THE USE AND CHALLENGE OF MODAL ANALYSIS IN DIAGNOSTICS

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Streszczenie
W pracy przedstawiono możliwości zastosowania eksperymentalnej analizy modalnej do diagnozowania konstrukcji mechanicznych. Przedyskutowano metody eksperymentalnej analizy modalnej, które mogą być stosowane dla celów diagnostyki eksploatacyjnej. Omówiono również metody wnioskowania diagnostycznego na podstawie zidentyfikowanych modeli modalnych konstrukcji. Przedstawiono przykłady zastosowania analizy modalnej do diagnostyki wybranych konstrukcji mechanicznych.

Słowa kluczowe: diagnostyka oparta na modelu, analiza modalna, detekcja i lokalizacja uszkodzeń

ANALIZA MODALNA W DIAGNOSTYCE KONSTRUKCJI – ZA I PRZECIW

Summary
In the paper applicability of modal analysis in diagnostics of structures is discussed. Methods of modal analysis which can be applied for operational diagnostics are presented and post-processing methods for diagnostic decision based on identified modal models are discussed. Several of presented methods are applied for diagnostics of laboratory structures, for validation and employed for real mechanical systems diagnostics.

Keywords: Model assisted diagnostics, experimental modal analysis, damage detection and localization

1. INTRODUCTION

Nowadays many new diagnostic methods have been formulated and developed. Several of them are commonly use for many different structures. One of the methods which are in practical used is model based diagnostics [1]. The scheme of model based diagnostics is shown in figure 1. The main idea of application of models in diagnostics is monitoring of model parameters variation during operation. This approach requires knowledge of models for undamaged structure, models of structure with particular damages and knowledge of model in current state. To detect damage during operation the current modal parameters should be compared with undamaged structure parameters (global diagnostics), if damage is recognized the parameters can be compared with damaged model to localize damage position (local diagnostics).

This approach requires many experiments to define relations between damage localization and dimension and variation of modal parameters. Because the sensitivity of modal parameters on damage dimension depends on many no measurable quantities which varying during operation sometimes they are recognized as damages but they are not damage only variation of modal parameters due to variation of temperature or soil moisture. There are many models which can be useful for diagnostic purposes, but mainly modal model of the structure is employed in practical applications. The modal model is defined as set of natural frequencies, damping coefficients and mode shapes [2]. The modal model can be applied for damage detection, damage localization and damage assessment. In this approach measurable changes of modal parameters are mapped to health of a structure and location of damage if it is recognized.

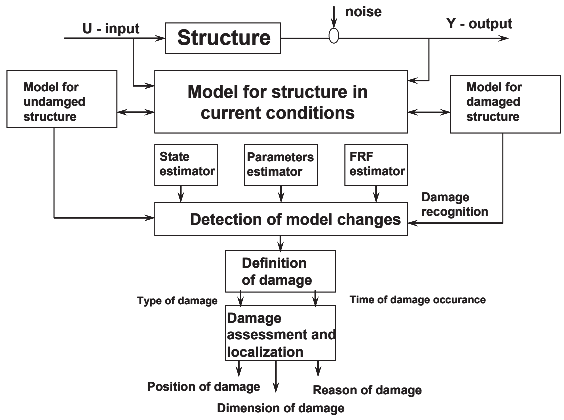

Fig.1. Scheme of application of models for diagnostics

But there are many difficulties in application of modal models in diagnostics of mechanical structures. The classical modal analysis requires at least measurements of excitation forces and responses (vibrations) of the structures, but there is a big problem to measure excitations [3] during operation. Fortunately, modal analysis methods based on output only measurements have been developed [4] and implemented in software. Short description of the methods can be found in a next paragraph of this paper. But if methods of in operation modal analysis are applied there is a problem of distinguish of harmonics and structural modes [4]. To solve the problem modal damping should be carefully studied for each detected vibration mode. The scheme of damage detection methodology based on modal models is shown in figure 2.

