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VIBRATION AND DAMAGE DETECTIONS OF COMPOSITE BEAMS WITH DEFECTS

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Abstract

In this work, the geometrically nonlinear vibrations of composite beams subjected to harmonic loading and thermal changes are used to study the sensitivity of selected vibration response parameters to the presence of damage (delamination). The damage detection criterion formulated earlier for non-heated plates, based on analysing the points in the Poincaré sections of the damaged and healthy plate, is modified and tested for the case of beams additionally subjected to elevated temperatures. The importance of the actual temperature in the process of damage detection is shown.

Key words: *beams, nonlinear vibrations, delamination detections, numerical simulations, Poincaré maps.*

INTRODUCTION

Structures made of advanced composites are widely used in many modern branches of industry due to advantageous balance among their weight, stiffness and strength. However, the mechanical properties of composite laminates can be significantly reduced by damage, which can occur due to fibre rupture, matrix cracking, debonding, transverse-ply cracking and delamination. Delamination, in particular, is a major problem in multilayer composite structures and may be difficult to detect experimentally using existing methods.

Vibration-based structural health monitoring (VSHM) methods are widely used for damage detection. They are based on the fact that damage will alter the stiffness, mass or energy dissipation properties of the structure which in turn will alter its measured vibration response.

Most of the previous efforts of researchers on VSHM were directed towards methods based on linear modal analysis [1-3]. One of the main problems with these methods comes from the fact that in general damage starts as a local phenomenon and does not necessarily affect significantly the modal characteristics of the structure. Frequency shifts and mode shape changes due to damage (delamination) have been found [4] and are an indicator of damage or structural changes that might be taken into account. However, it seems that the lower order resonance frequencies and mode shapes are not always very sensitive to damage, except for cases with very large damage [3,5,6]. To address some of the above mentioned problems, some authors started to study recently the possibility to employ measured time series of the structure response and non-linear dynamics theory. Most of the studies in this field are devoted to the extraction of damage sensitive features from the structural vibration response. In [7] the authors use the beating phenomenon for damage detection purposes. In [8] new attractor-based metrics are introduced as damage sensitive features.

In authors' previous works [9 and 10] a numerical approach to study the geometrically non-linear vibrations of rectangular plates with and without damage was developed. A damage index and a method for damage detection and location, based on the Poincaré map of the response, have been proposed. The suggested damage assessment method shows good capability to detect and localize damage in plates. The main objectives of this study are twofold: (i) to study the influence of defects on the dynamic characteristics of the laminated composite beams and on their geometrically nonlinear dynamic response; (ii) to test the criteria for identification of defect (delamination) in composite beams proposed in [9] and [10] by analysing the Poincaré map of the vibration response. The influence of the temperature on the damage detection process will be also briefly commented.

1. THEORETICAL MODEL

The object of investigation is a symmetrically laminated beam with length l and width b, having N_l number of layers, symmetrically disposed around the mid-axis (Fig. 1).

The thickness of k-th layer is $h^{(k)}$ (located at $z^{(k)}$ distance from the mid-axis), its Young's modulus $E^{(k)}$, Poison's ratio $\nu^{(k)}$, density $\rho^{(k)}$ and the coefficients of thermal expansion $\alpha_T^{(k)}$. The beam is subjected to transverse load $p(x,t)$ and to temperature variation ΔT (with respect to a reference temperature) leading to large amplitude vibrations. In general, the distribution of ΔT can be assumed as non-uniform along beam's thickness. The geometrically nonlinear version of the Timoshenko beam theory is used to model the beam behaviour, so that the shear deformation and rotary inertia are taken into account. At each point of the mid-axis of the beam, the displacements in the x and z directions are denoted by u and w, respectively. $\psi_x(x,t)$ is the angle of rotation of the normal of the cross-section to the beam mid-axes.

