SMALL-SIZED TEST BED FOR DIAGNOSING THE GIGACYCLE FATIGUE PROCESSES

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Summary

The purpose of this paper is to develop, for highly-resistant materials, a method of forecasting and analysis of gigacycle fatigue durability ($10^8 \div 10^9$ cycles) relying on vibroacoustic signal analysis. The method proposes the use of results of vibroacoustic signal analysis obtained during accelerated fatigue tests conducted in dedicated test bed constructed specially for this purpose and operating in the frequency range of 10 kHz which corresponds to the resonance frequency of vibration of samples.

The presented test bed is a unique small sized structure compared to the foreign solutions which have been constructed while using the supporting structures of classical machines used for durability testing. Thanks to the small dimensions and mass, the test bed can be located on the vibration shaker, thus introducing resonant frequencies modulation.

Vibroacoustic diagnosis methods enable not only the detection of surface defects but also detection of defects occurring in the core of a sample. Thus it becomes possible to try to learn the nature of increased durability to fatigue and to try to use the features of vibroacoustic signals in forecasting the gigacycle fatigue durability.

Keywords: vibroacoustic diagnosis, gigacycle fatigue processes, piezoelectric generators.

MAŁOGABARYTOWE STANOWISKO DO DIAGNOZOWANIA GIGACYKLOWYCH PROCESÓW ZMĘCZENIOWYCH

Streszczenie

Celem pracy jest opracowanie, dla materiałów o wysokiej wytrzymałości, metody prognozowania i analizy gigacyklowej trwałości zmęczeniowej ($10^8 \div 10^9$ cykli) na podstawie badania sygnału wibroakustycznego. W metodzie proponuje się wykorzystać wyniki analizy sygnału wibroakustycznego, uzyskiwane podczas przyspieszonych badań zmęczeniowych, prowadzonych na specjalnie do tego celu skonstruowanym i zbudowanym stanowisku badawczym, pracującym w zakresie częstotliwości rzędu 10 kHz, odpowiadającym częstotliwości drgań własnych próbek.

Powyższe stanowisko badawcze jest unikatową, małogabarytową, konstrukcją w porównaniu z konstrukcjami zagranicznymi zabudowanymi w ramach od maszyn wytrzymałościowych. Dzięki małym wymiarom i masie stanowisko badawcze można umieszczać na wzbudniku drgań, tym samym wprowadzając modulację częstotliwości rezonansowych.

Metody diagnostyki wibroakustycznej umożliwiają nie tylko detekcję uszkodzeń powierzchniowych, ale również wykrycie uszkodzeń występujących w rdzeniu próbki. Możliwym staje się podjęcie próby poznania natury zwiększonej trwałości zmęczeniowej oraz próby wykorzystania w prognozowaniu gigacyklowej trwałości zmęczeniowej cech sygnałów wibroakustycznych.

Słowa kluczowe: diagnostyka wibroakustyczna, gigacyklowe procesy zmęczeniowe, generatory piezoelektryczne.

1. INTRODUCTION

In 1960's and 1970's solutions which put stress on the possibility of controlling the growth of cracks and faults that initially existed in the material were applied when designing structures subjected to variable loads, which could lead to the effect of fatigue-related damage. Another approach assumed that the existing cracks propagated only until reaching the assumed threshold value. Both methods referred to the principles and methods having origins in the mechanics of cracking. Development of high-speed vehicles and machines with high-speed motors as well as increasingly broader use of new materials, especially the high performance materials, led to the need for revising the 19th century assumptions regarding the possibility of occurence of infinite resistance of structural materials to fatigue. Above all it turned out, in the case of such materials the assumption related to the asymptotic run of Wohler's curve after exceeding the limit of $10^6 \div 10^7$ cycles was not fulfilled, which could have been the reason for occurence of critical defects and catastrophes with extensive consequences, since in many cases fatigue-related defects of these materials were noted after exceeding $10^8 \div 10^9$ cycles.

Meanwhile it is worth noting [1] that the required resistance of modern car engines to fatigue is 10^8 cycles while for big Diesel engines used in ship or high-speed locomotives it is 10^9 cycles. Some elements of turbine engines (e.g. the rotor shaft) should demonstrate fatigue resistance in the range of 10^{10} cycles.

