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A METHOD OF FATIGUE STRENGTH TESTING OF WHEEL RIM FRAGMENTS AT THE PRODUCTION PROCESS STAGE

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Abstract

The paper describes a method of accelerated fatigue strength testing of elements with the use of inertia forces. The presented test method is dedicated to the selected materials, constructions and joints used in the production of wheel rims for motor vehicles, tractors and special vehicles. The analysis of the fatigue process in machinery components and the evaluation of its state in terms of product quality control can be divided into: quasi-static analysis, resonance analysis, and the one generally used today – virtual fatigue analysis. Virtual analysis is applicable to new components and/or structures released to production according to the concept based on the interaction of theoretical and working models in the context of service life prediction. The purpose of this paper is to present a tool for examination, and a method allowing the identification of the beginning of the fatigue cracking process in structural components. The demonstrated method belongs to the destructive testing group. Cracking process analysis and identification is based on a multiparameter analysis of vibration signals in the amplitude-frequency domain. Inertia force is used in the test piece destruction process. The discussed method is applicable to a wide range of fatigue tests for structural components in the quality control process for materials and combinations of these materials. The method has been employed in the production of low-speed and special machinery wheel rims by Polkar Warmia Ltd.

Keywords*: fatigue strength testing, vibration spectrum analysis, destructive tests, crack detection, wheel rim*

1. Introduction

Cold-bent profiles are among the structural components, which are most frequently used in engineering. They are commonly used in simple structures of pipeline manometric connections, systems used to fit photovoltaic or solar panels, or grips for road signs and advertising banners. Among other examples of bent profiles, there are also more complex and reliable components, such as, e.g. airplane wings, airscrew blades, or wheel rings.

Material fatigue takes place under the influence of loads, which are variable in time and constitute typical loads in various machinery setups. This process precedes nucleation, thus determining the development of cracks in a structure.

The identification and location of defects in structural components bound by cyclic load is directly related to fatigue cracking [1, 5, 7]. Defects of this sort are the most frequent cause of failures occurring in engineering structures. Resistance to fatigue damage should be foreseen at the design stage and controlled at different stages of the production process. This approach is observed in the automotive and aircraft industries, where tests are performed at each design and production stage in order to verify durability, reliability and resistance to damage in various service conditions. This approach allows manufacturers to specify reasonable technical survey dates, and the service life of structures.

The analysis of the fatigue process in machinery components and the evaluation of its state in terms of product quality control can be divided into: quasi-static analysis, resonance analysis, and the one generally used today – virtual fatigue analysis. Virtual analysis is applicable to new components and/or structures released to production according to the concept based on the interaction of theoretical and working models in the context of service life prediction. Detailed information concerning this type of analysis is available in [3, 7, 15].

Quasi-static analysis is basically intended to evaluate the life of parts characterised by high rigidity, e.g. rocker arms, load-bearing beams, or frames, which prove to have a high structure safety factor. Up-to-date knowledge concerning the strength of materials and mechanical vibration theory is used very efficiently in the case of this analysis. Either experimental tests carried out on true components in service or laboratory conditions will effectively complete missing knowledge on fatigue damage processes. Moreover, experimental studies are intended to verify the approved design methods and techniques.

The approach according to the resonance method is dedicated for components, which may be operated within ranges of up to and above free vibration frequency. Most often, components of this sort are characterised by low weight, and low rigidity resulting from design constraints, etc. In the case of structures of this sort, and in particular new products, static or dynamic loads and operating conditions defined for frequency in the form of, e.g. PSD (Power Spectral Density) signal are unavailable. The analysis of the fatigue damage process in the resonance method is carried out on the basis of modal analysis of excitation source signal and is examined object response.

The wheel rim, especially in low-speed and special vehicles, is an example of a structure which resonance analysis should be applied to. In fact, no detailed and precise requirements concerning fatigue tests and their procedures have been specified for vehicles of this type. General test specifications are available in the standards ASTM, ISO, KS, JIS and L73/413 [13], but they do not reflect all parameters. There are no test characteristics for wheel rim operation in off-road conditions, on dirt roads, or in fields. The lack of this information significantly obstructs the process involving the design of new wheel rim structures for special or specialised applications.

