USE OF HILBERT-HUANG TRANSFORM OF A VIBROACOUSTIC SIGNAL IN THE RESEARCH RELATED TO THE GIGACYCLE FATIGUE PROCESS

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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 proposed method involves 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. Let us note that the process of defect formation may lead to both, the intensification of non-linear phenomena as well as the occurrence of non-stationary effects even if during the early stages the intensity of defects is small while the growth of the level of vibration and noise is negligible, as contrasted with emergency states. A useful method is to test the higher order spectra, which respectively define the non-linear effects. The conducted analyses point to high usability of Hilbert spectrum through the EMD examining the non-stationary character of signals.

The main goal of these investigations is to examine the signal processing method for gigacycle fatigue durability and impact of dynamic stress. Efficient signal analysis would be especially important for high frequency loading which dominates in rotating machinery diagnosis.

Keywords: Vibroacoustic diagnosis, gigacycle fatigue processes, piezoelectric generators, bispectrum, Empirical Mode Decomposition, Hilbert Huang Transform.

ZASTOSOWANIE TRANSFORMATY HILBERTA-HUANG SYGNAŁU WIBROAKUSTYCZNEGO W BADANIACH GIGACYKLOWEGO PROCESU ZMĘCZENIA

Streszczenie

Celem pracy jest opracowanie, dla materiałów o wysokiej wytrzymałości, metody prognozowania i analizy gigacyklowej trwałości zmęczeniowej (108÷109 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. Zauważono, że proces kształtowania się uszkodzenia może prowadzić zarówno do nasilenia zjawisk nieliniowych jak również do wystąpienia efektów niestacjonarnych nawet wtedy, kiedy podczas wczesnych stadiów uszkodzeń ich intensywność jest mała a wzrost poziomu drgań i szumu jest pomijalny, porównując go z poziomem przy stanach zagrożenia. Użyteczna jest w tym wypadku metoda widm wyższego rzędu, która odpowiednio definiuje efekty nieliniowe. Zamieszczone w publikacji analizy wskazują na dużą użyteczność widm Hilberta a w szczególności empirycznej dekompozycji sygnału (EMD), która pozwala na analizę niestacjonarnego charakteru sygnału.

Głównym celem badań było znalezienie skutecznej metody przetwarzania sygnałów dla gigacyklowych wytrzymałościowych procesów zmęczeniowych oraz zbadanie wpływu obciążeń dynamicznych. Efektywny sposób analizy sygnału jest szczególnie ważny w diagnostyce maszyn obrotowych gdzie występują wysoko częstotliwościowe obciążenia.

Słowa kluczowe: diagnostyka wibroakustyczna, gigacyklowe procesy zmęczeniowe, generatory piezoelektryczne, bispektrum, dekompozycja sygnału EMD, transformata Hilberta Huanga.

1. INTRODUCTION

The publication presents the possibilities of extracting diagnostic information while relying on the methods which use the results of analysis of a vibroacoustic signal obtained during accelerated fatigue tests performed in a dedicated test bed which operates in a 20 kHz frequency range. This frequency corresponds to the proper frequency of vibration of the samples. Due to the difficulties associated with carrying such long tests on classical testing machines (which offer input frequencies in the range of 30 Hz), research of such a type has not been conducted in Poland and hence no attempts have been made of formulating the assssment of the process while relying on the information contained in vibroacoustic signal. Non-familiarity with phenomenon as well as lack of possibilities of conducting qualitative, and especially quantitative measurements of the process in whose case the predominant part of defect formation period is associated with the crack nucleation phase and it brings the threat of oocurence of catastrophic defects. If a fact is taken into account that the situation concerns modern means of transport (airplanes, ship, fast trains) as well as equipment in conventional electrical power plants and while taking into account the contemplated strategic plans of development in Poland of nuclear power plants whose failures could have catastrophic consequences, then carrying out such research as well as undertaking the task of developing the algorithms which will forecast the useful life become a necessity for the Polish scientific and technical community.

