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CRACK DETECTION IN COMPOSITE LAMINATED PLATES USING OPTIMIZATION TECHNIQUES BASED IN CHANGES IN NATURAL FREQUENCIES

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Abstract - **The damage detection becomes very important when the subject securities are taken into account for a possible application of given equipment. Following the idea of studies on the detection of damage in mechanical structures, this work has developed a study via numerical simulations to assess damage detection techniques applied to composite materials, because the application of these materials in components and structures has replaced metallic materials due to their high mechanical performance. Most non-destructive inspection techniques used in composites need high level of operator experience to its successful completion and later interpretation of results. We carried out the modeling by means of finite element method (FEM) and employed to optimize heuristic techniques coupled to FEM model such as genetic algorithms, to minimize objective functions, written in terms of the dynamic parameters of the analyzed structure (natural frequencies). The structure studied is constituted of a damaged laminate of carbon fiber with a crack model induced. The result of the optimization algorithms shows good efficacy in the detection of structural damage.**

Keywords — **Damage Detection, Genetic Algorithm, Natural Frequency, Composite Materials**

I. INTRODUCTION

A particular type of structural damage can be characterized as the presence of holes, cracks and other irregularities that leads to a change in structural properties of mass, stiffness or damping of the structure. According to [1], the interest in the ability to monitor a structure and detect damage at the earliest stage possible permeates the fields of mechanical, aerospace and civil engineering. The vast majority of current damage detection methods are located using visual or experimental methods such as ultrasound or acoustic methods, magnetic particles, x-rays, eddy currents and other methods. All these techniques require that the experimental damage of the neighborhood is known a priori and the structure to be inspected is easily accessible. The need for additional methods of detection of global injury that can be applied to complex structures has led to the development of methods that examine the changes in the vibration characteristics of the structure. The basic idea is that the modal parameters (natural frequencies, mode shapes and modal damping) are functions of the physical properties of the structure (mass, rigidity and damping). Therefore, the changes cause changes in the physical properties of the modal properties.

According to [2], the application of advanced materials as composite materials, components and structures evolved due to the need to reduce weight and improve structural performance. Other attributes of composite materials, such as corrosion resistance, excellent surface finish, good fatigue resistance capability and high structural performance, have also been significant contributions to the rapid increase of the application of these materials. However, composite materials are subjected to high structural applications because of its performance, which entails measures to specific criteria of damage. However, the evaluation of the criticality of the defects and damage in composite materials, and the subsequent repair requirements are presently a challenge. Most non-destructive inspection techniques used in composites require high levels of operator experience to its successful completion and subsequent interpretation of results. From those reasons come the interest to the structural health monitoring in such materials.

In this work, we employed the finite element method due to the complexity of an anisotropic material (carbon fiber composite) with several layers of laminated material, which does not adapt using the contour methods that are widely used for structures with two-dimensional simplification. Optimization using heuristic methods such as genetic algorithm (GA) are used as the optimization procedure for being able to find a global optimum efficiently and not get stuck in a great location, allowing properly locate the damage, as well as no need for derivatives valuation the objective function, which can become a problem for cases where discontinuities may be present. The optimization routines of damage detection were performed using the MATLAB® software working linked with the commercial finite element software ANSYS® for creation of inverse and direct problems respectively.

II. STRUCTURAL DAMAGE DETECTION VIA DYNAMIC PARAMETERS

The Structural Health Monitoring (SHM) aims to give, at every moment during the structure's life, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole. The state of the structure must remain in the domain specified in the design, although normal aging due to usage can alter this, by the action of the environment, and by accidental events. Thanks to the time-dimension of monitoring, which makes it possible to consider the full history database of the structure, and with the help of Usage Monitoring, it can also provide a prognosis (damage evolution, residual life, etc.). [3]

Knowing the integrity of in-service structures on a continuous real-time basis is a very important objective for manufacturers, end-users and maintenance teams. In effect, SHM: allows an optimal use of the structure, a minimized downtime, and the avoidance of catastrophic failures. A very efficient tool of the SHM is the use of inverse methods to detect the damage. The structural damage detection method based on inverse methods combine an initial structural model and experimental data, to improve the model or test a hypothesis. In practice, according to [9], inverse methods combine an initial model of the structure and measured data to improve the model or test a hypothesis. In practice, the model is based on finite element analysis and the measurements are acceleration and force data, often in the form of a modal database, although frequency response function (FRF) data may also be used.

