IDENTIFICATION OF THE DAMAGE ZONE IN A COMPOSITE PLATE BY USING FREQUENCY CHANGES

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Introduction

Due to some advantages, e.g., stiffness and strength, compared with homogeneous materials, composite materials are being increasingly used in a variety of engineering applications, such as aircraft, automobiles, sporting goods, and electronics. On the other hand, the mechanical properties of composites can degrade severely in the presence of some damage, which can grow as a combination of such failure modes as matrix cracking, fibre pullout, fibre fracture, fibre-matrix debonding, and delamination between the plies. The structure failure as a result of the damages can lead to tragic consequences. Therefore, damage detection and identification are currently the area of active research. Doebling *et al.* [1] and Zou *et al.* [2] provided an excellent overview on the methods for detecting, localizing, and characterizing damages by examining the changes in the measured vibration parameters registered over the last 30 years. The basic idea is that a damage as a combination of different failure modes in the form of loss of local stiffness in the structure alters its dynamic characteristics, i.e., the modal frequencies, mode shapes, and modal damping values. In such cases, a change in the vibration parameters can be used as an indicator for detecting the damage.

According to the process of treating the measured modal parameters, the vibration-based damage identification methods can be classified as the model- and nonmodel-based ones. The model-based methods identify damages by correlating analyses of structural models, which are usually implemented by the finite-element theory, with experimental modal data of the damaged structure. The model-based damage identification methods are based on modification of the structural model matrices, such as mass, stiffness, and damping, to reproduce as closely as possible the measured static or dynamic response from the data. These methods are based on solving the updated matrices (or perturbations of the nominal model that produce the updated matrices) by forming a constrained optimization problem employing the structural equations of motion, the nominal model, and the measured data. A comparison between the updated matrices and the original correlated matrices provide an indication of damage and can be used to quantify its location and extent [3-5].

In the present study, a model-based damage detection method employing the frequency shifts is presented. The problems on damage detection using the changes in natural frequencies have been widely discussed in the literature. Depending on the approach used, methods based on frequency changes can be classified as the forward and inverse ones.

The forward method consists of calculating the frequency shifts from the known type of damage. The damage is usually modelled mathematically, and the measured frequencies are compared with the frequencies predicted for determining the damage. As an example, Cawley and Adams [6] give a formulation for detecting damage in composite materials from the frequency shifts. Friswell et al. [7] present the results of an attempt to identify damage based on the known catalogue of likely damage scenarios. Juneja et al. [8] present a forward technique called contrast maximization to match the response of the damaged structure to a database of structural responses for locating the damage. They also developed a predictive measure of damage detectability. Other approaches to the forward problem are presented in [9-11].

The inverse problem consists in calculating the damage parameters from the frequency shifts. Stubbs and Osegueda [12, 13] developed a damage detection method using the sensitivity of modal frequency changes that is based on the study by Cawley and Adams [6]. In this method, an error function for each mode and each structural member is computed assuming that only one member is damaged. The member that minimizes this error is determined to be the damaged member. Morassi [14] presents an inverse technique for localizing notch effects in steel frames using the changes in modal frequency. Koh et al. [15] use a recursive method grounded on the static condensation to locate damages based on measured modal frequencies. Further examples of inverse methods for examining changes in modal frequencies for damage indication are presented in [16-29].

The purpose of this study is to develop an experimental numerical method for damage identification. This model-based identification technique employing the method of experiment design and the response surface approach is intended to solve the damage identification (inverse) problem. The response surface approximations are used to build the inverse relations (identification functional) between the experimentally measured and numerically calculated parameters of structure response (modal frequencies). By minimizing the identification functional, the damage parameters are obtained.

Damage Characterization

The general classification system for damage-identification methods includes four levels of damage identification [30].

- Level 1. Determination of the fact that damage is present in the structure.
- Level 2. Level 1 plus determination of the geometric location of the damage.
- Level 3. Level 2 plus quantification of severity of the damage.
- Level 4. Level 3 plus prediction of the remaining service life of the structure.

