setup

Laboratory tests were carried out using the measurement setup shown in Figure 1. The setup consists of a reciprocating motion generator (crank gear), to which a clamp holding the samples is fixed.

The setup allows for the generation of sample oscillatory motion at specific frequency (*f*) and constant displacement amplitude. Due to the oscillatory motion and one-side fixing of a sample, generated forces of inertia cause its elastic strains.

The following sensors were employed to identify dynamic parameters of the system: two piezoelectric sensors for vibration accelerations (ICP-100) and a rotational speed sensor for the shaft of inverter-controlled driving motor. A multi-channel KSD-400 recorder based on the NI 6343 card supported by LabVIEW was used for the purposes of acquired data recording, visualisation and analysis.

Visual assessment was carried out in two stages. Initial process involved identification of cracks through penetrant testing according to the PN EN ISO 3452-1:2013-08E and PN EN ISO 3059:2013-06Estandards. The second stage of surface evaluation for selected samples was performed with a JEOL JSM 5310LV type scanning electron microscope, working in a digital configuration.

No sample surface polishing was applied, so as to maintain surface condition of sheet metal used for structural components and to show the impact of surface condition on the occurrence of cracks.

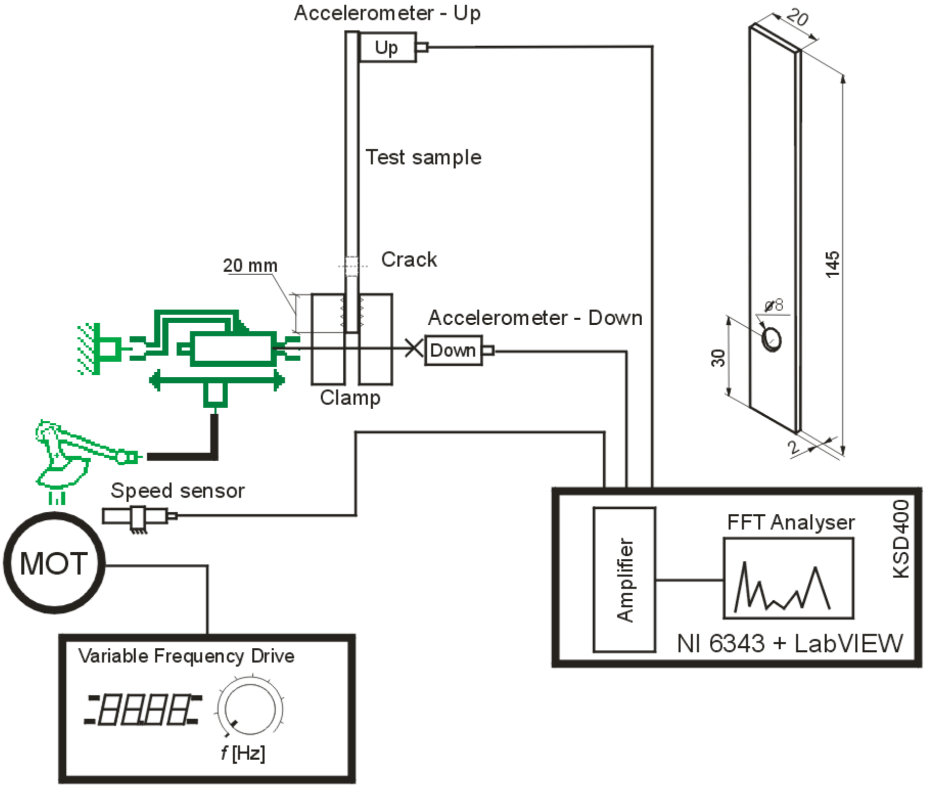

Fig. 1. The structure of setup for experimental tests and general view of test sample

The tested object

The tested object was a flat rectangular sample shown in Figure 1. A notch in the form of a hole was made in the sample, where stresses were accumulating during the tests due to the smallest cross-section of the whole sample. The used samples were made of 1.4301 stainless steel and S235JR steel. The sample surface was left untreated following manufacturing process. The surface roughness was assessed using the Hommel Tester T1000E, profile measurement gauge, according to the ISO 4287/1 standard.

The surface roughness is considered as an important factor influencing fatigue strength. Many researchers have carried out much work to evaluate the effects of the surface roughness on fatigue (ALANG et al. 2011, KYRRE et al. 2008). In those works mostly Ra is used as a roughness parameter. Due to the fact that in the study of fatigue resistance local changes of surface topography are important, it was decided to include the Rz parameter, to characterize surface of the samples. Sample roughness parameters are specified in Table 1.

