VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

Paulius RAGAUSKAS

IDENTIFICATION OF ELASTIC PROPERTIES OF LAYERED COMPOSITE MATERIALS

SUMMARY OF DOCTORAL DISSERTATION

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Introduction

Topicality of the problem

Layered composite materials are now widely applied in various industries such as aviation, automotive manufacturing, etc. Knowledge of the elastic characteristics of composite materials is essential for the design and analysis of structures.

Composites are heterogeneous in opposition to isotropic; therefore, identification of elastic characteristics of layered composite materials is more complicated, but still can be determined by conventional static or ultrasound methods.

Static testing is based on the strain field measurements. The main constraints of such tests are the difficulties of ensuring proper conditions for specimens and obtaining homogeneous strain / stress fields. Usually, several static tests are needed. For example, three static tests are necessary to identify four elastic characteristics of unidirectional layered material. In addition, majority of laminates are filled with polymer material which is viscous – this as well poses problems for identification of elastic characteristics of composites.

The main problem in ultrasound testing is that layered composite materials often have high damping characteristics and therefore the ultrasonic wave diffraction and attenuation yields inaccurate results.

For these reasons, indirect methods of identification of elastic characteristics of materials receive special attention recently. One of the methods of indirect identification is measuring of structure reactions to the vibration-excitation, and then simulation of the same structure using numerical methods with guessed elastic characteristics of material trying to obtain the same structural behavior. Guess of elastic characteristics of the material – test is formulated as problem of global optimization where objective function equals difference between experimental and numerical natural frequencies of specimen.

The proposed technology is based on the double numerical experiment: elastic characteristics of material and geometrical parameters close to any real material specimen are selected and converged solution of eigenvalues is obtained using finite element method. Then, elastic characteristics of material are obtained using the proposed technology. A certain kind of information from natural testing is involved in these experiments: not all the eigenfrequencies are retrieved during the experiments, therefore in the numerical experiments only the lower eigenfrequencies are included, to reed from natural experiments as far as possible.

Thus, proven technology then can be applied for identification of elastic characteristics of real materials.

Current digital-physical and optimization technologies of identification of elastic characteristics of materials are still in development and are being used for non-industrial purposes. The main shortcoming of the existing technologies is that the elastic characteristics of layered composite materials are found with poor accuracy. The Poisson's ratios have the lowest accuracy of identification.

Proposed technology is non-destructive and therefore can be used directly in manufacturing process. Despite these shortcomings, technology is developed intensively in order to create an engineering tool for accurate and quick identification of all the elastic characteristics of material with sufficient accuracy.

The object of investigations. Samples of isotropic, composite one-layer and layered, unidirectional and perpendicular reinforced materials, their elastic characteristics. Elastic characteristics of materials are identified by eigenfrequencies of stimulated samples.

Aim and tasks of the work. The aims of present work are as follow: to create effective technology for precise identification of all elastic characteristics of the sample using global optimization algorithm; to investigate identification accuracy and sensitivity of elastic characteristics.

The main task is to develop and perform tests of technology that would identify all elastic characteristics of the material with sufficient precision. This requires:

- to optimize the geometric parameters of the sample for more accurate results of identification of elastic characteristics;
- to identify mode shapes of the sample and adjust their positions in the objective function to minimize its distortion;
- to create algorithms of the proposed technology and verify their capabilities experimentally.

Research methodology. The numeric methods are used in dissertation. In the objective function difference of numerical and natural eigenfrequencies of specimens is minimized. Data to calculate the objective function is derived from natural experiment and finite element method. The optimization is performed using genetic algorithms.

Scientific novelty. The two-step technology effectively identifying elastic characteristics of the samples with sufficient accuracy is proposed and programmatically realized. The technology includes never previously in a single algorithm used sample side ratio optimization and mode shape recognition and their place regulatory in objective function tools, which allow speed up identification of the elastic characteristics significantly and increase the accuracy of the results.

Practical value. Developed software tools for identification of the elastic characteristics of various materials with uniform accuracy. The proposed technology can be used in research laboratories, manufacture of composite materials, which today are fast growing industries all over the world. Their products are widely used in aviation, maritime, land transport and construction industries.

Defended propositions

1. The proposed optimization of the geometry of the sample and the sample mode shape identification allows identify elastic characteristics of material more efficiently and accurately.
2. More accurate solution (elastic characteristics) could be found using several material samples with geometry, optimized for a certain elastic characteristic.

Approval of the job. Five reports on the topic of dissertation were presented in scientific conferences in Lithuania and abroad, and four articles were published.

The structure of the research paper. The research paper consists of four chapters: an introduction; literature review; the proposed technology tests; technology performance improvements; description of technology software and user interface; summary of results.

The total volume of the dissertation is 110 pages, 32 numbered equations, 54 pictures, 23 tables and 116 references.

1. Overview of the identification technology of elastic characteristics of materials and optimization algorithms

The main and the most popular task of identification of elastic characteristics of materials – presently there is no universal method, without any essential changes suitable for identification of elastic characteristics of many materials. This is caused by the samples used, namely their size, shape and other geometric characteristics. In the technology proposed in this thesis offers the usual material elastic characteristics identification algorithm supplemented with the sample geometry optimization tools. According to several tests of the proposed technology and on the basis of the global practice optimal samples in common are submitted.