In the present study, the presence of damage in the general global sense is assumed *a priori*. The location and severity of the damage serve as parameters of identification. The location of a single damage in the structure can be expressed in terms of one parameter x_i in one-dimension model or through the vector of parameters **x** in 2-D and 3-D models

$$\mathbf{x} = \left[x_1, x_2, ..., x_K\right]. \tag{1}$$

These parameters can be evaluated through the identification procedure by using the experimental eigenfrequencies of the system.

Damage Identification Technique

The eigenvalue equation for harmonic vibrations of a plate without damping has the form

$$\mathbf{K}\mathbf{u}_i = \omega_i \mathbf{M}\mathbf{u}_i \text{ for } i = 1,2,...,n, \tag{2}$$

where **K** is the global stiffness matrix of the plate, **M** is the mass matrix, ω_i and $\mathbf{u}_i$ are the ith eigenvalue and eigenvector, respectively, and n is the number of computed natural frequencies and mode shapes. Since the stiffness matrix **K** of the eigenvalue problem (2) is a linear function of identification parameters **x,** the eigenvalues (natural frequencies) are convex functions of the identification vector **x.** In the following theoretical development, let the experimental eigenfrequencies be designated by $\overline{\omega}_1, \overline{\omega}_2, ..., \overline{\omega}_I$, where I is the number of measured eigenfrequencies $\bar{f}_i$ ($\overline{\omega}_i = 2\pi \bar{f}_i$), and the corresponding numerical (damage parameters **x** are used to build the finite-element model**)** eigenfrequencies $\tilde{f}_i$ ($\tilde{\omega}_i = 2\pi \tilde{f}_i$) are represented by $\tilde{\omega}_1, \tilde{\omega}_2, ..., \tilde{\omega}_I$. The functional to be minimized is the deviation between the measured and numerically calculated frequencies

$$\Phi(\boldsymbol{x}) = \sum_{i=1}^{I} \frac{\overline{\omega}_i^{\exp} - \tilde{\omega}_i^{FEM}(\boldsymbol{x})}{\overline{\omega}_i^{\exp 2}}. \tag{3}$$

It is seen that criterion (3) is a non-linear function of the identification parameters $\boldsymbol{x}$. The identification of the damage parameters $\boldsymbol{x}$ is performed based on the information obtained by measuring I lowest frequencies. The identification problem is formulated as follows

$$\min_{\mathbf{x}} \Phi(\boldsymbol{x}). \tag{4}$$

Subjected to

$$x_i^{\min} \le x_i \le x_i^{\max}; \quad i = 1,2,...K, \tag{5}$$

where $x_i^{\min}$ and $x_i^{\max}$ are the lower and upper side constraints, respectively, and K is the number of identification parameters. The upper and lower limits of the identification parameters are chosen different for each case of damage identification.

Numerical Example

To evaluate the possibility of employing the changes in modal frequencies for identifying the size and location of damage, it was suggested to substitute the natural experiment by a numerical one.

For this reason, the work on damage identification carried out by Rikards in [31] was repeated. In that study, two identification parameters (the location of the centre x_1 and the width x_2 of the damage zone) were introduced (see *Fig.1*). The damage of a transversely isotropic plate was introduced by reducing the stiffness of the damaged zone by 50%.

$$E_1^* = 0.5E_1; \qquad E_2^* = 0.5E_2; \qquad G_{12}^* = 0.5G_{12}. \tag{6}$$

The location and the width of the damaged zone in a quadratic orthotropic plate (a=b=140 mm, h=2mm) are given by x_1^{exp} = 0.591a and x_2^{exp} =0.273a, respectively. The structure analyzed was a glass-fibre-reinforced epoxy composite plate. The material properties are given in *Table 1*. The laminate lay-up for the plate was $[90/0/90/0]_s$.