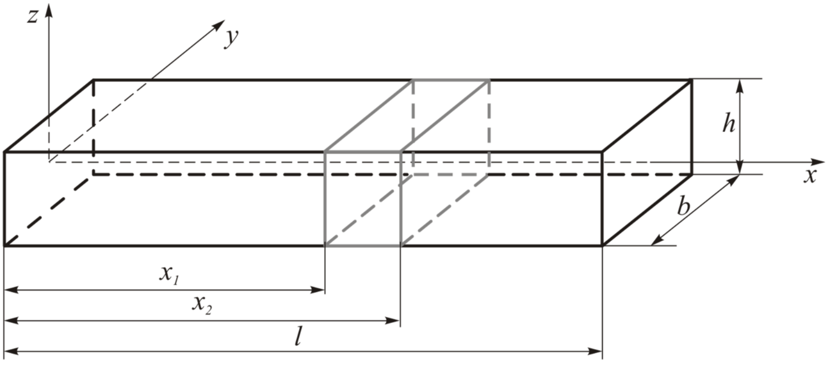

Figure 1. Geometry of the beam. x_1 and x_2 denote the beginning and the end of damaged area

The governing equations for a beam with symmetric lay-ups subjected to mechanical and thermal loading can be written in the following form [11, 12]:

$$\frac{\partial}{\partial x}\left\{A_{11}\left[\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2-\alpha_T\Delta T\right]\right\}=0 \tag{1}$$

$$
\begin{aligned}
&-\frac{\partial}{\partial x}\left(D_{11}\frac{\partial \psi}{\partial x}\right)+k^s A_{55}\left(\frac{\partial w}{\partial x}-\psi\right)-RI\frac{\partial^2\psi}{\partial t^2}=0\\
&k^s\frac{\partial}{\partial x}\left[A_{55}\left(\frac{\partial w}{\partial x}-\psi\right)\right]+A_{11}\left[\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2\right]\frac{\partial^2 w}{\partial x^2}-A_{11}\alpha_T\Delta T\frac{\partial^2 w}{\partial x^2}-RH\frac{\partial^2 w}{\partial t^2}=-p
\end{aligned}
\tag{1}
$$

Here by A_{11}, A_{55} and D_{11} are denoted the well know laminate stiffness coefficients (see for example [11]):

$$
\begin{aligned}
&A_{11}=b\sum_{k=1}^{N_l}E^{(k)}(z^{(k)}-z^{(k-1)})=b\sum_{k=1}^{N_l}E^{(k)}h^{(k)}\\
&A_{55}=b\sum_{k=1}^{N_l}G^{(k)}(z^{(k)}-z^{(k-1)})=b\sum_{k=1}^{N_l}G^{(k)}h^{(k)}\\
&D_{11}=\frac{b}{3}\sum_{k=1}^{N_l}E^{(k)}(z^{(k)^3}-z^{(k-1)^3}),\quad \alpha_T=\sum_{k=1}^{N_l}\alpha_T^{(k)}
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
&RI=b/3\sum_{i=1}^{N_l}\rho^{(i)}\left(z^{(i)3}-z^{(i-1)3}\right)\\
&RH=b\sum_{i=1}^{N_l}\rho^{(i)}h^{(i)},
\end{aligned}
$$

In Eqns (1) the well know assumption that the longitudinal inertia forces can be neglected is accepted.

The solution of the problem is based on the numerical approach which is similar to the one developed in [9 and 13].

2. DAMAGE IDENTIFICATION TECHNIQUE

The identification of damage is based on the criterion suggested in [9] and [10].
Based on these works the following damage index is suggested:

$$
I_i^d=\frac{\left|S_i^u-S_i^d\right|}{S_i^u},
$$

$$
S_i^u=\sum_{j=1}^{N_p-1}\sqrt{\left(w_{i,j+1}^u-w_{i,j}^u\right)^2+\left(\dot{w}_{i,j+1}^u-\dot{w}_{i,j}^u\right)^2},\ S_i^d=\sum_{j=1}^{N_p-1}\sqrt{\left(w_{i,j+1}^d-w_{i,j}^d\right)^2+\left(\dot{w}_{i,j+1}^d-\dot{w}_{i,j}^d\right)^2}
\tag{3}
$$

