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Experimental Stress Analysis

Investigation of C/PPS Composites Degradation Process Using Acoustic Measurement

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Abstract: The article deals with assessment of fatigue degradation of C/PPS composites using simple acoustic measurement technique. Changes in natural frequency and attenuation decrement were chosen as indicators of fatigue damage accumulation in the studied composite material. New testing device was developed for acoustic measurement. The experimental setup was designed to chime the specimen by repeatable force of stiff striker exciting a specific natural mode of vibration and to record the acoustic response of the specimen to the impact simultaneously. From the power spectral density of the signal the natural frequency was obtained. Using the same signal, the attenuation decrement was estimated from regression of the its envelope. Presented high precision non-destructive method allows to conclusively measure the natural frequency and its change with a deviation smaller than a few tenths per cents. To demonstrate its suitability, the technique was applied on study of the dependence of composite's material properties on temperature and then on estimation of material's fatigue degradation with satisfactory results.

Keywords: Material degradation, Acoustic measurement

1. Introduction

Residual mechanical properties of materials in cyclic loading are of highest importance for fatigue research. These properties indicate remaining service life of the material, can be used in failure criteria and coupled with micromechanical studies.

Applied measurement method shall be non-destructive, simple, reliable and suitable not only for fatigue degradation degree assignment, but also for testing material properties variations in elevated temperatures. Questioned requirements leaded up to creation of the new acoustic testing method and related testing device.

A reliable description of material life-time behaviour and it's mechanical properties degradation due to fatigue are the main subject in this paper. The paper is focused on investigation of relationship between specimen's acoustic quantities and its extent of fatigue degradation by cyclic loading. The contribution also describes main issues of development of specialized experimental method and tools.

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2. Material description

Carbon fiber/polyphenylene sulphide (C/PPS) composite is relatively new material used in aerospace industry and in other hi-tech applications. it is quasi-isotropic 8-ply of carbon fabric bonded by thermoplastic matrix. The matrix is the main difference from more common composites based on epoxy resin, i.e. thermosets. Modulus of elasticity of carbon fibers reinforcement prepared from high-stiffness Poly-acrylonitrile (PAN) is in range from 40 to 400 GPa [1]. Stiffness to density and strength to density ratios of this material are fully comparable with established metal alloys. Other mechanical properties of C/PPS composite are in detail described in manufacturer's datasheet [2]. The set of specimens with 'dog bone' shape and rectangular shape with dimension of 250×25×2.5 mm were prepared using computer controlled water cutting machine.

3. Basic principle of acousting testing

The basic principle of acousting testing of composite material specimen is based on the fact, that specimen's natural frequency and it's attenuation decrement change in dependence on materials's degradation caused by mechanical fatigue. It follows from the simple modal analysis that any shift of natural frequencies of the specimen is caused by change of its mechanical properties [3]. Therefore study of natural frequencies can be used for observation of material's degradation. This assumption allowed creation of measurement process of questioned acoustic quantities. The nature of the measurement is an impactor that streams on specimen at the reproducible conditions and so it excites always the same type of sound response. Sound emitted by specimen is recorded via microphone to laptop, where it is evaluated using spectral analysis for acquirement of natural frequency values. Attenuation decrement is obtained using data selection and it's exponential regression. Intact and fatigued specimen show mutual offset of their natural frequencies. For receipt of the most precise and most consistent data the own testing device was constructed.

4. Testing device

Designed testing device has had to match up to these requirements:

- **High stiffness** – if the device did not have the appropriate stiffness, the natural frequency of specimen and natural frequency of the device would mix together
- **Smallest contact area** – specimen fixation in the device has to have minimal contact area. Passing this condition ensures the least possible attenuations of an emitted sound
- **Temperature resistance up to 200 °C** – experiments in autoclave for assignment of fatigue properties at high temperatures are expected
- Vast possibility of **geometrical parametres correction** for affecting trajectory and impactor's kinetic energy and simultaneously ability to durable fixation at each position to make test series with the same conditions

By application said requirements the construction shown in Fig. 1 was realized. Device base is made of wooden rectangle on that specimen fasten frame and impactor control mechanism are situated.As an impactor has been selected steel pellet with diameter 4 mm and as its direction leader an alluminium tube with inner diameter 6 mm. Tube is incorporated with mechanism which allows to set many geometrical parametres (at most identity of specimen‘s longitudinal axis plain and tube axis).