Majority of materials fail to fulfill such assumptions [1], thus there exists the need for looking for new high performance materials.

While acccounting for the above raised issues attempts are made more and more frequently at conducting accelerated wear-and-tear tests with the use of piezoelectric or magneto-restrictive generators and processors characterized by high frequencies, in the range of 10-30 kHz, which enables shortening the research on gigacycle wear and tear process down to reasonable periods (10^9 cycles can accordingly be obtained in 30 hours).

However, due to the limited power of the signal, the research has to be conducted in the bandwidth of a sample's resonant vibration in contrast with the forced vibration to which a sample is subjected in the classical low-frequency testing equipment.

Exemplary sizes of samples, for specified own frequency vibration values, as well as the duration (hours) of the experiment for the assumed number of cycles are presented in [2].

For example the sample (three-point bending, sample (HxW) 8mm x 5mm made from steel) length for frequency 10kHz is 254 mm and the duration of the experiment for 10^8 cycles is 28 hours, the sample length for frequency 20kHz is 127 mm and the duration of the experiment for 10^8 cycles is only 14 hours.

While accounting for proper (own) vibration frequency to examining the gigacycle material fatigue process, we need to solve numerous problems from the area of machine dynamics, determine the range of the sample's resonance vibration, depending on a material's dynamic properties, type of mounting and the sample's geometry as well as the structure and analysis of vibroacoustic measures characterized by high sensitivity to individual stages of the wear and tear process.

Early attempts of explaining the phenomenon of destruction in the gigacycle range of resistance to fatigue refer to the models and the experience acquired during research of low and high-cycle resistance to fatigue. One could point here to the attempts of applying methods involving the stress intensity factor [3], use of assessment of residual stress evaluation in the zone preceding the cracking, the effects of regular strengthening and weakening [2]. In parellel we could observe the use of various methods of reaching the information regarding the occuring degradation processes, from use of laser interferrometers to measurement of crack growth in a unit of time corresponding to the assumed number of cycles.

Attempts are made to learn more closely the physical aspects of gigacycle process of fatigue-related damage. E.g. in [4], when discussing the results of lab tests attention is drawn to the high scatter of resistance to fatigue. Various mechanisms of crack initiation process are pointed as the main reasons of obtaining such results: occurrence of inclusions disturbing the homogenous structure of the material is the reason of initiation of cracks in the range of high maximum stress values, while in the case of smaller maximum values of stress it is inclusions or surface damage that are considered to be the reason of a crack on a sample's surface. Additional factors having influence on the course of the fatigue-related defect development process make it difficult to forecast the shape of the stress – fatigue-related damage curve in the $10^8 \div 10^9$ cycles range [2]. Problems are in the definition of infinite fatigue lifetime curve or straight line shape and also in the definition of gigacycle fatigue lifetime curve or straight line shape.

In the real operating conditions of critical kinematic nodes, the resistance of elements to fatigue will be influenced by factors correlated with the mechanism of changes of surface layer parameters, thus having varied influence on the process of vibroacoustic signal generation [5]. Below we have discussed an example of a testbed for examining the gigacycle fatigue processes.

2. TYPICAL TESTBED FOR EXAMINING GIGACYCLE FATIGUE-RELATED PROCESSES

Till the present moment there have not existed any norms regarding the method of conducting the tests of gigacycle fatigue processes. Laboratories dealing with such research, e.g. in the USA, Austria, France [1], China, Japan, Slovakia are at the stage of developing their own research procedures. In spite of the fact that the machines used for durability tests in these labs differ, still they have several common features. Most important of them include:

1. high-frequency generator which generates sinusoidal electrical signal with frequency of 10÷20kHz, usually powered with voltage of 100÷1000V;
2. piezoelectric (or magnetorestrictive) processor, which processes electrical signal

into mechanical vibration, standard parameters include stroke of 5-20 μm, resonant frequency above 20 kHz;

3. controlling unit – a PC which enables controlling the frequency of the generator and, depending on the other additional systems found in the test-bed, it enables controlling the temperature, the pressure, force value and direction of vibration, etc.

Early devices of this type enabled only uni-directional research at constant amplitudes, the latest devices allow tests under varying loads and with adjustable amplitudes at high or low temperatures, torsional or multi-directional tests.