Genetic algorithms for the identification of material elastic characteristics are selected from all stochastic algorithms reviewed in thesis. Deterministic algorithms are rejected due to unknown objective function gradients. In other words, it is too expensive to calculate the derivative numerically.

Solving optimization problems using genetic algorithms properly identified genetic parameters has significant influence to precision – number of generations, crossover and mutation probability values. These values have to be chosen on the basis of the algorithm operation tests. Genetic parameters for material properties identification problem are chosen individually according to the task characteristic and the context of global practices.

The proposed technology is tested in two phases on different materials. In the first phase elastic characteristics of the materials are identified using samples with non-optimized geometric parameters. Then sample geometry is optimized and elastic characteristics of materials are re-identified. The obtained results are compared with the similar tests results found in scientific literature.

2. Identification technology of elastic characteristics of materials

Elastic characteristics of material are found in two steps. The first step is a natural experiment, a test from which eigenfrequencies of material are obtained. In the second step numerical and experimentally obtained sample eigenfrequencies with assumed elastic characteristics are compared. Discrepancies are minimized in objective function (difference between natural and calculated eigenfrequencies). The first step of identification of elastic characteristics is substantially equal for all materials. In the second step number of identified parameters and used eigenfrequencies depend on problem content. In optimization procedure the variables are genetic parameters only.

Sample is suspended on thin strings simulating free conditions in all the samples sides. The sample is continuously stimulated by piezoceramic disc and its surface reaction is measured by laser. The eigenfrequencies of sample are calculated out of surface reaction.

Finite element model of material is updated by replacing elastic characteristics till it coincides with eigenfrequencies of natural experiment with the required accuracy. It is considered that elastic properties of numerical model of material and natural specimens properties coincides if difference of the frequencies satisfies allowed tolerance.

Objective function *F(K)* of identification of elastic characteristics of materials problem is:

$$F(K) = \sum_{i=1}^{n} \frac{(f_i^{FEM} - f_i^{NE})^2}{(f_i^{NE})^2}, \qquad (1)$$

where [f_i^{FEM}] – calculated eigenfrequencies of specimen, [f_i^{NE}] – natural eigenfrequencies of specimen.

Squared deviations are taken so that the objective function was always positive. State variables of problem are eigenfrequencies, and design variables are the elastic characteristics of material.

Restrictions *k* are applied in order to achieve more effective problem solution:

$$k_i^{\min} \le k_i \le k_i^{\max}\text{, where i = 1, 2,... , 9.} \qquad (2)$$

After that, the differences between frequencies of specimen and a digital model are minimized:

$$\min F = F(x,[K]), \qquad (3)$$

where [*K*] – stiffness matrix of the structure, *x* – vector of variables.

Classical FEM equation to calculate the eigenfrequencies of specimen:

$$\det([K] - \omega^2 [M]) = 0, \qquad (4)$$

where [*M*] is mass matrix and ω – eigenfrequencies.

The full spectrum of eigenvalues is obtained from the test (natural or digital). Numerical experiments show sufficient part of spectrum for the identification of the elastic characteristics of materials. Equation of eigenfrequencies is following:

$$f_i(x,[K]), i = 1,2...,n, \qquad (5)$$

where *n* – part of spectrum of the eigenvalues.

Data used in the test sample is divided into measurable and enumeration of parameters, i.e. elastic characteristics. Solution of identification problem is derived from the measured independent parameters of the model. These parameters are as follows: the sample length (*a*), width (*b*), thickness (*h*), angle of orthotropy (γ) and eigenfrequencies (f_i). Material density ρ is defined not as a variable, but as a digital constant. The vector of variables:

$$x = \{a, b, h, \gamma, f_i\}^T . \tag{6}$$

Stiffness matrix is function of elastic modules *E*, shear modules *G* and Poisson's ratios υ (quantity of elastic characteristics depends on the material). For example, when isotropic material is analyzed, the material is described by E and υ elastic characteristics only; whereas orthotropic material is described by nine independent elastic characteristics:

$$[K] = f(E_1, E_2, G_{12}, \upsilon_{12}, \upsilon_{13}, \upsilon_{23}, E_3, G_{13}, G_{23}) . \tag{7}$$

Identification technology of elastic characteristics of materials consists of three parts. The main part is the proposed technology (Fig. 2.1) which consists of FEM and optimization procedures. These elements are involved in the sample geometry optimization as well as in identification processes of elastic characteristics of material. User interface allows manage this technology. Sample eigenfrequencies are input data, and the result is the identified elastic characteristics of material, submitted through the user interface.

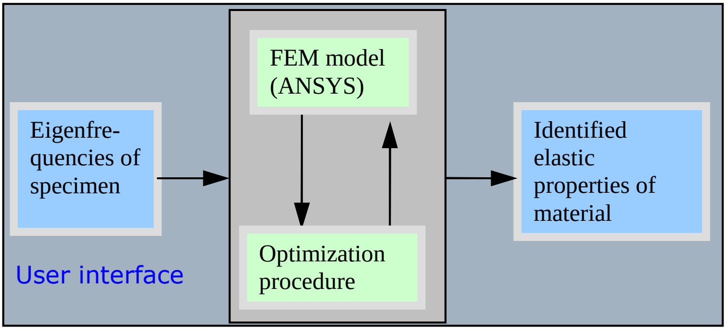

Fig. 2.1. Identification technology of elastic properties of materials

Handling this technology elastic characteristics of material, namely Young's modules E_i, shear modules G_{ij} and Poisson's ratios ν_{ij}, are found. The identification cycle consists of five stages: optimization algorithm, FEM simulation (ANSYS package), evaluation of discrepancies, inspection of cycle completion, and the output of results.