Table 1

Surface roughness parameters for the tested samples

Material	Roughness parameters [μm]	
	Ra	RzI
1.4301	0.17	1.9
S235JR	0.87	6.22

The progress and results of tests

The experimental research was carried out for the frequency ranging from 20 Hz to 50 Hz. However, the paper shows the results of research for the frequency of 30 Hz only. The reason of that was that an excitation frequency of 30 Hz was the resonance frequency for applied sample. This excitation frequency guaranteed quick progress of the sample destruction process within approx. 4,000 s.

Acceleration amplitude and the form of vibrations in frequency domain (the FFT analysis) were used to identify the sample section destruction process.

All the test results presented below were obtained for the following test parameters:

– vibration excitation frequency 30 Hz;

– sample holder displacement amplitude A = 1 mm (the size of displacement is coused by the crank throw);

– mass of sensor (125 g) mounted on upper end of a sample.

For selected samples the tests were interrupted at the moment of pinpointing the beginning of the sample damage process identified in the diagnostic signal trajectory. All the samples were put through penetrant testing, and those for which penetrant testing did not show any cracks, were subject to microscopic examinations.

Figure 2 shows a sample cascade amplitude-frequency trajectory of the test sample response process for an excitation frequency of 30 Hz, recorded by the acceleration sensor fitted on the sample upper end – Up (see Fig. 1).

It was observed that the progress of the sample section damage process is implemented in the following way:

– as regards initial sample condition, its vibration displacement amplitude for excitation frequency (f_0) is constant, shown as area *A* in Figure 2, and

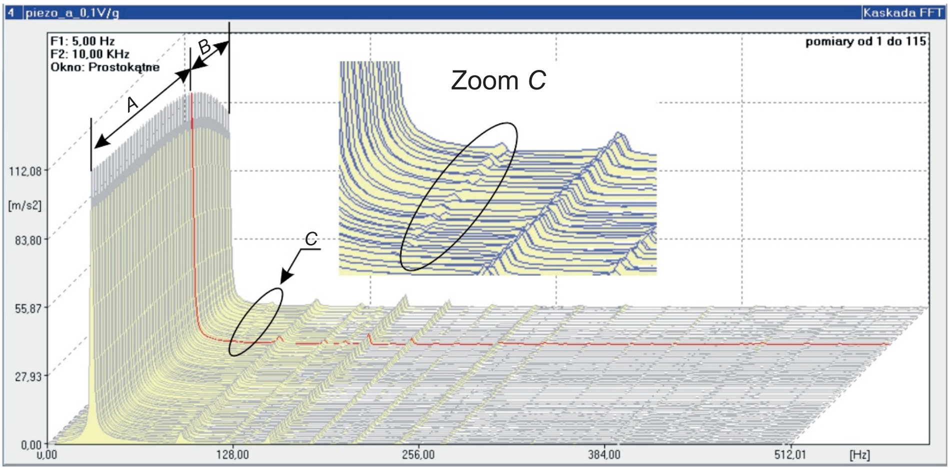

Fig. 2. Cascade view of test sample amplitude – frequency trajectory, signal recording source – acceleration sensor – Up. The red line indicates the beginning of crack in sample section notch structure. Assembly mass with acceleration sensor (125 g)

at the same time there are harmonic frequencies of higher orders visible ($3f_0$ = 90, $4f_0$ = 120 Hz, etc.) with equally constant amplitude values,

– the occurrence of a change in the condition of the sample notch section is indicated by systematic decrease of vibration acceleration amplitude for excitation frequency (shown as area *B* in Fig. 2) and observed increase of vibration amplitude for the second harmonic frequency (area *C*) – until then not identified in the vibration spectrum,

– initiation of crack in the sample notch section corresponds to the highest value of vibration acceleration amplitude for harmonic frequency (f_0). As a result of further excitation of the sample vibration, we observe a drop in the displacement amplitude compared to the nominal condition of the sample. Due to the purpose of tests, the process of further sample destruction was not identified.

The sample section destruction process progressed much the same for all tested samples, regardless of the excitation frequency, and the only difference was in the initiation time of the process of sample surface or section mechanical damage.

Visual analysis of sample damage process

The purpose of microscopic examination was to verify whether the observed changes in the amplitude of the sample vibrations are connected with cracks on the surface of the sample. Observations of the sample were carried out on the notched weakened area.

