Industrial Tests of the SHM System Based on Modal Filtration

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ABSTRACT

In the paper the developed SHM system based on modal filtration is described. The system consists of independent 16-channel measuring-diagnostic unit and modal analysis software which also provides the estimation of reciprocal modal vectors – modal filter coefficients. Both hardware and software are presented in detail and additionally their practical implementation to structural changes detection in technical objects. For these tests the elements of aviation structures were used: wing of the training jet fighter and blade of the propeller of a small agricultural aircraft.

INTRODUCTION

Vibration based methods are still the most popular group of methods in SHM. They are based on the observation of changes in the system's vibration responses, which result from damage occurrence. Some of them use model-based diagnostics defined in the following way: the model of a particular system in an undamaged state is given, and this model is compared to the model identified from the data measured on the object in the current state. Differences between these two models indicate the object modification (e.g. stiffness or mass decrease), which may be caused by damage. A detailed description of the methods can be found in [1, 2 and 3].

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The most convenient model, which can be applied in the described approach, is a modal model, i.e. a set of natural frequencies, modal damping coefficients and modal vectors describing the dynamics of the tested object. The modal model is relatively easy to identify and, by means of operational modal analysis, may be identified from response data only; it is, therefore, very useful in diagnostics. On the other hand modal model-based diagnostics within damage detection has several limitations and faults. First of all, modal model-based diagnostics involves difficulties with the automation of procedures. Despite the current development of autonomous modal analysis procedures in many scientific centers, the total independence of an engineer's interference is still problematic in practice. Additionally, diagnostic symptoms in the form of natural frequencies, modal damping coefficients and modal vectors are estimated periodically, and depend on the subjective assessment of a testing team. Further, there is a serious problem distinguishing between the changes in parameters resulting from damage and those caused by environmental changes e.g. temperature or humidity. There is however a method which uses vibration data as well as a modal model of the object but overcomes all of above difficoulties. This is the advantage of modal filtering applied to the data recorded on the object.

The modal filter was used for the first time for damage detection and SHM by [4]. Other applications of modal filter for structural damage detection can be found in [5] and [6].

One more way of using modal filtering for damage detection is presented by [7]. The 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 imperfectly filtered natural frequencies. On the other hand, a global change in entire stiffness or mass matrix (due to changes in ambient temperature or humidity) does not corrupt the filter and the filtered characteristic still has one peak, although it is slightly moved in the frequency domain. In [8] the pre- and post-processing algorithms was added to make the method more useful for operational data. A different way of interpreting results was also presented. The damage detection procedure proposed in the last paper was the basis for the SHM system development.

DESCRIPTION OF DEVELOPED SHM SYSTEM

At the beginning of the system development one main assumption was made: 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 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. In this mode the following actions are performed: acceleration / displacement of vibration measurements, selected characteristics

estimation, modal filtration of the above characteristics, damage index calculation, and finally visualization of the filtered characteristics,

III. Operation in monitoring mode. In this mode the actions performed by the system are identical as in the mode II but they are done periodically and at the end of each diagnostic procedure the results are reported to the central unit.

Measuring - diagnostic unit

The diagnosis process form the measuring device point of view 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 and reporting processing results. The block diagram of measuring – diagnostic unit is presented in Figure 1.

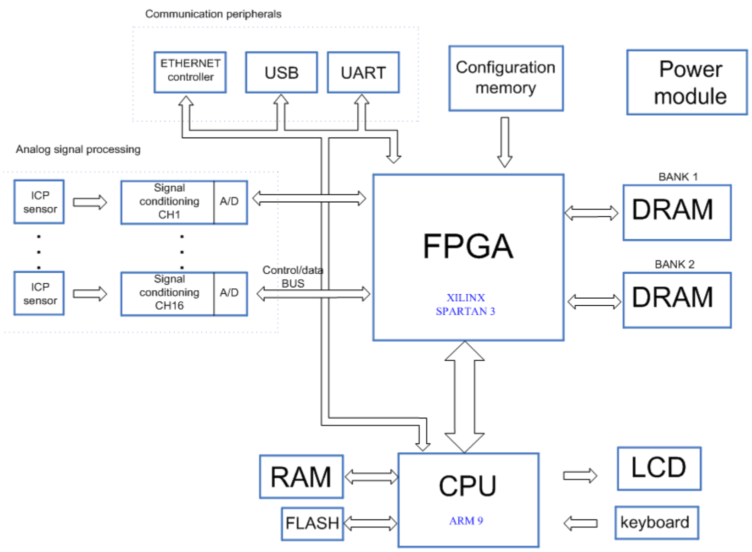

Figure 1.Block diagram of designed device.