The purpose of this paper is to present a tool for examination, and a method allowing the identification of the beginning of the fatigue cracking process in structural components. The demonstrated method belongs to the destructive testing group. Cracking process analysis and identification is based on a multiparameter analysis of vibration signals in the amplitude-frequency domain. Inertia force is used in the test piece destruction process. The discussed method is applicable to a wide range of fatigue tests for structural components in the quality control process for materials and combinations of these materials. The method has been employed in the production of low-speed and special machinery wheel rims by Polkar Warmia Ltd.

2. Methodology of tests

2.1. Tested object

The discussed destructive testing method is used to identify selected "life" parameters useful in the process of assessing engineering and operating properties of products (sheet metal) or semi-finished products (sheet metal joints – "weld" quality) used in the process of manufacturing wheel rims for agricultural, work, and specialised vehicles by Polkar Warmia Ltd. The matter of the test is based on a method involving the comparison of the obtained results referring to archived examinations considered by the internal research unit of the company as a reference or comparative scale.

The discussed methodology of tests may be applied either to complete wheel rims, the semi-finished products the rims are made of (the material itself – at the stage of accepting it for storage), or joints (welded joints, etc.). Material samples or their combinations may be taken from the ready wheel rim, or prepared individually. In order to increase the force destroying the test piece section, an extra weight is fixed to its free end. Example test pieces used according to the method are shown in Fig. 1.

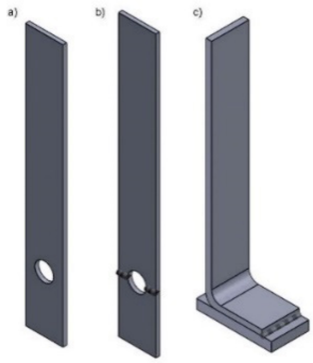

Fig. 1. Examples of test pieces used according to the demonstrated method: a) B type – taken from metal sheet, b) PS type – joining two metal strips with butt weld, c) PSP type – joining wheel disk and rim with fillet weld (obtained from wheel rim sized 12x4.25)

A "notch" in the form of a hole is made in the test pieces in order to force the location of test piece cracking as a result of the action of inertia forces, and to reduce test duration. Flat test pieces were cut out from semi-finished products, complete wheel rims, or metal sheet using "laser cutting", the "water" method, a guillotine, or band saw. Notches were made in the form of holes drilled in material, or in the case of shaped test pieces, they were made by boring with an engine lathe. No influence of the piece cutting method on its destruction process was observed during the tests.

2.2. Measurement setup and testing equipment

Laboratory tests were carried out using the measurement setup shown in Fig. 2. The setup for inertia testing consists of a reciprocating motion generator (crank gear), to which a clamp holding test pieces is fixed.

The setup allows for the generation of test piece oscillatory motion at a specific frequency (f) and a constant displacement amplitude. The process of this motion is monitored by two eddy current sensors and a driving motor speed sensor in order to identify the number of test cycles.

Eddy current displacement sensors are situated as shown in Fig. 2 and 3 in order to register the strain (displacement) on the free test piece end in relation to its notch position. Eddy current sensor locations are defined relative to the test piece notch position. Geometrical distances and displacement of the test piece allow the identification of the vibration amplitude change (response) of that piece, as well as many engineering and operating parameters, e.g.: stress in the test piece notch section, etc. A multi-channel KSD-400 recorder equipped with an NI 6343 card supported by LabVIEW was used for the purposes of acquired data recording, visualisation and analysis.

Penetrant testing according to [11, 12] was employed to identify and locate cracks, and in the case of a negative result the surface around the test piece notch was evaluated with a JEOL JSM 5310LV type scanning electron microscope, working in a digital configuration. This evaluation process was intended to verify diagnostic signals useful in identifying the beginning of the test piece section cracking process.

No test piece surface polishing was applied to maintain the surface condition of the sheet metal used for structural components and to show the impact of surface condition on the occurrence of cracks.

