SIMULATION VERIFICATION OF DAMAGE DETECTION ALGORYTHM

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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]. However to apply it in a real SHM system, it first needs to be extensively tested to verify its sensitivity to damage location, inaccuracy of sensor location in the consecutive experiments, measurements noise as well as changes in ambient conditions, such as temperature and humidity. This paper presents the results of numerical simulations that test the sensitivity of the modal filter based damage detection method to the factors listed above. For this purpose three numerical models of the physical systems were created and applied.

Keywords: modal filter, damage detection, ambient conditions.

WERYFIKACJA SYMULACYJNA ALGORYTMU WYKRYWANIA USZKODZEŃ

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]. Jednakże, aby zastosować go w rzeczywistym układzie monitoringu musi najpierw przejść szczegółowe badania symulacyjne w celu weryfikacji jego wrażliwości na takie czynniki jak lokalizację uszkodzenia, niedokładność umieszczania czujników w kolejnych pomiarach, zakłócenia toru pomiarowego oraz zmiany warunków otoczenia takich jak temperatura i wilgotność. W pracy tej przedstawiono wyniki weryfikacji symulacyjnej, sprawdzającej wpływ powyższych czynników na wyniki filtracji modalnej. W tym celu sporządzone zostały i zastosowane trzy modele numeryczne.

Słowa kluczowe: filtr modalny, wykrywanie uszkodzeń, warunki otoczenia.

1. INTRODUCTION

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 to verify its sensitivity to damage location, inaccuracy of sensor location in the consecutive experiments, measurement noise as well as changes in ambient conditions, such as temperature and humidity.

2. MODELS USED FOR SIMULATIONS

As stated above, three different models of the physical systems were created for the verification procedure. All the models were created using the finite element methodology. The first model was used to verify its sensitivity to damage location, inaccuracy of the sensors' location in the consecutive experiments and the noise of the measured characteristics. The FEM model was created directly using MSC.Patran 2008 R1 software. It represents a steel beam with dimensions of 20 x 4 x 1 m supported at its free ends. It was modeled with 69,000 solid elements and 68,500 nodes. Such a dense mesh was required for tests on the inaccuracy of the sensor location. For the influence of damage location analysis, 4 cracks were modeled as discontinuity of a finite element mesh in different locations on the beam. For the purpose of further analyses, the following normal mode analysis scenarios were considered: beam without crack (reference state), beam with crack numbers 1, 2, 3, and 4 consecutively. In Figure 1 the locations of the cracks are presented.

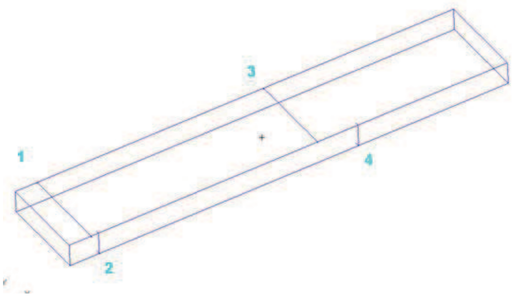

Fig. 1. Cracks in the beam model

The second model used for analysis was a metal frame and is presented in Figure 2. The model had a complex geometrical shape, was non-homogeneous (steel - aluminum), had realistic boundary conditions and thermal expansion was included. The main goal of this simulation was to investigate the influence of different temperature loads on the modal filtration and to compare it with the effect of damage. It was also modeled in MSC.Patran and meshed with 10,000 hex-8 elements (the number of nodes - approximately 14,000).

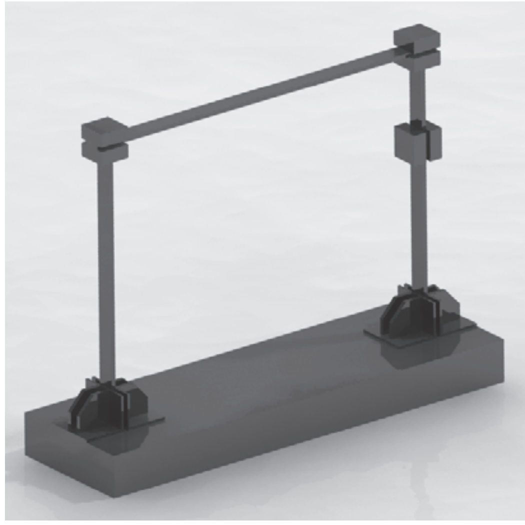

Fig. 2. 3D model of the frame

In order to investigate the behavior of a damaged frame, a horizontal beam crack was modeled as node disconnectivity. There were two crack stadiums - 5% and 10% of the cross-section area. The material properties applied to the model are listed in Table 1.