The four levels of the estimated damage primarily addressed by [4] are set as detection, location, quantification and prognosis. Detection is readily accomplished by methods of pattern recognition or detection of new structural changes. The key question for the inverse methods is the location, which equals the error location in the model. Since the damage is found, it can be parameterized with a limited set of parameters and quantified. A structural damage can be defined as the modification of the stiffness or mass of an element. One of the main ways to assess the presence of a local damage is to be based on the variation of structural dynamic parameters. This method assumes that the damage results in alterations in the properties of the structure, i.e., may cause a variation in the mass matrix, damping and stiffness in the classical equation of motion of a body, which in turn will lead to changes in the dynamic response of thereof, such as natural frequencies, vibration modes and modal damping.

A. Changes in Natural Frequencies

The observation that changes in the structural properties cause changes in the vibration frequency was the impetus for using modal identification of methods for monitoring the damage and structural integrity. According to [5] and [1], frequency changes have significant practical limitations for applications depending on the analyzed structure. The low natural frequency range of sensitivities requires very precise measurements or high levels of damage to detect.

The change of natural frequencies can be considered as a method of detecting prevalent in structural damage assessment procedures. When damage exists in a structure, the stiffness and the mass are reduced and consequently decreasing the natural frequency of the system can be observed. One major advantage of this detection technique is that frequency measurements can be quickly and easily performed. Moreover, the experimental techniques used for the determination of natural frequencies are classical measurement techniques of classical vibration. In addition, knowledge of the overall dynamic behavior of undamaged systems is very easy to obtain developments using analytical or finite element models; thus allowing the measurement points being properly chosen to not only a quick and efficient detection of changes in frequency, but also the identification of the location and severity of damage. [7]

A commonly known from the literature damage detection criterion being composed exclusively of a set of n natural frequencies is DLAC (Damage Location Assurance Criterion), which compares the frequency obtained experimentally with a finite element model to locate and quantify damage. The DLAC calculates the correlation between the change in frequency, $\{\Delta\omega\}$, expected from the finite element model and the actual changes, $\{\delta\omega\}$ estimated from experimental procedures. [18]

$$DLAC = \frac{\left|\{\Delta\omega\}^T\{\delta\omega\}\right|}{\left(\{\Delta\omega\}^T\{\Delta\omega\}\right)\left(\{\delta\omega\}^T\{\delta\omega\}\right)} \qquad (1)$$

The DLAC assumes the value of 1 for an exact pattern match between the sets of natural frequencies and 0 for patterns that are uncorrelated. This method only requires the measurement of a few frequency changes between the undamaged and damaged states of the structure, and the accuracy of the damage predictions is further improved by including antiresonances into the criterion. The accuracy of predictions damage can be further enhanced by inclusion of antiresonance frequencies the criterion. In the application, a DLAC value of 0.9 (90%) would be considered good correlation between the model and the actual structure, values above 0.9 are considered similar and values below 0.9 represent dynamic data that are significantly different. [8]

III. DIRECT AND INVERSE PROBLEM MODELING

The modeling of the damage detection problem addressed in this paper was formulated on two fronts: modeling the direct problem, modeled by the finite element method and the modeling of the inverse problem, if consisting of the optimization method for the search of variables great project for the identification of structural damage tax.

A. Direct Problem: Finite Element Model

Finite element models have a priori information available about the continuous models, behavior of the material and internal constraints. The response to a given excitation modeled by a finite element model is governed by a set of coefficients that are closely related to physical quantities like the mass or stiffness matrix coefficients. These physical quantities represent the parameters of such models. [9]

The optimal values to be calculated are determined to minimize the difference between the amounts of measured response (real) and planned (simulated). The identification of a structure finite element model continues becomes an important objective of the structural identification, such as typically used in direct problems. On the other hand, it is the only model that is potentially able to give location information on the structural properties, which are crucial for the detection of damage. [10]

The direct problem was modeled on a square plate side equal to one meter, or simply can take into account the value of a unit because there is no relevance to the optimization process. The structure is symmetrically laminated composite material consisting of four layers of different orientations. The laminate has dimensions of a square unit of one meter side. The layer thicknesses are all t = 0.0025 m oriented symmetrically $[0/90]_s$. Please note that this work is intended solely to the study of the damage detection method in laminated composite material using optimization algorithms, giving emphasis on geometric parameters and specific characteristics of the laminate material.