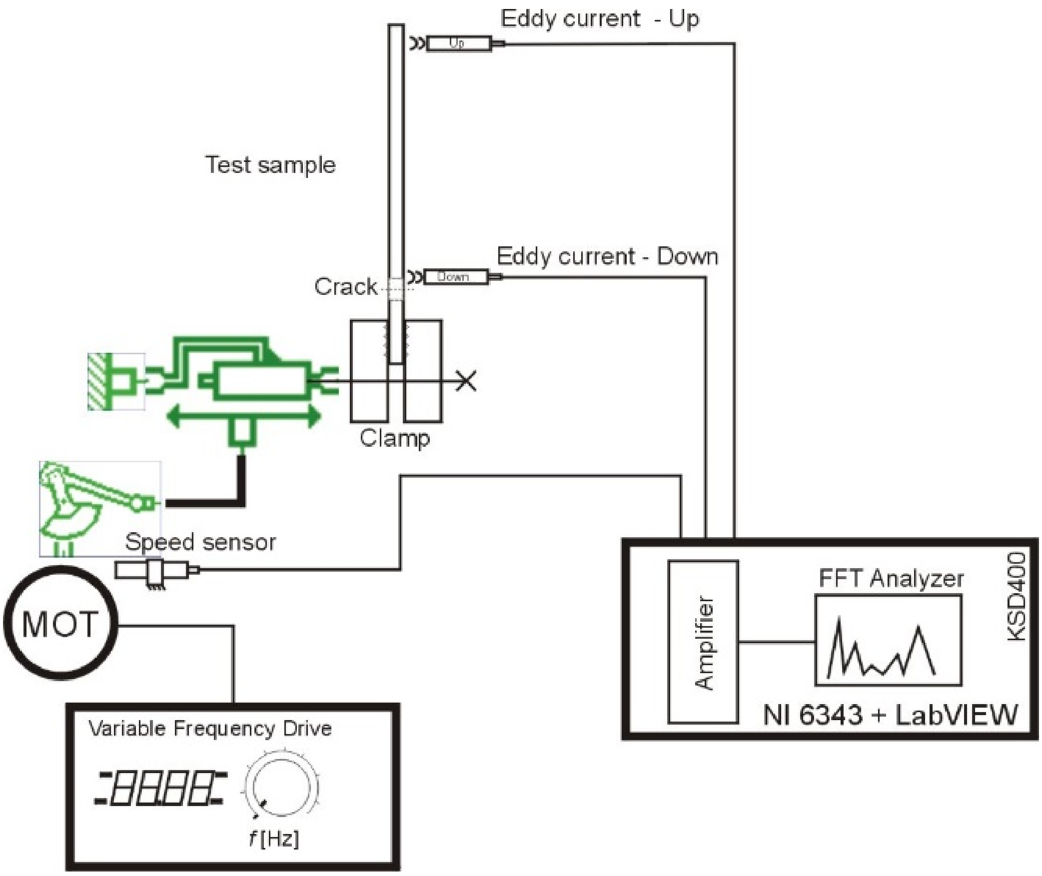

Fig. 2. The structure of the setup for experimental tests carried out using the inertia method

2.3. Mathematical model of the testing process

In the presented method, inertia force is responsible for the destruction of the test material notch section. It is generated by the mass of the free test piece end relative to the foot of the piece held in the test apparatus clamp performing reciprocating motion. This way of test piece operation corresponds to the functionality of a two-part beam divided by an articulated joint. One part of the beam is permanently hardened (test piece foot), and the other has the capacity of free vibration. Both parts of the beam are coupled with a notch (articulated joint), which has decidedly lower structure section parameters than the nominal section of the beam.

The formula below presents the general equation of motion for the free test piece end after digitisation according to the Euler-Bernoulli beam theory excluding the constant component of the reciprocating motion.

$$[M]\{\ddot{x}(t)\} + [K]\{c(t)\} = \{F(t)\}, \tag{1}$$

where:

[M] – the matrix of elementary masses of the free test piece end,
[K] – the matrix of the test piece notch (articulated joint) rigidity,
{c(t)} – the vector of the test piece notch damping factor,
{F(t)} – the inertia force generated by the mass of the free test piece end.