Table. 1. Material properties selected for simulation

	Steel (20°C)	Aluminum (20°C)
Young modulus [MPa]	$2.1*10^5$	$0.69*10^5$
Poisson's ratio	0.3	0.33
Density [g/cm^3]	7.85	2.71
Thermal expansion coefficient [1/K]	$1.5*10^{-5}$	$2.35*10^{-5}$
Thermal conductivity [W/m*K]	47	193
Specific heat capacity [J/kg*K]	420	880

Because the Young modulus varies with temperature, temperature-dependent material properties were applied. The material properties of aluminum were applied only to the horizontal beam. To take into account temperature-dependent material properties, each design scenario was carried out in two sub-stages; first – coupled mechanical-thermal analysis to obtain the temperature distribution, second – normal mode analysis. The following cases were analyzed: frame without crack – ambient temperature 20 °C (reference state), frame with 10% crack on upper beam, frame without crack – ambient temperature 25, 30, 35, 40, 50, 0 and -50 °C, frame without crack – upper beam heating (30 s) with 50 °C, frame without crack – local heating of the right vertical bar (30 s) with 50 °C.

The last model of a railway bridge used for the analysis of the damage detection procedure effectiveness was developed for two reasons. Firstly, to examine how the ambient humidity can disturb the procedure, and secondly, to verify how it will work for such a complex structure. The CAD model was based on documentation of a real structure. The bridge is 27 meters long and consists of steel (beams, barriers, rails, and reinforcement of main plate), concrete (main plate and pavements), soil and wood (sleepers) elements. The CAD model is shown in Figure 3. Afterwards, based on the CAD model, a FEM model was built in MSC.Patran. This consists of approximately 28,500 elements and 30,500 nodes. Solid, shell and beam elements were used in the model. The FEM model is shown in Figure 2b. There were three cracks introduced in the model. The first and second are vertical cracks in the web, the third is a flange crack. Crack localization was based on linear-static stress analysis. The crack was modeled as discontinuity of the finite element mesh. Localization of the cracks is shown in Figure 4.

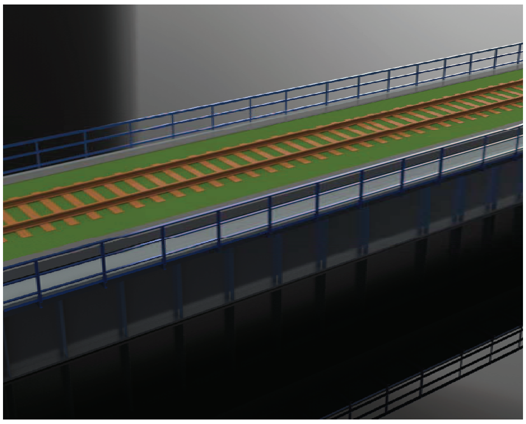

Fig. 3. CAD model of the bridge

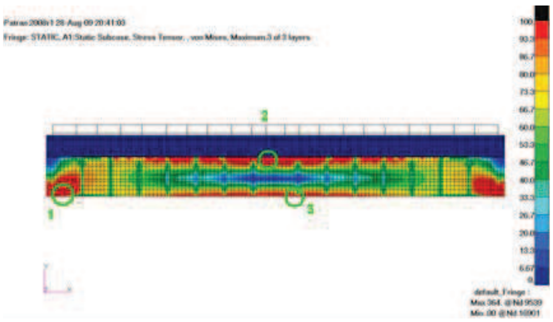

Fig. 4. FE mesh of the bridge model with cracks localization

To take into account the influence of moisture, different material densities were used. Dependent on the analysis, material densities were appropriately adjusted. The following normal mode analysis scenarios were considered: bridge without crack – dry (reference state), bridge without crack – moist, bridge without crack – wet, bridge with crack numbers 1, 2, and 3 consecutively.