Frame is made of thick-walled steel die-castings. To provide high stiffness grade of the frame high-strength thread rods providing overstress are mounted in it's upper section. Fastening mechanism consists of two coaxial cap screws with sharp tip. Fastened specimen has 1 degree of freedom (rotation around screw's longitudinal axis). Connection between sharp-tipped screw and the frame is provided by wing nuts. Very important part of this connection are silicone underlays that provide mutual soundproofing between the frame and the specimen. Detail of fastened specimen and needles shows Fig. 2.

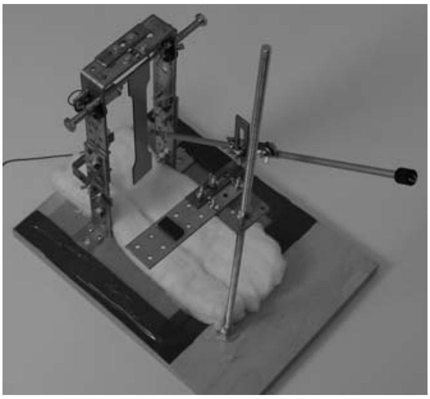

Fig. 1. Testing device during experiment

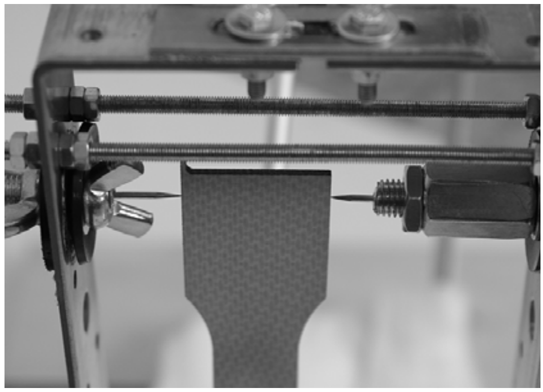

Fig. 2. Detail of fastened specimen

5. Experiment description

It is necessary to select carefully impact position on the specimen and impactor kinematics attributes. Initial measurements showed, that intensity and harmonics of resultant sound is most affected by impactor‘s impact velocity (longitudinal gradient of tube) and its weight. By proper selection of device options, the optimal natural frequency's spectral density layout is acquired. The microphone position in addiction of impact zone was found as very important during initial testing. When the microphone was situated too close to the impact zone, the input sound signal was higly revived. Change of microphone position during a testing (step by step changes also), when many positions of impact zone were used, resulted to distortion of the obtained signals and especially their mutual relations. Best results were reached by constant position of microphone during whole experiment.

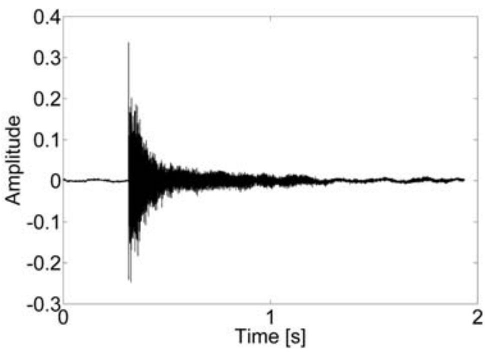

Fig. 3. Recorded sound signal

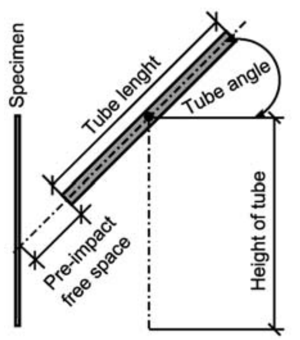

Fig. 4. Imperative geometrical parametres of the measurement

In the early stages of experimental setup development double contact of impactor with specimen‘s surface was occurring in certain configurations. Proper slope and cotton wool padding of the device base eliminated this issue. Due to this reason the careful analysis of the recorded signal and absolute silence while measurement pending are necessary. Example of the recorded sound signal is shown in Fig. 3. Sound recording and following signal processing is provided by MATLAB software. Testing device parametres are displayed in Fig. 4.