In the above equations i=1,2…N, where N is the number of nodes, N_p is the number of points in the Poincaré map for each node and $(w_{ij}^u,\dot{w}_{ij}^u)$ and $(w_{ij}^d,\dot{w}_{ij}^d)$ denote the j^{th} point on the Poincaré maps of the undamaged and the damaged states, respectively. Damage index described above depends on the location of the point on the beam's x-axis and consequently it is a function of the beam coordinate x. One can expect that the maxima of the curve $I^d(x)$ will represent the locations of the damage, i.e. $I_{\max}^d(x_d)=\max_i\left\{I_i^d\right\}$. The damage criterion based on this index presumes setting a threshold value T^d for the damage index.
Thus, if the following criterion is fulfilled:

$$
I^d(x,\Delta T)>T^d \tag{4}
$$

one can conclude that the beam is damaged. Moreover, the sets of points (x) for which Eq. (3) is fulfilled, form the damaged area (areas). It is important to note that the temperature changes should also be taken into account. For this reason the damage index defined by Eqs. (3) is calculated at equal values of ΔT for the healthy and damaged beams.

3. RESULTS AND DISCUSSIONS

The study focuses on delamination of a symmetric cross-ply laminated beam composed of 10 orthotropic layers, each 0.25 mm thick. On the basis of real composite material characteristics effective properties were calculated: E_{ef}=41.92 GPa, ν_{ef}=0.32991. The defect was modelled by prescribing to a small part of the beam (10 % of the beam length) reduced rigidity =25.15 GPa. The beam was discretized by 40 linear beam finite elements. The aim of the following examples is to study the dynamic response of composite beams with and without defects, to test numerically the capability of the procedure for damage detection to detect and localize damage (delamination) and then to check it experimentally. Numerical test were performed for fully clamped and cantilever beams. The numerical results shown here concern clamped beams. For cantilevers the results were similar.

The numerical modal analysis of the beams performed by FE method shows, that the introduced defect causes very small changes in the natural frequencies (0.45% decreasing of the first natural frequency in the case of clamped beam). The influence of the defect on eigen frequency was a little higher for the case of the cantilever beam. Obviously such small changes cannot be used as an indicator for damage.

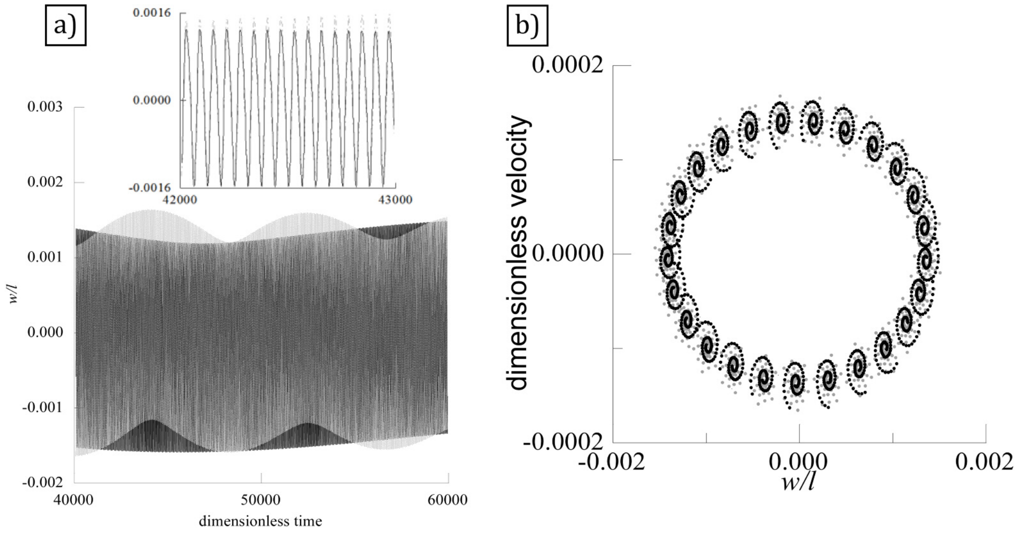

Figure 2. Time-history diagram (a) and Poincaré map (b) of the response of the beam centre of healthy (black colour) and damaged (grey colour) beam. ω_e= 5665 rad/s

