EXAMINATION OF THE IMPACT OF AMPLITUDE-MODULATED VIBRATION ON THE COURSE OF A FATIGUE TEST (HCF)

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Summary

The purpose of this paper is to develop a method of forecasting and analysis of high-cycle (HCF) resistance to fatigue relying on vibroacoustic signal analysis. It proposes using the 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 proper frequency of vibration of samples.

Thanks to the small dimensions and mass, the test bed can be located on the vibration inductor, which enable investigations of the amplitude modulation's influence.

Additionally, it's described a problem of, phenomena oriented, diagnostics information's detection.

Keywords: vibroacoustic diagnosis, high-cycle fatigue processes (HCF), piezoelectric generators, amplitude modulation.

BADANIE WPŁYWU AMPLITUDOWO ZMODULOWANYCH DRGAŃ
NA PRZEBIEG TESTU ZMĘCZENIOWEGO (HCF)

Streszczenie

Celem pracy jest opracowanie metody prognozowania i analizy wysokocyklowej (HCF) trwałości zmęczeniowej na podstawie badania sygnału wibroakustycznego. 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.

Dzięki małym wymiarom i masie stanowisko badawcze może być umieszczone na wzbudniku drgań, co umożliwia badanie wpływu modulacji amplitudy.

Dodatkowo opisano zagadnienie detekcji informacji diagnostycznej, zjawiskowo zorientowanej.

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Słowa kluczowe: diagnostyka wibroakustyczna, wysokocyklowe procesy zmęczeniowe (HCF), generatory piezoelektryczne, modulacja amplitudowa.

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.

Majority of materials fail to fulfill such assumptions [1], thus there exists the need for looking for new high performance materials, we can examine in high-cycle fatigue testing (HCF) or gigacycle fatigue testing (VHCF). This aspects was presented in [2]. Much more information about this methods we can find in paper’s of Murakami [3, 4].

Authors proposed to develop a method of forecasting and analysis of high-cycle fatigue testing (HCF) or gigacycle fatigue durability ($10^8 \div 10^9$ cycles) for the metal-based, highly resistant materials used in high-speed motors and turbines. The method relies on the results of analyzing the vibroacoustic signal obtained during accelerated fatigue tests performed on a dedicated test bed which operates in the samples’ proper vibration frequency range of 10 kHz [2].

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. More about that test beds was presented in [2].

It was built a test bed for high-cycle tests of fatigue processes (Fig. 1). We have calculated the initial dimensions of a sample (HxWxL): 10mm x 5mm x 30mm. For the preset maximum deformation from 5÷40 µm range as well as the generated frequency of 10kHz, we selected a piezoelectric actuator - type PPA80L with parameters: max. no load displacement: 90 µm, blocked force 3500 N, resonance frequency (free-free: 7000 Hz, capacitance: 26,6 µF, height: 97 mm, width: 18 mm. This actuator can be powered with 150V current, which interworks with LA75C amplifier. The typical high-cycle test beds rely on the frames of machines used for testing the fatigue durability and are usually of big dimensions and weight. The authors proposed a small-dimension test bed for diagnosing the high-cycle fatigue processes, with dimensions of usually 0.2x0.2x0.2 m and its weight does not exceed 2 kg, with a titan head mounted directly on the piezoelectric generator. To do away with play, the beam in the head is mounted by means of an eccentric cam (to preventing of moving the beam in the head). Small dimensions result from the proposal of mounting the test bed on TIRA TV 5500/LS shaker. Such an application of the inductor will enable examination of the tested sample’s response to an input being a compilation of a carrier frequency and low-frequency modulating function, which will enable examination of more complex mechanisms of initiation and development of fatigue-related cracks [2].

