18th International Conference
ENGINEERING MECHANICS 2012
Svratka, Czech Republic, May 14 – 17, 2012

pp. 231–237
Paper #241

COMPARISON OF COMPOSITE MATERIAL DEGRADATION ASSESMENT METHODS USING ACOUSTIC ANALYSIS AND LASER VIBROMETRY

T. Fíla [*], S. Urushadze [**], D. Kytýř [*], J. Valach [*], M. Šperl [**]

Abstract: *Assessment of degradation rate of material can be carried out by many experimental techniques differing in complexity and sophistication. A relatively simple method based on acoustic analysis is described in this contribution. Degradation of material's properties due to fatigue loading is detectable in decrease of their modulus of elasticity that can be derived from natural frequencies of specimens, which were acquired by the presented method. These measurements utilize self-designed device capable of specimen excitation and acquisition of its vibration. The recorded signal is then processed by spectral analysis enabling determination of natural frequencies. Usefulness of the above mentioned acoustic method can be seen in the fact that the measured changes of material's parameters are comparable to those obtained by laser vibrometry, which is by several orders more expensive technique.*

Keywords: ***natural frequency, material degradation, laser vibrometer, acoustic measurement***

1. Introduction

Reliable assessment of material degradation rate is very actual and discussed problem. Degradation rate can be carried out by many experimental techniques. Measurement of material sound exposure and so its typical acoustic characteristic is one of them. The characteristic is mainly represented by natural frequency and attenuation decrement. These magnitudes correspond with Young's modulus. Their changes represent material state and its degradation [Pirner & Urushadze, (2004)]. Use of these premises led to development of custom-designed acoustic measurement device that has been able to determine specimens natural frequencies and their decreases due to continuous material degradation [Fíla et al., (2011)]. Effort to prove that data acquired by this device and technique are correct and can be compared with other similar method led to comparative experiment. Laser vibrometer was selected as comparative device. Experiment setup, progress and conclusion are discussed in this paper.

2. Basic principles of acoustic testing device

Basic principle of acoustic testing is based on fact, that if it was possible to measure sound characteristics of specimen repeatedly with constant conditions, any measurable change in natural frequency value would be labeled as material degradation indication [Rojek et al., (2007)]. Custom-designed testing device was fabricated in order to accomplish this premise. Device description can be divided in two parts. Their functions are following:

– Specimen fasteners - Specimen is hanged up by two needles. This constraint enables specimen's moves with one degree of freedom (rotation round fasteners). Specimen can rock on needles during mechanical impacts on its surface. Fastening scheme is shown in Fig. 1.

– Working part - This part consists of alluminium tube that can be set and locked in four directions (angulary vertical, angulary horizontal, tube's end height and tube's end distance from specimen surface). This arrangement allows testing repeatedly at same conditions. Overall view of the acoustic measurement device is displayed in Fig. 2

[*]Bc. Tomáš Fíla, Ing. Daniel Kytýř Ph.D., Ing. Jaroslav Valach Ph.D.: CTU in Prague, Faculty of Transportation Science, Department of Mechanics and Materials, Na Florenci 25, 110 00 Prague 1, CZ, e-mail: [xfila, kytyr, valach]@fd.cvut.cz
[**]Ing. Shota Urushadze Ph.D., Ing. Martin Šperl P.hD.: Academy of Sciences of the Czech Republic, Institute of Theoretical and Applied Mechanics, v. v. i, Prosecká 809/76, 190 00 Prague 9, CZ, e-mail: [urushadze, sperl]@itam.cas.cz

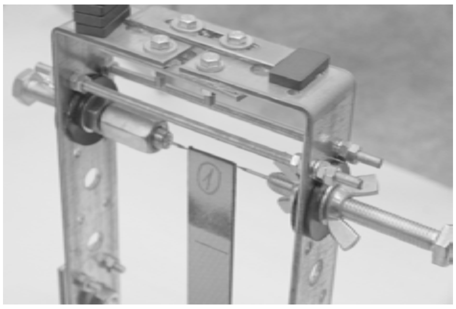

Fig. 1: Fastening of specimen to the acoustic device

Small pellet made of steel is inserted in alluminium tube that provides rigid lead to specimen surface. Sound emitted during impact is recorded by microphone fixed to the device and analyzed. Sound analysis is provided by transformation to get frequency spectrum. Sound is filtered and trimmed to normalized length prior natural frequency peaks determination.