Identification technology of elastic characteristics of materials was tested on four different materials. First was chosen isotropic material – aluminum, then advanced materials such as single layer glass and carbon fibers, unidirectional and perpendicular reinforced multilayer laminates. Technology tests on the advanced materials have revealed deficiencies, which have led to solutions to overcome them.

Elastic characteristics of aluminum were identified (Table 2.1) and the results analyzed. Identification technology of elastic characteristics of materials identifies all characteristics of an isotropic material, since all three specimens used in test were identified with a sufficient accuracy, i.e. at approximately 0.1% error.

Table 2.1. Identified elastic characteristics of aluminum

Elastic characteristics	Ref.	SP1	Δ, %	SP2	Δ, %	SP3	Δ, %
E_1, *GPa*	68.9	70.04	0.016	68.71	0.003	68.24	0.01
G_{12}, *GPa*	26	25.89	0.004	24.85	0.046	26.49	0.018
ν_{12}	0.33	0.3526	0.064	0.3825	0.137	0.288	0.146

Identified elastic characteristics of the glass and carbon fibers (Table 2.2) show that the longitudinal Young's modulus E_1 is found with satisfying accuracy, but the shear modulus G_{23} is found with high error because the sample is thin enough (2 mm) and at such thickness shear modulus does not affect the eigenfrequencies of sample. The same goes to E_3 , G_{23} and ν_{23} : small sample thickness yields poor influence on the eigenfrequencies.

Table 2.2. Identified elastic characteristics of glass and carbon fiber

Elastic characteristics	Glass fiber			Carbon fiber		
	Ref.	Res.	Δ, %	Ref.	Res.	Δ, %
E_1, *GPa*	45.2	45.3	0.22	229.4	228	0.61
E_2=E_3, *GPa*	10.8	10.8	0.00	10.8	12	10,00
G_{12} =G_{13}, *GPa*	4.57	4.54	0.66	4.57	5.16	11.43
G_{23}, *GPa*	3.96	6.21	36.23	3.96	6.72	41.07
ν_{12}=ν_{13}	0.31	0.321	3.39	0.32	0.348	8.01
ν_{23}	0.36	0.384	6.42	0.39	0.351	11.02

As for unidirectional single-layer composite, longitudinal modulus of unidirectional layered material is found particularly accurately (Table 2.3). Out of plane elastic characteristics are found with poor accuracy because the sample thickness does not affect the characteristics of a sufficient sample eigenfrequencies. As shown in Table 2.3, the elastic characteristic of the first sample are found sufficiently precise, unlike the second. This could happen due to physical defects of the second sample. With such performance difference the sample should be rejected as inappropriate.

Table 2.3. Identified elastic characteristics of unidirectional material

Elastic characteristics	LA-UD-SP1			LA-UD-SP2		
	LTLC	LT	Δ, %	LTLC	LT	Δ, %
E_1, GPa	171.05	169.63	-0.837	171.37	170	-0.806
$E_2=E_3$, GPa	10.44	10.24	-1.953	11.20	10.6	-5.660
$G_{12}=G_{13}$, GPa	6.07	6.19	1.939	6.35	6.15	-3.252
G_{23}, GPa	7.71	7.22	-6.787	4.57	4.00	-14.250
$\nu_{12}=\nu_{13}$	0.48	0.47	-2.128	0.23	0.34	32.353

Analysis of identification results suggests that the proposed technology is appropriate to find some (with high influence to the sample eigenfrequencies) elastic characteristics of unidirectional layered material.

Like the unidirectional layered material, for perpendicular reinforced layered material to the longitudinal Young's modulus is found particularly accurate, but identification accuracy of the Poisson's ratio is far too low (Table 2.4). Despite the fact, that Poisson's ratio is found with sufficient accuracy in one experiment, the average test results are unsatisfactory. It is concluded that traditional technology does not ensure identification of elastic characteristics of perpendicular reinforced layered material with sufficient accuracy.

Table 2.4. Identified elastic characteristics of perpendicular reinforced material

Elastic characteristics	Ref.	Res.	Δ, %
E_1, GPa	23.30	23.362	0.2654
$E_2=E_3$, GPa	13.80	14.23	3.0218
$G_{12}=G_{13}=G_{23}$ GPa	2.70	2.71	0.3690
$\nu_{12}=\nu_{13}=\nu_{23}$	0.217	0.2566	15.4326

Using traditional material properties identification technology all material elastic characteristics can be found with sufficient accuracy if mathematical model of material is simple (e.g., isotropic). Materials described by more than two elastic characteristics are identified with a considerably larger error. Tests have shown that longitudinal Young's modulus of various materials can be found with sufficient accuracy, but other elastic characteristics are identified with significantly too low accuracy.

