APPLICATION OF THE MODAL FILTRATION TO THE DAMAGE DETECTION IN TRUSS STRUCTURE

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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 on the truss structure. The testing object was an element of the roof girder in reduced scale. It was mounted in the specially designed and built hydraulic stand [9, 10]. The laboratory test program included series of measurements on undamaged and damaged object. The main part of measurements, however was focused on analyses of damage detection.

Keywords: modal filter, damage detection, laboratory testing, truss structures.

ZASTOSOWANIE FILTRACJI MODALNEJ DO WYKRYWANIA USZKODZEŃ DŹWIGARA KONSTRUKCJI DACHOWEJ

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. Obiektem testów był element dźwigara konstrukcji dachowej zamontowany na specjalnym hydraulicznym stanowisku pomiarowym [9,10]. Program testów laboratoryjnych obejmował serię pomiarów na obiekcie bez oraz z uszkodzeniem. Główna część pomiarów dotyczyła wykrywania uszkodzenia.

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 described the results of the laboratory measurements, which were performed on a single truss mounted on specially built test stand.

1. 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 designed 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.

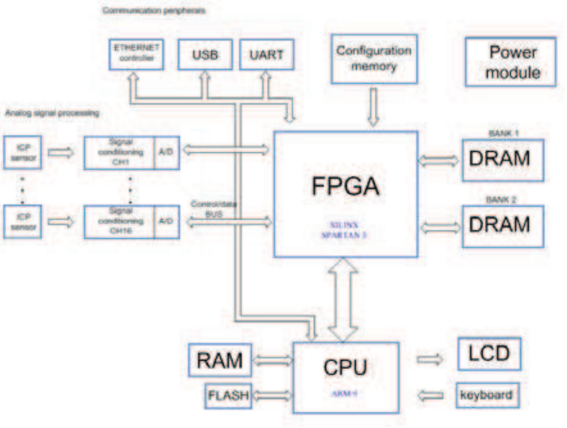

Fig. 1. Block diagram of design device

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 with 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.

In other words, the FPGA module act as a coprocessor, which shortens time necessary for full measure cycle and therefore allow for power savings.

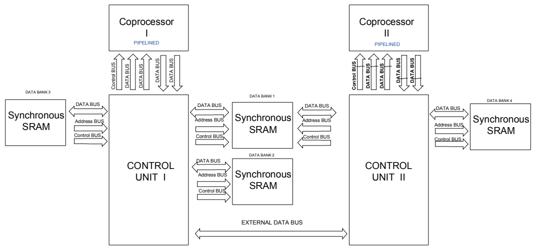

Fig. 2 FPGA processing module block diagram

The FPGA data processing module is designed using multi path, pipelined architecture, which can be easily extended to support more signal channels, and less processing time as required.

MDU also contains non-volatile memory for data recording purposes.

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 3.

Fig. 3. 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, 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.

Analog signal processing circuit also contains programmable gain amplifier (PGA) for three different values of gain: 1, 10 and 100. It also includes a set of analog antialiasing filters (with cutoff frequency set to: 10Hz, 50Hz, 250Hz, 500Hz and 1kHz) and 24–bit ADC converter.

MDU contains 16 identical analog signal processing channels, each for every analog input. The ADCs of every data channel are configured to provide synchronous signal acquisition, so that every sample gathered by first ADC is accurately synchronized in time with those coming from other ADCs.

With this hardware solution it is possible to detect and continuously monitor ICP status (whenever the input is shorted, opened or work in it is normal working conditions). It is also possible to detect input signal overshoots, so that device will not take such distorted data into account during measures.

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

It was assumed that in order to fluently visualize the mode shapes it is necessary to refresh screen 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.