High-frequency systems for fatigue tests usually operate at frequencies of 10÷20 kHz. According to [6] they are composed of the following components:

a) A generator (usually with the power of 1000÷2500 W) – it ensures sinusoidal signal with frequency of 10÷20 kHz;
b) Piezoelectric (or magnetorestrictive) processor (processing electrical signal into mechanical vibration) and high-frequency amplifier of mechanical vibration;
c) A controlling unit which enables:
    - measurement of shift and stress, control of amplitude and frequency, cycle meter;
    - control by a computer, including amplitude presetting (required especially for a variable load amplitude), programming of force pulses, classification and recording of amplitudes on-line, control of frequency ranges;
d) Additional equipment, including a cooling unit (to prevent temperature growth), environmental chambers (furnace, corrosion chamber, pool), devices for measuring crack development (a microscope, video camera);
e) Frame and devices for applying static and dynamic compressive or stretching loads (mode I $R \neq -1$) or applying transverse loads (modes II and III), usually relying on the frames of machines for testing the resistance to fatigue.

In order to achieve specific and sufficiently high amplitudes, the high frequency machines must operate in a resonant mode. This means that each vibrating element, including the sample, must have specified geometry and mechanical properties. A sample is usually symmetrical along the center-line (with circular or square cross-section) while its length must enable emergence of a longitudinal stationary wave at 10-20 kHz with maximum stress and pressure in the center of the sample and maximum deformation at the ends of the sample. The sample should have a constant cross-section or the cross-section should be reduced in the middle of the sample (usually having the shape of a bell or an hour-glass in order to increase the amplitude). Flexible deformation at the end of the sample is measured with the use of strain gauges or shift detectors. The measured signal is sent in a feedback loop to the amplitude controlling unit. The maximum deformation of ε is calculated based on deformation amplitude or it is measured in the center of the sample where maximum deformations occur. If the relationship between the stress and the deformation is known (e.g. based on Hooke's law), then stress can be calculated based on deformation. If the sample is mounted only at one end, then without applying external load we deal with stretching-and-compressing load ($R = -1$). Amplitude is controlled with the use of PID-type integrating-differential controller which guarantees that the preset amplitude value is achieved with high precision (99% in latest devices). Apart from amplitudes, it is also the frequencies that are controlled to maintain the resonance. This is achieved with the use of PLL (phase loop). Frequency monitoring can be used for performing automatic operations, e.g. switching-off a device when a crack occurs.

Special attention is devoted to temperature growth caused by high frequencies of applied load, which can be very big depending on the amplitude and load of the examined material. One of the possibilities of preventing the growth of a sample's temperature is applying the load in the form of pulses with breaks from time to time. The duration of the pulses of 25÷100 ms (500÷2000 cycles) can be applied with breaks of 50 and 1000 ms. In addition cooling by fans or spraying of liquid can be applied. Otherwise there may occur e.g. fatigue-related corrosion.

Test-beds relying on use of high frequencies can be used not only for measuring the fatigue-related lifecycle but also for examining the process of development of cracks due to mechanical reasons. Currently such research assumes that determination of stress intensity factor of ΔK is decisive. The amplitude of deformation or change of speed at the end of a sample or stress at the center of a sample are used to determine ΔK. The maximum value of stress intensity coefficient $K_{\max}$ can be calculated based on vibration amplitude u at the end of a sample or speed v of the end of a sample, length of crack a, and width of sample W. In practice it is the calibration relying on the amplitude of deformation at the center of a sample (the crack plane), which can be measured with the use of relevant devices, and which proves more useful and relevant. Deformation ε, for a hypothetical crack length equal zero, which is directly proportional to vibration amplitude or vibration speed, defines the size of the load. The coefficient of stress intensity is calculated while relying on formula (1), where Y_u is a correction applied at the moment when we control the amplitude, while correction Y_v is applied when it is the amplitude of the speed of the sample's end that is decisive. The difference between Y_u and Y_v is caused by growth of resonant frequency which accompanies the growth of the crack's length, which in turn has influence on the amplitude of the sample end's speed [2].

$$K = f(\varepsilon, E, a, W, Y_u, Y_v) \qquad (1)$$

where:

$$Y_u = f(a, W),$$
$$Y_v = f(a, W)$$

The publications [1] include various test-beds which depend on the type of research.