Poisson's ratios and shear modules do not have such evident effect on eigenfrequencies of the sample in opposition to Young's modulus. In order to accurately identify these values a change in geometrical characteristics of the sample (aspect ratio, thickness, orthotropic angle) should be made; these changes highlight effect of elastic properties to eigenfrequencies of sample.

Identifying elastic characteristics of unidirectional and layered materials mathematical material models have been simplified from three-dimensional to two-dimensional eliminating out of plane elastic characteristics. This helped to speed up calculations and obtain more accurate results, since in the optimization problem was fewer design variables.

Square samples, as revealed by testing, are inappropriate for identification of the elastic characteristics of materials, as they observed phenomenon when two adjacent modes are mirror images of each other and their frequencies are identical or very close, so there are unnecessary information loaded in objective function and computation time is prolonged. In order to avoid this in identification of elastic characteristics of material such modes are omitted.

3. Improving the identification results of elastic characteristics of materials

Experiments performed with various materials exposed shortcomings of the traditional identification technology of elastic characteristics of material, discussed in the previous chapter. It is supposed that optimization of geometrical parameters of sample to certain elastic characteristics of material will affect identification accuracy.

In the process of identification of elastic characteristics of materials the identification of switched modes has considerable significance. During the calculations changing the elastic characteristics of material, a certain (usually higher order) modes may change their place in spectrum. In search of elastic characteristics of composite materials at a certain combination of design variables there can be more switched modes, hence, the accuracy of final result would worsen.

Mode shape identification tool is added to algorithm of the proposed software (Fig. 3.1), as during identification process of the elastic characteristics of material eigenfrequencies can change their sequence, so it will distort the objective function value and the accuracy of result. In order to avoid this phenomena a mode forms identifying and regulating their sequence procedure are created, which determine whether modes are properly positioned in relation to natural experiment results.

Proposed to identify mode shapes and arrange their sequence on the list by the displacement of the FEM grid points in z axis. Normalized list of displacements in z axis of a digital sample list (comparable) is created and compared with natural samples analogous list (standard). Similarity of mode shape is determined if both lists coincide and vice-versa. Coincident modes are assessed with the number of overlapping points determined by testing, and is called the overlap factor, expressed as percent. As the mode number in identification of elastic characteristics of materials process rarely exceeds 15–20, modes are arranged using simple linear search algorithm.

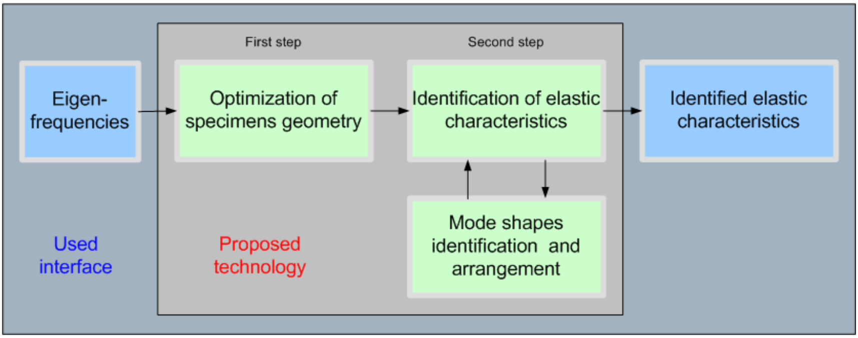

Fig. 3.1. Location of mode shapes of sample identification in the proposed technology

In order to fine-tune the algorithm of mode shape identification a number of tests was carried out and overlap factor was experimentally determined. It emerged that mode shape identification algorithm gives the best result if overlap factor is 62%.

If the mode shape does not match with the reference, sometimes it is found identical to the standard shape, but rotated by 90^o or 180° angle. Such modes are called mirrored and both frequencies are equal, but forms are mirrored. Such modes need to be identified and eliminated from the objective function, as inappropriate.

It is known that the change of Poisson ratio and shear module have poor influence on frequencies of sample compared to other material properties (as it is shown in Frederiksen works). This leads to a relatively large uncertainty in the process of identification of elastic characteristics of material. Under certain geometric properties of the sample (plate aspect ratio, orthotropic angle, sample thickness), identification of elastic characteristics can be more precise, but these parameters differ for each material is and has to be determined before each identification of elastic characteristics.

The proposed technology was tested by repeating Frederiksen results with the abstract material ($E_1 = 1$, $E_2 = 0.1$, $\nu_{12} = 0.3$, $G_{12} = 0.05$, $G_{13} = 0.05$, $G_{23} = 0.03$). Poisson ratio effect on the sample frequencies is shown in the scale of the objective function gradient and sample side aspect ratio (Fig 3.2).

