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A modal approach for dynamic response monitoring from experimental data

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ABSTRACT

The objective of this paper is the definition and verification of an iterative procedure for the detailed monitoring of the dynamic response of a structural system based on the experimental modal model of the system on ground and a limited number of measurements in the operating condition. The method is formulated starting from a linear model, but it can be applied to weakly non-linear system, because of the iterative nature of the algorithm. It does not require the definition of a numerical model, but an experimental representation in the modal coordinates, achievable with a preliminary modal survey with an arbitrary large amount of experimental points. The proposed method is presented as well as its implementation and several numerical test cases in order to validate its formulation. Experimental analyses are performed on a uniform beam and on a full-scale aeronautical composite component with promising results.

1. Introduction

The monitoring of the conditions of a structural system during its operations offers the possibility of improving the safety of a mission. Fatigue deterioration, affecting all structural systems, represents, in fact, one of the major issues regarding mission safety that needs to be addressed during the entire life of each dynamic component [1,2]. The efficacy of structural monitoring is however often undermined by the practical limitations connected to the measurement system in terms of cost and weight. It is usually possible to monitor the response at a very limited number of locations, that need to be chosen to best represent the most critical parts of the system during every operation. This limitation could be overcome by reconstructing the full-field response of the structure based on the measured response.

If a numerical model of the system is available, expansion methods are capable of reconstructing the motion at all degrees of freedom of the finite element model based on measured information and the model itself [3]. The reconstructed response can then be used for test-model correlation, to update numerical models, and to identify damage [4,5]. These shape expansion approaches define model reduction transformation matrices to reconstruct the complete mode shapes

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based on few experimental measurements. Classical approaches, such as subspace methods, for example, select a subspace of possible displacements using the low frequency mode-shapes and/or static responses to loads or displacements and/or dynamic responses. Methods based on low frequency modes are known as modal/SEREP expansion. They aim to reconstruct the mode shapes at unmeasured locations based on a combination of the measured mode shapes and the numerical mode shapes [6]. However, the quality of the reconstruction is case-dependent and is adversely affected by the complexity of the mode shapes. Their advantage is that random measurement errors do not affect the quality of the expanded mode shapes. The Guyan reduction method, instead, uses static response to unit loads applied at the sensors to reconstruct the deformation of non-measured degrees of freedom. The quality of results is however limited by the assumption that inertial forces are negligible [7,8]. In the attempt to take into account the presence of inertial forces, dynamic expansion methods, as the name suggests, use dynamic responses to unit loads at the frequency at which the modes need to be reconstructed [8,9]. The main limitation is its high computational cost due to the necessity of a different base for the expansion at each frequency of interest [8]. To overcome all these issues, the generalized dynamic expansion defines an arbitrary reduction basis to relate harmonic loads collocated at the sensors to the reconstructed degrees of freedom.

Another class of approaches directly reconstructs the response field of the whole system based on few measured locations and a set of interpolation functions that relate the quantities involved [3,10–15]. In this case, the estimate of the response field would provide additional and more accurate information on the dynamical behavior of the structure and, as a consequence, on its fatigue life.

In this paper, the desire is to expand current approaches for shape expansion in order to eliminate the need for an a priori dynamic model and work in the experimental domain only [16]. This approach is based on the Load Confluence Algorithm (LCA) [14,17]. The numerical model is replaced with an initial experimental model obtained through detailed ground vibration tests, that is used to project the monitored response during operations. Initial detailed measurement of mode shapes and static response has in fact recently gained a lot of attention due to the possibilities offered by laser scanning vibrometers and high speed cameras with digital image correlation [18,19]. These initial tests provide detailed information on the mode shapes, natural frequencies and frequency response functions (FRF). During operations, the response of the system is tracked at a limited number of locations with more traditional experimental setups. By combining this information with a simple iterative approach, based on a modal representation of the system, the dynamic response is monitored during operations at all the locations at which the reference modal quantities are measured.

If an experimental model is built through an Operational Modal Analysis (OMA) approach, some modal parameters are not known and the frequency response functions are affected by a bias. In fact, the mode shapes obtained through OMA can be normalized only by performing a second test campaign characterized by changes in the structural properties of the system under investigation [20]. Moreover, the Hilbert Transform Method is capable of providing an estimate of the frequency response functions that differ from the real ones for a gain factor [21]. Therefore, the full-field dynamic response identification is slightly affected by the unknown excitation and the related uncertainty on the OMA estimates. The influence of using OMA approaches to estimate modal parameters will be discussed in the paper.

This paper presents a conceptual description of the approach, as well as its detailed mathematical formulation. It demonstrates the abilities of the algorithms in a numerical framework, in which the experimental environment is simulated with beam models. Then, experimental applications to a uniform one-dimensional structure show the robustness of the method for different loading conditions. At the end, the approach is applied to analyze the response of a full-scale composite flexbeam for a hingeless helicopter tail rotor.

2. Response monitoring approach

The objective of the approach is to update the values of the external loads based on response measurements at few points from which it is possible to accurately represent the response in the whole domain of interest. The first assumption of the approach is that the initial system on which ground vibration tests are performed and the system during operations are equivalent in terms of dynamic properties, but differ for the estimate/measure of the external loads.

The response monitoring approach consists of two modules, a first module that estimates the response in all the domain of interest, a second module that from the experimental response at few locations extracts a correction to be applied as input to the first module to improve the initial estimate. The procedure is represented in Fig. 1 and summarized as the following sequence of steps:

1. Evaluate natural frequencies ω_n, damping ratios ζ_n, modes $\boldsymbol{P}$[1] and frequency response functions $\boldsymbol{H}(\omega)$ of the system from a ground vibration test with an arbitrary large amount of measurement and excitation points, in order to achieve detailed information on the system in all the domain of interest.
2. Measure the response $\boldsymbol{e}_{exp}$ during operations at few locations (that are the master or control points) of the system chosen by applying the best positioning approach (see Section 2.5) with the Fisher's information matrix of the normal modes [22].

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[1] Throughout the work the matrices are represented by upper-case letters in boldface ($\boldsymbol{M}$), while the corresponding element is denoted by generic subscript notation (M_{ij}). Similar notation is used for the vectors with lower-case letters in bold face ($\boldsymbol{v}$) and for the elements with subscript (v_i).