Before meshing the model, and even before you build it, it is important to think about the concept of free and mapped mesh is suitable for analysis. A mesh mapped typically has a regular pattern, with ordered elements, allowing greater control over the elements, but requires more time and computational effort to generate these. Thus, it took shell elements freely generated on the structural surface. Figure 1 shows the results of modeling the laminate square geometry, with open mesh (in this case without the presence of damage, the fabric was uniform due to the symmetry and simplicity of the structure) generated on the surface of the structure studied.

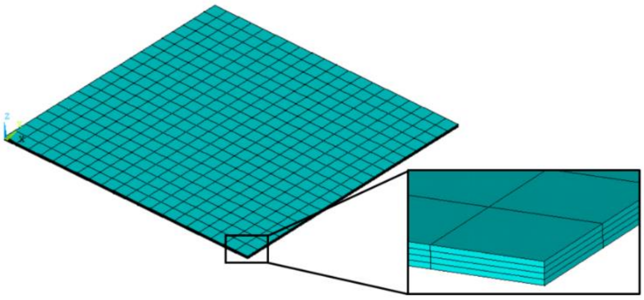

Fig. 1. Laminated composite plate created by finite element method with shell elements.

A. Damage Models

For the damage case, this study aimed to the detection of structural cracks in the laminate board. Such damage was modeled after a hexagon with their peripheral sides extended, as shown in Fig.2. It sets up a constant thickness of 1 mm to crack, being of greatest interest to search for the location; extent and orientation of such damage in the structure under study, being permissible in future make a prediction of structural integrity and decision-making of appropriate measures to structural safety. The finite element model, stood at 10 the number of elements to be discretized in the board edges by inserting a refinement in the mesh in the crack region, to better accuracy of the results, because it is a very little damage in the structure. In the reverse process optimization modeling the crack four design variables were included, they are the location of the bottom edge of the set, consisting of the x and y position. The extent of damage, being modeled as the total length L and the orientation θ of this damage (Figure 2). In this context, it remained the thickness of the constant set, as stated in the previous paragraph, because cracks models do not have significantly large thicknesses to be considered in this process. Then , the decision variables are grouped in a vector α given by $\alpha = \{x, y, L, \theta\}$.

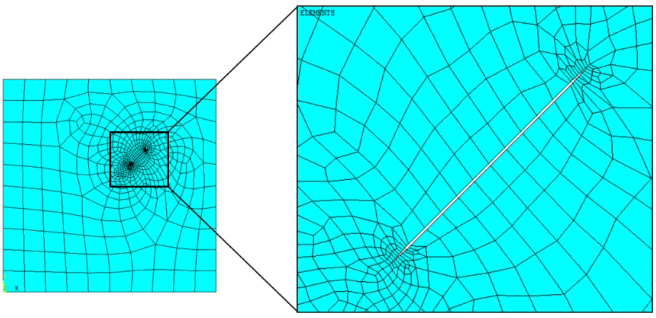

Fig. 2. Crack modelling as damage on the laminated composite plate.

B. Inverse Problem: Genetic Algorithm Optimization

Find the best solution for a given problem is an important area of research and has application in various fields of engineering. Several optimization problem can be identified in the monitoring area of structural integrity. Genetic algorithms are now frequently applied to problems of maximizing or minimizing a given objective function, often subject to some constraints. Genetic algorithms have been applied to a wide range of optimization problems in engineering which have this form. The genetic algorithm works with an initial population which may, for example, correspond to numerical values of a particular variable. The size of this population may vary and is generally related to the problem under consideration. The members of this population are usually strings of zeros and ones i.e. binary strings. In practice, the population may be far larger than this and the strings longer. The strings themselves may be the encoded values of a variable or variables that we are examining. This initial population is generated randomly and we can use the terminology of genetics to characterize it. Each string in the population corresponds to a chromosome and each binary element of the string to a gene. A new population must now develop from this initial population and to do this we implement the analogue of specific fundamental genetic processes. These are: reproduction based on fitness, crossover and mutation.

As mentioned in previous paragraphs, the solution damage detection problems in the location of the damage and its quantification are parameters to be determined are necessary data corresponding to the vibrational response of the structure under study. The vibrational response can be obtained by means of a laser vibrometer and accelerometers, which are input data transmitted to a processing unit, which ultimately determines the location and extent of the damage with the use of specific algorithms (Fig.3). This work will be undertaken experimental data (simulated a real case of a damaged structure) and information related to natural frequencies of the real-damaged structure and model for a first objective function and a second function adds the acquisition of data the accelerations corresponding to the vibration plate of a certain natural frequency.