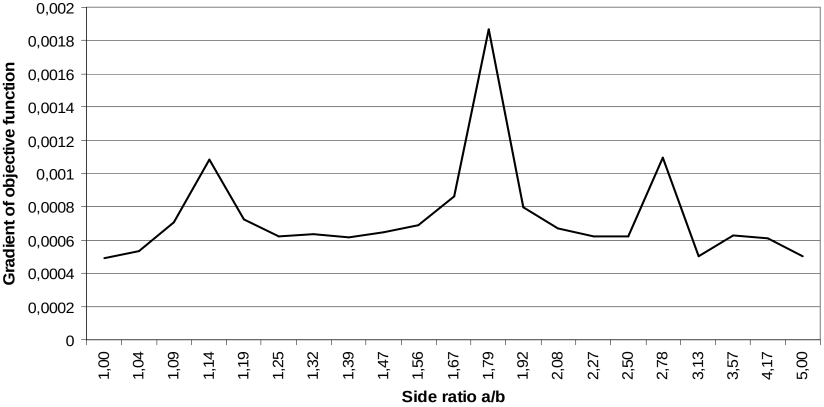

Fig. 3.2. Objective function gradient of sensitivity of Poisson's ratio

The largest digital gradient between two adjacent solutions using central difference scheme is searched for. Two objective functions are calculated with two Poisson's ratio values *dv* differing from prognostic value *pv*. Digital gradient produced by the two objective functions subtracted one from the other and divided by the step of Poisson's ratio:

$$\Delta T = \frac{\partial T}{\partial \nu} \cong \frac{T_2 - T_1}{d\nu} . \tag{8}$$

In the first stage of optimization problem approximate elastic characteristics of material (or similar known material) are used. Then the geometric characteristics of the sample are optimized in order to increase sensitivity of eigenfrequencies of specimen to certain elastic characteristic, or in other words, the maximum gradient of the objective function change is searched for sample aspect ratio, orthotropic angle and / or sample thickness:

$$\max \quad \Delta T(x) \ . \tag{9}$$

With restrictions:

$$\begin{gathered} a = const \\ \frac{1}{4}a \le b \le a \\ \frac{1}{100}a \le h \le \frac{1}{10}a \\ 0^{\circ} \le \gamma \le 90^{\circ} \end{gathered} \ . \tag{10}$$

To identify all the material elastic characteristics accurately, a number of different specimens of the same material should be prepared, which will highlight effect of desired elastic characteristic to specimens eigenfrequencies.

Based on the world practice of elastic characteristics identification the results of research are directed to the Poisson ratio identification, since previous experiments revealed, this elastic characteristic was found insufficiently precisely.

For illustration of the proposed technology two unidirectional single-layered, unidirectional and cross-ply layered composite materials were selected. The Poisson's ratio of the materials was identified before and after optimization of geometry.

Identification error of Poisson's ratio of glass fiber sample decreases from 3.39% to 0.91% after sample geometry optimization (Table 3.1). Carbon fiber sample from 8.01% to 0.04% after sample geometry optimization respectively.

Table 3.1. Identified elastic characteristics of glass and carbon fiber

Elastic characteristics	Glass fiber			Carbon fiber		
	Ref.	Res.	Δ, %	Ref.	Res.	Δ, %
E_1, GPa	45.2	45.2	0.01	229.4	229.0	0.17
$E_2=E_3$, GPa	10.8	10.8	0.05	10.8	12.0	10.01
$G_{12}=G_{13}$, GPa	4.57	4.57	0.00	4.57	5.14	11.09
G_{23}, GPa	3.96	5.18	23.59	3.96	4.08	2.94
$\nu_{12}=\nu_{13}$	0.31	0.3129	0.91	0.32	0.3199	0.04
ν_{23}	0.36	0.4202	14.33	0.39	0.4879	20.06

After the unidirectional 16 layers composite sample geometry optimization Poisson's ratio identification error decreased from 2.128% to 1.266% (Table 3.2). Due to optimization of geometry of cross ply composite specimen, identification error of the Poisson rate has decreased from 15.4326% to 4.4053%. Although the sample was optimized in order to highlight the Poisson's ratio effect only, that shape of the sample increases the Young's module identification error: module E_1 from 0.2654% to 6.2374% and the module from E_2 3.0218% to 16.554% respectively.

Table 3.2. Identified elastic characteristics of unidirectional and cross-ply

Elastic characteristics	LA-UD-SP1			Cross-ply		
	Ref.	Res.	Δ, %	Ref.	Res.	Δ, %
E_1, GPa	171.05	171.42	0.2158	23.3	24.85	6.2374
$E_2=E_3$, GPa	10.44	10.46	0.1912	13.8	11.84	16.554
$G_{12}=G_{13}$, GPa	6.07	6.06	0.1650	2.7	2.71	0.369
G_{23}, GPa	7.71	6.59	16.99	-	-	-
$\nu_{12}=\nu_{13}$	0.48	0.474	1.266	0.217	0.2270	4.4053

Sample geometric parameters, namely aspect ratio, orthotropic angle and the thickness, shall be particular, because the presence of one or another of these parameters value improves or worsens identification of certain elastic characteristics. Optimization of the sample geometrical parameters focus on the identification of Poisson’s ratio, as in previous experiments this elastic characteristic was found with poor precision. Experiments exposed that the Poisson's ratio of sample with optimized geometrical parameters is identified from 2 to 8 times more accurately in comparison to the non optimized sample results. Experiments also exposed that for identification of elastic characteristics of material may be needed some samples of the same material optimized to highlight the desired elastic characteristic, because optimization of the sample for one elastic characteristic may worsen the identification of the remaining characteristics.

4. Description of the software

The "GAlib" software, GA package, developed by Matthew Wall (University of Massachusetts Institute of Technology) is used for thesis problem solution.

"GAlib" library uses two main classes: a genome and GA. Each genome (an individual) represents single solution of the problem. GA simulates the evolution mechanisms, the individual survival in the selection process, defines the objective function; for the development of new individuals uses genome operators and selection strategy.

