DAMAGE ASSESSMENT OF COMPOSITE STRUCTURES FROM CHANGES IN NATURAL FREQUENCY USING UNIFIED PARTICLE SWARM OPTIMIZATION

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ABSTRACT

Composite materials are highly sensitive to the presence of manufacturing and service-related defects that can reach a critical size during service condition and thereby can affect the safety of the structure. In order to avoid such safety issues, early identification of damage is necessary. In the present study, a numerical procedure is presented to detect and quantify damage in a composite beam like structure from changes natural frequencies using unified particle swarm optimization technique. The efficacy of the proposed methodology is demonstrated using some numerically simulated composite beam structures containing single and single and multiple damages.

Keywords: Damage assessment; composite structures; inverse problem; anisotropic damage; natural frequency; unified particle swarm optimization; finite element formulation.

Introduction

Due to its light weight and heavy load bearing capacity, nowadays, composite materials are widely used in aircraft structural components, civil and mechanical industries. However, composite materials are highly sensitive to the presence of manufacturing and service-related defects which can reach a critical size during service condition and thereby can affect the safety and stability of the structure. In order to avoid such issues, early identification of damage is necessary. Visual or local damage identification methods are extensively used to identify damages in such structure. However, several disadvantages confronted during identification of hidden damages, damages at an inaccessible location forced the researchers to find an alternate global damage identification method. In this regard, vibration based damage detection [Hao and Xia (2002), Hamey *et al.* (2004), Nanda *et al.* (2012 and 2014)] is being appraised as an effective alternative to tackle such situations. The inclusions of damages reduce the stiffness and other mechanical properties of the structure and thus affect the vibration response of the structure. Thus, an inverse approach is possible for damage assessment using changes in natural frequency and mode shape like vibration data.

Modal parameters based analysis has several advantages over alternative techniques such as modal parameters depend only on the mechanical characteristics of the structure and not on the excitation applied. In a damage detection problem two objectives have to be attained; the location of damage and its magnitude or severity. One prime requirement for damage identification problem is the requirement of a suitable damage indicator which can effectively be used to construct an objective function. Out of several objective functions available in literature, natural frequency is the most commonly used one. This is due to the fact that, natural frequency of a structure is easy to measure and it contains less amount of noise in comparison to other indicators like mode shape and its derivatives.

In this paper, a numerical procedure is presented to detect and quantify damage in a composite beam like structure. Natural frequencies are used as the candidate for formulating the damage identification inverse problem which is then solved by using unified particle swarm optimization algorithm [Parsopoulos and Vrahatis (2005)] to estimate damage conditions. The proposed methodology is demonstrated using a numerically simulated composite beam structure containing single and single and multiple damages.

Theoretical formulations

A. Unified particle swarm optimization:

The particle swarm optimization (PSO) algorithms, first proposed by Kennedy and Eberhart (1995), are inspired by the collective motion of insects and birds trying to reach an unknown destination, known as "swarm behavior". This process involves both social interaction and intelligence so that birds learn from their own experience and also from the experience of others around them. PSO algorithm has advantages lies with its simplicity in architecture and convergence speed. Further, to improve its efficiency many alternations and variations are proposed to the original algorithm, among which unified particle swarm optimization (UPSO) one that has the ability to harness both exploration and exploitation capacity simultaneously [Parsopoulos and Vrahatis (2005)] by balancing the influence of both global and local search directions simultaneously.

B. Finite element formulation:

The governing differential equations for the dynamic analysis of composite plate is developed using first order shear deformation theory. An 8-node isoparametric quadrilateral shell element is employed in the present analysis with five degrees of freedom *i.e.* $u, v, w, \theta_x, \theta_y$ per node. It is assumed that, the inclusion of damage changes the stiffness matrix of the structure while the mass matrix of the structure remains unchanged. The nature of damage is assumed as anisotropic and this is incorporated into the finite element formulation by considering a parameter called principal damage parameter Γ_i [Valliappan *et al.* (1990)], which is a representation of reduction in effective area and is given by $\Gamma_i = \left(A_i - A_i^*\right)/A_i$, where, A_i and A_i^* terms denotes the effective areas undamaged and damaged material (with unit normal) respectively and $i \in \{1, 2, 3\}$ terms are three orthogonal directions. Thus the Eigen equation associated with the damaged structure is given by:

$$\left[[\mathrm{K}_d] - \omega_{id}^2 [M]\right]\left\{\phi^{id}\right\} = \{0\} \tag{1}$$

Where, $[M]$ and $[K_d]$ terms denote the mass and stiffness matrices of the damaged structure. The terms ω_{id} and $\{\phi^{id}\}$ denote the i^{th} natural frequency and mode shape values respectively.

C. Objective Function

Natural frequencies obtained from the damaged structure are used for constructing the objective function as given by:

$$F = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\left(\frac{f_i^m}{f_i^c}\right)-1\right)^2} \tag{2}$$

The terms f_i^m and f_i^c are the measured natural frequencies for damaged structure and the natural frequency obtained from finite element simulation for damaged structure respectively. n is the number of input response parameters (i.e. natural frequencies).