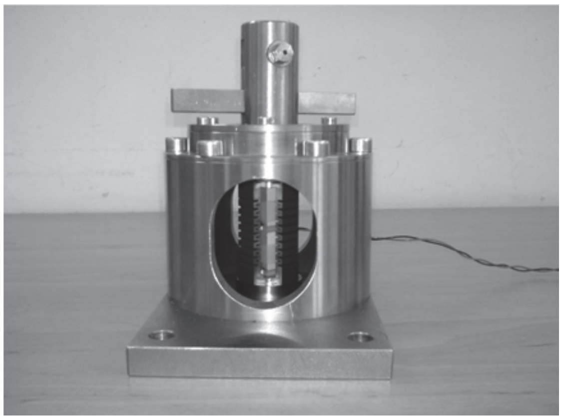

Fig. 1. High-cycle fatigue test bed

In this type of investigation it is problem of measurement amplitude of vibrating beam free end. It’s is almost unrealizable to mounting the accelerometer at the vibrating beam, we should use other source of the vibration signal. There were used a microphone Bruel&Kjær type: 4189-A-021, sensitivity 47,4 [mV/Pa], and a laser triangulation sensor MTI Instruments Inc. type: Microtrack II – LTC-050-10, range: 5 [mm], resolution 1 [µm], mounted at the ground-isolated stand. It was done comparison of signals from a laser sensor, and a microphone. The signal from the laser sensor alone might be insufficient (overload for example) at the moment when a fatigue crack is initiated and the amplitude of vibrations is rising very fast. Results received from the acoustic signal will serve to observe the resonant curve changes (the resonance frequency changes), together with the propagation of fatigue crack. Although was measured vibration signal from an accelerometer Bruel&Kjær type: 4507 B 004, sensitivity 10,22 [mV/ms^2].

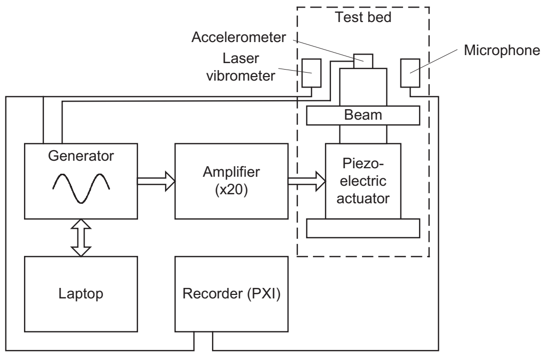

Fig. 2. Non-contact recording-control system

A recording-control program has been developed in the LabView 7.1 environment which has the task of tracking the resonant frequency of a beam based on the spectral analysis of a vibration signal registered by a use of the non-contact measurement system (Fig. 2) and the piezoelectric accelerometer. The frequency value estimated in this way is in the next step was sent to the generator in order to correct the frequency of the signal stimulating the piezoelectric converter. Thus it is possible to track the changes of frequency (at the resonant curve) of a beam's proper vibration (first mode of bending eigenfrequency) connected with the developing fatigue-related crack. Modes of eigenfrequencies were isolated, more information about it we can find in [5].

This investigations enables not only detection of surface failures, but also detection of failures appearing in the specimen core.

2. THE EXPERIMENT

Fatigue tests were conducted at the aforementioned test-bed. An item which becomes essential from the point of view of the strength of a structure subjected to vibration having a small amplitude is the issue of existence of a notch as well as the shape of such a notch. An experiment was conducted which was intended to define the impact of a notch on fatigue strength of a sample made of copper. We use of displacement amplitude of forced.

The size of the sample (height x width x length) was 10 mm x 5 mm x 40 mm, however there were notches in the sample in the place in which it was mounted (notch dimensions: width: 2 mm, depth: 1 mm). Three types of notches were examined:

- the P-type notch (rectangular) - Fig. 3.
- the V-type notch,
- the U-type notch.

Fig. 3. A specimen with a P-type notch

Fig. 4. View of the fracture of a beam with a P-type notch

The most interesting results were obtained for the sample with a P-type notch. The tests were conducted until the sample broke due to fatigue (Fig. 4), which occurred after around 2 million cycles.

Bispectrum from channel no. 2 (laser vibration meter), which measured the amplitude at the free end of the beam, was calculated during the measurements.