In the analysis method presented here, for simplification purposes it is assumed that a crack (a change in the structure of the test material notch section) is affected only by material rigidity, and therefore the issues of damping and rigidity will not be considered in more detail further in this paper. These problems are extensively described in works [10, 14].

Figure 3 demonstrates the issue of identifying the geometrical parameters used in the process involving the acquisition of the engineering and strength parameters of the test piece.

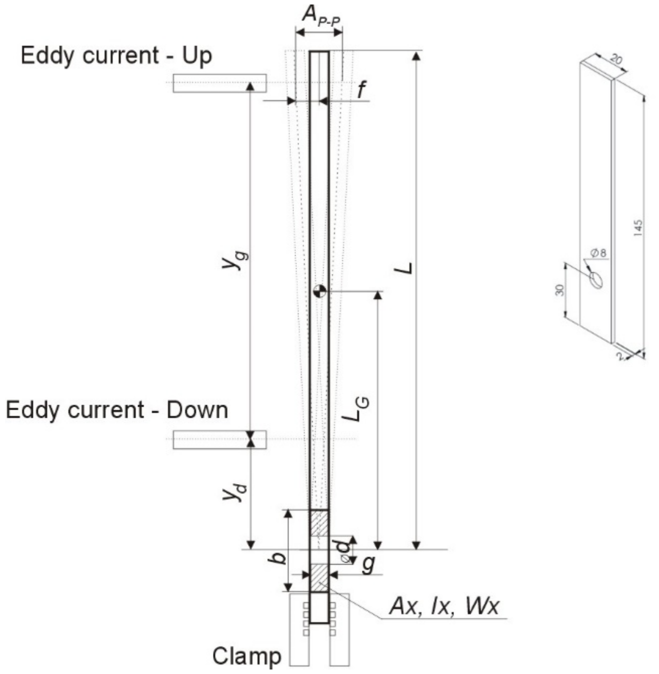

Fig. 3. Locations of measuring sensors and selected test piece parameters: $A_{P\text{-}P}$ – vibration amplitude (PEAK-PEAK), f – deflection, b – test piece width, g – test piece thickness, d – diameter of the hole in the test piece, L_G – the distance of the gravity centre of the free part of the test piece, L – height of the free part of the test piece, y_d – the distance between the lower eddy current sensor and the notch symmetry axis, y_g – the distance between the lower and upper eddy current sensors, Ax – cross-sectional area of the test piece notch, Ix – moment of inertia for the test piece notch section, Wx – bending index of the test piece notch section

The amplitude of free test piece end displacement was recorded during laboratory tests. These measurements provided the basis for obtaining amplitude-time spectra of vibrations, which were then transformed into the amplitude-frequency domain. That process was imposed due to the possibility of easier analysis and interpretation, and the potential to obtain a greater number of signal characteristics. Moreover, the amplitude-frequency trajectory allowed the identification of the dynamics of change in the amplitude of vibrations in time within a wide spectrum of frequencies.

At the same time, amplitude $A_{P-P} = \frac{f}{2}$ was obtained from the amplitude-time signal, which provided the basis to calculate stresses in the test piece notch section. The value of calculated stresses is correct until microcracks appear on the notch surface according to the following formula:

$$\delta(t) = \frac{3 \cdot f(t) \cdot E \cdot I}{(y_d + y_g)^2 \cdot W_x}. \quad (2)$$

2.4. The progress of tests and obtained results

Preliminary tests carried out for the discussed test piece allowed the determination of free vibration frequency. Then, basic tests were performed for that frequency or for polyharmonic. These parameters of sample vibration excitations guaranteed the shortest duration of the destruction process – fatigue cracks in the test piece notch section.

Figure 4 demonstrates a model frequency trajectory of the test piece response process for excitation frequency 36 Hz, recorded by the lower displacement sensor.

The analysis of trajectories showing test piece displacement in the function of excitation frequency proves that there are three harmonic frequencies (f_0=36, 2f_0=72, 3f_0=107 Hz) visible in the spectrum for an undamaged section. While the test piece is in the nominal state, the values of vibration amplitudes for these harmonics are constant (area *A* in Fig. 4). When a change in the test piece section state appears (area *B*), these values start to drop systematically, and at the same time, harmonics at higher frequencies begin to decline.

