LABORATORY TESTS OF THE SHM SYSTEM BASED ON MODAL FILTRATION

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Summary

A modal filter is an excellent indicator of damage detection, with such advantages as low computational effort due to data reduction, ease of automation and low sensitivity to environmental changes [4, 5]. The damage detection method has been already described and tested numerically by the authors [7]. To apply it in a real SHM system, the measuring diagnostic unit has been designed and built. The paper briefly describes the SHM system assumptions and presents results of its laboratory testing. The test program included series of measurements on undamaged object in different ambient temperatures and with new sensor positioning. The main part of measurements, however was focused on analyses of different damage scenarios. Additionally selected cases ware recorded parallel by the commercial measuring system for comparison.

Keywords: modal filter, damage detection, laboratory testing

BADANIA LABORATORYJNE UKŁADU MONITORINGU BAZUJĄCEGO NA FILTRACJI MODALNEJ

Streszczenie

Filtr modalny jest bardzo dobrym wskaźnikiem wykrywającym uszkodzenie, posiadającym takie zalety jak niewielkie wymagania obliczeniowe, łatwość automatyzacji procedury i niska wrażliwość na zmiany warunków zewnętrznych [4,5]. Metoda ta była już uprzednio opisywana i testowana symulacyjnie przez autorów [7]. Aby zastosować go w rzeczywistym układzie monitoringu, zaprojektowano i zbudowano urządzenie diagnostyczno pomiarowe. W artykule krótko opisano założenia konstrukcyjne systemu, a następnie pokazano wyniki jego badań laboratoryjnych. Program testów obejmował serię pomiarów na obiekcie bez uszkodzenia ze zmienną temperaturą otoczenia i przy powtarzanym rozkładaniu czujników. Główna część pomiarów dotyczyła różnych scenariuszy uszkodzenia. Dodatkowo dla celów porównawczych niektóre badania były rejestrowane równolegle przez komercyjny system pomiarowy

Słowa kluczowe: filtr modalny, wykrywanie uszkodzeń, badania laboratoryjne

1. INTRODUCTION

The vibration based methods are one of the widest described damage detection methods [1]. One of the techniques from this group is an application of modal filtration to the object characteristics. A modal filter is a tool used to extract the modal coordinates of each individual mode from a system's output [2, 3]. It decomposes the system's responses into modal coordinates, and thus, on the output of the filter, the frequency response with only one peak, corresponding to the natural frequency to which the filter was tuned, can be obtained. Very interesting way of using modal filtering to structural health monitoring was presented by Deraemaeker and Preumont in 2006 [4] Frequency response function of an object filtered with a modal filter has only one peak corresponding to the natural frequency to which the filter is tuned. When a local change occurs in the object – in stiffness or in mass (this mainly happens when damage in the object arises), the filter stops working and on the output characteristic other peaks start to appear, corresponding to other, not perfectly filtered natural frequencies. On the other hand, global change of entire stiffness or mass matrix (due to changes in ambient temperature or humidity) does not corrupt the filter and the filtered characteristic has still one peak but slightly moved in the frequency domain. The method apart from the earlier mentioned advantages, which results from its low sensitivity to environmental conditions has very low computational cost, and can operate in autonomous regime. Only the final data interpretation could be left to the personnel. This interpretation is anyhow not difficult and it does not require much experience. Another advantage of the method results from the fact that it can operate on the output only data.

Method described above was in 2008 extended to damage localization by K. Mendrok [5]. The idea for extension of the method by adding damage localization, bases on the fact, that damage, in most of the cases, disturbs the mode shapes only locally. That is why many methods of damage localization use mode shapes as an input data. It is then possible to divide an object into areas measured with use of several sensors and build separate modal filters for data coming from these sensors only. In areas without damage, the shape of modes does not change and modal filter keeps working – no additional peaks on the filter output. When group of sensors placed near the damage is considered, mode shape is disturb locally due to damage and modal filter does not filters perfectly characteristics measured by these sensors.