3. TESTING PROCEDURE

To test the influence of the factors listed in previous sections on the modal filter based damage detection procedure, the following operations were conducted. Firstly, the frequency response functions (FRFs) synthesis was performed for the models in reference states. The characteristics were synthesized for selected nodes of the models which simulated virtual measuring sensors with use of the following equation [6]:

$$H_{ij}(j\omega) = \sum_{r=1}^{n} \frac{2 \cdot j \cdot \omega_r \cdot \phi_{ir} \cdot \phi_{jr}}{\omega_r^2 - \omega^2} \qquad (1)$$

where: ω_r – r-th natural frequency,
ϕ_{ir} – i-th element of r-th modal vector

Based on the reference modal model and synthesized FRFs of the reference systems, the reciprocal modal vectors were calculated – modal filter coefficients. With use of these coefficients, sets of FRFs for the reference states and for consecutive derogations from these states were filtered. For the obtained results, damage index values were calculated according to the formula [7]:

$$DI_4 = \frac{\int_{\omega_s}^{\omega_f} \left| x_i(\omega) - x_{ref}(\omega) \right|^2 d\omega}{\int_{\omega_s}^{\omega_f} x_{ref}(\omega)^2 d\omega} \qquad (2)$$

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 damage index was calculated only for frequency regions, which are the direct neighborhood of the model's natural frequencies, except the one to which the modal filter was tuned. The bandwidth of the consecutive frequency intervals was established at 5 Hz.

4. RESULTS OF ANALYSES

In this section the results of analyses will be presented. Due to the small amount of space available for the paper, no plots of modally filtered characteristics will be shown. The damage index values are presented only for the modal filter tuned to the mode shapes for which the indication of the modeled crack was the best.

In the first stage of simulation, the influence of the damage location on its detectability was examined. In the beam model 4 cracks were introduced at different locations (see Fig. 1). The size of each crack amounted to 5 % of the beam's cross-section area. In addition, in this section the authors checked which natural frequency the modal filter should be tuned to, in order to best detect the expected damage. In Table 2, the maximal values of the damage index calculated for the consecutive damages are presented, together with information about the natural frequency to which the modal filter was tuned. In Figure 5 results of modal filtration performed for this simulation are presented. of damage is subjected to the largest deformation.

Table 2. Damage index for different damage locations

No. of Damage	Max Value of DI	No. of MF
1	3.5	7
2	13.5	5
3	12	1
4	810	1

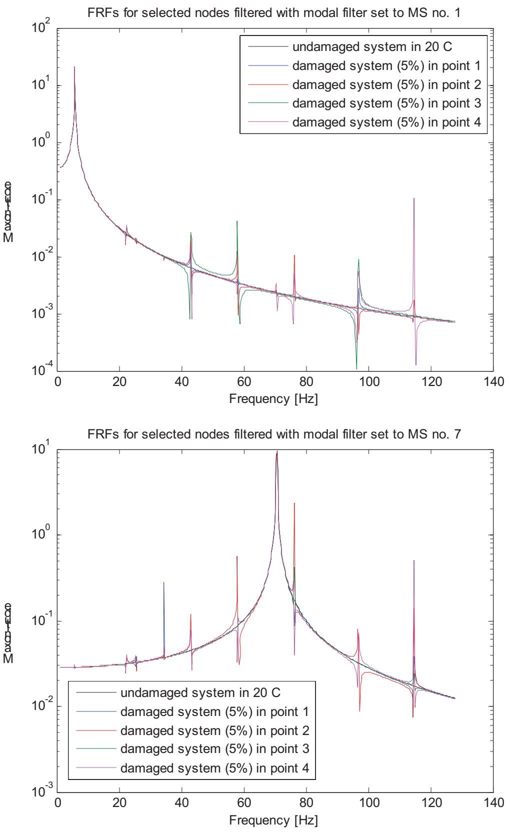

Fig. 5. Results of modal filtration tor different crack locations – modal filter set to natural frequency no.1 and 7

Best detectable damage is Crack 4 – in the middle of the beam, along the short side. The large difference in the damage index value between Crack 4 and the others results from the method of the damage index calculation – the square of the characteristics' difference is considered (1). The far worse results obtained for Damage 3 arise from the fact that it is much shallower than No. 4 (constant area with a much greater width). This is confirmed by the fact that among Cracks 1 and 2 the deeper one also gives higher values of the damage index. For Cracks 1 and 2, the highest damage index values were noted for filters tuned to Natural Frequencies 4, 7, 9 and 10, with a clear dominance of Natural Frequency 7. These frequencies correspond to torsional modes and higher bending modes. Cracks 3 and 4 are definitely best detected by Modal Filter 1 (tuned to Natural Frequency 1) - by far the highest amplitude of vibration in the fracture region. From the conducted analyses, it can be concluded that the detection of cracks should be performed with use of a filter which is set to the mode in which the region.