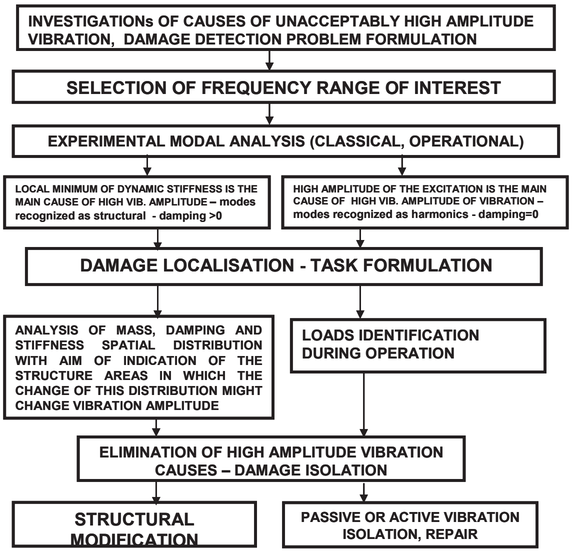

Fig.2. Scheme of application of in – operation modal analysis for damage detection

If the modal damping is detected to be near zero, the mode should be treats as harmonics and their amplitude depends on excitation amplitude. In a case of modal damping significantly bigger then zero, the structural mode should be investigated. The methods on structural modes selection based on damping assessment has been applied by author in many industrial cases for structural modes selection for turbine unit foundation, pomp installations treatments. There is one disadvantage of the approach, damping is less accurate estimated modal parameter, particularly if in – operation modal test technique is applied. One can observe the big variation of damping estimators which is stochastically distributed [5].

Applicability of modal models for damage detection in a structure depends on sensitivity of the modal model for structural parameters changes. The sensitivity depends on mode index, location of measurement points which is considered and location of point in which parameters are changed (damage location). In some cases one mode can be sensitive but not other. It make very difficult to applied modal model based methods for damage detection.

There are some problems with application of modal model for damage detection which are caused by variability of environmental conditions. It is observed mainly for civil structures like bridges and buildings. It has been proved that natural frequencies can be changed significantly due to change of air temperature. In the literature authors [6] described some examples of changing natural frequency of bridge more then 10% due to changes of temperature from -10^{o}C at night to 20^{o}C during a day. Such a big modal parameter variation can be detected as structural damage. For such a structure the weather monitoring should be a part of structural monitoring and diagnostic system.

Nowadays, many laboratories worldwide are working on implementation of modal analysis in monitoring and diagnostic systems using in-operation modal analysis algorithms, which are briefly explained in the next section of the paper.

2. IN OPERTATION MODAL ANALYSIS

There are three groups of in- operation modal analysis methods:

- time domain methods,
- frequency domain methods,
- ARMA model based methods.

All of these methods require measurements of a system response which is excited by ambient load. The measurements can be done during operation of a structure under monitoring. If vibration modes should be continuously monitored number of measurements point should be equal to number of required modal vector coordinates, in other case the reference points should be fixed on the structure. A time domain methods are based on the relation between correlation function and modal parameters of the structure in the form [3]:

$$R_{ij}(T)=\sum_{r=1}^{n}\frac{\Psi_{ir}G_{jr}}{m_r\omega_{rd}}\exp(-\xi_r\omega_{nr}T)\sin(\omega_{rd}T+\vartheta_r) \quad (1)$$

where; i,j are indexes of measurement points, phase shift ϑ_r and constant G_{jr} are given by the formula proofed in [8]. Ψ_{ir} ω_r ξ_r are r-th modal parameters of the structure. Measured correlation functions are approximated by complex exponential function in the form of (1) using LS methods in most popular estimation procedure. Different approach is formulated based on Hankel matrix build based on measured correlation functions. These methods are stochastic subspace methods and can be realized as Balanced Realization [8] or CVA [8] algorithms.

Frequency domain methods are based on relation between modal parameters and cross power spectral density function for responses measured in different points. The basic formula has the following form [7]:

$$G_{yy}(j\omega)=\sum_{k\in Sub(\omega)}\frac{d_k\varphi_k\varphi_k^T}{j\omega-\lambda_k}+\frac{d_k^{*}\varphi^{*}{}_k\varphi^{*T}{}_k}{j\omega-\lambda^{*}{}_k} \quad (2)$$

where; d_k is a scaling constant. A method based on relation (20) is named FDD method [7] and is very

popular to identify modal parameters of structure with small damping.
The third group of methods requires identifying ARMA model parameters for measured system responses. Based on knowledge of the model parameters modal damping and natural frequencies are determined [9]. The method can be realized on-line during structure operation and has been successfully applied by author for flutter monitoring in airplanes based on in-flight acceleration measurements.