Because the method looks promising it can be applied in a real SHM system, however it first needs to be extensively tested both on numerically generated data and next on the laboratory test stand. The simulation verification was already performed and its results are described in [7]. General conclusions from these analyses can be summarized as follows. The following cases has been considered: verification of the method sensitivity to damage location, inaccuracy of sensor location in the consecutive experiments, measurement noise and changes in ambient conditions, such as temperature and humidity. Additionally the applicability of the method was examined for very complex structure – rail viaduct with elements made of steel, concrete, wood and soil. After these numerical tests it can be stated that the method detects damage with good sensitivity but users have to be aware that there is a significant impact of the accuracy of the sensor location in the subsequent measurements on the results of modal filtration. Also the temperature has some impact on the results, however it is lower than in other vibration based methods. In this paper authors describe the results of the second stage of method testing – the laboratory measurements results.

2. GENERAL ASSUMPTIONS OF THE MONITORING SYSTEM

As it was showed in the previous section the modal filtration can be a great tool for damage detection and further for structural health monitoring. For this reason the authors decided to implement as a practical measuring – diagnostic system. Its main assumption was that it should be completely independent. It means that the potential user should be able to perform full diagnostic procedure without necessity of usage of any additional measuring device or software. To fulfill above requirement the original 16-teen channel measuring – diagnostic unit MDU was design and the dedicated modal analysis and modal filtration software was written. Generally the system composed of both hardware and software is supposed to work in one of the three modes:

I. Operation in dynamic signal analyzer mode for the purposes of the modal testing. In this mode the modal filter coefficients are estimated for the reference structure.

II. Operation in diagnostic mode:
- Acceleration / displacement of vibration measurements,
- Selected characteristics estimation (FRFs PSDs),
- Modal filtration of the above characteristics,
- Damage index calculation,
- Visualization of the filtered characteristics,

III. Operation in monitoring mode:
- Periodical acceleration / displacement of vibration measurements,
- Selected characteristics estimation (FRFs PSDs),
- Modal filtration of the above characteristics,
- Damage index calculation,
- Reporting of the object to the central unit.

3. MEASURING DIAGNOSTIC UNIT

From technical point of view the diagnosis process is divided into a few basic steps:
- simultaneous synchronous acquisition of analog signal (converted into digital domain) from 16 channels.
- digital signal processing applied to measured signal
- output processing results

The block diagram of MDU is described in Figure 1.

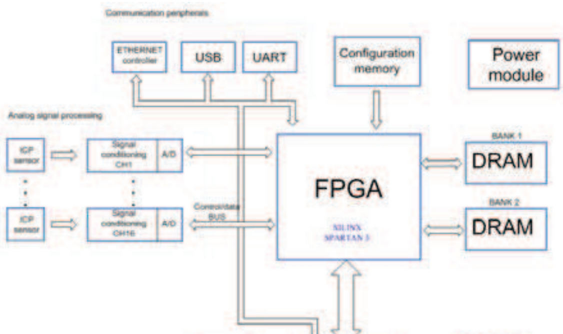

Fig. 1. Block diagram of design device

Diagnostic device contains of two fully independent and connected with each other modules: CPU and FPGA modules. The CPU module is included for control purposes – it implements user interface using some peripheral devices like keyboard, LCD display and communication peripherals. Using this interface it is possible i.e. to set gain or select required analog filter in each of 16 analog signal processing modules, or to start diagnostic process.

The FPGA module contains all logic modules needed for implementation of required digital signal processing. It is “seen” by CPU module as another peripheral device which can execute commands (like

start data processing command) and send processing results.
The MDU can be accessed via Ethernet or USB, which is needed in system calibration phase, or to read remotely processed results.
Analog signal processing module is shown in Figure 2.

Fig. 2. Analog part of the circuit measuring

The input analog signal is delivered from ICP accelerometer sensors mounted on examined object. ICP signal standard is based on 4-20 mA current signal transmission standard, which main advantage is the ability of transmitting signal (with 1 kHz frequency band wide) without any distortion at ranges of 100 m and more.

4. DEDICATED SOFTWARE

The main goal of the software written for the described SHM system is the estimation of the modal filter coefficients. For this purpose, the application provides the following functionalities:

- Geometrical model definition of the tested object.
- Measurement points definition, namely the assignment of specific points of a geometric model to the sensors placed on an object.
- Execution of measurement and presentation of the results (time histories, PSD, FRF and coherence), and data archiving.
- Execution of modal analysis by:
  - calculation of stabilization diagram,
  - estimation and visualization of mode shapes for selected poles,
  - estimation of modal filter coefficients and visualization of filtration results.