At the same time the researchers who indulge in atempts of conducting such research point out that crack nucleation period accounts for 90% of the time of development of the process of gigacycle material fatique [1, 2]. For obvious reasons, determining a clear boundary between crack nucleation and propagation phase is not simple.

In addition, the relationships between growth of a crack and intensity of the stress as well as the value of stress, which have so far been applied in mechanics, have not gained full acceptance in the conditions of gigacycle fatigue and at the present stage of the research they are subject to verification. From this point of view an urgent need exists for developing new research methods, adequate diagnostic models as well as for selection of the right methods of diagnostic information detection [3].

The purpose of the research was to demonstrate the possibility of reaching the diagnostic information by means of such methods of signal processing as: bi-spectral analysis, Hilbert Huang transform in order to analyze the gigacycle fatique durability ($10^8 \div 10^9$ cycles), for highly durable materials, while relying on examination of a vibroacoustic signal. The method uses the results of analysis of vibroacoustic signals obtained during accelreated fatigue tests which are conducted on a dedicated test-bed operating in the frequency range of the samples' proper vibration.

2. TEST-BED AND EXPERIMENT DESCRIPTION FOR EXAMINING GIGACYCLE FATIGUE-RELATED PROCESSES

The authors have designed and performed a small-size test-bed for diagnosing the gigacycle fatigue-related processes (Fig. 1) [4]. The test-bed has the form of a cube with dimensions of 0.2 x 0.2 x 0.2 m and its weight does not exceed 2 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).

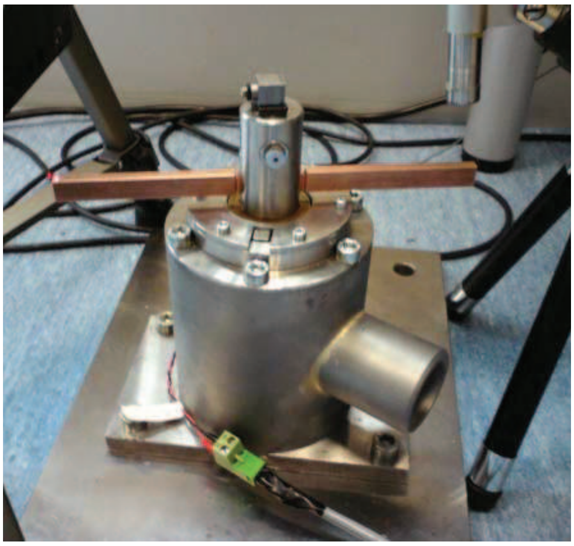

Fig. 1. Small-sized gigacycle fatigue test bed together with the specimen

A recording-control program has been developed in the LabView 7.1 [5] 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 and the piezoelectric accelerometer. The frequency value estimated in this way is in the next step 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 connected with the developing fatigue-related crack.

Fatigue tests were conducted in the aforementioned test bed. It is the existence of a notch as well as the shape of that notch that become essential from the point of view of durability of the structure. An experiment was conducted, which was intended to determine the impact that a notch has on fatigue durability of a sample. The assumptions of the experiment are presented more extensively in [6].

The dimensions of a sample were as follows (height x width x length): 10mm x 5mm x 40mm, however notches have been introduced, in a P-type (rectangular) sample, at the location of the mounting. The research was conducted until fatigue-related fracture of the sample occurred, which happened after ca. 2 million cycles.

3. SIGNAL PROCESSING FOR FATIGUE RELATED PROCESS DATA ANALYSIS

The paper focuses on use of bi-spectral metrics for evaluating and monitoring the evolution of a fatigue process. A different approach to the problem of extraction of information-carrying features of a signal is presented by the adaptation methods which rely on empirical data. These methods are exemplified by the Hilbert-Huang (HHT) transform [7] and they constitute the basis of this paper.