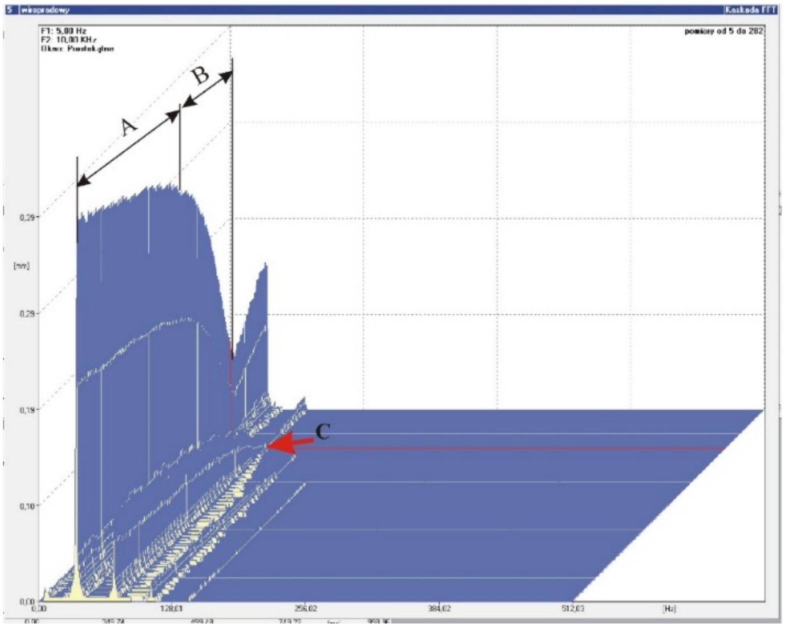

Fig. 4. A model process of test piece response during tests; B type – just before the occurrence of test piece damage (material: DD11, g=2 mm, excitation frequency 36 Hz), A – nominal state of test piece response, B – the beginning and development of the test piece damage process, C – crack in test piece notch section

The smallest value of vibration amplitude for harmonic frequency is registered during a mechanical crack in the test piece section (point *C*). As a result of the further extortion of the test piece vibratory motion, there is a visible increase in amplitude to the value of ca. 50% for the test piece nominal state, whereas higher harmonic frequencies do not occur, or very small values appear. According to the completed tests, area *B* of the process involving test piece section destruction until cracking continued to exist for 90 to 160 s. The process of test piece destruction ran in much the same way, regardless of the excitation frequency or the shape of the test piece section.

Figure 5 shows the trajectory of displacement for the free test piece end after removing the constant component (the crank arm of the crank mechanism) obtained for different numbers of oscillation cycles. The analysis of the obtained trajectories proves that the displacement amplitude for the free test piece end drops with the increasing number of test cycles.

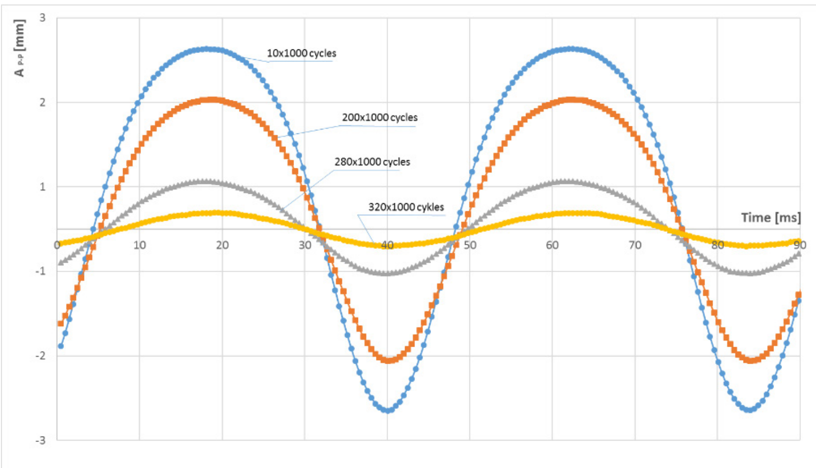

Fig. 5. The trajectory of change in oscillation amplitude for the free test piece end for a selected number of test cycles (material: DD11)