6. Results

After setting up experimental conditions, methodology of acoustic measurement and device functionality verification the series of tests was specified. Rectangular specimens with dimensions 250 mm height, 50 mm width, and 2.5 mm thickness were used within the measurement. Experiment results confirmed the dependence between natural frequency values and it's mechanical fatigue. Measured natural frequency changes are shown in Table 1.

Table 1. Natural frequency values for intact and fatigued specimen

Number of measurement	Natural frequency [Hz] Intact	Natural frequency [Hz] 2×10^5 cycles
1	5342	5251
2	5341	5253
3	5342	5254
4	5341	5250
5	5343	5250
6	5343	5251
Mean	5342	5251.5
Standard deviation	0.89	1.64
Median	5342	5251
Difference, [Hz]		**90.5**
Difference, [%]		**1.69**

Natural frequency value offset is well visible using a spectral analysis. Fig. 6 shows frequency spectrum of specimen. Fig. 5 depicts changes of frequency spectrum of the fatigued specimen and the intact one.

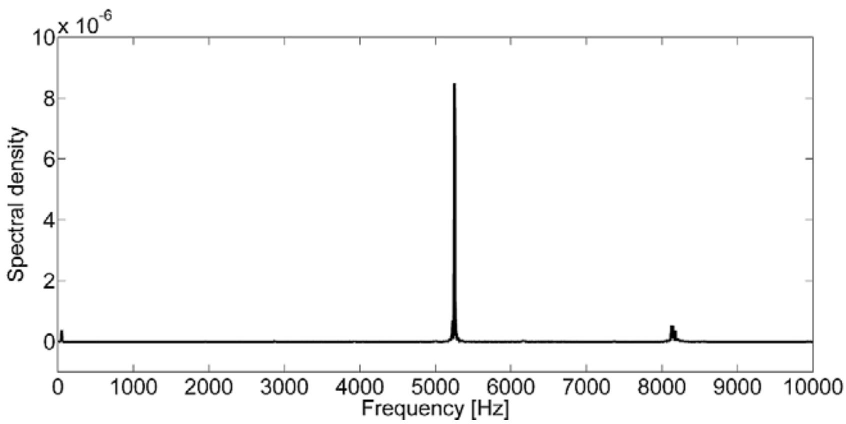

Fig. 5. Frequency spectrum of the specimen

Specimen fatigued by 200 000 cycles has a natural frequency offset -90.5 Hz against the intact one. It is 1.69 % relatively. In fact, that standard deviation of natural frequency result for higher count of measurements of identical specimen and identical fatigue rate was at most 1.69 Hz (0.03% relatively), we can find the results obtained by this method high accurate.

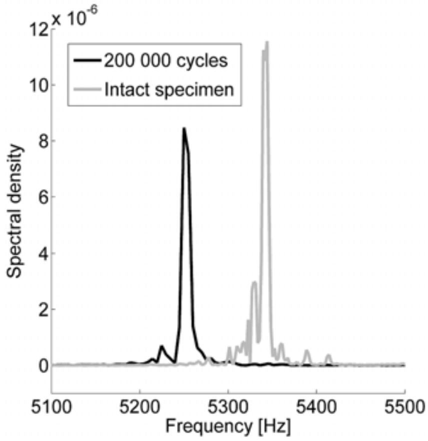

Fig. 6. Natural frequency offset of intact and fatigued specimen

Another characterization is natural frequency value descent rate in dependence on number of cycles. In current state the only available data include intact specimen and specimen with 50 000 cycles and 200 000 cycles. Summary of these data is displayed in Fig. 7.