3. DAMAGE DETECTION WITH USE OF MODAL MODELS

The application of modal models for damage detection in mechanical structure rest on calculation of certain features of the model which can help to distinguish undamaged and damaged structure based on modal parameters. In the literature there are described many methods. Within these methods, the following methods are in practical application, most often:
– methods based on modal parameters perturbation (natural frequency, modal damping) [10,11,12,13]
– methods based on FRF (stiffness and compliance) variation detection [14,15,16],
– methods based on mode shape analysis [17,18,19],
– methods based on detection on modes energy [20],
– methods based on Ritz vector variation detection, [21]
– methods based on detection of regression model parameters detection [22,23],
– methods based on detection of time-frequency characteristics [24,25]
– methods based on PCA and SVD analysis [26,27],
– methods based on FE model updating [28,29].
Several of pointed above methods will be described bellow, tested on experimental rig and applied for monitoring of real operating structure.

3.1. Damage detection based on modal parameters perturbation

In many papers results of test of the method are presented [10,11,12,13,30], historically the method has been used as a first application of the modal model parameters identification for damage detection of mechanical structures. But in practical application there are differences between sensitivity of the model parameters variations due to changes in system health. In some cases the method can be successfully applied but in others is not enough sensitive to be practically useful. The good results are observed in application for damage detection in laminate structures [10] and concrete beams [11,12]. The modal model parameters variations can be detected using NN based algorithm. In [30] the application of NN for modal parameters variations in tall building structure is presented. The modal damping parameter is more difficult to identify and its estimator is less accurate then estimator of natural frequencies of the system. But there are more and more application of modal damping variation for damage detection due to their bigger sensitivity on changes of structure's properties [31,32]. In [31] the modal damping is used for damage detection in hard disc driving system support. In [32] modal damping is applied successfully for crack detection in concrete beam but in [9] there is application of damping variation monitoring for flutter detection in airplanes structures.
The Multiple Damage Location Assurance Criterion (MDLAC) coefficient is defined to detect variation of both natural frequency and modal damping parameters in the structure. Idea of the coefficient is based on testing of correlation between predicted, using sensitivity theories and detected by experiment, variations of natural frequency and modal damping.
The MDLAC coefficient can be obtained form the following formula:

$$MDLAC(\{\delta D\}) = \frac{\left|\{\Delta f\}^T\{\delta f\}\right|^2}{\left(\{\Delta f\}^T\{\Delta f\}\right)\left(\{\delta f\}^T\{\delta f\}\right)} \tag{3}$$

where; $\{\delta f\}$ is variation of natural frequency predicted from sensitivity theory and $\{\Delta f\}$ is measured variation of natural frequency. In this approach damage coefficient δD_j indicates how much stiffness of the structure for j-th FE element is changed, but δD is a damage vector which is linear combination of δD_j. In this approach variation of k-th natural frequency can be obtained from the formula:

$$\delta f_k = \sum_{j=1}^{m} \frac{\partial f_k}{\partial D_j} \delta D_j \tag{4}$$

where; m is a number of finite elements in a system model and ∂f_k can be obtained form the formula:

$$\frac{\partial f_k}{\partial D_j} = \frac{\{\phi_k\}^T [K_j] \{\phi_k\}}{8\pi^2 f_k \{\phi_k\}^T [M] \{\phi_k\}} \tag{5}$$

where; M is mass matrix, K is stiffness matrix of FE model. The MDLAC factor is independent on scaling method and describes information only about relative value of damage [11]. But practical application of the method is difficult because 10 to 15 first vibration modes are needed and should be accurate identify. The finite element model should be updated to the measured mode which is very difficult to achieve for so many different modes. Different method of natural frequency variations application for damage detection is described in [33]. An idea of the method is based on solution of inverse eigenproblem. In order to obtain stiffness matrix elements the matrix is written in the form:

$$K = \sum_{i=1}^{n} \alpha_i J_i \tag{6}$$

where; J_i is joint matrix , α_i is a scaling factor for particular Finite elements. The factor is equal 1 if

element is not damaged, n is a number of finite elements in a model. Scaling factor is obtained from comparison of undamaged and current value of natural frequencies and mode shapes.
Damage factor can be obtained from the formula:

$$I_f(i) = \frac{1}{\sum_{j=1}^{p}\left(\alpha_i^j - \overline{\alpha}_i\right)^2} \qquad (7)$$

where; $\overline{\alpha}_i = \frac{1}{p}\sum_{j=1}^{p}\alpha_i^j$

Element for which the damage factor is the biggest, indicate location of damage in a structure.