3. SMALL-SIZED TEST-BED

The test-beds enabling gigacycle fatigue tests usually enable three-point bending with the sample set on two supports mounted on a foundation.

From the point of view of fatigue-related destruction of a tooth, the authors propose a test-bed for examining gigacycle fatigue-related processes for two-point bending. For the maximum deformation in the range 5÷40 μm and the generated frequency of ca. 10kHz, a system has been selected that can be powered with 230V current. It is a piezoelectric generator PPA40XL (Fig. 1) which interworks with LA75C power supply unit.

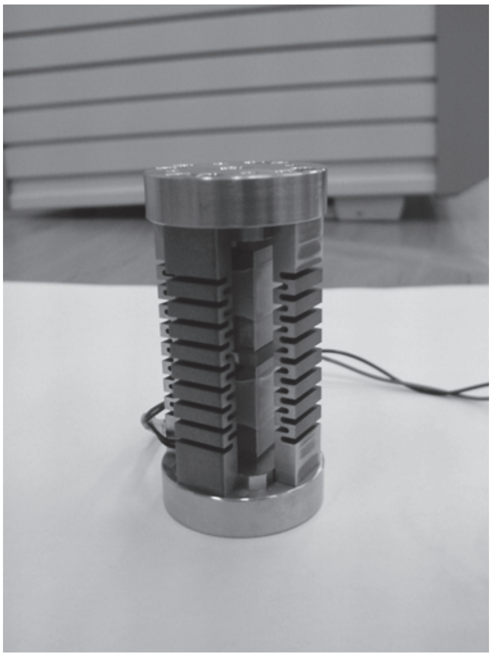

Fig. 1. Piezoelectric generator PPA40XL

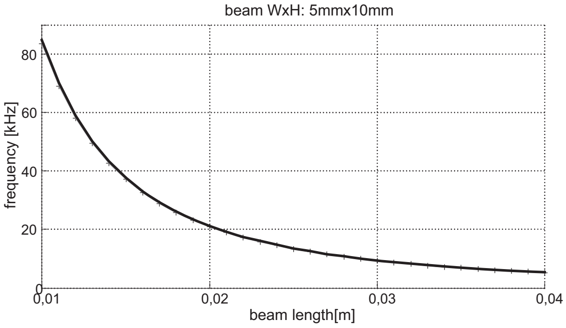

Fig. 2. Own vibration frequency depending on beam length

The preliminary dimensions were calculated of the sample (WxHxL): 5mm x 10mm x 30mm while assuming that resonance vibration eigenfrequency for the sample equals 10 kHz (Fig. 2). The beam can be made of titanium or high quality steel.

As was mentioned in item [2], the typical test-beds for gigacycle research usually rely on the frames of machines used for tests of fatigue life. These test-beds have relatively big dimensions and weight. The authors have designed a small-size test-bed for diagnosing the gigacycle fatigue-related processes (Fig. 3). The test-bed has the form of a cube with dimensions of 0.3x0.3x0.3 m and its weight does not exceed 10 kg. The head is made of titanium and mounted directly in the piezoelectric generator. The beam is mounted with the use of an circular cam (in order to do away with play). Small dimensions have been proposed to enable mounting the test-bed on TIRA TV 5500/LS shaker (Fig. 4) having the following parameters: nominal load – 4000 N, frequency range DC÷3000 Hz, maximum acceleration 54 g. Use of the shaker will enable generation of frequencies that modulate the beam's vibration eigenfrequency, thus enabling examination of more complex mechanisms of fatigue-related crack initiation and development.

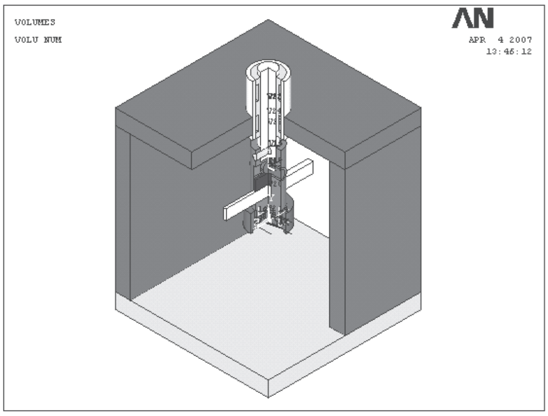

Fig. 3. Small-sized test-bed for diagnosing gigacycle fatigue-related processes

Fig. 4. TIRA TV 5500/LS shaker

The authors also analyzed the resonant frequencies of individual elements of the test-bed (Table 1) so as to avoid resonance of the test-bed when applying the beam's resonance frequency.