Figure 3 shows the notch zone for a sample made of S235JR steel. The sample penetrant testing did not show occurrence of any cracks. Microscopic examination of the notch area surface made it possible to observe a numerous cracks – lengths ranging from 24 to 40 fm, running perpendicular to the axis of the sample.

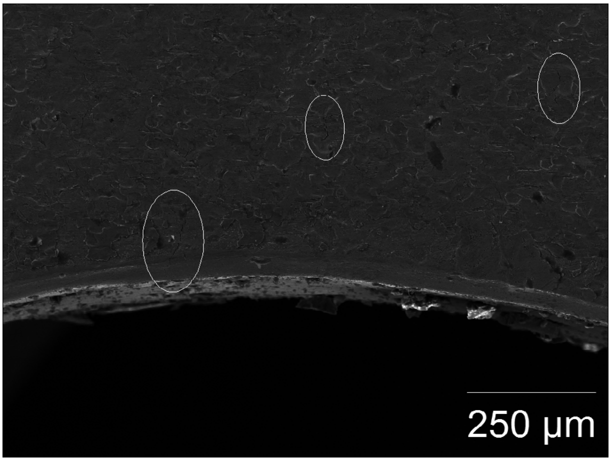

Fig. 3. View of surface – sample made of S235JR steel – cracks are marked

These cracks developed in narrowed area of the sample. The main crack was observed on both sides of the notch, starting on its edge (ca. 125 μm and 121 μm). These cracks are shown in Figures 4 and 5. The surface condition (roughness parameters was Ra = 0.87 and Rz = 6.22 μm) may have caused the initiation of other cracks in spots away from the notch.

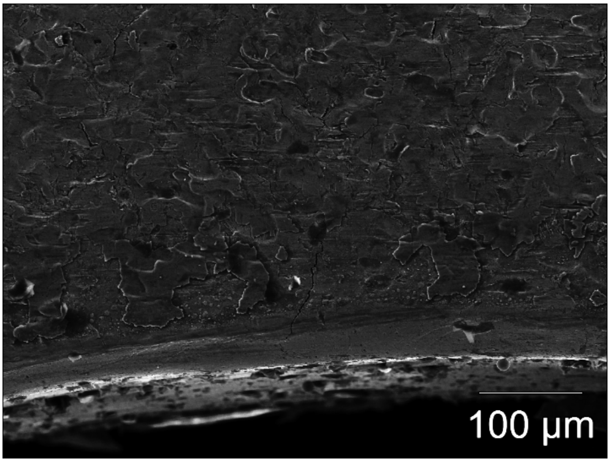

Fig. 4. The surface of a sample made of S235GJ steel with visible crack at the edge of the hole

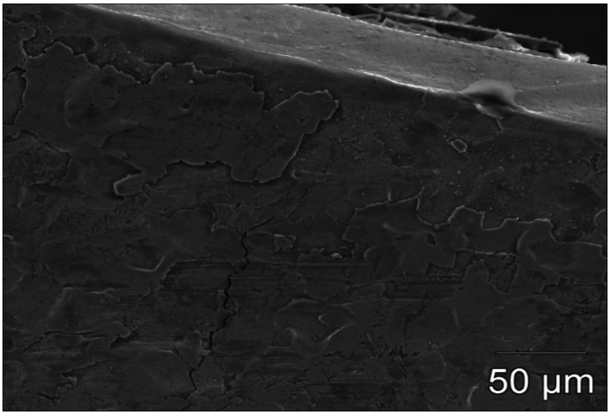

Fig. 5. The surface of a sample made of S235GJ steel with visible crack at the edge of the hole