3.2. Damage detection based on modes shape analysis

Within methods based on application of modes shapes analysis for damage detection the following methods can be distinguish:
- testing of correlation between modal vectors (MAC or CoMAC),
- analysis of mode shapes curvature,
- analysis of deformation energy for particular vibration natural modes.

The MAC coefficient is defined as scalar product of modal vectors that one is obtained for undamaged structure but the second one obtained from current experiment. The MAC factor can be obtained from the formula [2]:

$$\mathrm{MAC}(\Psi_{kr}/\Psi_{ks}) = \frac{\left|(\Psi_{kr}^{*T}\Psi_{ks})\right|^2}{(\Psi_{kr}^{*T}\Psi_{kr})(\Psi_{ks}^{*T}\Psi_{ks})} \qquad (8)$$

where; Ψ_{kr} is k-th mode shape for undamaged structure, Ψ_{ks} is k-th mode shape for currently identified mode shape of the structure. If the MAC is different then one mode shape is seriously modified due to damage. To localize damage in the structure Coordinate MAC (CoMAC) factor can be applied.
The methods based on analysis of mode shape curvature [18] have many advantages against mode shape direct analysis. The curvature is defined as first and second order derivatives of mode shape, which are more sensitive on shape changes, particularly if damage deformed mode shape only locally. But disadvantage of the method is in necessity to hale more measuring points during experiment to obtain enough accurate approximation of derivatives. Effectiveness of the method depends on location of damage in the structure [19, 34].
Knowledge of mode shape can be base to compute deformation energy related to particular mode. If the deformation energy for undamaged and damaged structure are compared, The damage factor can be defined based on comparison results [20]. To define damage factor in this method the energy of deformation with one particular mode shape should be estimated from the formula:

$$SER_{ij} = \frac{\phi_i^T k_j \phi_i}{\phi_i^T K \phi_i} = \frac{\phi_i^T k_j \phi_i}{\omega_i^2} \qquad (9)$$

where; ϕ_i is modal vector for i-th mode shape, ω_i^2 is i-th natural frequency, K is stiffness matrix for FE model, k_j is local stiffness matrix for j-th element.
The damage factor βij can be obtained from the formula:

$$\beta_{ij} = SER^u{}_{ij} - SER^d{}_{ij} \qquad (10)$$

where; index u indicate undamaged structure, but d damaged one. It has been proofed using simulation [35] the method is sensitive to very small changes of system stiffness.

3.3. Damage detection based on FRF analysis

A frequency response function (FRF) can be use for damage detection and can be obtained form modal parameters of the system or directly from measurement. The FRF can be defined as stiffness or compliance [2]. An idea of the method described in [14] is based on comparison of FRF for undamaged structures and damaged one. A damage vector in the method is given by the formula:

$$d = H^{-1}x - f \qquad (11)$$

where; H^{-1} is inverse of FRF matrix, X is displacement vector, f is excitation force vector. If in the structure occurred damaged, then in damage vector *d* non-zero elements will be fund. But the knowledge of excitation forces is required but not easy to acquire in practical cases. If there is not possible to measure excitation force damage factor can be obtained from the formula:

$$r = d + fr = H^{-1}x \qquad (12)$$

where; *d* is not known excitation force and x and f are specified for system with damage. The damage matrix in this case can be obtained form the formula:

$$D^2 = \frac{1}{f_2 - f_1}\int_{f1}^{f2} R \circ R^* df \qquad (13)$$

where; R = r x r*, ∘ is a scalar product, f_1 i f_2 are limits for frequency range. If damage occurs between points *i* and *j* on a structure the element D_{ij} of matrix D will be different then zero.
Because compliance of mechanical systems is dominated by mode shapes for lower frequency, which are relatively easy to identify, the compliance is more often in use then stiffness. An idea of application of system compliance for damage detection is described in [36]. But, the method based on checking of product of stiffness and compliance matrices seems to be very useful [37]. The product should be identity matrix:

$$F_d K_d = I \qquad (14)$$

where; F_d is compliance matrix, K_d is stiffness matrix.
If damage occurred, it can be described by variation of stiffness parameters:

$$K_d = K_u - \Delta K \quad (15)$$

where; ΔK is not known variation of stiffness due to damage. Index $_u$ indicates undamaged structure but index $_d$ damaged one.

Compliance matrix can be obtained from experimental test results based on modal model estimation. To get compliance matrix the modal matrix Φ_d and natural frequency matrix Λ_d are needed:

$$F_d = \Phi_d \Lambda_d^{-2} \Phi_d^T \quad (16)$$

Finally, combining formulas (15) and (16) the formula on base that ΔK can estimated using LS methods:

$$F_d \Delta K = F_d K_u - I \quad (17)$$

The method is very effective and widely use for localization and assessment of structural damages.