Table1. Material Properties of a Glass/Epoxy Composite

Property	Value
E_1, GPa	110.0
E_2, GPa	10.0
G_{12}, GPa	5.0
G_{23}, GPa	3.0
ν_{12}	0.3

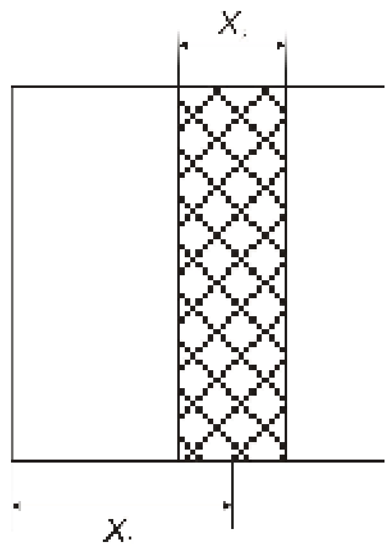

Fig. 1. Location of the damage zone in a composite plate (with K=2 identification parameters).

The above parameters were used for building the finite-element model of a damaged plate. In [31], a 22 x 22 regular finite-element mesh (using a triangular finite element with a shear correction) was considered. Since nowadays the computations take significantly less time, in the present study, a 100 x 100 regular mesh was taken in order to achieve a higher accuracy. The finite-element model was modelled by layered eight-node shear-deformable shell elements (ANSYS 11.0 [32]). Each node had six degrees of freedom, namely three displacements and three rotations. Further, the first 10 eigenfrequencies of the laminated plate with FFFF (all edges free) boundary conditions were calculated by solving the eigenvalue problem (2). These numerical frequencies were assumed as experimental frequencies of the damaged plate. The calculated frequencies of the intact and damaged plates are presented in *Table 2*. The changes (in percentage) are calculated as follows

$$\Delta = \frac{|\omega_i - \omega_d|}{\omega_i} \times 100\,. \tag{7}$$

Table 2. Natural Frequencies for the Intact and Damaged Plate

Mode No.	Natural frequency (Hz)		Change in %
	Intact	Damaged	
1	199.2	180.53	9.39
2	550.5	435.07	20.97
3	681.5	578.38	15.13
4	761.4	690.07	9.37
5	858.3	828.21	3.51
6	1242.6	1123.1	9.62
7	1514.5	1343.1	11.32
8	1623.7	1447.4	10.86
9	2082.2	1802.2	13.45
10	2083.2	1880.7	9.72

Then, the experimental design [33-37] with 25 sample points was used. Previous investigations [33, 34] show that the second-order polynomial approximations give very accurate approximations for the metamodels of eigenfrequencies. Therefore, the experimental design was planned using the criteria of *D*-optimality [34]. Unlike the classical *D*-optimal design, in the present method, designs of a Latin hypercube (LH) type [34] are employed. The minimal number of sampling points for a second-order polynomial with K variables is

$$N = \frac{(K+1)(K+2)}{2}\,. \tag{8}$$

Since in our case the FEM calculations are not time-consuming, 25 sampling points were used. The domain of interest was assumed as follows

$$\begin{aligned} 0.5a &\le x_1 \le 0.7a \\ 0.15a &\le x_2 \le 0.35a \end{aligned}\,. \tag{9}$$

In these sample points, the first 10 eigenfrequencies were calculated. The data were used to obtain the approximating functions [33-37] for all 10 frequencies. These functions were used in the identification functional (3). Minimizing this functional, the location of the centre x_1 and the width x_2 of the damage zone were obtained:

$x_1^* = 0.589\text{a}$, $x_2^* = 0.274\text{a}$.

As it is seen, the values of location and size of the damaged zone are very close to those introduced in the numerical experiment.

In order to expand this method, it was proposed to introduce two more damage-zone parameters: the location of the centre x_3 and the width x_4 of the damage zone in the *Y* direction of the plate (see *Figure 2*).