Results and Discussions

The damage detection procedures outlined in above sections are employed for developing a computer program in MATLAB environment. The efficacy of present damage assessment algorithm is demonstrated with a cantilever beam of length, breadth and thickness of 500 mm, 30 mm and 2.8 mm respectively (Fig. 1). The material properties for the composite beam are given in the Table 1. The algorithm is verified for both single and multiple element damage cases. For finite element simulation the beams are modeled with 10 orthotropic elements. First six numerically evaluated natural frequencies are used for constructing the objective function. Up to 1.0% noise is added to the numerical natural frequency to simulate the experimental condition. Table 2 shows the damage conditions considered for the study and the results of damage assessment for various noise levels.

Table 1: Material properties considered for the numerical composite beam

E_1 (GPa)	E_2 (GPa)	E_{45} (GPa)	G_{12} (GPa)	υ_{12}	ρ (kg/m^3)
9.5	6.8	4.18	1.4	0.14	1761

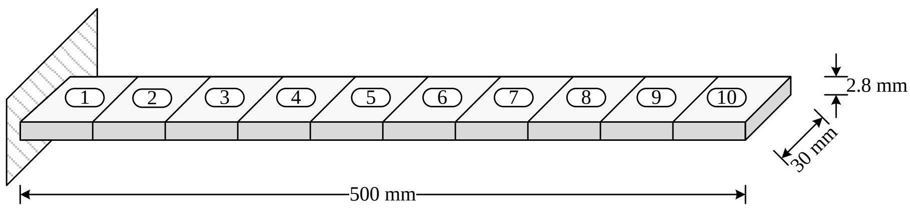

Fig. 1. Cantilever beam made of composite material.

Table 2: Damage cases selected for simulation studies and assessment results

Damage Case	Damage Cases	Damage Assessment Results [Element No. (Γ_1, Γ_2)]			
		Actual	0.00 % Noise	0.50% Noise	1% Noise
One element damage	J1	5 (0.50, 0.00)	5 (0.50, 0.00)	5 (0.50, 0.00)	5 (0.50, 0.00)
	J2	5 (0.00, 0.40)	5 (0.00, 0.40)	5 (0.00, 0.40)	5 (0.00, 0.41)
Two element damage	J3	2 (0.45, 0.00)	2 (0.45, 0.00)	2 (0.45, 0.01)	2 (0.46, 0.01)
		6 (0.60, 0.00)	6 (0.60, 0.00)	6 (0.60, 0.01)	6 (0.59, 0.01)

It may be observed from the Table 2 that, for all considered cases the algorithm could detect and quantify the damages to a significant accuracy. For example, the algorithm produces an error amounting 0.07 in absolute terms for the quantification of $\left(\Gamma_1 \,\text{and}\, \Gamma_2\right)$ values which is about 1.0% error when compared with full search ranges for these parameters. Moreover in all these cases the algorithm could detect the actual damaged element even with higher noise level of 1.0%. This signifies the efficacy and robustness of the present algorithm for damage assessment in composite beams. In a similar way few more single as well as multiple damage cases are simulated in both beam and plate like structure and the results obtained from the study is found to be quite impressive.

Conclusions

A numerical procedure is presented to detect and quantify damage in a composite beam like structure based on changes natural frequency data using unified particle swarm optimization technique. The proposed methodology is demonstrated using a numerically simulated composite beam structure containing single and single and multiple damages. As indicated by the simulation results, the proposed method is able to detect and quantify the damage accurately using first six natural frequencies for considered damage cases.

References

Hao, H. and Xia, Y. (2002), “Vibration-based Damage Detection of Structures by Genetic Algorithm”, Journal of Computing in Civil Engineering, 16.3, 222-229.

Hamey, C. S., Lestari, W., Qiao P. and Song, G. (2004), “Experimental Damage Identification of Carbon/Epoxy Composite Beams Using Curvature Mode Shapes”, Structural Health Monitoring, 3.4, 333-353.

Nanda, B., Maity, D. and Maiti D.K. (2012), “Vibration-based Structural Damage Detection Technique using Particle Swarm Optimization with Incremental Swarm Size”, International Journal of Aeronautical & Space Sciences, 13.3, 323–331.

Nanda, B., Maity, D. and Maiti D.K. (2014), “Crack Assessment in Frame Structures Using Modal Data and Unified Particle Swarm Optimization”, Advances in Structural Engineering, 17.5, 747-766.

Parsopoulos, K.E. and Vrahatis, M.N. (2005), “Unified Particle Swarm Optimization for Solving Constrained Engineering Optimization Problems,” Proceedings of the First international conference on Advances in Natural Computation - Volume Part III, Berlin, Heidelberg, 582–591.

Kennedy, J., Eberhart, R. (1995), “Particle Swarm Optimization”, IEEE International Conference on Neural Networks, IEEE Press, 4, 1942-1948.

Valliappan, S., Murti, V., and Wohua, Z. (1990) “Finite Element Analysis of Anisotropic Damage Mechanics Problems”, Engineering Fracture Mechanics, 35.6, 1061-1071.