3.4. Methods based on regression model parameters tracking

One of the most frequently applied models of dynamic systems in practice is regression model. There are many reasons of that, the regression model identification procedures have many commercial software implementation and the model parameters have defined relations to physical parameters of mechanical structures. The regression model can be relatively easy identifying on-line using recursive identification procedures based on system response measurements only. The regression model, which can be applied for diagnostics is AR type of model. The model equation has the following form [2]:

$$y(t) = \sum_{j=1}^{n} \varphi_j y(t-j) + e(t) \quad (18)$$

where; y(t) is measured response signal, φ_j is vectors of model parameters, but e(t) is model prediction error. The model can be transformed to discrete state space (for ARMA model):

$$x[n] = Ax[n-1] + W[n] \quad (19)$$

where; x[n] is measured, digitized vibration signal, A is discrete state matrix which can be obtained based on AR part model parameters, W[n] is matrix contains coefficients of MA part of the model. From discrete state space model modal parameters of the system can be obtain, but in most applications natural frequency and modal damping are needed:

$$\omega_r = \frac{|\ln(\tau_r)|}{\Delta t} \; and \; \xi_r = -\frac{\mathrm{Re}(\ln(\tau_r))}{|\ln(\tau_r)|} \quad (20)$$

where; τ_r is eigenvalue of matrix A

For regression type of models there are many different identification procedures that can help to obtain model parameters on-line. The procedures have recursive nature based on different formulation of LS method. The methods permit to obtain variations of modal parameters of the structure during operation for each signal sample [9].

Parameters estimation process is mainly realized using the following formula:

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)\varepsilon(t) \quad (21)$$

where; $\hat{\theta}(t)$ is current value of model parameters, ε(t) is model prediction error, K(t) is method related gain coefficient.

Applying formula (21) The model parameters are estimated but from formula (20) modal model parameters can be finally obtained.

Described above procedure has been applied by author for damage detection in airplane based on in-flight measurements [9]. There is more application of this method for power plants machinery and civil structures in the literature [21,23].

3.5. Method based on time – frequency system characteristics

The method is dedicated for systems which operate in nonstationary conditions which is common state of many industrial installations. Using the method modal parameters can be extracted from nonstationary signal measurements. To obtain modal parameters a wavelet transfer function has to be defined employing the following formula [24]:

$$AR(t,f) = \sqrt{\frac{D_i(t,f)}{D_j(t,f)}}$$

$$PH(t,f) = phase\left(\frac{D_i(t,f)}{D_j(t,f)}\right)$$

where; AR(t,f) is time frequency amplitude characteristics between two point on a structure, PH(t,f) is time frequency phase characteristics between two points i i j on a structure, D_i(t,f) is wavlets transform of vibration signal measured at point i on a structure. If in certain frequency range is located natural frequency, then in whole time period of measured signal the amplitude time frequency characteristic will have constant value. To recognize natural frequency from the time frequency characteristic the standard deviation in time domain of both AR and PH characteristics have to be obtained:

$$g(f) = \int_0^T AR(t,f)^2 dt$$

$$h(f) = \int_0^T PH(t,f)^2 dt$$

A natural frequency is located at the frequency for that minimum of standard deviation occurs. The application in diagnostics of structure is tracking of variations of standard deviation of AR and PH in time domain that variations of natural frequency and modal damping can be monitored. The big advantage of the method is possibility to apply its for nonstationary measurements results. The modal parameters can be extracted from wavelet transform of system response signal [38, 39] and use as damage indicator.

4. VALIDATION OF METHODS ON LABORATORY RIG

Chosen methods have been tested on laboratory rig. The frame model shown in figure 3 has been tested for different damage dimensions. The damage in frame system has been introduced changing the cross section of the bar by nicking the bar at point 7 shown in figure 3.