To carry out the next verification test, it was assumed that in the consecutive measurements the sensors are slightly shifted against the reference position. The values of these shifts were defined as 1.5%, 1% and 0.5% of the beam length. It was assumed that the sensor position error can be committed only along the X axis - to the right or the left and that, in a single measurement, sensors will be positioned with a constant error value (e.g. 1%). Taking 8 virtual sensors, there were 256 combinations to analyze for each considered value of inaccuracy. Modal filtering errors for all cases at the same assumed sensor shift value were at a similar level and the highest values were achieved by Modal Filter 1. In Figure 6 results of modal filtration are shown. For presentation in Table 3, the worst cases were chosen, that is, those where the accuracy of modal filtering was the worst. These results were compared with Damage 4.

Table 3. Damage index for incorrect sensors location

Simulation Scenario	Max Value of DI
Damage no. 4	810
Sensors Sift 0.5 %	890
Sensors Sift 1.0 %	2480
Sensors Sift 1.5 %	9920

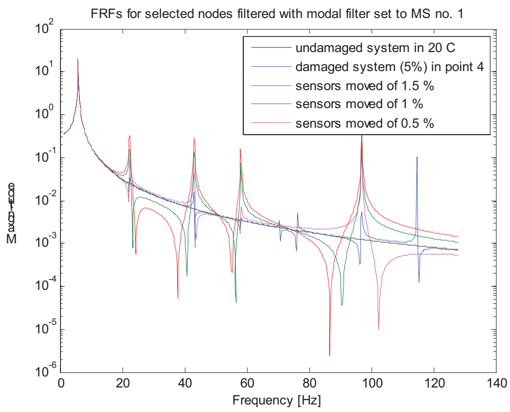

Fig. 6. Results of modal filtration tor incorrect sensors location – modal filter set to natural frequency no.1

The calculated values of the damage index confirm the significant impact of damage to the accuracy of the sensor location in the subsequent measurements on the results of modal filtration, and

thus the effectiveness of the method. In the case of the analyzed beam, the smallest sensor shift gives a comparable value of the index to 5% crack at the point where it is easiest to detect. The obtained results allow the following conclusions to be formulated:
- since the method depends on the mode shape, it requires high repeatability for the location of sensors, and therefore it is recommended for systems where a network of sensors is permanently attached to the object - a classic SHM system,
- if the method is used as an NDT technique, attention should be paid to the repeatable placement of sensors. Additionally, the level of damage that could be detected in this way should be raised to about 10% in order to avoid false alarms.

In the third stage of the simulation study, the impact of noise on the modal filtration results was tested. The simulations will test the influence of interference generated by the measuring equipment on the modal filtering errors. Considering the characteristics of the sensors, their attachment (character - not location), as well as disruptions in wires and recording devices, the signal to noise ratio for the entire measurement path is set at 40 dB, which corresponds to the noise of 0.01% recorded signal amplitude. To ensure a large enough margin error, it was decided to introduce noise of a normal distribution, zero mean and amplitude of 5% of noised characteristics. Results of modal filtration for this case are shown in Figure 7. In Table 4, the values of the damage index for the noised characteristics and Crack 1 were compared, both for Modal Filter 7.