The Hilbert-Huang transform consists of two techniques of signal analysis. The first one is the so-called empirical decomposition of the EMD signal while the other is the Hilbert's spectral analysis. The complex method can be successfully used in the case of both non-linear and non-stationary signals and as a matter of fact it is its time-and-frequency representation which can serve this purpose. The key part of the transform, and at the same time its advantage which consists of the ability to adapt to a real-life signal, is the so-called sifting process which leads to obtaining of individual components of the original function. Compared to majority of other methods, the EMD method is intuitive and simple, it operates without any information whatsoever about the analyzed function, and it is executed directly on the basis of the original time signal.

EMD relies on the assumption that each complex signal consists of intrinsic functions which are a representation of simple forms of vibration. Each of such forms, linear or non-linear, will contain the same number of extremes and zero places. In each point in time the function can have many various co-existing forms of vibration which are in super-position to each other. The decomposition of a given series of data relies directly on isolation of energy runs (functions) which are contained within the time run of the entire analyzed sample and it can be presented as propagation of information which corresponds to subsequent internal IMF's - intrinsic mode functions, however each such a function has to meet the following requirements:

- in the entire scope of the signal the number of extremes and zero places must be equal or must differ by one,
- at each point the average value of the envelope defined by local maximums and of the envelope defined as local minimums is equal to zero.

The ability to analyze and detect even momentary changes in the signal and adaptability are necessary for analyzing the non-linear and non-stationary runs. Each inherent IMF function represents a simple form of vibration which is considered to be identical to a single harmonic of a function. The obtained local sequences of energy changes and of momentary frequency, obtained from consecutive inherent functions, can be used for constructing the full energy-time-frequency distribution of analyzed data [8].

With the use of the theory of empirical decomposition of the EMD signal, each signal can be decomposed in the following way.

In the first step one should identify all the local extremes and then approximate two functions: one function which passes through the local minima and the other which passes through the local maxima. The obtained curves will be respectively the bottom and the top envelope of the analyzed signal. The average function between the envelopes will be marked as m_1, while the difference between the original signal x(t) and M1 will the first component of h_1:

$$x(t) - m_1 = h_1 \tag{2}$$

In the ideal case, if h_1 meets requirements for an IMF inherent function, then h_1 is the first component of function x(t).

If h_1 is not an IMF, then it is treated as the original signal and the above procedure is repeated:

$$h_1 - m_{11} = h_{11} \tag{3}$$

Various criteria of the alloy were developed to guarantee the physical sense of the function which emerges in the process of sifting. [9]. It can be, for example, expressed in the following way:

$$\sum_t \frac{[h_{k-1}(t) - h_k(t)]^2}{h_{k-1}^2(t)} < SD \tag{4}$$

where $h_k(t)$ is the signal obtained as a result of k-th sifting iteration, while SD (standard deviation) is usually assumed at around 0.2-0.3.

Then the identified form becomes a component:

$$c_1 = h_{1k} \tag{5}$$

The first component is obtained from the original signal and that is why it will have the biggest scale and the shortest period.

By isolating c_1 from the original signal (t), we get:

$$r_1 = x(t) - c_1 \tag{6}$$

Where r$_1$ is treated as the original signal and the whole above describe process of sifting is repeated for r$_1$. The second component of x(t) function should be obtained this way.

The whole process is rerun n times and thus IMF inherent functions can be obtained and then:

$$\begin{gathered} r_1 - c_2 = r_2 \\ . \\ . \\ . \\ r_{n-1} - c_n = r_n \end{gathered} \tag{7}$$

The decomposition process can be stopped when r$_n$ becomes a monotone function from which no inherent IMF function can be obtained anymore (Fig. 2).