The application was created in the .Net Framework 3.5 environment with use of additional external libraries:
- Developer Express v9.1 (tables and standard application controls)
- Steema TeeChart for .Net v3 (charts)
- Intel IPP (signal spectrum calculation)

All calculations related to the modal analysis are performed by the Matlab engine. The application provides the ability to debug these functions from Matlab level. For this reason, at the user-specified location, mat-files are stored that contain input parameters for the appropriate Matlab functions.

In Figure 3 the graphical user interface of described software allowing for impulse modal testing and mode shape visualization control is presented.

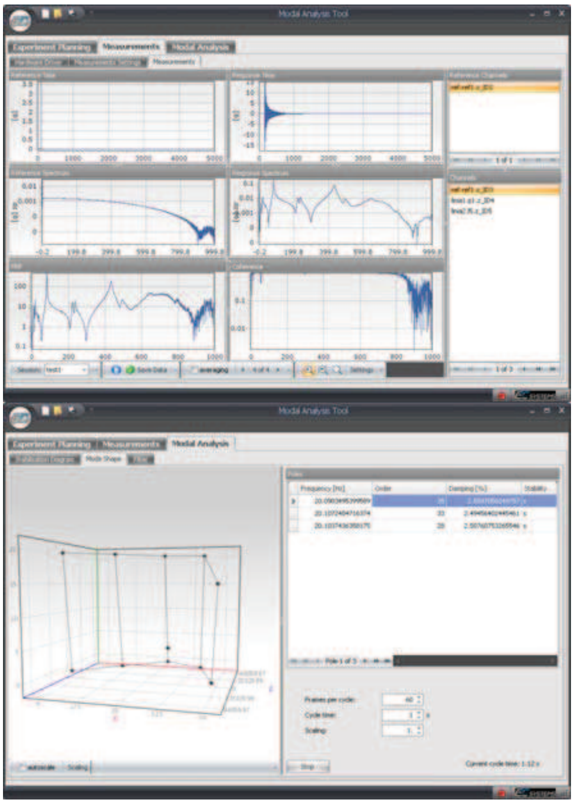

Fig. 3. GUI of described software

It was assumed that in order to fluently visualize the mode shapes it is necessary to refresh with a minimum speed of 30 fps. There are not available on the market sufficiently effective controls to allow the visualization and animation of 3D models with the assumed speed. Therefore, implementation of such control was done by using the XNA environment. The control uses a graphics accelerator which allows for refresh at 60 fps at 10,000 points of geometrical model.

5. PROGRAM OF TESTS

The tested object was a cantilever beam made of aluminum alloy. Its dimensions amounted 50 x 4 x 1000 mm. The object was divided into 9 measuring points equally spaced every 100 mm, placed along the longitudinal axis of the beam. The points were designated blk:1, …, blk:9 starting from the top. The beam was excited with the electro-dynamic shaker attached via stinger in point blk:1. The excitation force was measured together with the acceleration of vibrations by the impedance head. In remaining points the acceleration of vibrations were measured by piezoelectric accelerometers. In Figure 4 the measuring stand is presented.

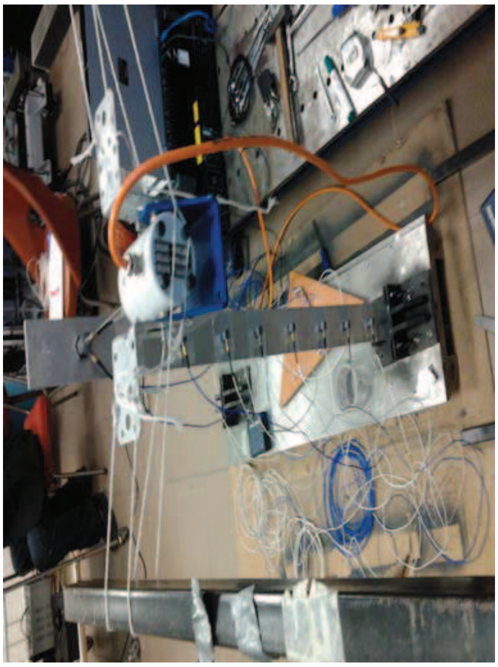

Fig. 4. Photo of the laboratory stand

The excitation signal had a band noise character with frequency range 0.1 – 512 Hz. The sampling frequency was set at 1024 Hz, the length of recorded time histories amounted 200 s.