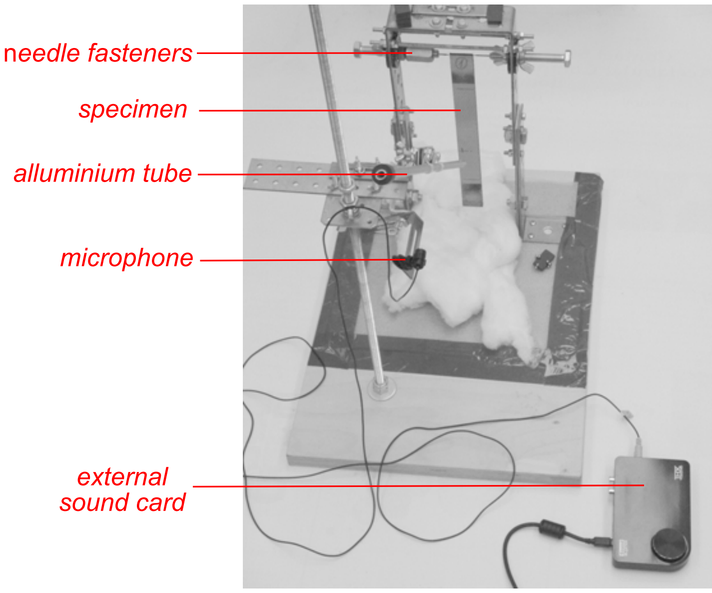

Fig. 2: Acoustic device with fastened specimen and external sound card

3. Material

Specimens of C/PPS composite material were measured. Carbon fiber/polyphenylene sulphide (C/PPS) composite is relatively new material used in aerospace industry and in other hi-tech applications. The matrix, that is made of thermoplastics, represents the main difference to more common composites based on epoxy resin, i.e. thermosets. Young modulus of this composite reaches 400 GPa and material mechanical properties are fully comparable with metal alloys [Kytýř et al., (2011)].

4. Experiment description

Comparative experiment of acoustic measurement and laser vibrometer was done. Laser vibrometer uses principles similar to acoustic measurement and is suitable for measurement of dynamic response and determination of fatique degradation [Pirner & Urushadze, (2002)].

Places appropriate for pellet impacts and for microphone and vibrometer positioning were selected. Pellet has to strike on specimen's surface clearly without any double-clicks or secondary impacts on laboratory desk. Furthermore, impact has to be sufficiently strong to produce enough sound energy for appropriate recording. Constant position of microphone during whole experiment had to be carefully adjusted and strictly adhered. Close distance causes distorted recordings (limitations of sound card sensitivity). By constrast, large distance causes absence of higher frequencies in the spectrum because of their higher attenuation. The setup could not be determined exactly with use of any empirical rules. It had to be adjusted by sensitive measurement and calibration. Aluminium tube gradient was set to 45 degrees and microphone distance was maintained 135 mm from specimen surface during all tests.

Every specimen was marked on three places. First two places served as a designation of impact zone (approximately in the center and on the bottom of specimen). Third place secured constant positioning of laser vibrometer sensor. The points were selected on basis of natural modes calculated using finite element simulation of modal analysis and are shown in Fig. 3.