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 measuring – diagnostic unit 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.

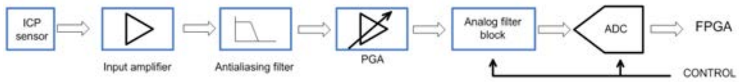

Figure 2. Analog part of the measuring circuit.

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. Basing on the above architecture the measuring device was built. Its photograph is placed in Figure 3.

Figure 3. Measuring—diagnostic unit.

The prototype of the measuring module was initially tested and compared with commercially available measuring devices. The experiments were conducted in the laboratory conditions. Results o of the tests are available in [9].

Modal analysis and modal filtration 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.

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.

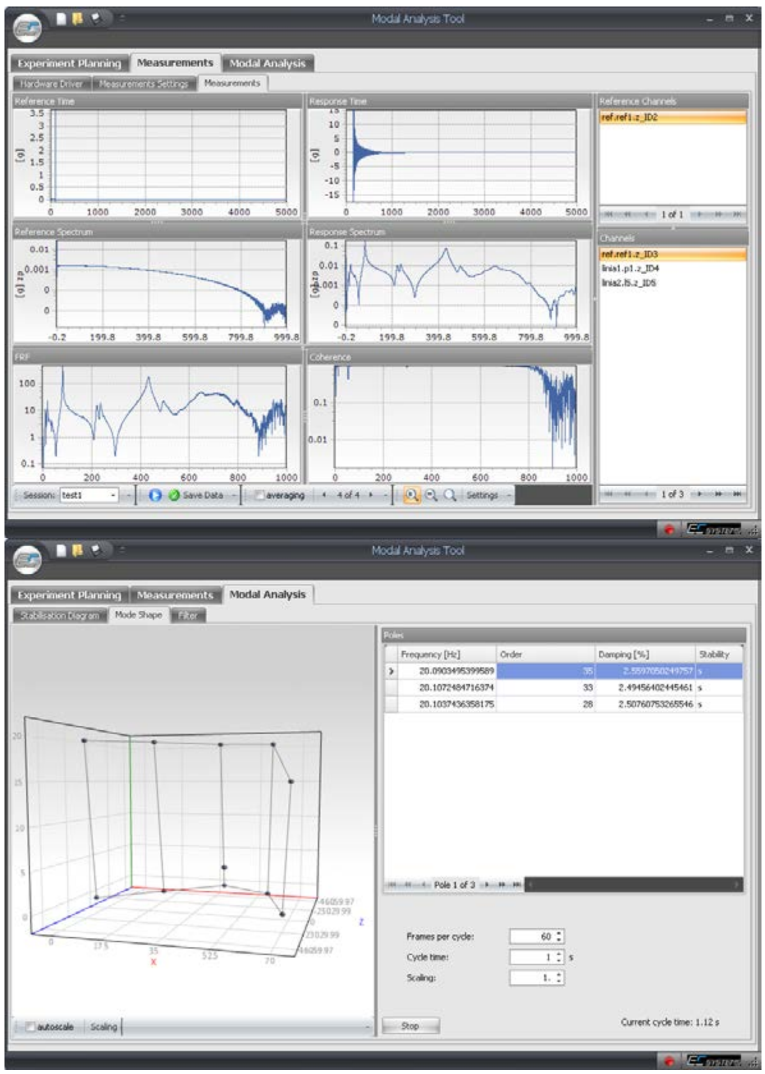

Figure 4. Exemplary windows of described software.

Also software was extensively tested and compared with other modal analysis programs. The results of these tests were satisfactory and can be found in [9].

TESTS OF DEVELOPED SHM SYSTEM ON AIRPLANE PART

The study was conducted in the State Higher Vocational School in Chelm. Object of the study was the training jet fighter PZL I 22 Iryda. The possibility of structural changes detection in the wing of the airplane was examined. During the tests the aircraft was set on wheels, the wing was tested in the closed state, the tail was in neutral position, fuel tanks were empty. Photo of the object during testing is shown in Figure 5.

Figure 5. Photograph of the tested wing.