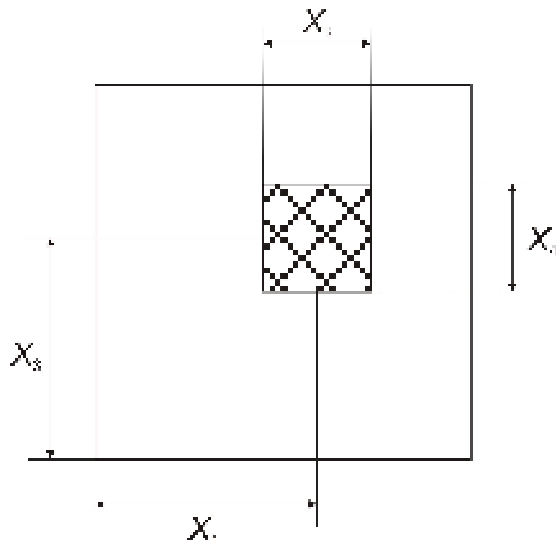

Fig. 2. Location of the damage zone in a composite plate (with K=4 identification parameters).

The location and the size of the damaged zone in the composite plate are given by $x_1^{exp} = 0.591a$, $x_2^{exp} = 0.273a$, $x_3^{exp} = 0.591a$, and $x_4^{exp} = 0.273a$, respectively. The finite-element mesh was taken 100 x 100, i.e., the same as for the previous example. Again, the first 10 eigenfrequencies of the laminated plate under FFFF boundary conditions were calculated and denoted as experimental frequencies of the damaged plate. Then, the experiment design with $K = 4$ variables and 75 sample points was selected. The domain of interest was assumed as follows

$$\begin{aligned} &0.5a \le x_1 \le 0.7a \\ &0.15a \le x_2 \le 0.35a \\ &0.5a \le x_3 \le 0.7a \\ &0.15a \le x_4 \le 0.35a \end{aligned} \qquad (10)$$

Applying the identification technique described above, following results were obtained:

$x_1^* = 0.581a$, $x_2^* = 0.273a$, $x_3^* = 0.584a$, $x_4^* = 0.270a$.

Again, the values of location and size of the damaged zone are very close to those introduced in the numerical experiment. Now, we will consider the effect of damage extent on the accuracy of identification. The location and size of the damaged zone in a composite plate were taken the same as previously. The damage extent was introduced by reducing the stiffness of the damaged zone by 10, 30, 50, 70, and 90%. The frequencies calculated for each damage scenario and a comparison with the natural frequencies of the intact plate are shown in *Tables 3* and *4*.

Table 3. Natural Frequencies for the Intact and Damaged Plates

Mode No.	Natural frequency (Hz)					
	Intact	Case 1 (10%)	Case 2 (30%)	Case 3 (50%)	Case 4 (70%)	Case 5 (90%)
1	199.2	198.4	196.6	194.8	192.8	190.5
2	550.5	546.3	536.6	524.5	508.5	483.9
3	681.5	680.5	678.3	675.8	672.2	648.7
4	761.4	755.4	740.9	721.5	694.6	671.7
5	858.3	857.0	854.2	851.2	847.9	843.2
6	1242.6	1235.6	1219.1	1198.6	1172.4	1137.2
7	1514.5	1508.4	1493.7	1473.4	1441.0	1365.9
8	1623.7	1622.1	1618.6	1614.6	1609.8	1600.4
9	2082.2	2071.8	2044.9	2007.0	1944.3	1778.8
10	2083.2	2076.6	2061.1	2039.1	2003.2	1932.1

Table 4. Changes in Natural Frequencies for the Intact and Damaged Plates

Mode No.	Changes in %					
	Intact	Case 1 (10%)	Case 2 (30%)	Case 3 (50%)	Case 4 (70%)	Case 5 (90%)
1	-	0.43	1.31	2.25	3.26	4.37
2	-	0.77	2.53	4.72	7.63	12.11
3	-	0.15	0.47	0.83	1.36	4.81
4	-	0.78	2.69	5.24	8.78	11.78
5	-	0.16	0.48	0.82	1.22	1.76
6	-	0.56	1.89	3.54	5.65	8.48
7	-	0.40	1.37	2.71	4.85	9.81
8	-	0.10	0.31	0.56	0.86	1.43
9	-	0.50	1.79	3.61	6.62	14.57
10	-	0.32	1.06	2.12	3.84	7.25