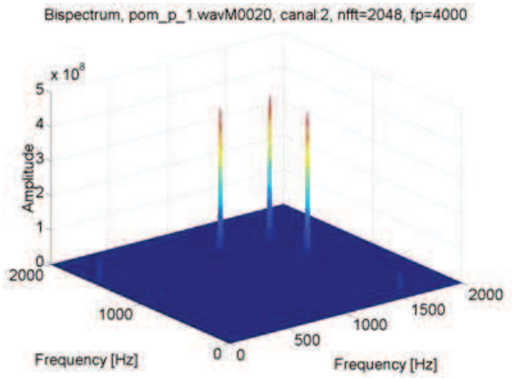

Fig. 5. Bispectrum - channel 2 (laser) at the start of the test

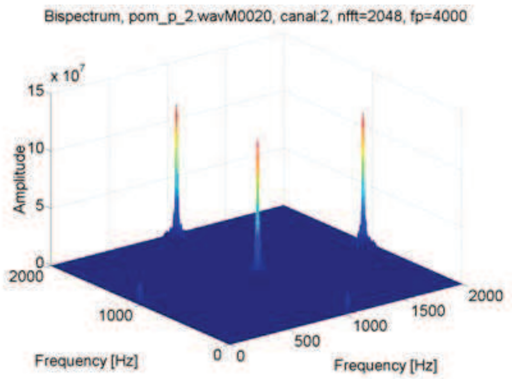

Fig. 6. Bispectrum - channel 2 (laser) after $1 \cdot 10^6$ cycles

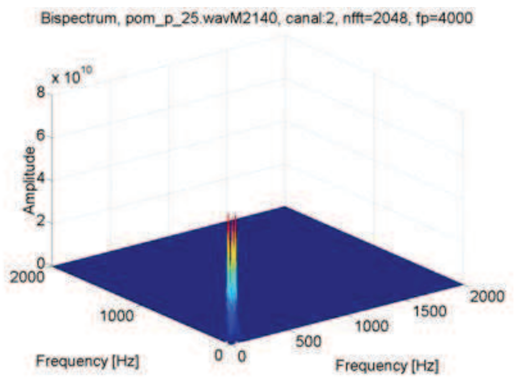

Fig. 7. Bispectrum - channel 2 (laser) after $2{,}1 \cdot 10^6$ cycles (close to the specimens break)

Fig. 5 shows the bispectrum drawn at beginning of the test, Figures 6 show the bispectrum during the test while, Fig. 7 shows the bispectrum at the end of the test, after $2 \cdot 10^6$ cycles. After $1{,}5 \cdot 10^6$ cycles the eigenfrequency was alone. It was caused by develop of nonlinear effect of fatigue crack, that is the influence of material properties structure. Modulating frequencies appeared at $2\cdot10^6$ cycles (Fig. 7), just before the sample broke.

Thus bispectral analysis can be a useful tool for detecting fatigue-related tracks. More informations about this investigations was presented in [6].

A similar effect was observed while building the bispectral measures in the function of change of the loads, including the maximum bispectrum and the diagonal bispectrum. The next step was to create a new measure which would be able to foresee the moment of emergence of a fatigue-related crack in a much better way. Integrals for the entire lifecycle of a sample were calculated based on the graphs of the maximum bispectrum (Fig. 8) and the maximum bispectrum calculated on the basis of a triangular matrix – the residual bispectrum (Fig. 9), which emerged as a result of cutting out the main diagonal which described the impact of modulation phenomena and non-linear effects. In addition the cut-off level for maximum amplitudes was applied at 0.25E8 [m/s^2] (everything which had a higher value than this level was reduced to this level). Then, the beam's resonant frequency curves, obtained during consecutive measurements (dot-and-dash line), were superimposed over the above graphs).

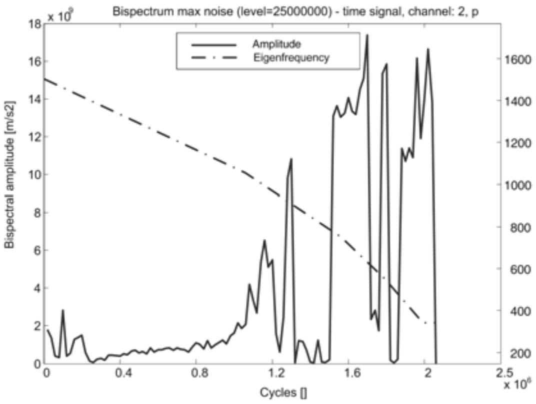

Fig. 8. Integrals from the maximum bispectrum graphs (level of 0.25E8 [m/s^2]) - full line and eigenfrequency of a beam (dot-and-dash line)

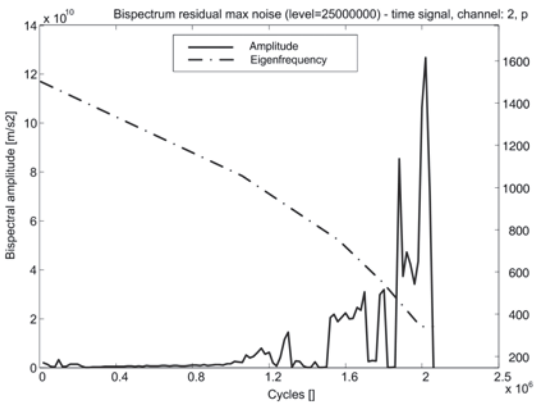

Fig. 9. Integrals from residual bispectrum graphs (level of 0.25E8 [m/s^2]) - full line and eigenfrequency of a beam (dot-and-dash line)