There are many different types of GA, but "GAlib" includes three: simple, steady-state and incremental. These algorithms differ in the way that they create new individuals and replace old individuals during the course of an evolution. "GAlib" provides two primary mechanisms for extending the capabilities of built-in objects. The most acceptable from C++ programming language point of view is that it is possible to derive custom classes and define new member functions. If only minor adjustments to the behavior of a "GAlib" class need to be made, it is possible to define a single function and indicate existing "GAlib" class to use it instead the provided one.

Identification tool of elastic characteristics of materials consists of three main parts. For management of program tools and information control panel was designed.

For managing the identification tool of elastic characteristics of material and convenience of usage the user interface was created. User interface has two main branches: identification of elastic characteristics of material and optimization of sample geometrical parameters in respect to selected elastic characteristic.

Once selected to identify elastic characteristics of some material the settings window appears in which the user has to set the sample geometric parameters, the density of material, modes used, identifiable elastic characteristics and their search limits. On the form recommended genetic parameters are given, nonetheless user can adjust them, since they may differ for each task.

While algorithm calculates elastic characteristics of material the identification process is indicated. Elastic characteristics, obtained objective function values of each individual's and the best solution to the file are recorded after the work is completed. Average of each generation value is provided. It shows how solution converges and, if this is not clear enough, user can adjust the genetic levels.

General conclusions

The conventional algorithm of identification of elastic characteristics of material is supplemented by the tool of sample geometry optimization as well as the instrument of mode shapes regulation in the spectrum. The proposed technology is tested with several different materials. Some experiments and theoretical calculation were performed and the following conclusions were made:

1. Updating the mathematical model with preliminary elastic characteristics of material during calculations, a certain usually higher order modes can change their places in spectrum. It was found that the objective function would be distorted by comparing different mode frequencies and result would have poor accuracy. As a solution of this problem the algorithm is proposed, which identifies and arranges modes in the spectrum prior to the calculations of the objective function.
2. It is known, that the influence of Poisson's ratio to the frequencies of the sample is low. Changing the side aspect ratio and orthotropy angle of the sample was noticed, that certain combination of these parameters increases the influence of Poisson’s ratio. For each material these parameters are different.
3. Several specimens optimized to highlight the desired elastic characteristic of the same material may be required for identification of the elastic characteristics of material. Optimization of samples to highlight one parameter, though, may lead to worse identification results of the remaining elastic characteristics.
4. Optimized geometry of the samples yields higher accuracy of identification of Poisson ratio: from two (laminates) to eight (single layered) times better in comparison with the results of non-optimized samples.
5. Numerical tests revealed that the genetic algorithm is effectively adapted for identification of elastic characteristics of materials and optimization geometrical parameters of samples, used in identification.
6. More than 500 tests have been performed and it was noticed, that the solution depends on the parameters of genetic algorithm. Recommended optimal values of genetic operators is: crossover – 0.9, mutation – 0.1 of probability, the smallest number of populations – 250, the minimum size of the population – 10 individuals.
7. The proposed technology can easily be adapted to identification of elastic characteristics of different materials (single and multi-layered). The technology can be used with various FEM packages (commercial and open source). It is recommended as an effective tool for identification of elastic characteristics of materials.

List of Works Published on the Topic of the Dissertation

In the reviewed scientific periodical publications

Ragauskas, P.; Skukis, E. 2007. Material properties identification. Comparison of two techniques // Mechanika. Kaunas: Technologija. 6(68): 39–44. ISSN 1392–1207.

Ragauskas, P.; Belevičius, R. 2009. Identification of material properties of composite materials // Aviation. Vilnius: Technologija. 13(4): 109–115. ISSN 1648–7788.

In the other editions

Belevičius, R.; Puiša, R.; Ragauskas, P. 2005. Atvirkštinės inžinerijos technologija medžiagų charakteristikoms nustatyti (Konf. pranešimų medžiaga). Kaunas, KTU. CD laikmena.

Šešok, D.; Ragauskas, P. 2007, Santvarų topologijos ir formos optimizavimas genetiniais algoritmais. Lietuvos matematikos rinkinys. Matematikos ir informatikos institutas, Lietuvos matematikų draugija, Vilniaus universitetas. spec. nr., 47: 484–488. ISSN 0132–2818

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SLUOKSNIUOTŲ KOMPOZITINIŲ MEDŽIAGŲ TAMPRUMO RODIKLIŲ IDENTIFIKAVIMAS

Problemos formulavimas. Sluoksniuotos kompozitinės medžiagos šiuo metu vis plačiau taikomos įvairiose pramonės šakose, pavyzdžiui, aviacijoje, automobilių gamyboje ir kt. Projektuojant ar analizuojant kompozitinių medžiagų konstrukcijas būtina pakankamai tiksliai žinoti šių medžiagų tamprumo rodiklius.

Sluoksniuotų kompozitinių medžiagų tamprumo rodiklius surasti yra žymiai sudėtingiau nei izotropinių, nes šios medžiagos yra nevienalytės. Tokių medžiagų tamprumo rodikliai gali būti nustatomi įprastiniais statiniais arba ultragarsinio tyrimo metodais.