The accuracy is estimated by summing the calculated residuals for each of the parameters to be identified

$$\Delta = \sum_{i}^{4} \frac{\left| x_i^* - x_i^{\exp} \right|}{x_i^{\exp}} \times 100 \,. \tag{11}$$

The results of identification are given in *Table 5.* The effect of damage extent on the accuracy of identification is shown in *Table* 6 and *Fig. 3*. As seen from the results obtained, this effect is not significant since the residuals are very small for each damage-case scenario. However, it should be noted that the accuracy decreases with increasing damage extent.

Table 5. Identified Damage Parameters for Each Damage Case

Damage parameter	Experiment	Identified				
		Case 1 (10%)	Case 2 (30%)	Case 3 (50%)	Case 4 (70%)	Case 5 (90%)
x_1	0.591a	0.591a	0.583a	0.581a	0.585a	0.591a
x_2	0.273a	0.275a	0.272a	0.273a	0.272a	0.268a
x_3	0.591a	0.590a	0.583a	0.584a	0.577a	0.569a
x_4	0.273a	0.275a	0.272a	0.270a	0.271a	0.276a

Table 6. Residuals for Identified Damage-Zone Parameters

Residuals	Experiment	Identified				
		Case 1 (10%)	Case 2 (30%)	Case 3 (50%)	Case 4 (70%)	Case 5 (90%)
Δ_1	-	0.00	1.35	1.69	1.02	0.00
Δ_2	-	0.73	0.37	0.00	0.37	1.83
Δ_3	-	0.17	1.35	1.18	2.37	3.72
Δ_4	-	0.73	0.37	1.10	0.73	1.10
sum	-	0.41	0.86	0.99	1.12	1.66

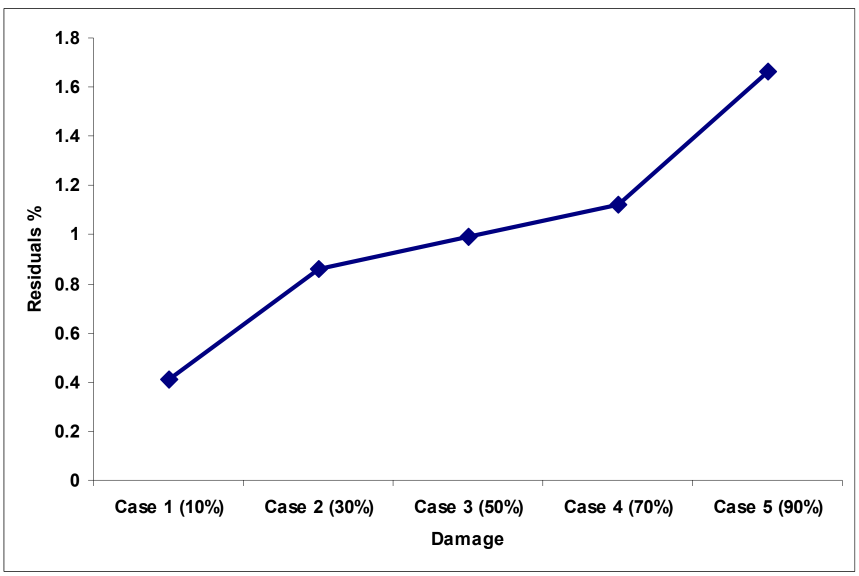

Fig. 3. Effect of damage extent on the accuracy of identification.

Apart from the damage extent, another significant parameter which can affect the accuracy of identification is the area of damage zone. To evaluate this effect, the finite-element calculations and identification of damage zone parameters were carried out by changing the area of damaged zone (x_2^{exp}, x_4^{exp}) in the previously defined domain of interest (8). The location of the damage zone was fixed (x_1^{exp} = 0.6a, x_3^{exp} =0.6a), and the damage extent was introduced by reducing the stiffness of the damaged zone by 90%. The results are shown in *Fig. 4*. It is seen that the area of the damaged zone has a noticeable influence on the accuracy of identification, which should be taken into account in the course of identification procedure.