The following measurements were performed:

- undamaged beam, ambient temperature 20^{O} C, measuring system – Scadas Mobile / TestLab 8A,
- undamaged beam, ambient temperature 20^{O} C,
- undamaged beam, ambient temperature 20^{O} C,
- undamaged beam, ambient temperature 20^{O} C, sensors reassembled,
- undamaged beam, ambient temperature 31^{O} C,
- damaged beam (added mass 4 g in point blk:5), ambient temperature 20^{O} C,
- damaged beam (added mass 4 g in point blk:9), ambient temperature 20^{O} C,
- damaged beam (added mass 15 g in point blk:5), ambient temperature 20^{O} C,
- damaged beam (added mass 15 g in point blk:9), ambient temperature 20^{O} C,

All the measurements except the first one were performed with use of the tested measuring-diagnostic unit. All the results were evaluated with use of damage index proposed in [6]:

$$DI = \frac{\int_{\omega_s}^{\omega_f} \left| x_i(\omega) - x_{ref}(\omega) \right|^2 d\omega}{\int_{\omega_s}^{\omega_f} x_{ref}(\omega)^2 d\omega} \quad (1)$$

where: ω_s, ω_f – starting and closing frequency of the analyzed band,
x_i, x_{ref} – characteristic in the current and reference state respectively..

Additionally the visual assessment of modal filtration results was performed.

6. RESULTS OF EXPERIMENTS

In this section the results of analyses will be presented. In the first step the measuring performance of the newly designed MDU was compared with the commercial modal analysis system provided by LMS Intl. In Figure 5 the comparison between corresponding FRFs measured and estimated with use of MDU and LMS system.

Then, on the basis of measurements performed in the reference state, modal analysis was performed and eigenfrequencies, the corresponding modal damping ratios and mode shapes were estimated. Table 1 shows the identified modal parameters using the LMS system and the authors software.

Table 1. Comparison of beam's modal parameters

MS no.	NF - LMS [Hz]	NF - MDU [Hz]	MDC - LMS [%]	MDC - MDU [%]
1	24.7	24.7	0.62	0.69
2	68.5	68.5	0.26	0.39
3	133.7	133.8	0.32	0.27
4	222.9	222.8	0.34	0.28
5	331.9	331.9	0.22	0.24
6	461.2	461.2	0.24	0.28

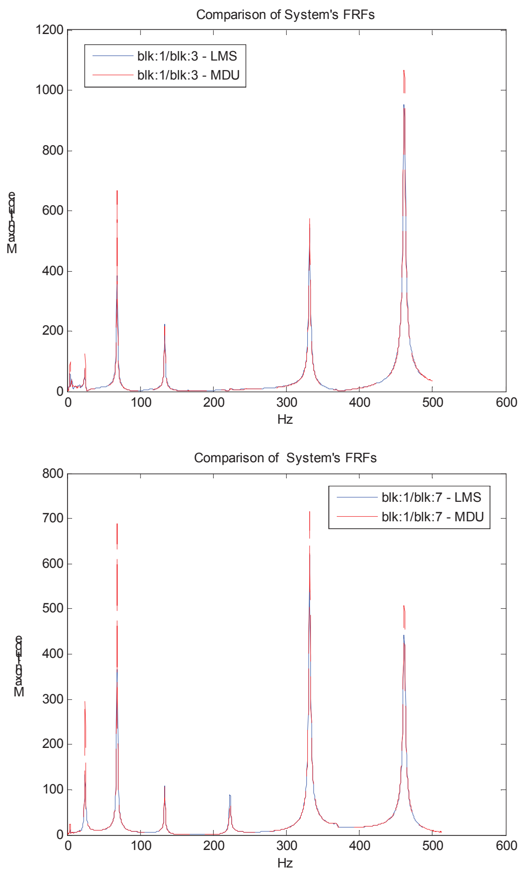

Fig. 5. Comparison of beam's FRFs obtained with use of two systems

Both results presented in Table 1 and characteristics from the Figure 5 seem to confirm the proper measuring performances of the MDU. Next its diagnostic abilities were investigated. All the measured scenarios listed in the previous section were evaluated for two cases. As a input to the diagnostic procedure based on modal filter two types of characteristics were considered: FRFs and PSDs. Firstly two measurements performed in identical condition were considered to verify the stability of the method and robustness for excitation differences (it has a form of band noise). In Figure 6 the damage index values calculated with use of Formula (1) for two measurements taken in the same conditions are presented. Both types of characteristics are considered – FRFs and PSDs.