Statiniai tyrimai remiasi deformacijų lauko matavimais. Pagrindiniai tokiuose bandymuose kylantys keblumai – sunku garantuoti tinkamas kraštines sąlygas bandiniams, gauti vienalyčius deformacijų/įtempimų laukus. Dažniausiai būtina atlikti kelis statinius bandymus. Pavyzdžiui, norint nustatyti keturis vienakryptės sluoksniuotos medžiagos tamprumo rodiklius reikia trijų statinių bandymų. Be to, dažnoje sluoksniuotoje medžiagoje užpildas yra polimerinė medžiaga, įprastai pasižyminti valkšnumu – tai taip pat kelia problemų nustatant medžiagos tamprumo rodiklius.

Pagrindinė problema ultragarsiniuose tyrimuose – sluoksniuotos kompozitinės medžiagos dažnai pasižymi aukštomis slopinimo savybėmis, todėl ultragarso bangų difrakcija ir slopimas lemia netikslius rezultatus.

Dėl šių priežasčių netiesioginiai medžiagų tamprumo rodiklių identifikavimo metodai pastaruoju metu sulaukia ypatingo dėmesio. Vienas iš netiesioginių tamprumo rodiklių identifikavimo metodų yra struktūros reakcijų į vibracinį sužadinimą matavimas ir vėliau, modeliuojant tą pačią struktūrą skaitmeniniais metodais ir spėjant medžiagos tamprumo rodiklius, bandymas gauti tą pačią struktūros elgseną. Medžiagos rodiklių spėjimas – bandymas formuluojamas kaip globaliojo optimizavimo uždavinys, kurio tikslo funkcija yra nesąryšis tarp bandymais gautų ir skaitmeniniais metodais suskaičiuotų tam tikrų tikrinių dažnių.

Sukurta technologija pagrįsta vykdant dvigubą skaitmeninį eksperimentą: parenkami artimi kuriai nors realiai medžiagai tamprumo rodikliai, artimi praktiniams bandiniams geometriniai jų parametrai, ir baigtinių elementų metodu gaunamas konvergavęs tikrinių reikšmių uždavinio sprendinys. Vėliau sukurtąja technologija bandoma gauti tuos pačius medžiagos tamprumo rodiklius. Vykdant šiuos eksperimentus pasitelkta tam tikra informacija iš natūrinių bandymų: juose pavyksta nuskaityti ne visus tikrinius dažnius/modas, todėl į skaitmeninius eksperimentus įtraukiami tik tiek žemesniųjų dažnių, kiek jų paprastai įmanoma nuskaityti natūriniais bandymais.

Taip patikrinta technologija vėliau gali būti taikoma realių medžiagų tamprumo rodiklių identifikavimui.

Darbo aktualumas. Šiuo metu siūlomos skaitmeninių-fizinių bei optimizavimo derinio medžiagų tamprumo rodiklių identifikavimo technologijos yra ne pramoninės paskirties, nuolat tobulinamos. Pagrindinis esamų technologijų trūkumas – sluoksniuotų kompozitinių medžiagų tamprumo rodikliai joms surandami nepakankamu tikslumu. Prasčiausiai iš tamprumo rodiklių surandami Puasono koeficientai.

Minėta technologija yra neardanti, todėl gali būti taikoma tiesiogiai gamyboje. Nepaisant minėtų trūkumų technologija intensyviai vystoma siekiant sukurti inžinerinį įrankį, leidžiantį tiksliai ir greitai surasti norimos medžiagos visus tamprumo rodiklius pakankamu tikslumu.

Tyrimų objektas. Darbo tyrimų objektas – izotropinių, kompozitinių vienasluoksnių ir sluoksniuotų, vienakrypčių ir statmenai armuotų medžiagų bandiniai, jų tamprumo rodikliai. Bandiniai priverstinai žadinami siekiant gauti jų tikrinius dažnius, iš kurių randami medžiagos tamprumo rodikliai.

Darbo tikslas ir uždaviniai. Pagrindinis darbo tikslas – panaudojant globalaus optimizavimo algoritmus sukurti efektyvią technologiją, leidžiančią vienodu tikslumu surasti visus bandinio tamprumo rodiklius. Ištirti bandinio geometrinių parametrų įtaką medžiagos tamprumo rodiklių identifikavimo tikslumui.

Pagrindinis darbo uždavinys yra sukurti ir išbandyti technologiją, kuri leistų vienodu tikslumu rasti visus bandinio tamprumo rodiklius. Tam reikia:

- optimizuoti bandinio geometrinius parametrus siekiant tikslesnių tamprumo rodiklių identifikavimo rezultatų;
- atpažinti bandinio modų formas ir reguliuoti jų vietą tikslo funkcijoje siekiant sumažinti tikslo funkcijos iškraipymus;
- sukurti pasiūlytų technologijų įgyvendinimo algoritmus ir eksperimentiškai patikrinti jų galimybes.

Tyrimų metodika. Darbe taikomi skaitiniai tyrimo metodai. Tikslo funkcija yra skaitinio ir natūrinio bandymų dažnių skirtumas, kurį siekiama minimizuoti. Duomenys tikslo funkcijai skaičiuoti gaunami natūriniu bandymu ir baigtinių elementų metodu. Optimizuojama genetiniais algoritmais.