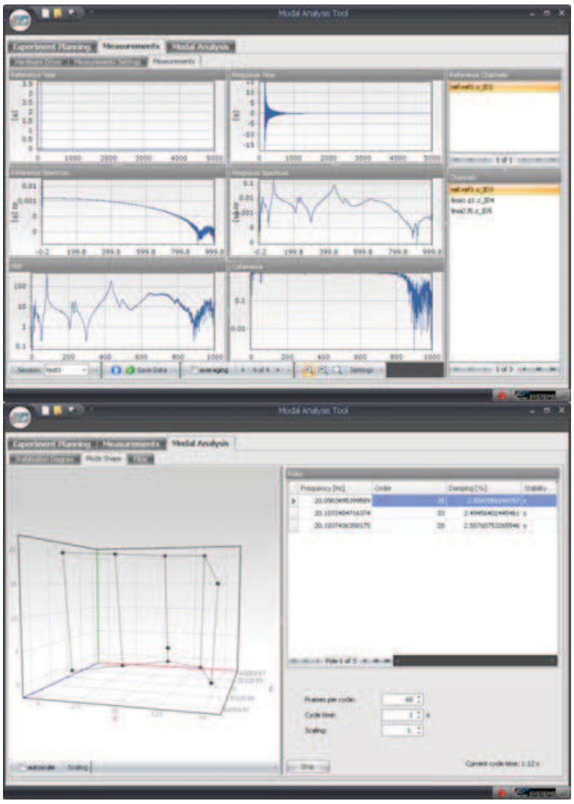

Fig. 4. GUI of described software

5. DESCRIPTION OF LABORATORY TEST STAND AND PROGRAM OF TESTS

The measurements could be successfully accomplished thanks to courtesy of interested staff members of the Faculty of Automotive and Construction Machinery Engineering at Warsaw University of Technology. The object of the test was a single truss shown in Figure 5 mounted on a specially built test stand in the laboratories of the Faculty of Automotive and Construction Machinery Engineering at Warsaw University of Technology [9, 10]. It is a typical element usually found in roof constructions, and it's damage may directly lead to roof crash. During the experiment a force was applied to the truss as shown in the figure.

The main goal of the test was to proof that modal filtration and designed system can be successfully used for damage detection for such objects.

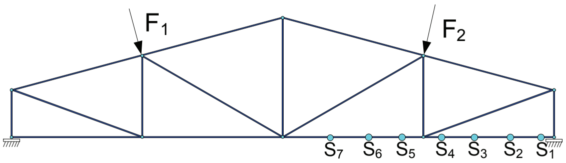

Fig. 5. Object of tests

A set of sensors was installed on the bottom beam of the truss.

A significant advantage of this approach is that it is not necessary to place a large number of sensors on examined object even if it is large. The user can place only a few sensors evenly distributed on the object.

The result in damage detection efficiency would be very similar. However a bit of experience is needed from the user to choose a proper area and sensors number.

What is more, position of each sensor cannot be changed during measurements, as it would affect damage detection quality [8].

As a matter of fact this method can be successfully used in applications where the measures are performed periodically. In this case sensors doesn't need to be installed permanently, however user have to ensure that every sensor is mounted exactly in the same point of the object as it was during reference measure. This can be achieved by using dedicated spacers (between object and sensors) mounted permanently on tested object.

At the very beginning MDU was connected to PC (with dedicated analytic software installed) in order to calculate modal filter coefficients for object in reference state. The reference state is defined as a state of object without damage in it's typical working conditions. In this case it was assumed a state of truss mounted on test stand with no force applied to it. The photo of MDU unit connected with PC is presented in Figure 6.

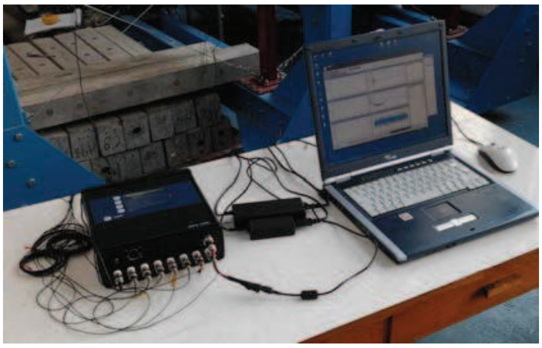

Fig. 6. MDU connected to PC

First step was to define object geometry. The software GUI used for object geometry definition is presented in Figure 7.

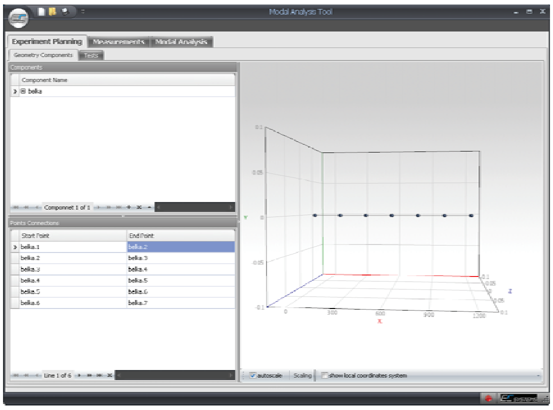

Fig. 7. Software GUI – object geometry definition

After that a set of measurements was performed. Every measurement had to be examined in order to check if it meet all requirements. If it does, it can be accepted and used further in model extraction phase. General rule is: more measurements performed – more accurate model will be generated. During measurements the sensors signal is presented in separate software GUI as shown in Figure 8.

Fig. 8. Software GUI – measurements

After measurements there is possibility to visualize mode shape for each of the estimated natural frequencies.

