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Dynamic response of laminated composites using design of experiments: An experimental and numerical study

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ABSTRACT

In addition to many advantages, composite materials constitute a new challenge in many industrial fields and applications. Vibration Based Methods (VBM) are relatively simple and at low cost to detect damage and fails in composite structures, but they are sensitive to variations in geometry and material properties. Recently, the main challenge in VBM is to establish a robust process to be applied on an industrial environment. In this work, a methodology to identify the effect of design parameters on the dynamic response of laminated composite plates is presented. For the case of composite materials, the production process plays an important role. Numerical dynamic analyses are run using the Finite Element code ABAQUS™ which is complemented with user subroutines written in Fortran and Python. A Design of Experiments (DoE) strategy is developed to reduce the number of experiments and to evaluate the effect of the design parameters. Two sets of composite plates were evaluated, $[0]_8$ and $[0/-15/15/0/-15/15]_s$, with natural frequencies used as response quantities. In addition, Frequency Response Functions are analyzed, as they are obtained by a full factorial design. Afterwards, the results are discussed with proper attention for the potential and for the limitations of the proposed methodology from the perspective of usage to detect damage and failure in composite structures.

1. Introduction

Many industrial applications require a good understanding of the structural integrity to prevent accidents and to improve the maintenance program. Most structures tend to degrade over time, with a negative effect on material properties due to different sources like environmental conditions and accidental events. Imperfect design and manufacturing imperfections inevitably introduce uncertainty into the system, which adds to the complexity of accurate modelling. Methodologies and systems to detect damage on the structure in an early stage, and to evaluate its severity are useful to avoid structural failure. As listed by Adams [1], structural damage may have different sources like micro-structural defects, corrosion, residual stress, cracking, fastener faults, adhesive faults, and other types of instabilities. Damage changes structural behaviour. Further, it is necessary to inspect the structure periodically to maintain the safety and reliability of the component. This is the reason why it is possible to find several non-destructive techniques (NDT) for the identification of damage in a structure [2].

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Successful damage detection in structures is essential for maintenance. NDE/NDT, which can identify damage, may be used for this purpose. However, most of the non-destructive methods, such as ultrasonic methods, require the location of the damage and that location must be accessible. The methods, which are based on vibration responses (VBM), usually do not show these limitations. The basis of vibration response methods is that damage changes the dynamic behaviour of the structure. Damage in a structure can alter the structural integrity, and therefore, the physical properties like stiffness, mass and/or damping may change, modifying the global structural dynamic response. The dynamic behaviour of a structure is a function of these physical properties and will, therefore, directly be affected by the damage. The dynamic behaviour can be described by time, frequency and modal domain parameters. The changes in these parameters (or properties derived from these parameters) are used as damage indicators. Ooijevaar [3] categorized the vibration based methods according to their damage sensitive feature and statistical classifier.

Commonly, when damage develops in a structure, the stiffness decreases and, consequently a reduction of some natural frequencies of the system can be observed. This hypothesis is used for many methods based on natural frequency analysis. A remarkable advantage of this detection technique is that frequency measurements can be conducted quickly and easily. This approach can identify the presence of the damage and, in some cases, the location [4–14]. Several methods and metrics have been proposed by the present authors in previous works in order to improve the detection of damage in composite structures, some of them are used in conjunction with numerical models and analysis to support the damage study, mainly via VBM. Sartorato et al. [15] presented a new shell finite element model based on a modified First Order Shear Theory (FOST) for piezoelectric composite laminates, to simulate thin structures with piezoelectric sensors via VBM. In addition, De Medeiros et al. [16] presented a combination of a vibration-based method and speckle shearography to identify, locate and quantify the damage in composite structures. A new damage metric and Frequency Response Functions (FRF) based method are used to identify damage in a first approach and an optical interferometric technique locates and quantifies the extent of damage in the structure. Additionally, De Medeiros et al. [17] proposed a new damage metric taking into account not only the amplitude, but also the phase of the FRF. The new metric was compared with other ones and experimental data, concluding that vibration-based metrics are a good option not only to identify the damage, but also to provide a prediction of the damage severity [18].

However, small variations on material and/or geometric parameters can also change the natural frequencies. These deviations from the nominal configuration pose challenges for establishing the reference structure (undamaged structure) to be compared to others (damaged structures). A relevant issue in VBM is the difficulty to know the nominal characteristics of the manufactured component, since the manufacturing process may have a significant effect on material values. The commonly used procedure is to acquire data from the manufactured component just after fabrication, and use it as a reference value to identify damage. However, for some kinds of damage, it is not possible to evaluate the same manufactured component before and after the incidence of damage. It is important to know the influence of each design variable on the dynamic response to create models and define better quality criteria for the manufacturing process. One way to approach this problem consists of applying a design of experiments methodology (DoE), which is a powerful tool for the identification of the influence of the most important process parameters in the structural response [19]. Kleijnen [20] lists different methodologies that may be useful. A second advantage of DoE is to provide more information than one-change-at-a-time traditional experimental methods. In fact, DoE methods allows to measure the significance of the design variables not only when they are acting alone, but also when combined effects are present. Computational simulations and DoE have shown to be an important tool for complex analyses and parameter optimisation. It opens the possibility to improve the search by optimal parameters, and evaluates the influence of variables in a process [21–24].

Based on the knowledge of the authors, in the literature, it is common to find methodologies to analyse only the damage response in composite structures. Thus, considering the scenario pointed above, this work aims to contribute to the development a new methodology, for manufacturing process verification, based on the dynamic response (VBM) to be applied on composite structures. In addition, the proposed methodology takes into account the most important design parameters, to determine a range of frequency to be considered, via vibration analysis regarding manufacturing process effects of composite structures. Also, a detailed description of the methodology analysis, considering the influence of the design variables in each mode shape is presented. Several experiments are required to cover the entire design space to evaluate the process. In addition, computational analysis is used to reduce the cost, in conjunction with a DoE strategy. Also, a detailed description of the methodology analysis, considering the influence of the design variables in each mode shape is presented. An expected range for the dynamic response is defined. In this case study, the four most significant parameters are identified among eleven variables of the composite plates. The variables include geometry parameters (width, length, central distance, ply orientation and thickness) as well as material parameters (Young's modulus in fibre and in transverse direction, shear modulus in ply plane and Poisson's ratio). These parameters are obtained from the experimental analysis of carbon fibre reinforced epoxy plates. Numerical analysis is performed by Finite Element Method to predict the modal parameters. First, free vibration analyses were carried out to find the natural frequencies. Afterwards, the set of Frequency Response Functions (FRFs) obtained from the variation of the most significant parameters are compared to the experimental ones. This comparison shows the influence of the range of parameters due to the manufacturing process on the dynamic response. Finally, there is a discussion on damage detection by VBM.