Then the forced response of the beam subjected to a harmonic loading is tested. The beam is subjected to two kind of loadings: (a) excitation with frequency of excitation equal (or very close) to the first natural frequency of the beams $\omega_e=\omega_1$ and (b) excitation equal to the half of the first natural frequency, i.e. $\omega_e=\omega_1/2$.

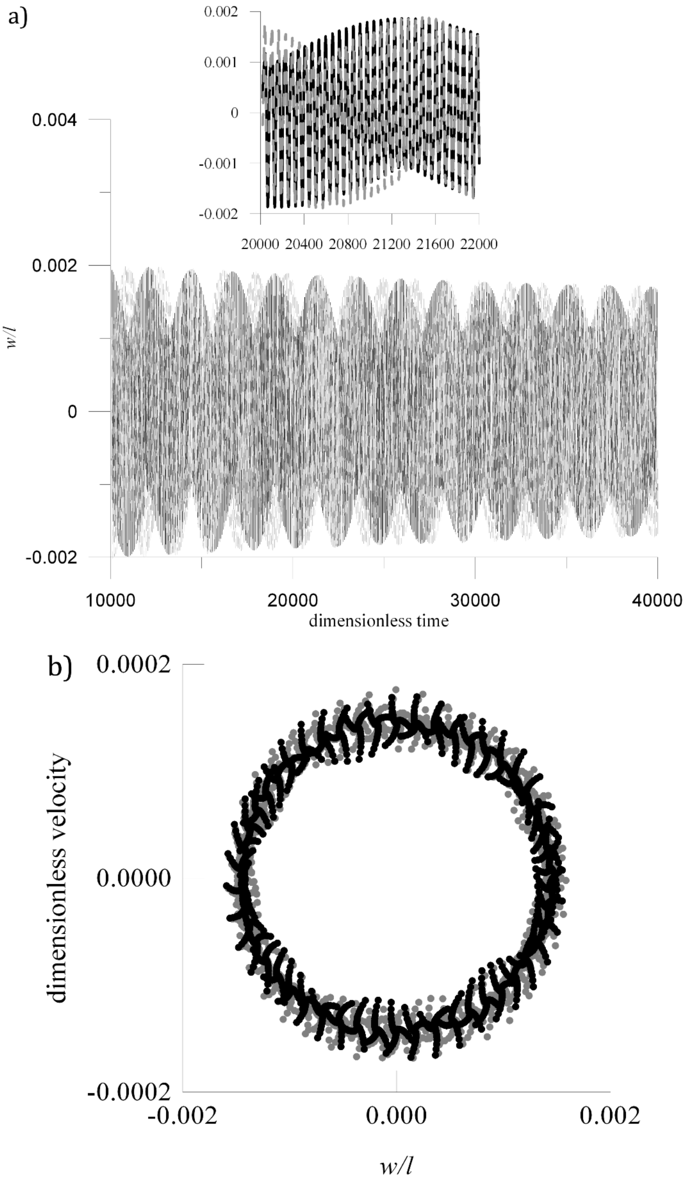

Fig. 3. Time-history diagram (a) and Poincaré map (b) of the response of the beam centre of healthy (black colour) and damaged (grey colour) beam. ω_e= 5665 rad/s. ΔT=10 K

In the cases when the excitation frequency is close to the first natural frequency of the beam a beating phenomenon occurs. From the time-history diagrams (see Fig. 2a) it can be observed that the considered damage leads to some changes in the period of beating and small changes in the amplitude of responses .The influence of damage on the Poincaré maps can be seen in Fig. 2 b.