In order to build a reference model and to estimate a modal filter coefficients, the modal impulse test was performed, which can be characterized by the following features: the impulse excitation in point wing:ref (connecting point of the front girder and the second frame from the tip of the wing), simultaneously the accelerations of vibrations were measured in 5 points evenly placed along the front girder of the wing (every 1200 mm), the frequency band was set up to 25 Hz with resolution 0.125 Hz. The following measurements were performed:

- 3 measurements in the same configuration as the reference one, performed every 0.5 h in order to check the stability of the procedure and the impact of environmental conditions on the results of its operations,
- Measurement after the strong deformation of the wing - the wing was loaded with approximately 1kN and then it was released - simulation of the measurement after the consecutive flight of the airplane,
- Measurement with the added mass of 3 kg in the measuring point 5 (the end of the wing),
- Measurement with the added mass of 3 kg in the measuring point 4,
- Measurement with the added mass of 3 kg in the measuring points: 3,
- Measurement after removing the extra mass.

Results of experiments

Firstly, the modal analysis was performed and on the basis of its results the modal filter coefficients were calculated for the reference measurements. Diagnostic testing was then performed using the test procedures implemented in the measuring – diagnostic unit. In the same configuration (without removing the sensors) consecutive impulse tests were performed in accordance with the scenario shown above. During testing the frequency response functions together with response spectra were estimated and stored. These characteristics were next filtered, and the results of modal filtration were used to calculate the damage index. In Figure 6 the exemplary results of the modal filtration for selected tests are presented.

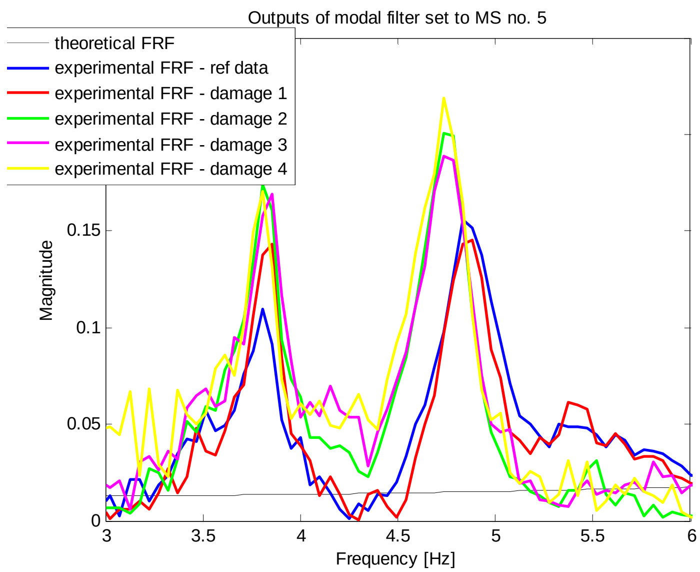

Figure 6. Output of modal filtrer with the filter tuned to 1st mode (region of 2nd and 3rd modes).

As it can be seen, in the region of 2nd and 3rd mode deterioration of filtration quality arisen as a result of the structural change. This effect is small, as used mass was only a little change in the weight of the entire wing. Since the effect was observed in the region of the first modes damage (added mass) did not affect the filtration accuracy. In the case of filters tuned to higher modes, the closer the added mass was to the antinode of the mode, the stronger filtration deterioration was observed - more detectable damage. Table 1 summarizes the damage indexes calculated for the subsequent tests by the measuring - diagnostic unit.

Table 1. Damage index values.

Test scenario	Summed damage index
Undamaged wing	0.8259
Applied and released 1 kN load	1.0681
Added mass in wing:5	5.5794
Added mass in wing:4	4.2769
Added mass in wing:3	4.3029
Undamaged after all measurements	1.2806

Values presented in the Table 1 confirm the applicability of the developer SHM system in real technical structures. The system detected properly all the damage scenarios although applied structural changes were rather small.

FINAL CONCLUSIONS

The paper presents the application of modal filtration in the SHM system. It includes the main theory according the method, description of developed hardware and software together. The most important part of the paper is the description of the tests and its results performed with use of the developed SHM system on the real technical object. Partial conclusions were presented in the previous sections 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.

ACKNOWLEDGEMENTS

Research funding from the Polish research project MONIT (No. POIG.01.01.02-00-013/08-00) is acknowledged by the authors.

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