There were 4 modal tests carried out for different damage dimensions and locations:

- TEST 1 for undamaged structure,
- TEST 2 for damage at point 7 with gash deep on 5 mm,
- TEST 3 for damage at point 7 with gash deep on 14 mm,
- TEST 4 for damage at point 7 with gash deep on 20 mm,

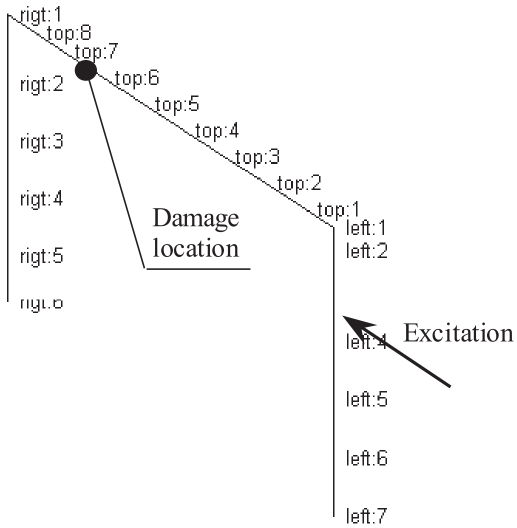

Fig. 3. Scheme of tested structure – laboratory model of frame.

The results are presented in table 1 and in figure 4 for first 8 modes. As it can be notice from presented results not all natural modes are sensitive on damage at point 7. The sensitivity seriously depends on location of gash on a frame. For considered case the 4th mode is most useful for early detection of damage, other modes don't indicate damage in the structure even damage is relatively big.

Table 1.

Comparison of natural frequency of the frame for different damage size.

Nr PDW	Test 1		Test 2		Test 3		Test 4	
	Cz. [Hz]	Δ %	Cz. [Hz]	Δ %	Cz. [Hz]	Δ %	Cz. [Hz]	Δ %
1	10,825	0	10,868	0,398	10,934	1,003	10,841	0,147
2	43,634	0	43,496	0,317	43,466	0,387	43,418	0,497
3	54,521	0	54,44	0,149	54,308	0,392	54,044	0,879
4	**109,487**	**0**	**107,644**	**1,684**	**105,298**	**3,892**	**100,026**	**8,985**
5	120,737	0	119,692	0,866	119,592	0,957	120,292	0,373
6	161,703	0	160,36	0,831	159,424	1,422	159,345	1,48
7	206,269	0	205,583	0,333	205,722	0,267	205,397	0,424
8	228,735	0	229,024	0,127	228,44	0,106	229,409	0,295

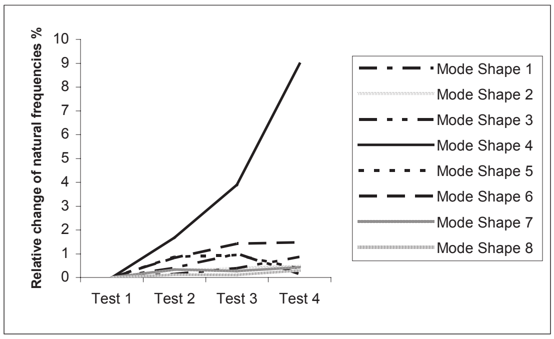

Fig. 4. Plots of natural frequency variations vs. damage size.

The second tested method is based on monitoring of variations of modal damping coefficient. The results are summarized in figure 5 and table 2.

Table 2.

Comparison of modal damping of the frame for different damage size

Nr PDW	Test 1		Test 2		Test 3		Test 4	
	WT %	Δ %	WT %	Δ %	WT %	Δ %	WT %	Δ %
1	7,01	0	5,44	22,397	6,04	11,03	4,38	27,484
2	1,53	0	1,69	10,458	2,87	69,823	2,99	4,182
3	1,99	0	2,07	4,021	2,11	1,933	2,05	2,844
4	1,39	0	1,34	3,598	0,64	52,239	0,95	48,438
5	1	0	1,33	33	1,23	7,519	0,92	25,204
6	0,7	0	0,77	10	0,85	10,39	0,72	15,295
7	3,01	0	3,49	15,947	2,88	17,479	3,08	6,945
8	1,23	0	1,07	13,009	1,23	14,954	0,79	35,773

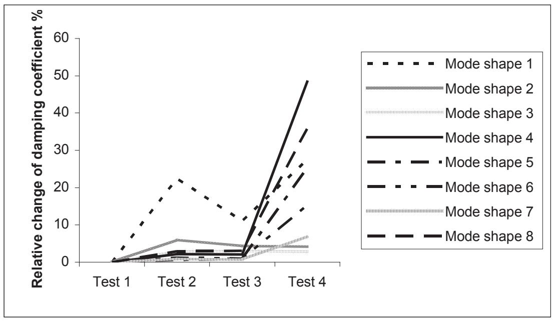

Fig. 5. Plot of modal damping coefficient vs. damage size.