The systematic drop in displacement amplitude for the free test piece end results from the occurrence of microcracks (gaps) along the external edges of the test piece section. These microcracks develop as a result of the strengthening of the material surface subject to greatest strain due to the cumulation of elastic and plastic strains [2, 8]. This phenomenon is called cyclic strengthening [4, 5, 16]. These gaps develop randomly in the surface strengthening zone in the direction of max. shear stress [9]. They develop deep in the test piece, forming an internal network of inter-crystalline or trans-crystalline cracks, which dissipates supplied energy, thus damping the amplitude of test piece motion in successive test cycles.

During the initial period, it can be assumed that the material of the test piece notch section is put to the bending process. After the occurrence of microcracks and the network of cracks, the test piece material section becomes smaller. Moreover, it is subject to a complex process of stresses in the form of radial bending and axial spreading.

When analysing vibration amplitude trajectories from Fig. 5, attention is drawn to the various shapes of oscillation trajectory above and under the axis. That difference in the shape of trajectory is due to the fact that in the farthest (extreme) position of the test piece relative to the eddy current sensor, the sensor goes beyond linear measurement characteristics.

Figure 6 shows the notch area in a test piece made of the DD11 material after fatigue crack (Fig. 6a), and for which the beginning of the cracking process was identified using the displacement amplitude analysis (Fig. 6b). Penetrant testing of the test piece from Fig. 6b did not indicate the occurrence of cracks. Microscopic examination of the area near the notch allowed the observation of a series of cracks, with lengths ranging from 24 to 40 μm, running perpendicularly to the test piece axis.

a) b)

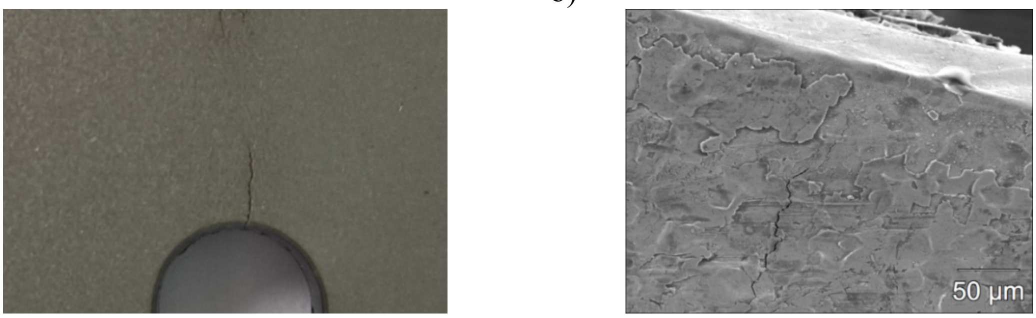

Fig. 6. View of steel test piece surfaces – DD11; a) – fatigue fracture – general view, b) – view of microcrack at hole edge

These microcracks developed in many places in the area of test piece narrowing. In test pieces of this sort, single cracks have not merged into the crack path yet, although such a tendency can be observed. That was the result of destruction process interruption.

3. Summary and final conclusions

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

- the demonstrated test method based on the inertia force may be applied both to accelerated strength tests for a selected wide range of components and types of test pieces,
- the described test method proved its suitability for the qualitative verification of materials and parameters of the process used to join components of wheel rims for work, agricultural and special machines,
- during the occurrence of change in the state of the test piece section through the initiation of microcracks, the systematic reduction of displacement amplitude values is observed, along with the decline of harmonics at higher frequencies. The smallest value of vibration amplitude for harmonic frequency is registered during mechanical cracking of the test piece section,

- the demonstrated method for identifying the beginning of the test piece section cracking process on the basis of the analysis of vibration amplitude parameters proved its suitability and effectiveness, which was confirmed by verification tests carried out using the penetrant and microscopic methods,
- the time of test piece section fatigue life is primarily affected by the test piece displacement value, not by excitation frequency, or accelerations applied to a test piece.

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