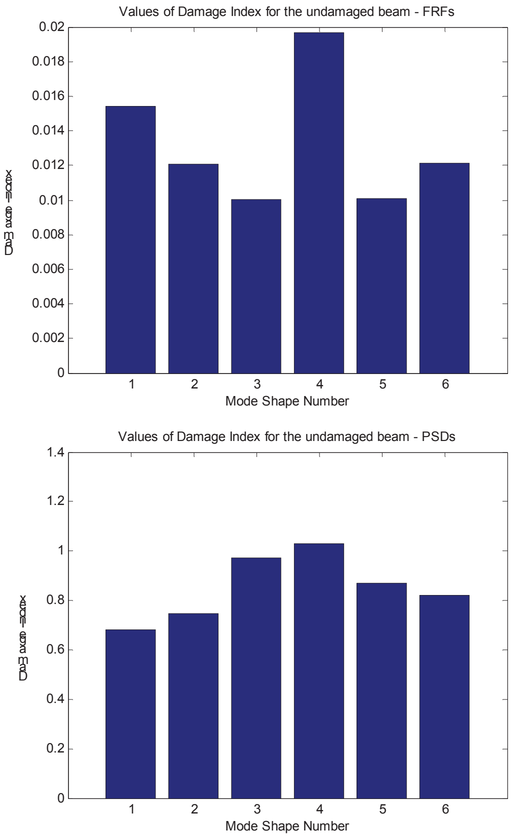

Fig. 6. Damage index values for the undamaged object

From the results placed in Figure 6 it is clearly visible that the method acts properly – damage index remained on very low level. It is however worth to notice that the PSDs taken to the analysis acts much worse than the FRFs. This difference result from the fact that the FRFs independent from excitation.

Further, the temperature in laboratory was increased of 11^{O}C and kept at this level for 1 h. In Figure 7 the damage index values calculated for the beam in different temperature are presented, again for both FRFs and PSDs

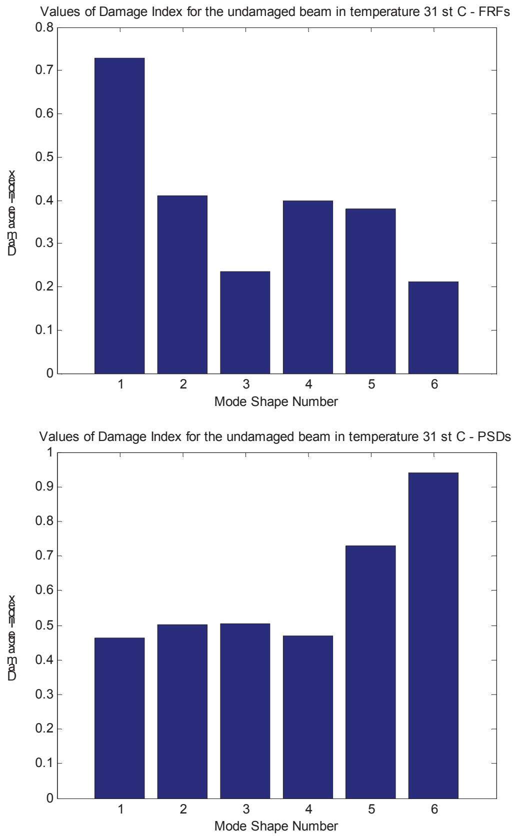

Fig. 7. Damage index values for different ambient temperature

This level of temperature difference does not affect the method. It influence is slightly visible on the FRF base calculations. Of course ambient temperature for the civil engineering object can change in bigger range than 11^{O}C but one of the assumptions made during SHM system designing was, that it should be equipped with modal filter bank, namely the reference data should be collected for a set of ambient temperatures changing every 10^{O}C. Results obtained during this analyses together with just mentioned assumption allow to state that the system is robust for ambient temperature changes.

Next stage of tests included the measurements also on the undamaged beam but this time the sensors were taken off an placed again possibly in the same position. In Figure 8 the damage index values calculated for this case are presented, again for both FRFs and PSDs.