Then the same computations were performed but the beams were additionally subjected to a thermal loading ΔT=10 K. The thermal loading lead to changes in the time- history diagrams and Poincaré maps of the healthy and damged beams as it can be seen in Fig. 3.

In Figs 4 a-b time history diagrams at excitation frequency almost equals to the first natural frequency of the healthy beam (ω_e= 11330 rad/s) are shown. From these time-history diagrams it can be concluded that the considered damage leads to small changes in the amplitude of responses but the time histories undergo significant changes in the period of beating . It can be seen that at the very beginning (t=0) the responses almost coincide. Then the phase shifts and the differences between the responses increase (see small figures inserted in the main figures where the time histories are shown for a very short period of time).

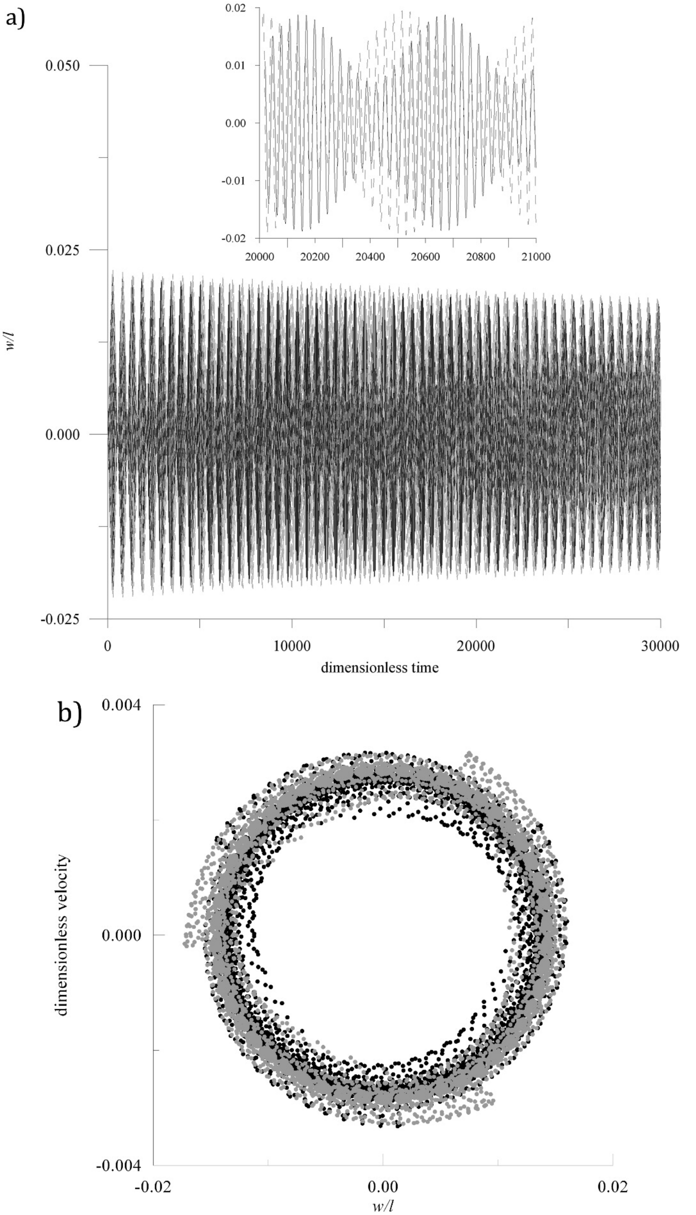

Figure 4. Time history diagrams (a) and Poincaré maps (b) for the response of the beam centre. p=50 N, ω_e= 11330 rad/s. Black line – healthy beam; gray line –damaged beam

For all cases the damage indexes were computed by using formulas (3). The damage index for the considered cases of damage show very precisely the location of the damage. The elevated temperature in the considered case increase the influence of damage and the values of the damage index.