Table 1. Resonance frequencies of the test-bed's elements

Item.	Name of the element	Resonant frequency
1	Head mounted on a piezo generator .	1442 Hz
2	Mandrel connected to the disk by a threaded connection	1456 Hz
3	Disk mounted on a piezo generator.	38764 Hz
4	Circular cam	> 50000Hz
5	Body of the test-bed	416 Hz

After analyzing the assumptions of the test-bed others discovered that it is a big problem to select a relevant kinematic node which could enable mating of the head with a sleeve in the upper plate of the test-bed (Fig. 5) and had durability of $10^8 \div 10^9$ cycles. The authors designed two solutions:

1. Mating of two very hard surfaces; was proposed covering the two mating surfaces, the head's pin and the sleeve in the test-bed's casing, with a coat of titanium nitrade (it is practically a pioneer solution in Poland and around the world);
2. Installing of aerostatic bearing in the casing (Fig. 6), thanks to which there would be no direct contact between pin and the sleeve while centering of both elements would be realized with the use of an air cushion, with the supply pressure of ca. 4 bar.

At the present stage a test-bed according to variant 2 will build, next the concept of applying the aerostatic bearing will build.

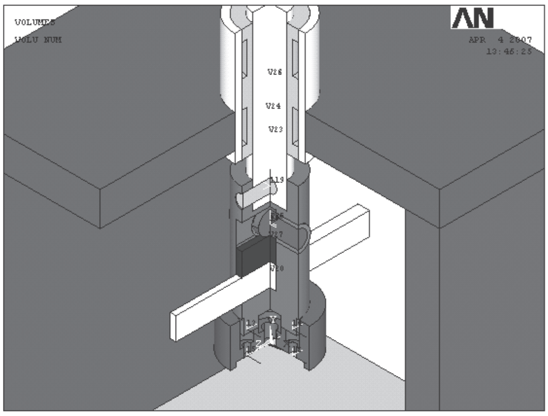

Fig. 5. Kinematic node in laboratory test-bed

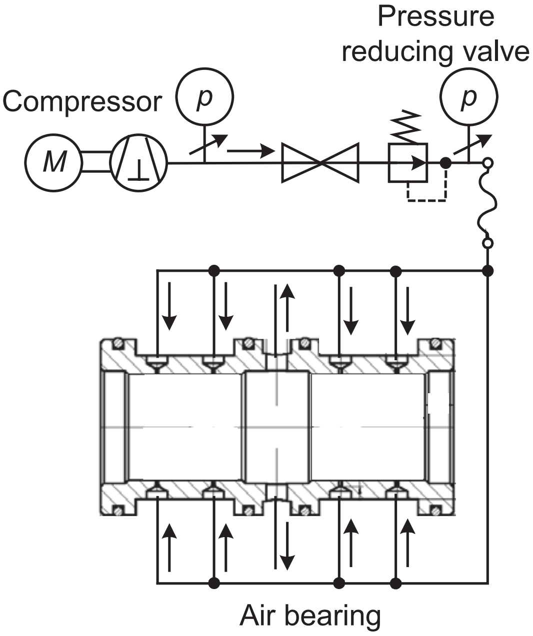

Fig. 6. Diagram of connections in the aerostatic bearing

4. CONCLUSIONS

Accelerated fatigue tests on a gigacycle test-bed with input frequency of ca. 10 kHz enable reduction of test duration down to economically-acceptable time (10^8 cycles can be achieved in 30 hours).

Small dimensions of the test-bed enable research which has not been done to-date, namely examination of the influence of modulating frequencies on the vibration eigenfrequency of the sample's, hence analysis of more complex aspects of fatigue-related cracks' initiation and propagation.

Thus the main outcome is the development and construction of a relevant test-bed for examining gigacycle fatigue processes as well as testing procedures accounting for not taken to-date anywhere in the world attempts of using the features of vibroacoustic signals in forecasting the gigacycle resistance to fatigue.

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