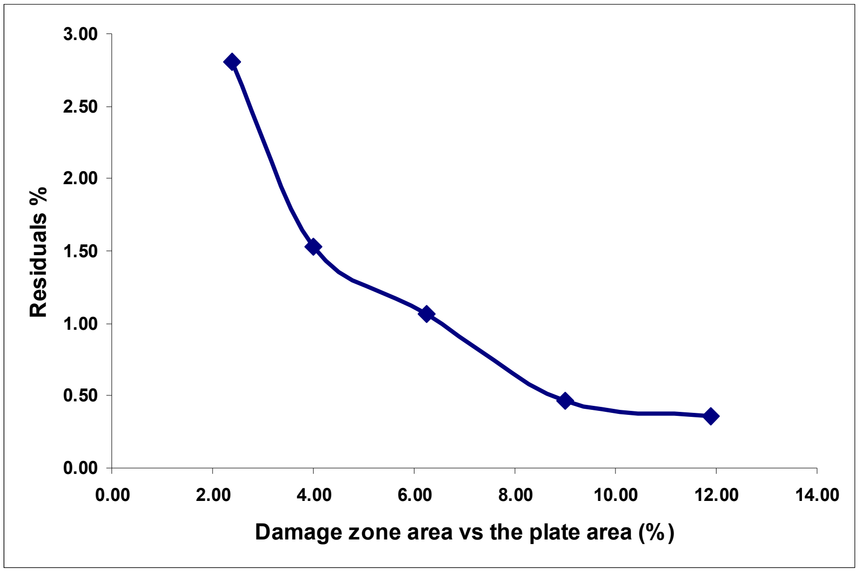

Fig. 4. Effect of damage-zone area on the accuracy of identification.

Since in the real structures the damage extent is one of the parameters of identification, it was suggested to add the damage extent as the fifth variable x_5 to the identification vector. In order to realize the possibilities of the proposed damage identification method after the introduction of the damage extent as the fifth identification parameter, the location and size of the damaged zone as well as the damage extent in the composite plate were taken the same as in previous example of damage identification with four damage parameters: $x_1^{exp} = 0.591a$, $x_2^{exp} = 0.273a$, $x_3^{exp} = 0.591a$, and $x_4^{exp} = 0.273a$, $x_5^{exp} = 0.5$. The finite-element model was built, and the first 10 eigenfrequencies were calculated. In this case, the experimental design with five variables and 101 sample points was used. The domain of interest was selected as follows

$$\begin{aligned} &0.5a \le x_1 \le 0.7a \\ &0.15a \le x_2 \le 0.35a \\ &0.5a \le x_3 \le 0.7a \\ &0.15a \le x_4 \le 0.35a \\ &0.45 \le x_5 \le 0.55 \end{aligned} \qquad (13)$$

By minimizing the identification functional (3) following results were obtained

$$x_1^* = 0.589a,\ x_2^* = 0.274a,\ x_3^* = 0.589a,\ x_4^* = 0.274a,\ x_5^* = 0.51.$$

It should be noted that in the process of search, the limits of the domain of interest can be moved if, for example, the identified constants are beyond the limits or if the search accuracy should be increased. From the process of search, it is seen that, in order to achieve a satisfactory accuracy, the range of the domain of interest for the damage extent should be small, i.e., not exceed 10%.

Conclusions

The damage zone parameters (location and extent) in a laminated composite plate were determined by using the identification technique based on the method of experimental design and the response-surface approach. The identification procedure was realized by substituting the natural experiment by a numerical one. It was shown that the values of location and size of the damaged zone obtained are very close to those introduced in the numerical experiment. However, from the results obtained, several moments should be emphasized.