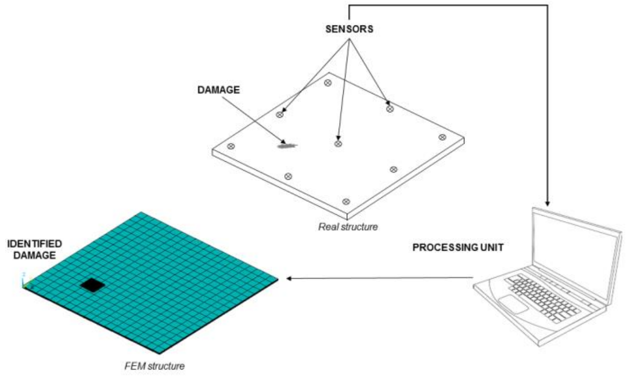

Fig. 3. Damage detection method using signal acquisition and CAD models.

The first objective function J_1, is based on the root mean square error (RMSE) of the first n natural frequencies of the plate. The minimization of this objective function suggests that the natural frequencies of the real damaged plate are equal to the frequencies obtained by optimization, that is, the minimum value will equal zero ($J_1 = 0$). However, aiming at improving damage detection process, it is essential to work with an appropriate objective function, aiming to lower computational time and better identification. According to [11], parameter selection is a key issue in process optimization. Reliance on different parameters measurement of test values and initial estimates can be expressed through weights in the objective function. Weighting factors (weights) suitable can improve significantly optimize results, however, this requires a good deal of knowledge about the assumptions used in finite element modeling system as well as the possible sources of error in the analysis. The damage detection methods, which take into account natural frequencies of higher order are more reliable. Therefore, the objective function J_1, becomes a weight vector C composed of scalar c_i ascending order, C = {1 2 3 4 5 6} in order to give greater importance to higher order of frequencies.

$$J_1 = RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n} c_i\left(1-\frac{\omega_i^{real}}{\omega(\alpha)_i^{model}}\right)^2} \qquad (2)$$

Where n is the number of natural frequencies obtained, c_i the scalar weighting factor to higher natural frequencies, ω_i^{real} the natural frequencies corresponding to the actual damaged structure and $\omega(\alpha)_i^{model}$ the natural frequencies of the structure modeled by finite element comprising by one or more damages, according to a parameterized vector design of variables α.

Variations of natural frequency have significant limitations for practical applications in certain types of structures. The low frequency sensitivity in the presence of an injury requires very precise measurements or high levels of structural damage to be detected efficiently. In addition, frequencies are a global property of the structure, and it is unclear why the changes in this parameter can be used to identify more than the mere existence of damage. In other words, the frequencies cannot generally provide spatial information about structural changes, but a global code. [1]

The detection method developed in this work, briefly, will take place in two steps. The first step of damage detection, combine data from a finite element modeled structure without damage and with a structure modeled damage previously known, which simulates the actual case of a damaged structure. This first step will employ the DLAC criterion for detecting whether or not the presence of an injury. The second step is the damage identification process. This identification routine optimization algorithm is introduced to make the search for damage to the geometry of the structure, with interaction between the finite element software where the model structure is adapted to receive the design variables and optimization software that will hold a series of calculations in order to generate input data for the finite element software. The flowchart of the Figure 5 displays the steps to be performed during the damage searching. The method for detecting damage in this study meets three of the four criteria proposed by [4], the detection, localization and quantification of damage (damage models studied).

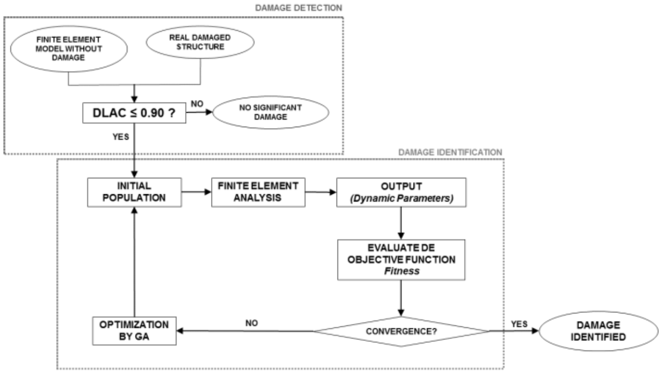

Fig. 4. Damage detection flowchart.