Table 4. Damage index for noisy data

Simulation Scenario	Max Value of DI
Damage no. 1	3.5
5 % Noise on the Data	0.39

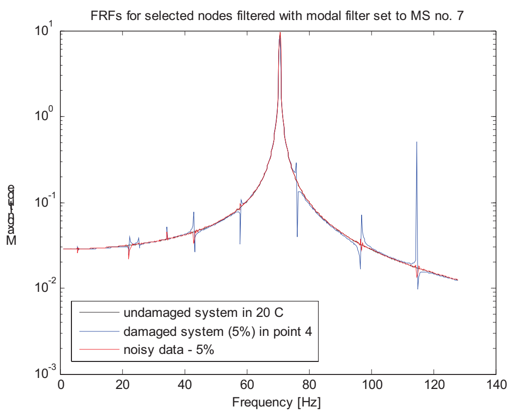

Fig. 7. Results of modal filtration tor noisy data – modal filter set to natural frequency no.7

On the basis of this part of the simulations, it can be concluded that the noise associated with the measuring path does not affect the operation of the proposed method of damage detection

One of the most important issues in the analysis of damage detection method properties is their sensitivity to changes in external conditions, especially ambient temperature. Therefore, it was decided to carry out extensive simulation studies devoted to the influence of ambient temperature changes on the results of the modal filtration. The tests were performed for various values of ambient temperature where the entire object had the same temperature as the environment, and for two special cases. The first one reflects the situation where the sun heats one of the parts of the object, while the others remain in the shade or are additionally cooled by their proximity to the river. In this scenario, the simulated model was heated from above at the time, which prevented its total warming. The second special case is the situation where the temperature changes only in one fragment of an object as the result of some artificial source of heat. In Figure 8 results of modal filtration performed for this simulation are presented. Table 5 shows the damage index values collected for all changes in temperature as well as for the damage of 5% and 10%. In all cases the modal filter was tuned to Natural Frequency 2.

Table 5. Damage index for temperature changes

Simulation Scenario	Max Value of DI
Damage 5 %	5.8×10^6
Damage 10 %	3.6×10^8
Ambient Temp. 25 ^{O}C	2.7×10^5
Ambient Temp. 30 ^{O}C	9.2×10^5
Ambient Temp. 35 ^{O}C	2.5×10^7
Ambient Temp. 40 ^{O}C	15.6×10^7
Ambient Temp. 50 ^{O}C	1.9×10^8
Ambient Temp. 0 ^{O}C	8.8×10^6
Ambient Temp. -50 ^{O}C	2.3×10^9
Upper Heating 50 ^{O}C	4.5×10^7
Local Heating of the Right Bar 50 °C	5.7×10^9

After analysis of the damage index values, it can be seen that the impact of 5% damage is greater than a temperature change of 5 ^{O}C. However, if one wants to use the method for a wider ambient temperature range, it is suggested some kind of modal filter bank should be built. In such a bank, one would have the reference model of the system identified for various ambient temperatures. In order to decide on the bank of filters designated for every 10 ^{O}C, it is recommended to increase the minimum size of recognizable damage to about 10%. The damage index calculated for such damage is higher than the value of the difference in temperatures reaching up to 30 ^{O}C. In addition, the heating frame from the top gives a lower value of the damage index than the damage. The worst of the simulated cases were the temperature change of 70 ^{O}C (ambient temperature -50 ^{O}C) and heating only the vertical bar of the frame. Both of these cases, however, do not disqualify the method, since the 70 ^{O}C difference in temperature using even a small bank of filters should not occur, and local high temperature change should be detected, because it can be regarded as a failure.