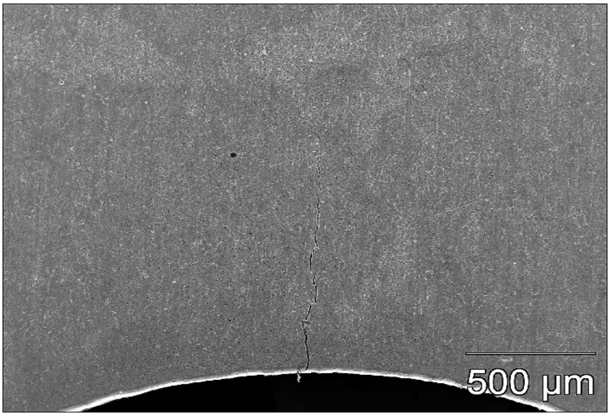

Fig. 6. Crack visible on the surface of a sample made of 1.4301 steel

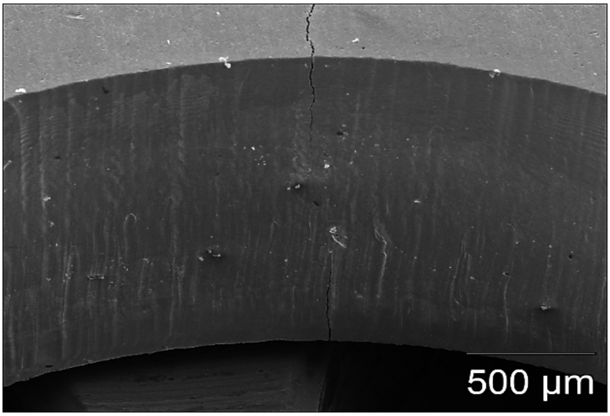

Fig. 7. Crack in cross-section of a sample made of 1.4301 steel

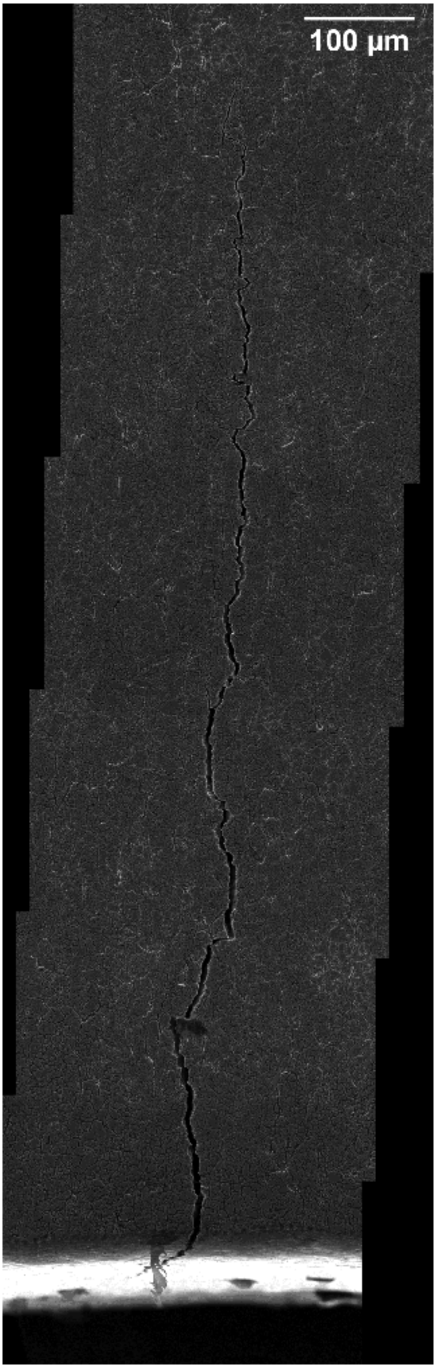

Fig. 8. Crack on the surface of sample made of 1.4301 steel

There is one crack (1 mm in length) visible on the surface of a sample made of 1.4301 stainless steel, developing from the edge of the hole (Fig. 6). In this case, the crack was visible after penetrant testing. Microscopic examinations of the surface did not show occurrence of any additional cracks accompanying the observed one.

The observed crack visible from the side of the hole is shown in Figure 7. The picture shows the crack developing inside the hole, deep into the material on both sides of the sample.

A larger zoom of the view of the whole crack is shown in Figure 8. It seems that the roughness surfaces was decisive on occurrence of cracks away from the notch edge. The microscopic observations showed that changes in the vibration amplitude of the sample are associated with the appearance of the cracks on its surface.

Conclusions

Based on the completed tests and simulations the following conclusions may be formulated:

– it is not possible to identify through penetrant testing the beginnings of the mechanical destruction processes for samples determined on the basis of distinguished signal characteristics;

– sample section destruction time is affected by the volume of mechanical work the sample section is subjected to – in other words, energy needed to destroy the sample may be defined as the area under the sample section stress curve;

– regardless of the shape and localization of the notch, the sample destruction process runs in much the same way; the only differences may occur as changes of vibration amplitude values;

– obtained test results and their further verification lets assume the suitability of the discussed vibro-acoustic method to detect material structure micro-cracks interpreted as modal parameters of the examined object.

– high surface roughness of the sample made of S235JR steel, promotes the initiation of cracks in a away from the edge of the notch. In the sample characterizing with lower roughness (1.4301 stainless steel) only one crack starting from the edge of the notch was observed.

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