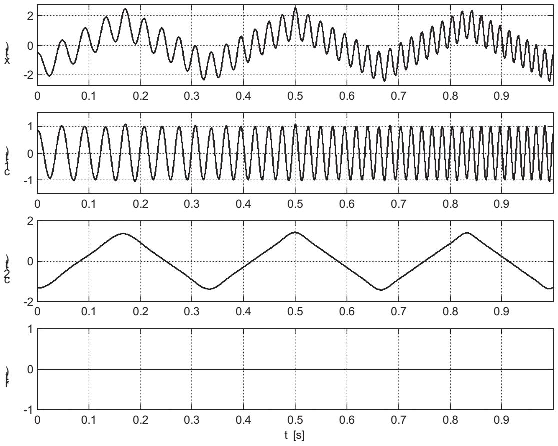

Fig. 2. An example of operation of the method of signal distribution to EMD empirical modes

To recapitulate the whole process:

$$x(t) = \sum_{j=1}^{n} c_j + r_n \tag{8}$$

This way (as in Fig. 3) we can obtain decomposition of a signal into n empirically obtained functions and residue r$_n$, which is the average trend of function x(t). Subsequent IMF c$_1$ c$_2$ c$_3$….,c$_n$ contain further varied frequency bands of the original signal, from the band with the highest to the band with the lowest frequency.

Empirical decomposition of signals, as proven by many publications [10, 11, 12], is a method which introduces a new quality and possibilities to analysis of complex non-stationary as well as non-linear signals. It has been tested in a wide scope of diagnostic tasks, i.e. in diagnosis of bearings, toothed gears as well as complex technical systems. EMD is capable of adapting to the signals coming from the above listed technical objects and to effectively identify the processes taking place in a signal's structure which correspond to changes of a machine's technical condition. The presented properties of Hilbert Huang transform have induced us to try to use this technique of signal processing to analyze the vibroacoustic signal in a gigacycle experiment.

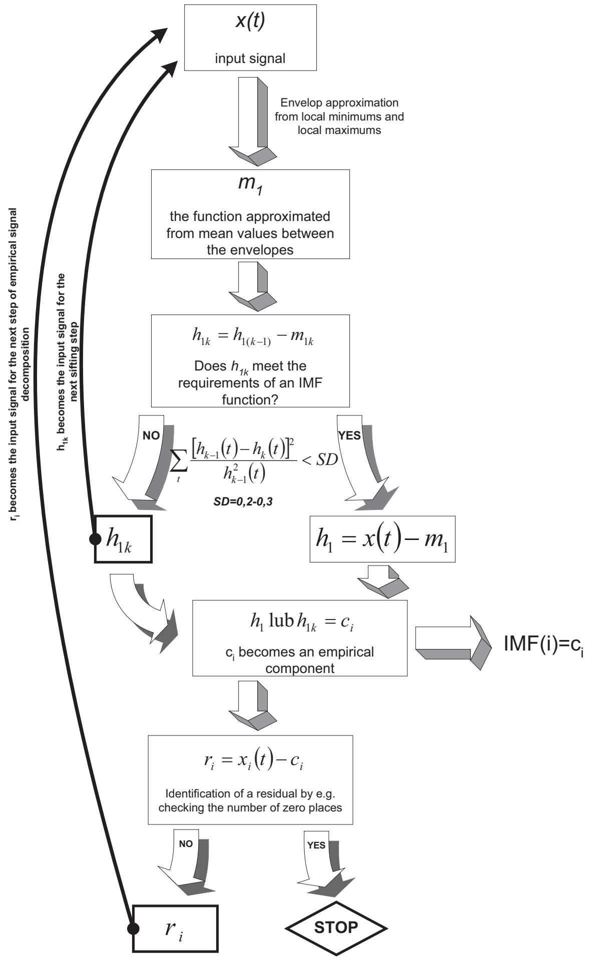

Fig. 3. Block diagram of the EMD shifting algorithm

4. THE EXPERIMENT

During the experiment a laser vibration meter was used to measure the vibration of the end of a beam. In the case of the analyzed test, the beam broke after ca. 2 million of vibration input cycles. Analysis of vibration signals by means of the Hilbert Huang transform enabled detection of a signal's features and the changes occurring in the signal, which are of key importance for analyzing the condition of an object in the case of examination of fatigue processes.