IV. NUMERICAL RESULTS AND DISCUSSION

For the initial part of the inverse problem of damage detection, it needed a proper study of the direct problem of modeling using the finite element method in order to have adequate confidence in the results generated by the finite element method, not only effecting a treatment data for the inverse problem optimization, having as motivation the future application of this method to real monitoring service structures. The main hypothesis of this work is that the presence of structural damage, it is modeled as a crack generates a variation of the mass matrix, rigidity and damping. structural dynamic responses, such as natural frequencies, mode shapes and acceleration are directly dependent on such matrices, they are obtained from the equation of motion, just the presence of an arbitrary damage will generate a different response from that which damage is not present in a particular structure.

It is observed that there is a good credibility in the results for the amount of chosen elements, being a global error acceptable for this study. A comparison of the dimensionless natural frequencies [12] in Table 1 adds a good confidence in the proposed model, the error being calculated by taking only the dimensionless analytical frequencies and the frequencies obtained by the FEM.

Table 1. Non dimensionalized fundamental frequencies and numerical error.

Analytical ([15], p.284)	**Numerical (20 elem.)**	**Error [%]**
2,5190	2,5200	0,0134
4,9860	5,0159	0,0028
8,5150	8,5612	0,0005
10,0770	9,9836	3,0027

A. Crack Model

Machines and structural components potentially require continuous monitoring for the detection of cracks and crack growth for ensuring an uninterrupted service in critical installations. Cracks can be present in structures due to various reasons such as fatigue, impact, corrosion and external and environmental factors like temperature, relative humidity, rainfall and the general properties of structures. Complex structures such as aircraft, ships, steel bridges, sea platforms etc., all use metal plates. The presence of a crack does not only cause a local variation in the stiffness, but can affect the mechanical behaviour of the entire structure to a considerable extent. For this importance given to this kind of damage, drew up an optimization algorithm aimed at detecting and quantifying, meeting the first three criteria [4], and allows structural measures are taken, it is intended to know the direction where the crack will propagate (θ), preventing accidents and ensuring the structural integrity of machinery and equipment.

The results for the detection of cracks considering random noise are shown in Table 2, showing that there was a global error increase when there is an increase in noise levels. It was simulated with noise levels up to 10% because it was enough to get differing results in relation to the objective values. In the case of a more complex and less damage model, the inclusion of incomplete data (noisy) significantly affected the response obtained by the AG. From the values obtained in the optimization process, it was observed that the variable θ showed higher levels of variation and its error, making it difficult for direct mode to obtain a prediction of damages, since this variable permits a relevant study of structural integrity, giving forecasting future failures and direction of crack growth. However, noise-free data, or even data considering a low noise (1% in this study) can detect damage with significant efficacy when the objective is to obtain structural region where there is a real damage (Fig5).

Table 2. Crack detection results considering random noise data.

	x	***y***	***L***	***θ***	***Error [%]***
Real Damage	0,6000	0,6000	0,1000	45,0000	-
No noise	0,6242	0,6289	0,0608	48,6667	14,7
1% noise	0,6692	0,6788	0,0821	50,0000	13,4
5% noise	0,6554	0,5994	0,0663	12,0000	29,1
10% noise	0,2786	0,2590	0,1481	53,0000	44,1

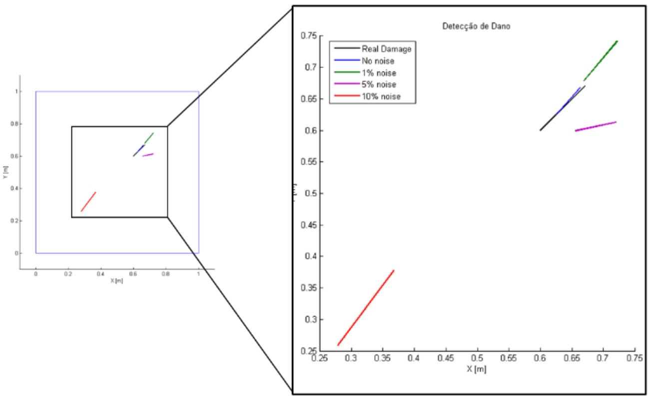

Fig. 5. Crack detection results considering random noise data.