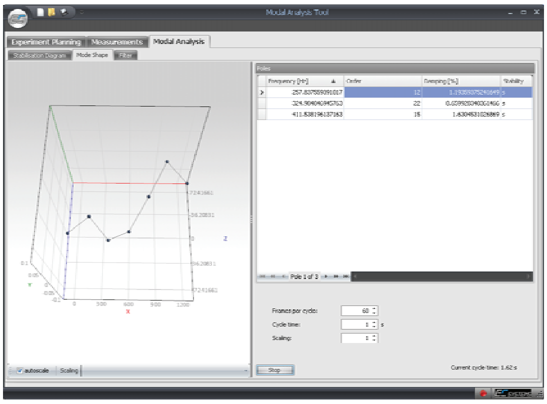

Fig. 9. modal shape visualization

Next step is to choose proper poles on stabilization diagram. This is actually the last phase when a bit of experience is needed from the user. Next modal filter coefficients are estimated. After model extraction user is able to verify quality of designed filter (which is shown below in Figure 11).

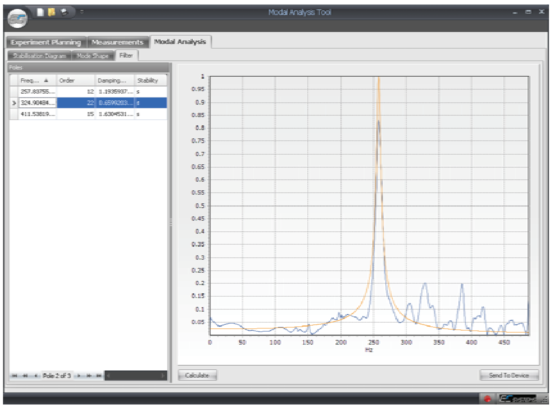

Fig. 11. software GUI – filter quality verification

As the result, three modal filters had been calculated, each for different natural frequency and corresponding mode shape.

Coefficients of these filters were then transferred to MDU, which enabled it to work independently and calculate damage index values for each defined filter.

Next step was to run reference measure in MDU, after which MDU was ready for measurements.

6. RESULTS OF EXPERIMENTS

In this section the results of analyses will be presented.

There was 7 sensors mounted on bottom beam as shown in Figure 5. Each sensor is connected directly to the measurement system, so that the truss state was continuously monitored.

During the experiment, load was slowly increased in several steps, until the first symptoms of damage appeared.

As an input to the diagnostic procedure based on modal filter only one type of characteristics was considered: FRFs.

All the results were evaluated with use of damage index proposed in [6]:

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

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..

The measure results are presented in Table 1.

No	Measure Results			comment
	DI[0]	**DI[1]**	**DI[2]**	
1	1.46E-02	4.53E-02	2.82E-02	REF. MEASURE F=0kN
2	8.07E-01	8.17E-01	4.00E-01	F=5kN
3	8.83E-01	7.59E-01	4.80E-01	F=10kN
4	9.60E-01	9.24E-01	6.98E-01	F=20kN
5	1.03E+00	1.11E+00	7.52E-01	F=25kN
6	1.11E+00	1.30E+00	8.31E-01	F=30kN
7	1.44E+00	1.31E+00	1.34E+00	F=35kN
8	8.54E-01	8.71E-01	7.10E-01	F=15kN
9	2.07E-01	4.39E-01	3.50E-01	F=0kN
10	1.35E+00	1.16E+00	1.13E+00	F=35kN

Table 1 measurement results

For every measure there are three damage index values calculated for different modal filter.

Measurement 1 was performed in object reference state. We can notice relatively small values, which may lead to conclusion that there is little or no change in truss internal structure since the reference measure was done.

Next step was to increase value of force applied to the object and measure damage index values for each step. As we can see in Table 1, larger force values means higher damage index values. This fact fully agree with theory, as internal structure stress have an impact on modal response.

The load was increased up to the value of 35 kN, when the object started to deflate.

Fig. 12. deformed truss after first loading cycle

The object deflation was confirmed by other measurement techniques used in parallel with our system during tests.

After that a value of force was step-by-step decreased up to the point where no force was applied to the object.

Looking at Table 1, we can easily notice the difference in damage index values between Measurements 1 and 9.

If there were no internal change in the structure of truss, measured damage index values would be similar. However, these values are over 10 times greater, which means that internal structure of truss had changed. This conclusion had been confirmed by measures, as the object remained deformed after load removal.

Fig. 13. Deformed truss in the point of jack mounting

7. SUMMARY

The paper presents the results of laboratory tests for a damage detection procedure and monitoring system based on modal filtration. The object of test was a single truss mounted on specially build laboratory test stand, which imitate real working conditions for this object.

A general conclusion is that the SHM system detects damage with good sensitivity.

However, the sensors should not be replaced during system operation, as this could affect measurement results.

In the further development of the SHM system based on modal filtration, authors plan to install it on other type of real structures such as bridge to verify its monitoring ability.

ACKNOWLEDGEMENT

Research funding from the Polish research project MONIT (No. POIG.01.01.02-00-013/08-00) is acknowledged by the authors.
Authors would like to also express their special thanks to Professor Stanislaw Radkowski, dr Jędrzej

Mączak and mgr inż. Adam Gałęzia for the possibility to make measurement on the stand in Warsaw University of Technology.

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