It turned out that the resonant frequency of the beam's vibration carries the information on the wear of the beam. As the number of cycles increased, the resonant frequency decreased. The analysis of the form of signals following the EMD (Empirical Mode Decomposition) decomposition for the beam’s vibration signals enables tracking and shows how the resonant frequency changes after a certain number of input cycles. The graphs (Fig. 5÷8) show the spectra of relevant components of the signal which have been obtained by applying the Hilbert Huang Transform (HHT), which consecutively correspond to the measurements: a – at the beginning of the experiment, b – after 1 million cycles, c - after 1.5 million cycles, d – after 2 million cycles. It is clearly visible how rapidly the resonant frequency decreases along with the growth of the number of cycles which have direct impact on crack development (Fig. 4) – it is the physical symptom of a defect. Such observation is in line with the course of the experiment and the general knowledge on development of fatigue processes.

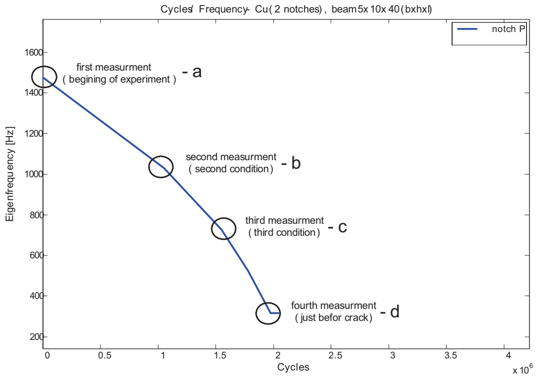

Fig. 4. The beam’s resonant frequencies as a function of consecutive cycles, with the places marked at which HHT was calculated

Further graphs present the spectra for respective decompositions of time signals developed for the signals registered in various phases during the fatigue-related experiment (Fig. 5-8). Subsequent components of the signal, which correspond to various frequency bands, are obtained as a result of “sifting” while using the HHT method.. First the highest frequencies are discovered, which are followed by further lower frequencies corresponding to a band which is by half smaller than the preceding one. While analyzing a series of spectra obtained this way in our fatigue experiment, we can see how the resonant frequency, which contains diagnostic information, changes its position to one corresponding to a lower frequency but it also changes the position related to obtaining its pattern in a different empirical component. This can be seen in the figure, where for the third stage the measurement was performed after 2.5 million cycles, and we do not find any resonant frequency in the spectrum of the first component – the resonant frequency can be discovered only after the next operation of empirical decomposition of the signal. This additional relation between crack development stage and the property of Hilbert Huang transform can prove useful for diagnostic inference.