There is no relations in presented results relations between modal damping coefficient and damage size measured as gash dimension. This is due to fact of small accuracy of modal damping identification in mechanical structures.

The next tested method is based on analysis of variation of frequency characteristics of the system. The damage coefficient is computed from formula (0 in this case. The plots of frequency characteristics for different damage size are shown in figure 6. But damage coefficients are shown on plots (figure 7).

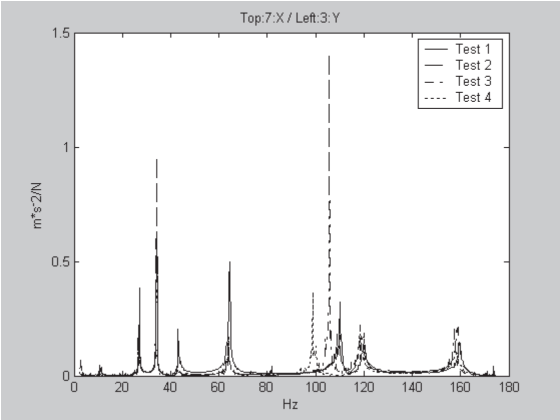

Fig.6. Amplitude frequency characteristics for different size of damage.

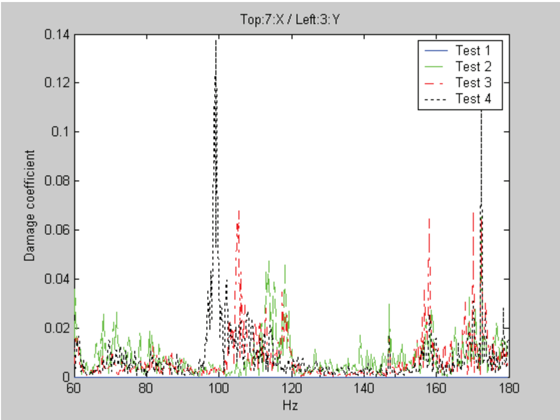

Fig. 7. Damage coefficient for different damage size.

As it can be notice the method is very sensitive on changing of damage dimension.
The results are summarized over all measured frequency range (tab. 3)

Table 3.
Damage indicator for particular damage size.

Test number	Integrated damage coefficient
Test 1 (verification)	0
Test 2	0,0135
Test 3	0,0450
Test 4	0,0939

The methods based on modes shape analysis has been implemented and tested for the frame.
The modes shapes for the frame without damage have been compared with damaged one using MAC factor. For damage localization the CoMAC has been applied. Results of both methods are summarized in Table 3 and Table 4.

Table 4.
MAC factor for different damage size.

	PDW 1	PDW 2	PDW 3	PDW 4	PDW 5	PDW 6	PDW 7	PDW 8
Test 2	0.7096	0.6575	0.5608	0.6406	0.4059	0.4523	0.2064	0.5517
Test 3	0.7019	0.5569	0.5144	0.6267	0.4234	0.3415	0.4280	0.4388
Test 4	0.6944	0.5631	0.5358	0.4743	0.4178	0.4321	0.2420	0.4314

Table 5.
CoMAC factor for different tests (different size of gash)

– for test 2

	Punkt 1	Punkt 2	Punkt 3	Punkt 4	Punkt 5	Punkt 6	Punkt 7
PDW 1	0.9959	0.9933	0.9923	0.9930	0.9982	0.9956	0.9873
PDW 2	0.9845	0.9999	0.9998	0.9998	0.9993	0.9986	0.1032
PDW 3	0.9995	0.9992	0.9631	1.0000	0.9993	0.9975	0.8154
PDW 4	0.8099	0.9318	0.9638	0.9891	0.9944	0.9179	0.4850
PDW 5	0.9929	0.9995	0.9993	0.9987	0.9712	0.9968	0.1671
PDW 6	0.9183	0.9994	0.9986	0.9200	0.9836	0.9619	0.5019
PDW 7	0.7669	0.8884	0.9051	0.8291	0.9759	0.9938	0.1505
PDW 8	0.7757	0.9911	0.9935	0.9598	0.9692	0.9953	0.8526