In both graphs (Fig. 8 and Fig. 9) we can observe an upward trend of the amplitude which accompanies the presumed development of a fatigue-related crack. This trend is similar to falling of beam's eigenfrequency, causing by developing of fatigue crack (changing of beam's cross section) of While by analyzing Fig. 9 it could be concluded that the fatigue-related crack most probably started developing from measurement no. 2500 (1.2 million cycles) and reached the critical (pre-failure) level at measurement no. 4700 (1.9 million cycles). Thus, based on these findings it is possible to build a very sensitive and reliable diagnostic parameter which describes the development of a fatigue-related crack.

Then a test was conducted to see if existence of amplitude modulation would lead to faster destruction of a sample.

3. IMPACT OF MODULATION – TESTS ON A SHAKER

Small dimensions were proposed so as to enable installing the test-bed on the TIRA TV 5500/LS shaker (Fig. 10) which had the following parameters: nominal load – 4000 N, frequency range – DC÷3000 Hz, maximum acceleration – 54 g. Use of the shaker enabled generation of frequencies which modulated the frequency of the beam's proper vibration thanks to which it became possible to examine more complex mechanisms of initiation and development of fatigue-related cracks. The frequency of the input generated by the inductor was by ca. 20÷30 Hz smaller than the frequency of input generated by a piezoelectric stack, thanks to which the phenomenon of beating of the end of the beam occurred (Fig. 11). The dimensions of the beam were the same as in the case of modulation tests and just the same the beam had a P-type notch. We use a use the same the non-contact measurement system (Fig. 2).

Fig. 12 presents change of the value of the beam's resonant frequencies, associated with the development of the degradation process, in the function of subsequent cycles. This time the tests were interrupted after $2{,}5\cdot10^6$ cycles due to occurrence of a visible crack in the beam. Let us note that the monotonous, in its essence, decrease of the proper vibration's value prevents determination of the phase of fatigue-related crack's initiation. Such a possibility is created by the observation of phase coupling, including the analysis of the residual bispectrum. This time we have applied a cut-off level for maximum amplitudes equal to 0.5E8 [m/s^2] (Fig. 13). While observing the trend, we can note that a qualitative change of the run occurs after ca. 1.8 million cycles. Most probably the change indicates transition to the next phase of degradation – initiation of fatigue-related crack.

Scientific publications devoted to examining the impact of modulation, show that the samples subjected to vibration generated by modulated vibration become destructed after a much smaller number of cycles. The conducted research did not confirm such results, however one should note that the maximum amplitudes measured at the end of a sample were of the same order as in the case of incitation with a signal having a constant amplitude. This resulted from the limited power of the shaker on which the head containing the sample was mounted. The future investigations require the shaker with much more power.