For this case damage index values rose a slightly up, but they are still on the acceptable level. On the other hand, one has to keep it in mind that the sensors were re-mounted immediately after removing. In real non-destructive testing the period between measurements is usually much longer, and this increases the likelihood of committing bigger error in sensors placement. It is then recommended to apply the permanent or embedded sensor network.

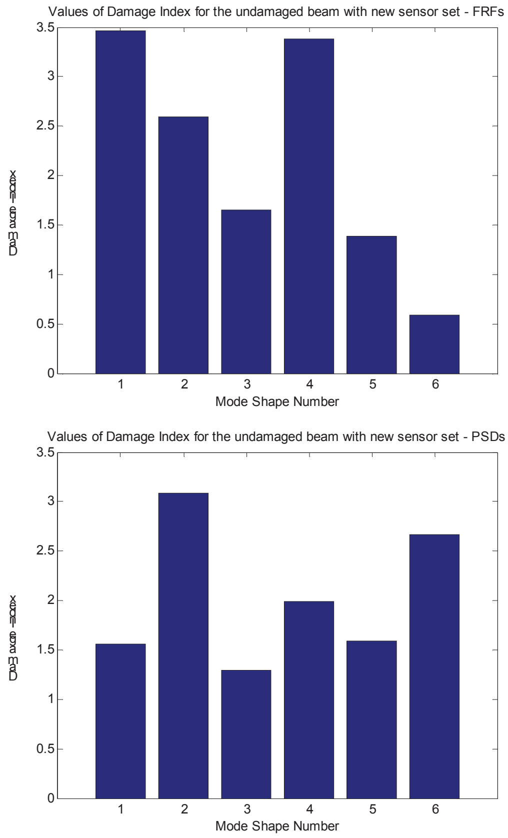

Fig. 8. Damage index values for the sensors re-mounted

Additionally in Figure 9 the comparison of modally filtered characteristics for the modal filter tuned to mode shape no. 1 is shown.

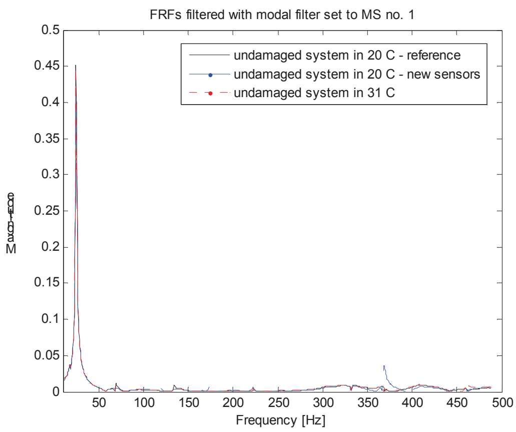

Fig. 9. Modally filtered FRFs for the sensors re-mounted an different ambient temperature

Figure 9 shows that the filtration is almost perfect for the different ambient temperature and there are very small peaks in regions of system natural frequencies for the case of sensors re-installation.

The last group of tests concerned the damage detection by the proposed system. Before the beginning of the tests, laboratory was cooled down to the stable temperature 20^{O}C, and reference modal filter coefficients were calculated for the data obtained after sensor re-installation. The damage was introduced in form of added mass to allow further tests on the beam. Total mass of the beam amounted 0.544 kg, added masses amounted 3.7 g and 15.5 g. It represents 0.68 % and 2.85 % of the beam mass and 6.8 % and 28.5 % of the 100mm surrounding (distance between consecutive measuring points) respectively. First added mass location was chosen in the middle of the beam – point blk:5, second location was near to the beam fastening – blk:9. In the figures from 10 to 13 damage index values for all damage cases are placed.

General conclusion that can be drawn from the results presented in the figures 10 to 13 is that all the damage cases were properly detected. Damage index values grew significantly and they are much bigger than for all undamaged beam cases. It can be observed that different damage location affects different modal filters, and as it was concluded in [6] the best detectability occurs when the modal filter is tuned to the mode shape that has biggest deflection in damage location. What is also interesting, the damage indexes calculated for PSDs differ from the ones calculated for FRFs. Different modal filters react on particular damage location. But apart from this difference the damage index values distribution