- It can be seen from Table 4 that the changes in natural frequencies increase from Case 1 to Case 5 with increasing damage extent. For the first two cases, the changes in natural frequencies are very small and hardly exceed the measurement error; therefore, this fact should be taken into account when performing the identification procedure in the natural experiment.
- When the damage extent is used as an identification parameter, the domain of interest must be chosen very carefully, and the difference between the upper and lower bounds should not exceed 10%.
- It is seen that the area of the damaged zone noticeably affects the accuracy of identification, which must be taken into account in the identification procedure.
- To achieve satisfactory results for the real structure by using the identification method proposed, other dynamic characteristics (mode shapes, modal damping, and mode shape curvatures) should be added to the identification functional.

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Ručevskis S. Bojājuma zonas noteikšana kompozītmateriāla plātnē izmantojot pašsvārstību frekvenču izmaiņas

Pateicoties kompozīto materiālu stinguma un stiprības priekšrocībām, tie tiek plaši lietoti tādās nozarēs kā avio būve automobiļu būve, elektronika, sporta inventāra ražošana. Bet tai pašā laikā šīs mehānisko īpašību priekšrocības var strauji mazināties, ja materiāls tiek bojāts. Dotajā rakstā tiek apskatīta skaitliski eksperimentāla metode bojājuma identifikācijai. Identifikācijas metode, kas balstīta uz skaitliskā eksperimenta plānošanas un atbildes virsmas metodes piegājieniem, tiek izmantota, lai risinātu identifikācijas uzdevumu. Atbildes virsmas metodes aproksimācijas tiek izmantotas, lai būvētu apgrieztās sakarības (identifikācijas funkcionāls) starp eksperimentāli nomērītiem un skaitliski aprēķinātiem konstrukcijas dinamiskajiem parametriem (pašsvārstību frekvences). Bojājuma parametri tiek iegūti minimizējot identifikācijas funkcionāli. Identifikācijas metode tiek pārbaudīta aizstājot dabisko eksperimentu

ar skaitlisku. Skaitliskā eksperimenta uzstādītie bojājuma zonas parametri tika atrasti izmantojot identifikācijas metodi. Iegūtie rezultāti ir tuvi uzstādītajiem bojājuma zonas parametriem.

Ručevskis S. Identification of the damage zone in a composite plate by using frequency changes

Due to some advantages, e.g., stiffness and strength, compared with homogeneous materials, composite materials are being increasing used in a variety of engineering application, such as aircraft, automobiles, sporting goods, and electronics. On the other hand, the mechanical properties of composites can degrade severely in the presence of some damage. In the present study, a numerical-experimental method for the damage identification is described. For this purpose, a model-based identification technique based on the method of experiment design and the response-surface approach is suggested for solving the damage identification (inverse) problem. The response-surface approximations are used for constructing the inverse relations (identification functional) between the experimentally measured and numerically calculated parameters of the response of structure (modal frequencies). By minimizing the identification functional, the damage parameters are obtained. The identification procedure is realized by substituting the natural experiment with a numerical one. It is shown that about the values of location and size of the damaged zone obtained are similar to those determined in the numerical experiment. The effect of the damage extent and the size of damaged area on the accuracy of identification is also investigated.

Ручевскис С. Идентификация зоны повреждения в композитной пластине используя изменение частот

Благодаря таким свойствам композитного материала как высокая удельная прочность и жесткость, позволяет широко использовать данный материал в различных промышленных областях: авиастроение, автомобилестроение, производство спортивных товаров и в электронике. Однако механические свойства композитного материала ухудшаются при некоторых повреждениях материала. В данной работе описывается численно-экспериментальный метод для идентификации данных повреждений. Метод идентификации основывается на численно-экспериментальном методе планирования и использования поверхностного отклика для решения идентификационной проблемы. Аппроксимация метода частотного отклика используется для создания обратной зависимости (функционал идентификации) между данными эксперимента и численными данными расчета по динамическим параметрам (собственные частоты). Используя функционал минимизации, были получены параметры повреждения. Метод идентификации был проверен заменой экспериментальных данных на численные данные. Полученные экспериментальные результаты размера и места зоны повреждения, совпадают с результатами численного расчета. Дополнительно проведено исследование влияния размеров зоны повреждения на точность идентификации.