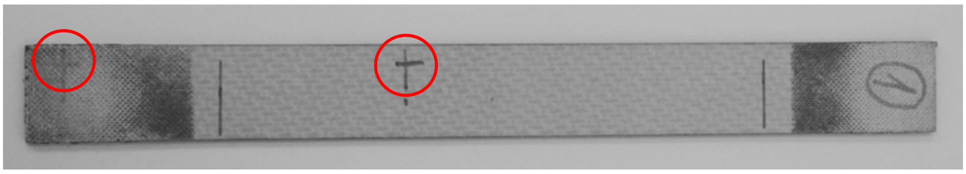

Fig. 3: Measured specimen with designated impact zones

Sound recordings were taken with 96 kHz sampling frequency and 24-bit quality. Vibrometer recordings were taken with 100 kHz sampling frequency and in maximal possible 24-bit quality. Recordings were captured simultaneously for each specimen. Every click had its own ordinal number that allowed data evaluation for both recordings with synchronous time. Specimens were repeatedly measured after degradation by given number of cycles. Measurement were made for 0, 1000, 10 000, 50 000 and 100 000 cycles.

Recorded data were evaluated using MATLAB and DEWESOFT software. Data influented by negative noise (in case of vibrometer floor vibrations and undesirable sound in case of microphone) were excluded from the analysis. The data were then normalized to identical length. This was very important for time synchronization and consequential results comparation. Bandpass filter was applied for elimination of undesirable low and high frequencies (below 50 Hz and above 5000 Hz in this case). Finally, spectral analysis was carried out and natural frequency was determined. Overall experiment setup is shown in Fig. 4.

5. Results

Four specimens (no. 1, 2, 3, 4) were used at the beginning of experiment. Results seemed to be satisfactory after evaluation of first two tests. Therefore, only two specimens (no. 1, 2) were selected to continue in rest of the experiment (due to lack of samples for other research). Unfortunately, specimen no. 2 cracked prematurely with degradation of only 77 000 cycles. This was probably caused by combination of large loading force (75 percent of material strength), high frequency of loading and repeated fastening into fatique testing machine [Meyers & Chawla, (2009)]. For these reasons results of first two tests are presented for all four specimens and last results only for specimen no. 1.

First results consists of evaluation of the first natural frequency that was very easy to be measured by laser vibrometer. Results of the measurement are shown in Tab. 1 (abbreviation M means microphone data and D represents vibrometer data). Values in the table represent mean values of natural frequencies calculated for each click (every specimen was measured ten times). The highest values of standard deviation were 0.47 Hz in case of laser vibrometer and 2.17 Hz in case of microphone. Data in Tab. 1 representing first natural frequency value was not be able to determine degradation rate of specimen.

However, potentional decrease of lower frequencies was hidden in measurement inaccuracy. The decrease was more significant in higher frequencies and could be measured. Natural frequency approximately 3 000 Hz was chosen for determination of the decrease. The frequency was still able to be satisfactory measured by laser vibrometer and its occurrence in vibrometer frequency spectrum was al-

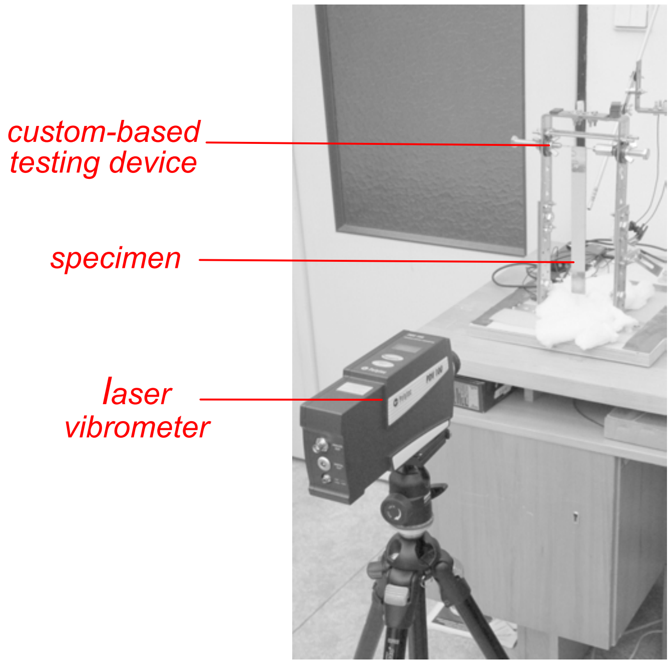

Fig. 4: Acoustic testing device and laser vibrometer during measurement

Tab. 1: First natural frequency results (mean values)