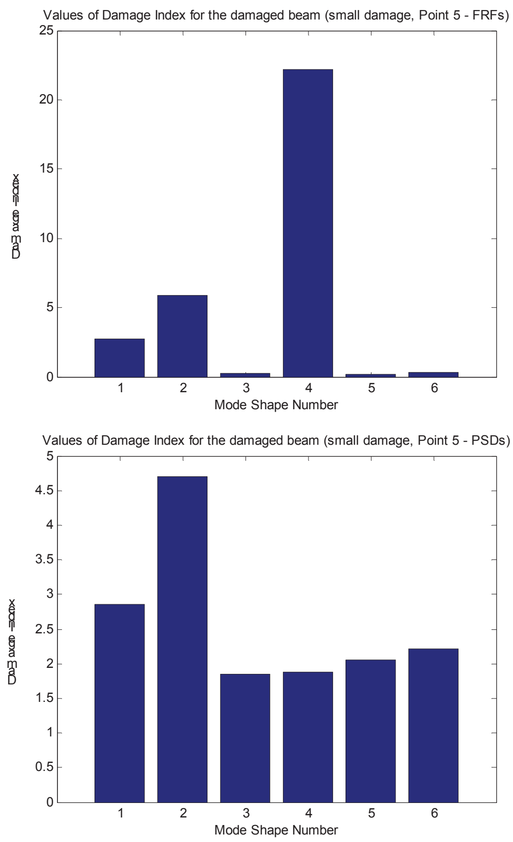

Fig. 10. Damage index values for the 3.7 added mass in point blk:5

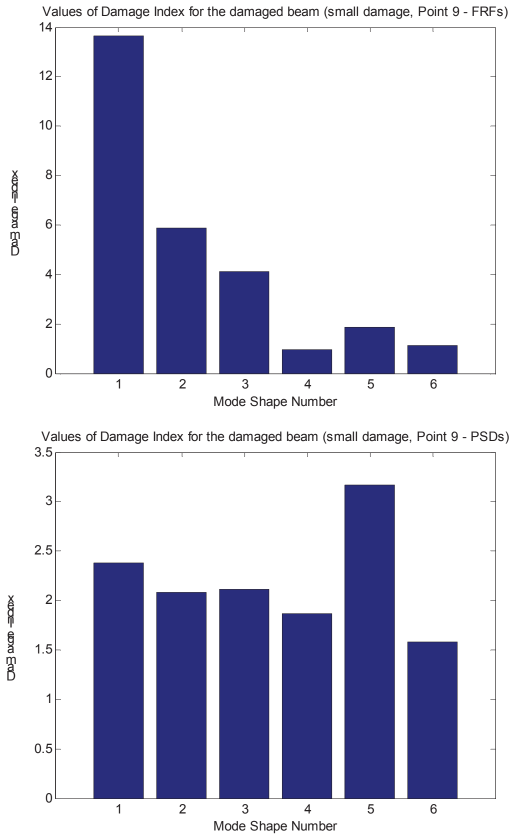

Fig. 11. Damage index values for the 3.7 added mass in point blk:9

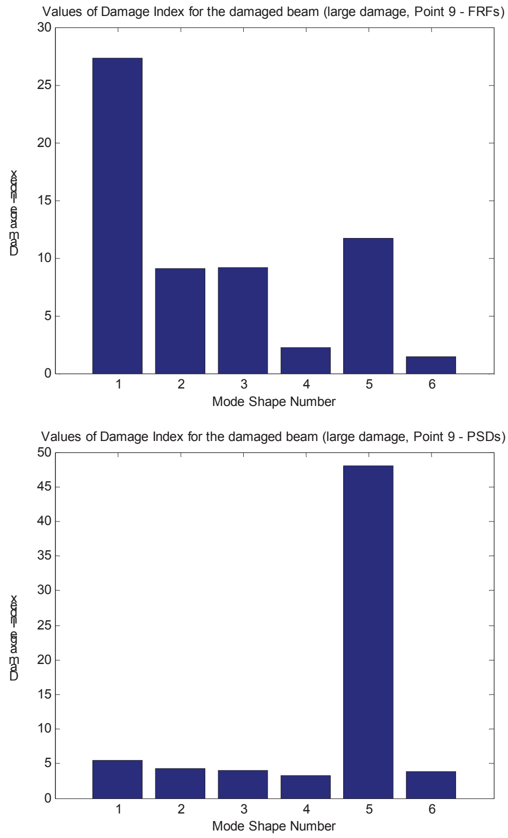

Fig. 13. Damage index values for the 15.5 added mass in point blk:9

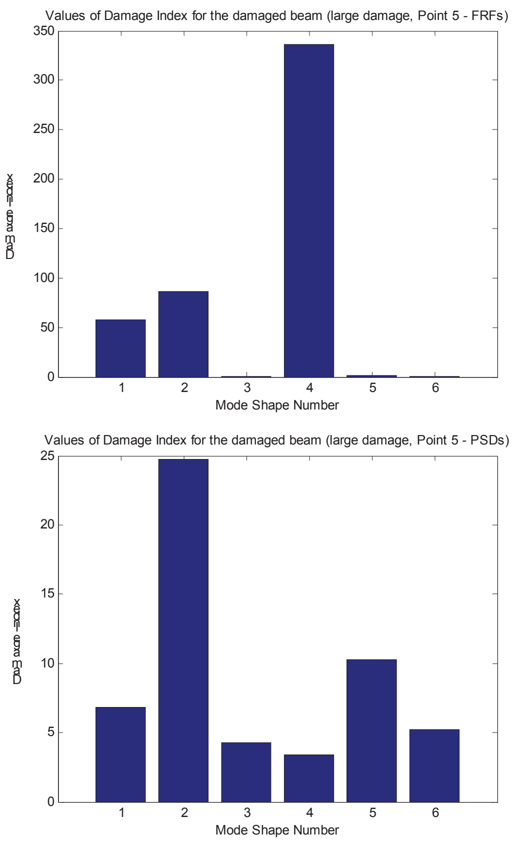

Fig. 12. Damage index values for the 15.5 added mass in point blk:5

looks similar for the selected damage location and filtered characteristic. Furthermore in Figure 14 the modally filtered characteristics (FRFs and PSDs) for the modal filter tuned to mode shape no. 5 for larger damage are shown.

In both plots from Figure 14 the damage is clearly visible in form of peaks near the 6^{th} and 4^{th} natural frequencies.

7. SUMMARY

The paper presents the results of laboratory tests for a damage detection procedure and monitoring system based on modal filtration. The following cases has been considered: verification