Mokslinis naujumas. Pasiūlyta ir programiškai realizuota dviejų žingsnių technologija, kuria efektyviai pakankamu tikslumu randami bandinių tamprumo rodikliai. Technologija apima anksčiau viename algoritme nenaudotus bandinio kraštinių ilgio santykio ir ortotropijos kampo optimizavimo, modų formos atpažinimo ir jų vietos reguliavimo tikslo funkcijoje įrankius, kurie leidžia padidinti tamprumo rodiklių identifikavimo tikslumą.

Praktinė vertė. Sukurti programiniai įrankiai, skirti įvairių medžiagų tamprumo rodiklių radimui pakankamu tikslumu. Ši technologija gali būti panaudota mokslinių tyrimų laboratorijose, kompozitinių medžiagų gamyboje, kuri šiandien yra viena iš sparčiausiai besivystančių pramonės šakų pasaulyje. Jos gaminiai plačiai naudojami aviacijoje, sausumos, jūrų ir kelių transporto, statybos pramonės šakose.

Ginamieji teiginiai

1. Pasiūlytas bandinio geometrijos optimizavimas ir bandinio modų formos atpažinimas leidžia efektyviai ir tiksliai rasti medžiagų tamprumo rodiklius.
2. Keletas vienos medžiagos bandinių, kurių geometrija optimizuota tam tikro tamprumo rodiklio jautrumui leidžia surasti tikslesnį sprendinį (tamprumo rodiklius).

Darbo rezultatų aprobavimas. Disertacijos tema perskaityti penki pranešimai Lietuvos bei kitų šalių konferencijose ir paskelbti keturi straipsniai.

Darbo struktūra ir apimtis. Disertaciją sudaro įvadas, keturi skyriai: literatūros apžvalga, medžiagų tamprumo rodiklių technologijos aprašymas ir praktiniai pavyzdžiai, gautų rezultatų gerinimas ir sukurtos programinės įrangos aprašymas.

Darbo apimtis yra 110 puslapių, tekste panaudotos 32 numeruotos formulės, 54 paveikslai ir 23 lentelės. Rašant disertaciją buvo panaudoti 116 literatūros šaltinių.

Bendrosios išvados

Įprastinis medžiagų tamprumo rodiklių identifikavimo algoritmas papildytas bandinių geometrijos optimizavimo ir modų formos reguliavimo spektre įrankiais. Siūloma technologija patikrinta su keliomis skirtingomis medžiagomis. Atlikus eksperimentus suformuluotos šios išvados:

1. Skaičiavimų eigoje atnaujinant matematinį medžiagos modelį preliminariais tamprumo rodikliais, tam tikros, paprastai aukštesnės eilės, modos gali keisti savo vietas tikrinių dažnių spektre. Nustatyta, kad to neįvertinus, tikslo funkcijoje būtų sugretinami skirtingų modų dažniai, dėl to nukentėtų galutinio rezultato tikslumas. Šios problemos sprendimui pasiūlytas algoritmas prieš tikslo funkcijos skaičiavimus atpažįstantis modas ir pagal natūrinio bandymo duomenis jas surikiuojantis spektre.
2. Žinoma, kad Puasono koeficiento įtaka bandinio tikriniams dažniams yra menka. Keičiant bandinio kraštinių ilgių santykį ir ortotropijos kampą nustatyta, kad šio tamprumo rodiklio įtaka padidėja esant tam tikram geometrinių parametrų deriniui, kuris kiekvienai medžiagai yra skirtingas.
3. Ieškant medžiagos tamprumo rodiklių gali būti reikalingi keli tos pačios medžiagos bandiniai, optimizuoti norimo tamprumo rodiklio išryškinimui. Bandinio optimizavimas vienam kuriam nors dydžiui gali lemti prastesnius likusiųjų rodiklių radimo rezultatus.

4. Optimizavus bandinių pasirinktus geometrinius parametrus Puasono koeficientas surandamas nuo 2 (sluoksniuotoms medžiagoms) iki 8 kartų (vienasluoksnėms) tiksliau, palyginus su neoptimizuoto bandinio rezultatais.

5. Skaitiniai bandymai parodė, kad genetiniai algoritmai yra efektyviai pritaikomi medžiagų tamprumo rodiklių paieškai, naudojamų bandinių geometriniams parametrams optimizuoti.

6. Atlikus daugiau kaip 500 skaitinių bandymų buvo pastebėta, kad uždavinio sprendinys priklauso nuo genetinio algoritmo parametrų. Rekomenduojamos optimalios genetinių operatorių reikšmės: kryžminimo – 0,9, mutacijos – 0,1 tikimybės, mažiausias populiacijų skaičius – 250, mažiausias populiacijos dydis – 10 individų.

7. Siūloma technologija gali būti pritaikoma įvairių medžiagų (vienasluoksnių ir sluoksniuotų) tamprumo rodiklių radimui. Joje galima naudoti įvairius baigtinių elementų metodo paketus (komercinius ir atvirojo kodo). Rekomenduojama kaip efektyvi priemonė medžiagų tamprumo rodiklių radimui.

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IDENTIFICATION OF ELASTIC PROPERTIES OF LAYERED COMPOSITE MATERIALS

SUMMARY OF DOCTORAL DISSERTATION
TECHNOLOGICAL SCIENCES, MECHANICAL ENGINEERING (09T)

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