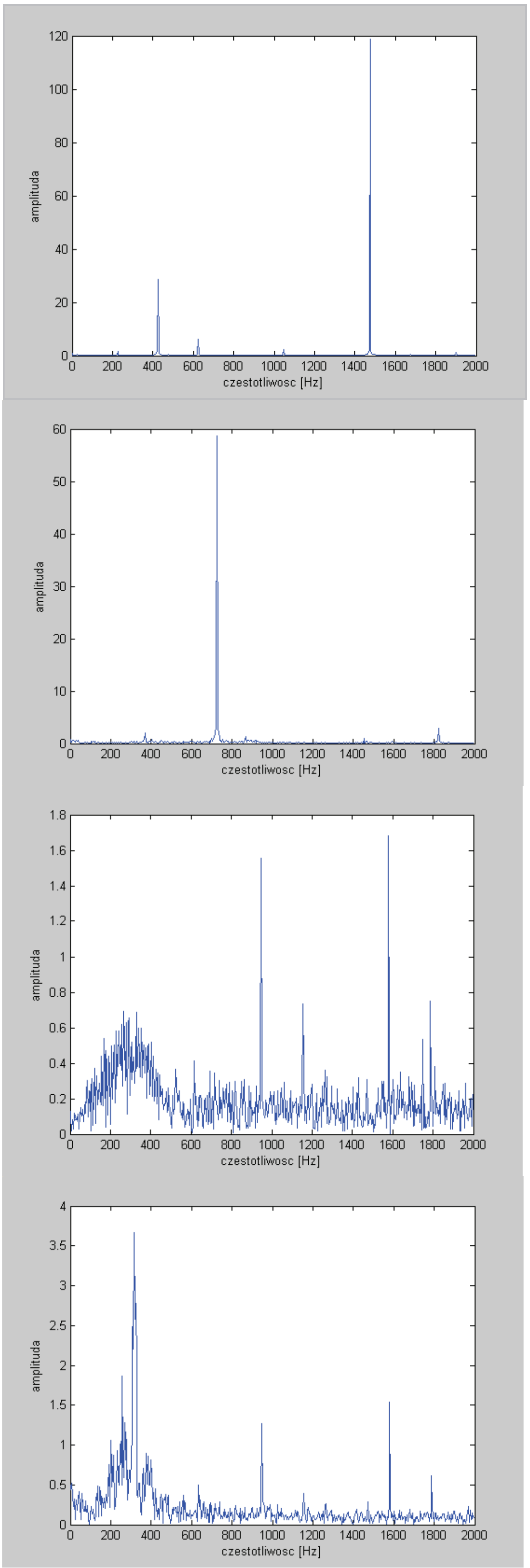

Fig. 5. Entire spectrum – obtained from the first form of the signal after EMD – further states which correspond to the measurement points on the graph

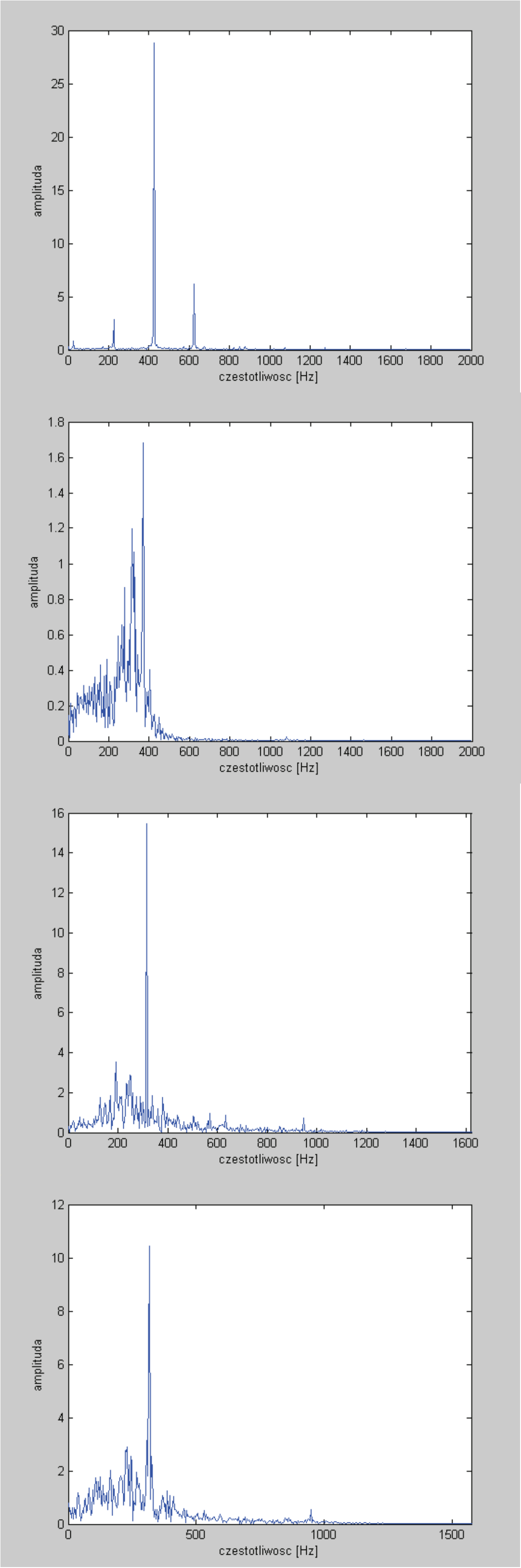

Fig. 6. 1/2 of spectrum – obtained from the second form of the signal after EMD – further states which correspond to the measurement points on the graph