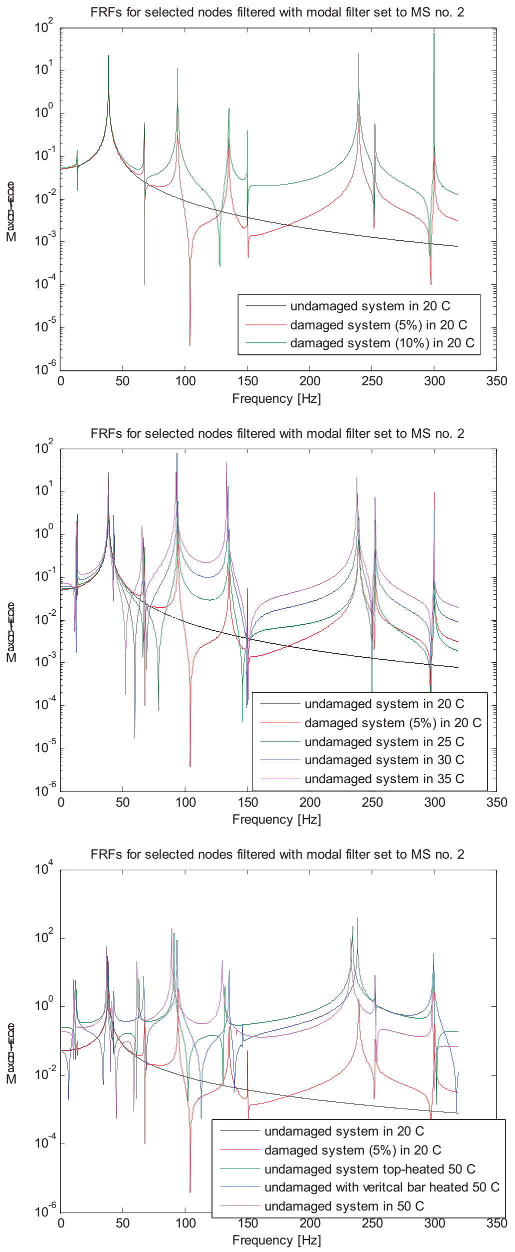

Fig. 8. Results of modal filtration for temperature changes – modal filter set to natural frequency no.2

To examine the operation of the method for a complex civil engineering object (real structure), and check the effect of humidity on the efficiency of the damage detection method again, the modal filter coefficients were calculated for the reference model, which is a dry bridge without any damage. Results of modal filtration for the bridge are shown in Figure 9. In Table 6, one can find the damage index values for 3 cracks introduced to the bridge consecutively and for a moist (relative humidity 99%) and wet (after intense rainfall) bridge. All results are for Modal Filter 10.

Table 6. Damage index for bridge simulations

Simulation Scenario	Max Value of DI
Damage no. 1	7210
Damage no. 2	2.7×10^{4}
Damage no. 3	7.3×10^{7}
Moist Bridge	1670
Wet Bridge	3.2×10^{9}

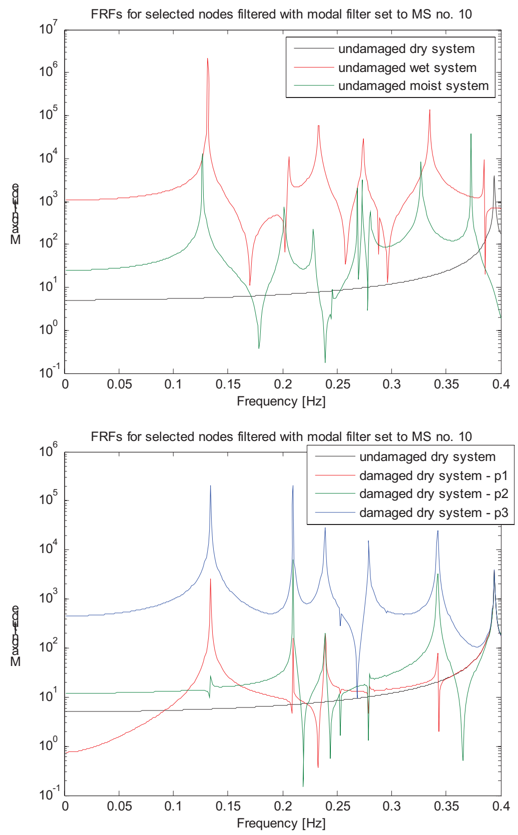

Fig. 9. Results of modal filtration for bridge simulations – modal filter set to natural frequency no.10

The analysis of the damage index values confirmed the lowest detectability of Damage 1 - close to the support. To obtain the higher values of the damage index for this crack, one should take into account the modal filters tuned to higher modes – the ones which greater deform the region of Damage 1. Regarding the impact of humidity changes, it is quite significant - the weight of soil and wood changes by over 10 percent and is a significant share of the object's total mass. On this basis, it is concluded that the method should not be applied to objects which change their mass so heavily due to moisture. On the other hand, the method has shown its effectiveness in detecting small-scale damage for such a highly complex technical facility.

5. SUMMARY

The paper presents the results of numerical tests for a damage detection procedure based on modal filtration. 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. Partial conclusions were presented in the last section after the results of each study. A general conclusion is that the method detects damage with good sensitivity but users have to be aware that, since the method is based on the modal model, it can be influenced by other factors which change the modal model parameters. On the other hand basing on the results of the earlier studies of the authors [1] it can be stated that the method is much less sensitive to environmental changes than other modal model based methods.

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