of the measurement accuracy and modal parameters estimation results, stability of the method for invariant conditions, sensor re-mounting in the consecutive experiments, changes in ambient temperature and finally damage in different locations and sizes. Partial conclusions were presented in the previous section after the results of each study. A general conclusion is that the SHM system detects damage with good sensitivity, and ambient temperature does not affect the results under the assumption that there is bank of modal filters for different temperatures applied. Also the sensors should not be replaced during system operation. In the further development of the SHM system based on modal filtration, authors plan to install it on the real structure such as bridge or football stadium to verify its monitoring ability.

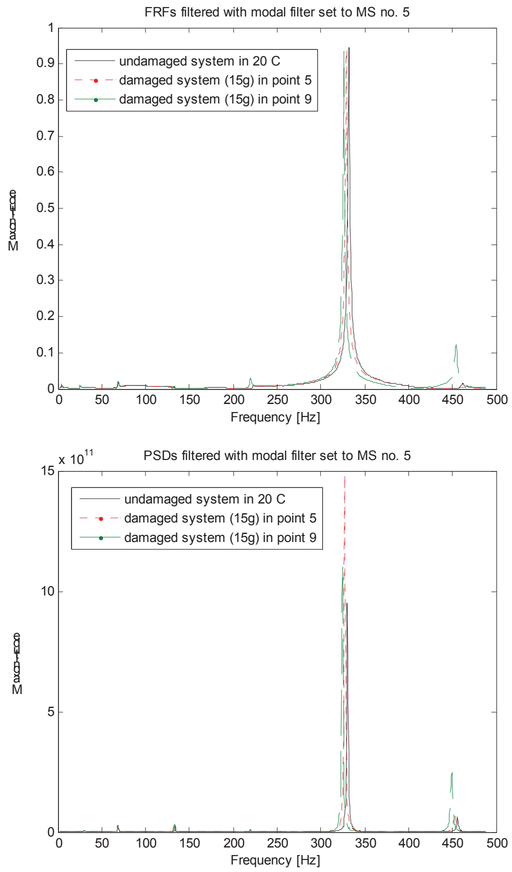

Fig. 14. Modally filtered FRFs and PSDs for the large damage

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