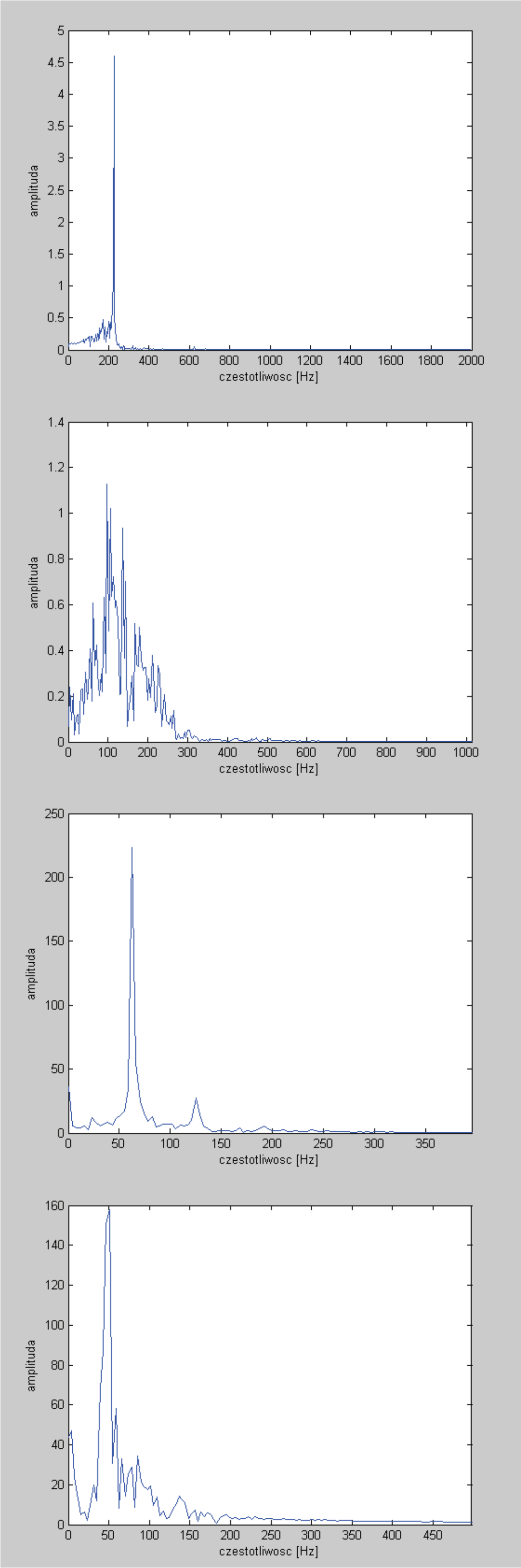

Fig. 7. ¼ of spectrum – obtained from the third form of a signal after EMD – further states which correspond to the measurement points on the graph