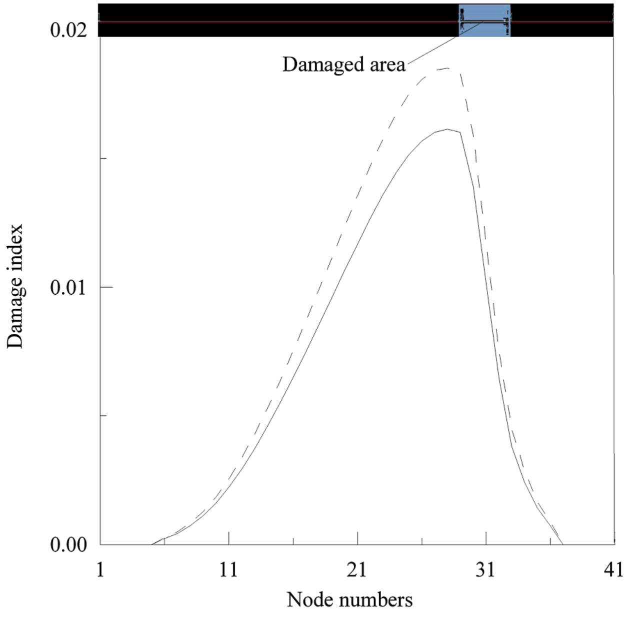

Figure 5. Damage index for a beam subjected to harmonic mechanical loading with an amplitude p=50 N, excitation frequency ω_e= 5665 rad/s for two different temperatures. Solid line ΔT=0 K, dashed line ΔT=10 K.

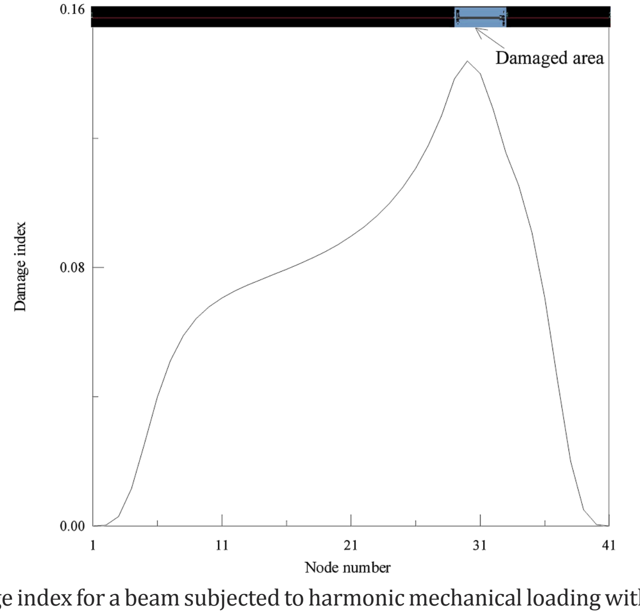

Figure 6 Damage index for a beam subjected to harmonic mechanical loading with an amplitude p=50 N, excitation frequency 11330 rad/s

4. EXPERIMENTAL TEST

The preliminary tests for the applicability of the suggested damage detection criterion were performed.

Laminate composite beams were considered. Two different cantilever beams were fixed at one end in a shaker clamp. A special clamp was designed in order to model precisely the clamped boundary conditions. By using this clamp the first three measured and computed natural frequencies were practically identical. The length of the samples was 93mm counting from the clamp. The sequence of glass-epoxy plies was the following: [+45º/-45º/+45º/-45º/0º]s (10 layers). The laminates were fabricated by a "prepreg" technology. Single preimpregnated ply had a thickness of 0.255mm. Fiberglass had a form of roving tapes. One composite beam was called healthy as it had no delaminated area. The damaged beam had a delaminated area located at 40mm from the clamp. The length of the delamination (along the beam axis) was 10 mm. Delamination (damage) was artificially introduced in the mid-plane of the laminate by a PTFE foil (0.02mm thick) on the whole width of the beams. It was found by three point bending test that this delamination leads to reduction of the Young's modulus in the damaged area by 40 %. Vision Research's Phantom v9.1 high speed camera was used for observation and measurement of the composite beams responses. The camera provides 14-bit image depth and 1016 frames per second at full resolution (1632x1200 pixels). The camera is controlled by a PC with a special software "TEMA".