No.	Position	0 cycles		1000 cycles		10000 cycles		50000 cycles		100000 cycles	
		M [Hz]	V [Hz]	M [Hz]	V [Hz]	M [Hz]	V [Hz]	M [Hz]	V [Hz]	M [Hz]	V [Hz]
1	Center	154.857	151	150.25	151	151	152	153.8	151	149.4	151
	Bottom	149.375	151	149.222	151	149	152	148.1	151	146	151
2	Center	146.5	150	148.09	149	148.778	149	151.5	149		
	Bottom	153	150	148.875	150	148.778	149	146.5	149		
3	Center	153.143	151	148.875	150						
	Bottom	149.6	150	148.222	150						
4	Center	147.875	149	146.333	149						
	Bottom	149.6	149	144.44	149						

most regular. Characteristic frequency spectrum measured by vibrometer and by microphone is shown in Fig. 5.

Mean values of selected natural frequency near 3 000 Hz are shown in Tab. 2 and Tab. 3 (abbreviation C means center mark on specimen surface, B represents bottom mark). Its decrease values are shown in Tab. 4. Graphical summary of the data is displayed in Fig. 6.

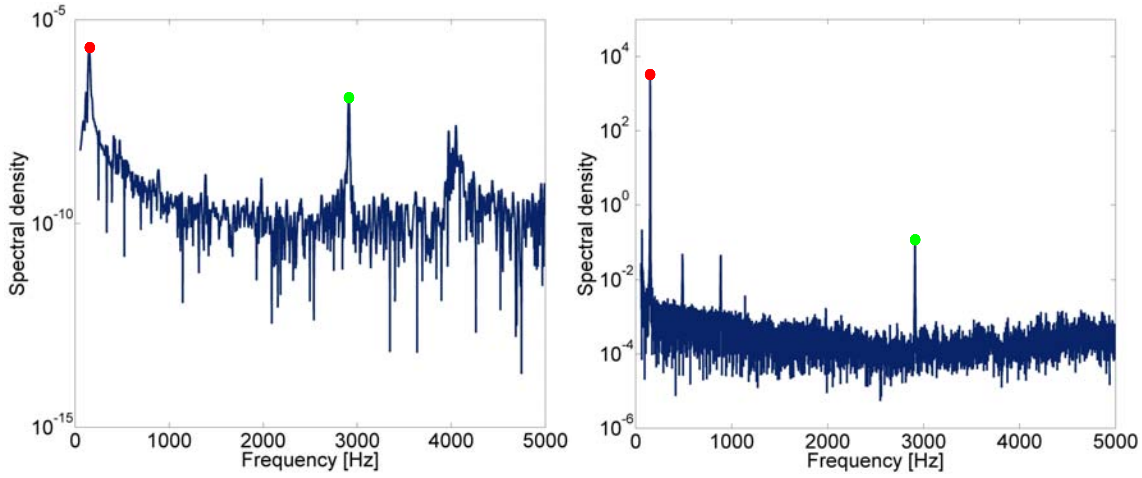

Fig. 5: Frequency spectrum measured by microphone (left) and by vibrometer (right) - (specimen no. 2, 1000 cycles, click no. 9). Red dot represents first natural frequency peak, green dot represents natural frequency peak used for evaluation of degradation.