According to [13], dynamic models in finite element need be correlated with the measured data to ensure accuracy of numerical models. Small modeling errors of the finite element model can propagate, causing unpredictable errors in the responses. Adjusting the finite element model using measured data is a challenge for the field of structural dynamics. When the calculated modes are not correlated with the measured data, there may be significant and unknown irregularities in the results of vibration. These inaccuracies can result from discrepancies in both modes of vibration or modal frequencies. Thus, correlation procedures are employed to try to combine the real and computer data both included the natural frequencies and mode shapes. The general perception is that any discrepancies between the test and analysis are solely due to modeling uncertainties. The model properties into finite element are modified and then the new numerical results are compared with the actual test results. The process is repeated until satisfactory agreement is reached between the experimental and numerical results.

V. CONCLUSION

The study was focused on the detection and identification of structural damage based on dynamic parameter of vibration of a square plate composed of composite material, including numerical modeling by finite elements, the inverse problem damage detection programming using a genetic algorithm with an optimization technique adopted. The problem of vibration of a laminated composite material was numerically validated by finite element tool, allowing a choice of the correct parameters for modeling the inverse problem.

The finite element method has proven to be a powerful tool in solving problems which in many cases do not have trivial solutions. The modeling of the direct problem by MEF, when compared to known analytical case had small errors due to numerical accuracy. The genetic algorithm used to solve the inverse problem of detection of damage could evaluate efficiently the proposed problem. However, these algorithms are complex and need to be aware of the objective function values in question at various points, so you do not lose your income in the search by optimal values. This drawback can be solved by inserting a parameter identification technique, i.e., artificial neural networks, significantly reducing the total simulation time to identification of damage parameters.

When we took into account the modeling of minor damage, such as cracks, the genetic algorithm could detect them, yet it took to raise the number of objective function evaluations. The insertion of a white Gaussian noise in this model affected more significance compared to all other models injuries treated in this study. Despite the difficulties faced by modeling minor damage and treatment variables with noisy data, we obtained a damage detection with remarkably effective when it is intended to obtain a damaged framework region, as this is relevant higher than the geometry of the damage.

The evolution of the ability of computational tools of mathematical modeling, numerical simulations beyond the modern computer processing power allow the application and expansion of damage detection method ever more accurate and sophisticated and practical applicability in highly complex structures large number of elements beyond the processing capacity of a vector composed of several design variables in optimization process with use of global heuristics.

VI. REFERENCE

[1] B. Corona, M. Nakano, H. Pérez, “Adaptive Watermarking Algorithm for Binary Image Watermarks”, *Lecture Notes in Computer Science, Springer, pp. 207-215, 2004*.

[2] Doebling, S.W.; Farrar, C.R.; Prime, M.B.; Shevitz, D.W. Damage Identification and Health Monitoring of Structural And Mechanical Systems from Changes in Their Vibration Characteristics: A Literature Review. Los Alamos National Laboratory Report, LA-13070-MS. 1996.

[3] Heslehurst, R. B.; Defects and Damage in Composite Materials and Structures. CRC Press. 2014.

[4] Balageas, D.; Fritzen, C.; Guemes, A.; Structural Health Monitoring. ISTE. 2006.

[5] Rytter, A.; Vibration Based Inspection of Civil Engineering Structures, Ph. D. Dissertation, Department of Building Technology and Structural Engineering, Aalborg University, Denmark. 1993.

[6] Cawley, P.; Adams, R. D.; The Location of Defects in Structures from Measurements of Natural Frequencies. Journal of Strain Analysis. Vol 14 no 2. 1979.

[7] Sinou, J. J.; A review of damage detection and health monitoring of mechanical systems from changes in the measurement of linear and non-linear vibrations. Robert C. Sapri. Mechanical Vibrations: Measurement, Effects and Control, Nova Science Publishers, Inc., pp.643-702, 2009.

[8] Ewins, D.; Modal Testing theory, practice, and application. Hertfordshire: Research Studies Press LTD. 2000.

[9] Friswell, M.; Penny, J. and Garvey, S. A combined genetic eigensensitivity algorithm for the location of damage in structures. Computers and Structures v. 69, p. 547-556. 1998.

[10] Morassi, A.; Vestroni, F. Dynamic Methods for Damage Detection in Structures, CISM Courses and Lectures. Vol. 499. 2008.

[11] Jakharfani, R.; Masri, S. F. Finite Element Model Updating Using Evolutionary Strategy for Damage Detection. Computer-Aided Civil and Infrastructure Engineering. 2011.

[12] Reddy, J. N.; Mechanics of Laminated Composite Plates and Shells: Theory and Analysis. CRC Press. 2ed. 2003

[13] Pak, C. Finite Element Model Tuning Using Measured Mass Properties and Ground Vibration Test Data. Journal of Vibration and Acoustics. 2009

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