Each composite beam was clamped at one of its ends (cantilever beam) and was subjected to harmonic kinematic excitation with frequency 123 Hz by "TiraVib" TV 50101 shaker. The vibration isolators of the shaker frame save the camera from undesired vibration of the laboratory foundation.

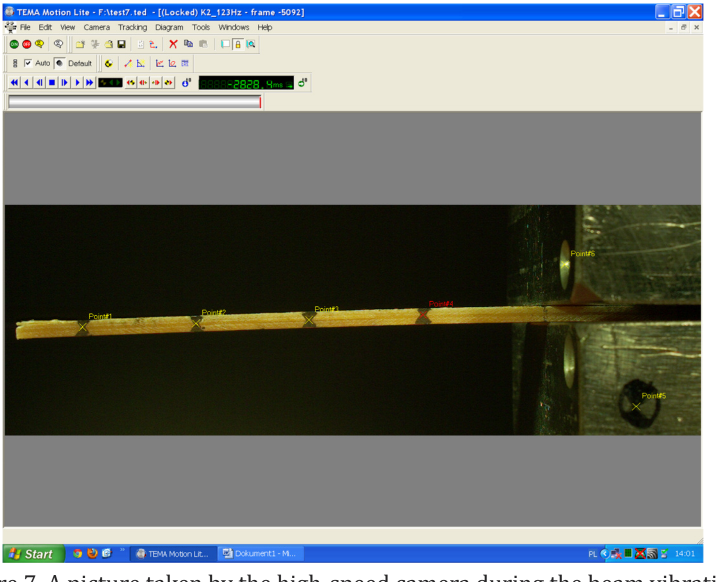

Figure 7. A picture taken by the high-speed camera during the beam vibrations

In Figure 7 a picture form the high speed camera is shown. The recorded values of the displacements and the velocity were proceeded in order to obtain the Poincaré maps for healthy and damaged beams and then the damage index was computed. The results are plotted in Figure 8.

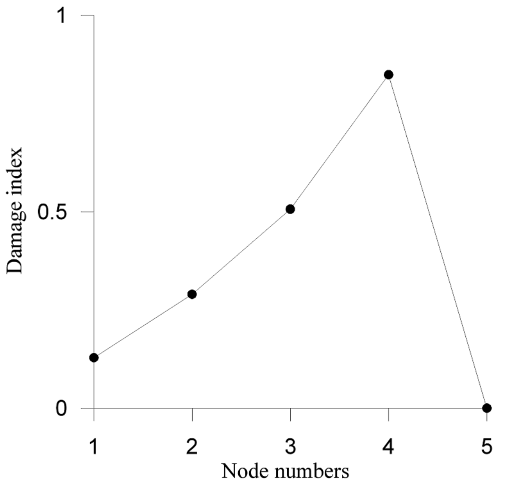

Figure 8. Damage index along the beam length obtained experimentally.

The vibration response was measured in four points only (see Fig. 7) but the results show a good prediction of the damage. These experimental results should be considered as a preliminary and we don't make a general conclusions only on the base of these results. A new tests with an improved experimental set up will be performed and more results for composite structures with different damages will be tested in order to estimate the sensitivity and applicability of the method.

CONCLUSIONS

Computed time-domain responses have been used to analyse the behaviour of either intact or damaged beams. Based on these analyses a conception of damage index developed previously was adapted and applied for damage detection and location. It was demonstrated that damage can influence substantially the time-domain response of a beam despite its very small influence on the beam natural frequencies.
The preliminary experiments confirmed the applicability of the method.