Tab. 2: Selected natural frequency (approx. 3000 Hz) results measured by vibrometer (mean values)

No.	0 cycles		1000 cycles		10000 cycles		50000 cycles		100000 cycles	
	C	B	C	B	C	B	C	B	C	B
	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]
1	2960	NaN	2940	2941	2933	2933	2900	2900	2886	NaN
2	2933	2934	2909	2909	2899	2899	2881	2881		
3	2933	NaN	2917	2916						
4	2921	NaN	2900	2901						

Tab. 3: Selected natural frequency (approx. 3000 Hz) results measured by microphone (mean values)

No.	0 cycles		1000 cycles		10000 cycles		50000 cycles		100000 cycles	
	C	B	C	B	C	B	C	B	C	B
	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]
1	2959	2959	2941	2941	2930	2930	2901	2901	2887	2886
2	2934	2931	2909	2910	2898	2897	2881	2881		
3	2932	2931	2916	2916						
4	2920	2922	2901	2899						

Tab. 4: Mean values of natural frequency decrease (approx. 3000 Hz)

No.	1000 cycles		10000 cycles		50000 cycles		100000 cycles	
	M	V	M	V	M	V	M	V
	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]	[Hz]
1	-18	- 19.5	-29	-27	-58	-60	- 72.5	- 74
2	-23	- 24.5	-35	-34.5	-51.5	-52.5		
3	-15.5	- 16.5						
4	-21	- 20.5						

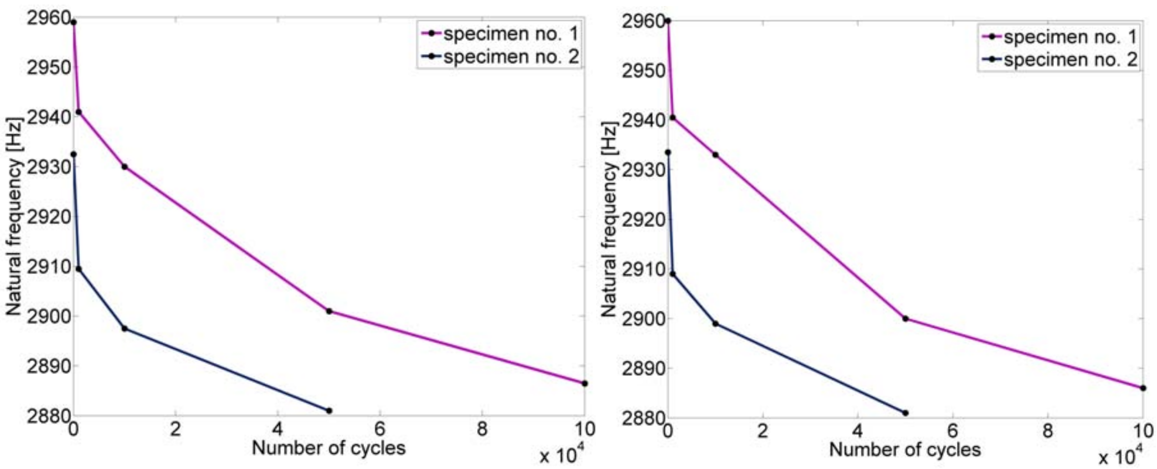

Fig. 6: Frequency decrease measured by microphone (left) and by vibrometer (right)

6. Conclusions and discussion

Correlation between natural frequency value and number of cycles of the specimen was confirmed. Data measured using acoustic method are fully comparable with data measured by laser vibrometer. Differences of spectral density peaks position (natural frequencies) reached repeatedly maximally 5 Hz. Absolute error of natural frequency determination remained constant through whole frequency spectrum. However, natural frequency decrease could not be determined in case of first natural frequency. The decrease was too small to be measured at lower frequencies (in this case up to 1000 Hz). The decrease was able to be determined at higher natural frequency (about 3000 Hz) where measurement using laser vibrometer began to be more complicated because of higher level of noise. Measurement by acoustic method at these frequencies did not produce any problems and results reached high accuracy. To conclude, the acoustic measurement using custom-designed experimental device proved ability to evaluate material degradation. This was proved in terms of precision, reproducibility and reliability by the comparative experiment.

Acknowledgments

The research has been supported by RVO: 68378297, by the Grant Agency of the Czech Republic (grant No. P105/10/2159), Grant Agency of the Czech Technical University in Prague (grant No. SGS12/205/OHK2/3T/16) and Ministry of Education and Sports (research plan No. MSM6840770043).

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