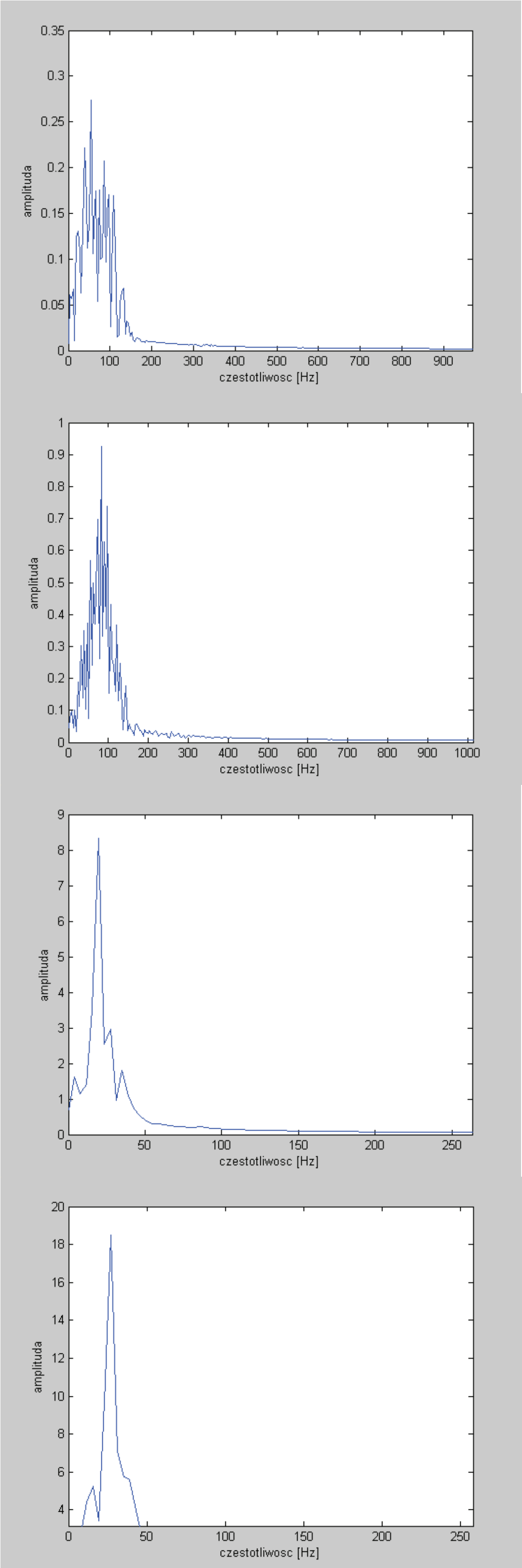

Fig. 8. 1/8 spectrum – obtained from the fourth form of a signal after EMD – further states which correspond to the measurement points on the graph

As we have already demonstrated, development of degradation processes leads to decrease of frequency of an object's proper vibration. In our case the object was a vibrating beam. Use of the Hilbert Huang transform has enabled discovery of the fact that the dynamics of decrease of resonant frequency depend on the phase of crack of development. In the early phases of fatigue the resonant frequency changes significantly as a function of consecutive cycles and then the dynamics of its decrease become reduced as the critical values of cracking are approached. In the case of the analysis relying on HHT, this property leads to exposition of amplification of low frequency bands (respectively for ¼ and 1/8 of the spectrum (Fig. 6 and 7)) – a relevant level of signal decomposition has to be reached in order for this to be observed. To recapitulate, observation of spectra for further components of empirical signal decomposition (1/8, 1/16 spectrum) and to be more precise the growth of energy which occurs in low frequency bands, offers information on the approaching stage of fatigue-related crack emergence (Fig. 8).

4. CONCLUSIONS

The paper proposes development of assessment of the phases of fatigue-related defect development while relying on the defect-oriented analysis of a vibroacoustic signal's parameters. The results of the research, which has been conducted to-date in the Laboratory of the Mechatronics System of Vehicles and Construction Machinery of Warsaw University of Technology, confirm the possibility of developing, on such basis, of both qualitative and quantitative measures of fatigue-related defects' development.

It has been demonstrated that Hilbert spectrum obtained after applying signal sifting with the use of HHT method is a good measure of degradation process development while selection of a relevant level of decomposition enables determination of the degradation phase. The quantitative and the qualitative analysis of a vibroacoustic signal processed this way enables construction of relevant diagnostic measures which define the phase of defect development.

The obtained results of research, which involved an experiment conducted at a unique test-bed for gigacycle analysis of fatigue-related processes as well as use of relevant research procedures, which included unique worldwide attempts of exploiting the vibroacoustic signals' features for forecasting of gigacycle fatigue strength, point to the big possibilities offered by such a method of research and analysis, and they should be continued.

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