– for test 3

	Punkt 1	Punkt 2	Punkt 3	Punkt 4	Punkt 5	Punkt 6	Punkt 7
PDW 1	0.9973	0.9984	0.9973	0.9930	0.9930	0.9900	0.9915
PDW 2	0.9867	0.9918	0.9951	0.9956	0.9931	0.9720	0.0947
PDW 3	0.9779	0.9989	0.5137	0.9981	0.9993	0.9967	0.7948
PDW 4	0.8191	0.8462	0.8910	0.9535	0.9906	0.8181	0.3500
PDW 5	0.9955	0.9991	0.9986	0.9959	0.9620	0.9916	0.1654
PDW 6	0.8181	0.9976	0.9983	0.9475	0.9814	0.9489	0.3900
PDW 7	0.0913	0.8343	0.4521	0.0120	0.9463	0.9740	0.1098
PDW 8	0.9598	0.9740	0.8131	0.6578	0.9684	0.9918	0.4791

– for test 4

	Punkt 1	Punkt 2	Punkt 3	Punkt 4	Punkt 5	Punkt 6	Punkt 7
PDW 1	0.9983	0.9895	0.9922	0.9904	0.9943	0.9890	0.9912
PDW 2	0.9597	0.9942	0.9971	0.9976	0.9966	0.9853	0.1064
PDW 3	0.9990	0.9997	0.7955	0.9974	0.9977	0.9987	0.8110
PDW 4	0.5811	0.7415	0.7299	0.7893	0.8745	0.6617	0.0685
PDW 5	0.9960	0.9982	0.9972	0.9924	0.9299	0.9887	0.1551
PDW 6	0.9610	0.9996	0.9988	0.9739	0.9786	0.9487	0.3893
PDW 7	0.8270	0.9530	0.8047	0.4007	0.9925	0.9934	0.0679
PDW 8	0.4418	0.9176	0.9044	0.6881	0.9620	0.9915	0.7053

As it can be notice from the results the method is more sensitive as methods based on monitoring of natural frequencies and modal damping. But localization of damage is possible only for particular chosen vibration mode. For the considered case 4th mode is most sensitive and can be applied for damage localization.
The method based on deformation energy computation for selected vibration modes has been implemented and tested, also. The results are shown in figure 8.

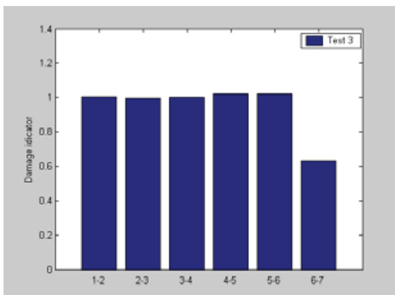

Fig.8. Damage indicator for test 3 on the laboratory frame.

The results obtained from all tests indicated on possibility of damage localization but for rather high damage dimension

5. CASE STUDY

The modal analysis based damage detection methods are employed to identify damage in airplane SKYTRUCK M28.The natural frequency and damping has been monitored on-line using regression model based method. to perform monitoring procedure [9] the special electronic unit has been build and tested. The results are shown in figure 9.

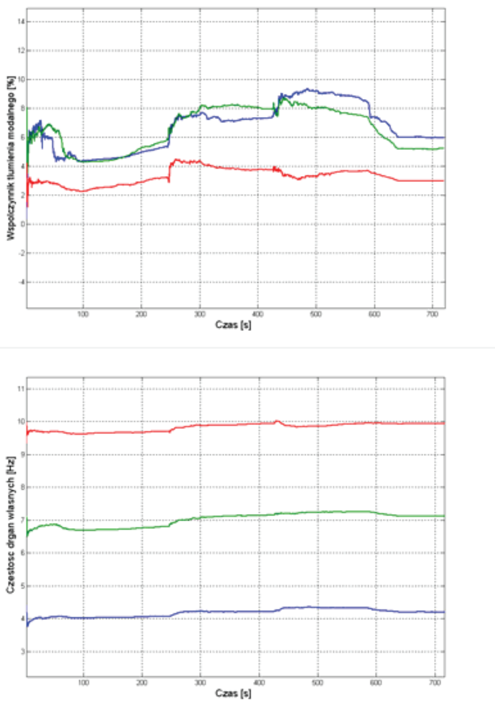

Fig. 9. The results of monitoring of damping and natural frequencies variations for SKYTRUCT M28 .

The method is applied for monitoring of flutter during flight based on vibration measurements, but in the airplane for these flight conditions there is no flutter.

6. CONCLUSIONS AND FINAL REMARKS

The methods tested on laboratory frame have different sensitivity for damage detection of the tested frame. The method based on modal damping in the application of crack detection in tested frame gave worse results then others one. The best results have been achieved using modes shapes based methods.

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