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REFERENCES

[1] Zou, Y., Tong, L., Steven, G. P., 2000, Vibration based model- dependent damage (delamination) identification and health monitoring for composite structures – a review. Journal of Sound and Vibration 230(2), 357-378.
[2] Verboven, P., Parloo, E., Guillaume, P., Overmeire, M. Van, 2002, Autonomous structural health monitoring—part I: modal parameter estimation and tracking. Mechanical Systems and Signal Processing, 16, 637–657.

[3] Doebling, S.W., Farrar, C.R., Prime, M.B. , Shevitz, D.W., 1996, Damage identification and health monitoring of structural systems from changes in their vibration characteristics: A Literature Review, Report LA- 12767-MS, Los Alamos National Laboratory, NM, USA.
[4] Shen, M.H., Grady, J. E., 1992, Free Vibrations of Delaminated Beams. AIAA Journal 30 (5), 1361- 1370.
[5] Banks, H.T. , Inman, D.J., Leo, D.J. , Wang, Y., 1996, An experimentally validated damage detection theory in smart structures. Journal of Sound and Vibration 191, 859-880.
[6] Reddy, A.D., Rehfield, L.W., Haag, R.S., 1984, Influence of prescribed delaminations of stiffness-controlled behaviour of composite laminates, Effects of Defects in Composite Materials, ASTM STP 836, American Society for Testing and Materials, 71-83.
[7] Cattarius, J. , Inman, D.J. , 1997, Time domain analysis for damage detection in smart structures. Mechanical Systems and Signal Processing 11, 409-423.
[8] Todd., M., Nichols, J. M., Pecora, L. M., Virgin, L., 2001, Vibration-based damage assessment utilizing state space geometry changes: local attractor variance ratio. Smart Materials and Structures, 10, 1000-1008.
[9] Manoach, E. Trendafilova ,I. Large Amplitude Vibrations and damage detection of rectangular plates J. Sound & Vibrations , 315 (3), pp. 591-606 (2008).
[10] Trendafilova, I., Manoach, E. Vibration Based Damage Detection in Plates by Using Time Series Analysis. Mech. Systems and Signal Processing 22 (2008) 1092-1106.
[11] Altenbach, H., Altenbach, J., Kissing, W., 2001, Structural Analysis of Laminate and Sandwich Beams and Plates. An introduction into the mechanics of composites. Lubelskie Towarzystwo Naukowe, Lublin.
[12] Reddy, J.N., 2003, Mechanics of Laminated Composite Plates and Shells: Theory and Analysis. (second edition) CRC press.
[13] Manoach, E., Ribeiro P., 2004, Coupled, thermoelastic, large amplitude vibrations of Timoshenko beams. International Journal of Mechanical Sciences, 46, 1589-1606.

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DRGANIA A WYKRYWANIE USZKODZENIA W BELKACH KOMPOZYTOWYCH

Streszczenie

W niniejszej pracy omówiono wykorzystanie drgań nieliniowych belek kompozytowych, poddanych wymuszeniom harmonicznym i obciążeniom cieplnym, do celów wykrywania uszkodzenia (delaminacji). Przestudiowano czułość wybranych parametrów opisujących dynamiczną odpowiedź układu na obecność wady w strukturze. Kryterium uszkodzenia, sformułowane we wcześniejszych pracach autorów dla niepodgrzewanych płyt, oparte na porównywaniu map Poincaré dla płyty zdrowej oraz uszkodzonej, zostało zmodyfikowane i przetestowane na strukturach belkowych. W modelach numerycznych belek zastosowano dodatkowo działanie podwyższonej temperatury. Pokazano w ten sposób istotne znaczenie temperatury na proces wykrywania uszkodzenia. Zaprezentowano także pierwsze wyniki badań doświadczalnych.