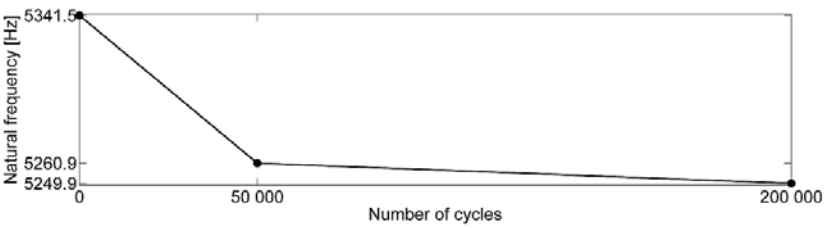

Fig. 7. Natural frequency descent rate

6.1. Comparative ultrasonic measurement

The pulse transmission ultrasonic technique, a fast and simple non-destructive method, was chosen as a comparative method to natural frequency measurement. The first impulse to use this method was the fact that a good agreement between the ultrasonically determined and mechanically measured elastic moduli have been reported [4]. On the other hand, our previous experience [5, 6] suggest that moduli determined by bending and by US evolve in the course of fatigue loading differently. The experiment was carried out using USG 20 (Krompholz Geotron Elektronik, FRG) used with a 20 kHz transceiver (USG -T) and receiver (USE-T). The first measurement was focused on time of wave propagation from which the wave velocity and also elastic modulus can be determined.. The invariability of time of wave propagation reveals fully elastic behavior and integrity of carbon fibres, through which the sound is transmitted. On the other hand, the second measurement - attenuation of the wave amplitude - correlates with a bending stiffness decrease (listed in 2)- that can be explained in terms of matrix degradation and also weakening of interface between fibre and matrix. Lower signal, i.e. lower difference between voltage at receiver at the rest and the peak voltage associated with arrival of sound wave, indicates friction at interfaces caused by decohesion. As the Table 2 shows, fatigued specimens exhibited substantially lower voltage difference. The promising results of attenuation studies are reliable up to certain level: sometime attenuation in material is obscured.

Table 2. Signal attenuation in ultrasonic measurement results

Specimen number	Number of cycles	Min [V]	Max [V]	Amp [V]	%	T [μs]	%
0	0	-2.16	0.66	2.82	100	47.4	100.0
10	0	-2.22	0.64	2.86	101.4184	47.6	100.4
7	50000	-2.1	0.58	2.68	95.03546	47.8	100.8
1	200000	-1.96	0.5	2.46	87.23404	47.6	100.4

7. Conclusions and discussion

Dependence between natural frequency values and it's mechanical fatigue were verified. The constructed device described in this paper allows reliable, non-destructive and precise measurements of the specimen acoustic characteristics. Further research of fatigue states using this device will also concentrate on description of fatigue degradation in terms of attenuation of specimen's emitted sound, as the knowledge of the evolution of this parameter during fatigue can be successfully used as damage indicator. Attenuation decrement should be acquired by using regression analysis. Unsatisfactory result of attenuation decrement exponential regression is shown on Fig. 8. This research couldn't be carried out due to issues with "Automatic Gain Control" circuit on the computer sound card. This circuit interferes with sound intensity measurement and has to be bypassed by external sound board. This topic will be a subject of the future research.

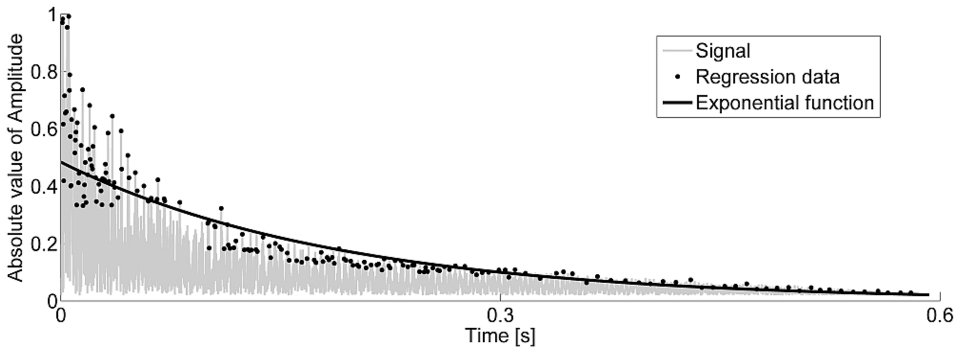

Fig. 8. Applied exponential regression of attenuation decrement

Concerning the future research, we would also like to make some acoustic tests in climatic chamber, where specimen's temperature would be increased to maximal matrix temperature, and to extend this testing method not only as a method suitable for composite materials, but also as a general purpose testing method.

To conclude, as implied by the published results the presented simple device and experimental method utilizing variation of natural frequencies of specimens in the course of fatigue tests have proved useful as damage accumulation indicator in the studied material.

Acknowledgment

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