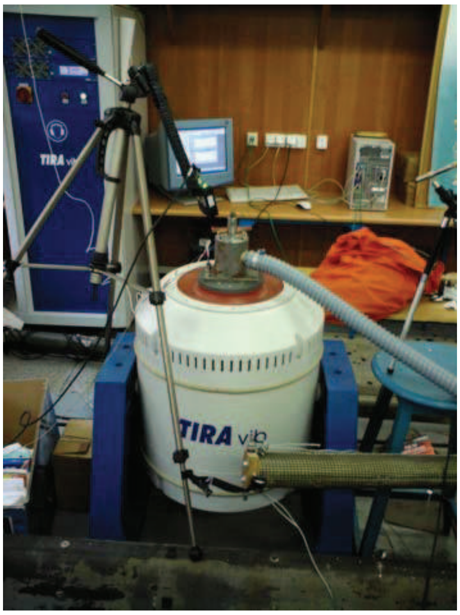

Fig. 10. High-cycle test bed on TIRA TV 5500/LS shaker

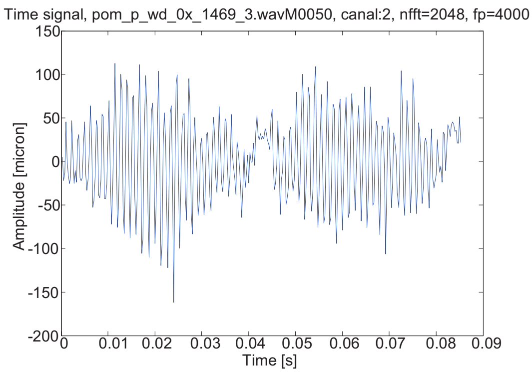

Fig. 11. Time run of the signal – amplitude of vibration at the end of the beam

The authors contemplate additional possibilities of increasing the amplitude of vibration of the examined sample. Such a possibility is created by introduction of coupling of the linear structure with an adaptive non-linear dynamic system and exploitation of the phenomenon of energy transfer to a non-linear system [7]. Occurrence of energy transfer is possible if relevantly big residual energy is supplied and if the non-linear resonance of an oscillator occurs.

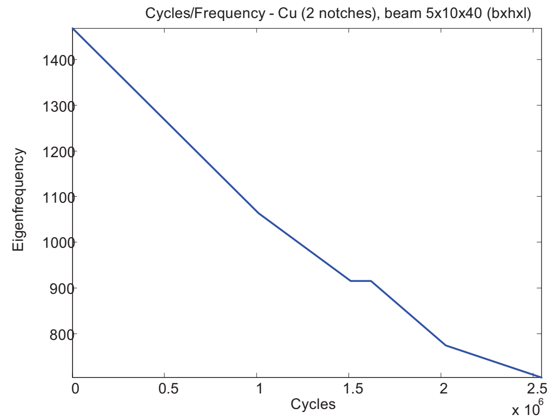

Fig. 12. Eigenfrequency of a beam

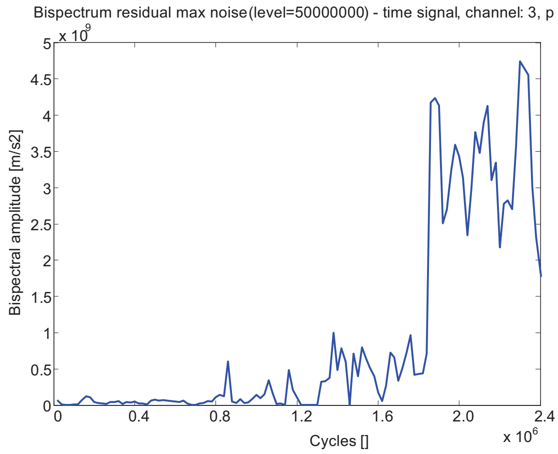

Fig. 13. Integrals from residual bispectrum graphs (level of 0.5E8 [m/s^2])

4. CONCLUSIONS

A unique, comparatively small-size test-bed has been designed and built. It operates based on the resonance of the examined sample, within the frequency range of up to 10 kHz, has a system for tracking the frequency of a sample's proper vibration and is accommodated to conducting tests in the conditions of combined frequency inputs generated by an additional inductor. It has a head made of titanium which is mounted to a piezoelectric generator. To do away with any play, the sample is mounted in the head by means of an circular cam.

A program has been developed. Its task is to track the resonant frequency of a beam based on the spectral analysis of a vibration signal registered by high frequency acceleration meter. Thus it is possible to track the changes of the beam's proper vibration frequency which are associated with the growing fatigue-related crack.

A contact-free method of vibration measurements has been developed. It relies on two independent sensory-measurement systems – a laser vibration meter and a condense microphone.

A method has been developed for analyzing higher order spectra for forecasting and identification of the degree of degradation of a sample's dynamic properties. Residual bispectrum has been proposed as a measure enabling determination of initiation of a beam's fatigue-related crack.

One should stress that independently of the type of input, whether it has a constant amplitude or whether the input is modulated, we have been able to confirm the sensitivity of the residual bi-spectrum to occurrence of consecutive phases of development of a crack in a sample. Bispectral analysis is very sensitive type of analysis. It can detect the structural changes of material's parameters, much more before the organoleptic changes.

The conducted research did not confirm that impact of modulation, show that the samples subjected to vibration generated by modulated vibration become destructed after a much smaller number of cycles. However one should note that the maximum amplitudes measured at the end of a sample were of the same order as in the case of incitation with a signal having a constant amplitude. This resulted from the limited power of the shaker on which the head containing the sample was mounted.

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