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An integrated approach for non-periodic dynamic response prediction of complex structures: Numerical and experimental analysis

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A B S T R A C T

In this paper, a combined numerical and experimental method, called Extended Load Confluence Algorithm, is presented to accurately predict the dynamic response of non-periodic structures when little or no information about the applied loads is available. This approach, which falls into the category of Shape Sensing methods, inputs limited experimental information acquired from sensors to a mapping algorithm that predicts the response at unmeasured locations. The proposed algorithm consists of three major cores: an experimental core for data acquisition, a numerical core based on Finite Element Method for modeling the structure, and a mapping algorithm that improves the numerical model based on a modal approach in the frequency domain. The robustness and precision of the proposed algorithm are verified through numerical and experimental examples. The results of this paper demonstrate that without a precise knowledge of the loads acting on the structure, the dynamic behavior of the system can be predicted in an effective and precise manner after just a few iterations.

1. Introduction

The definition of an accurate model for mechanical and aeronautical structures subject to complex dynamic loads is a crucial step for better understanding the dynamic behavior of the structure, specifically in health monitoring applications [1–4]. This is usually a daunting task due to complexity of the structure and lack of information about its mechanical properties or the applied loads. Among many approaches in the literature to define a reliable platform for such systems, there are still many insufficiencies when they go from the theoretical side to the real applications. Some of these approaches assume having access to a detailed model of the structure [5,6]; however, the lack of availability of such detailed models often makes these methods non-feasible and impractical [7]. While many of these methods are based on a linear model of the structure, equipping the method with the capability of accounting for nonlinearities in the dynamic response would contribute a lot to the field specifically in case of rotating machinery which mainly relies on nonlinear responses [7,2].

Response identification methods are among the approaches in which the need for a detailed structural model is diminished by the help of experimental measurements. In these methods the dynamic response of the structure can be

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estimated either by focusing on the evaluation of the applied loads (Force Reconstruction methods) or the dynamic response (Shape Sensing methods).

A review of Force Reconstruction methods was done in [8]. In [9], Bousman used a Force Reconstruction method (FR) to estimate the loads of a helicopter blade. In his work, modal analysis and bending moment measurements are used to estimate the normal airloads of a helicopter blade. Compared to the FR methods, Shape Sensing methods (SS) have been shown to be more propitious because they need less computational burden and experimental measurements [10].

Examples of SS methods are presented in [11,12]. In [11], SS is used to predict displacements of a system by using modal analysis and some experimental data gathered from the strain gages. Inverse Finite Element method (iFEM) was used as a shape sensing method in [12] for response reconstruction from strains measurements. In this work, Timoshenko beam theory was applied to a thin-walled cantilevered beam subjected to different static and dynamic loads to predict the deflection of the beam. A later work on the shape sensing methods with the capability of accounting for the existence of nonlinearities in the structure was proposed by Chierichetti et al. [13,14]. In [13], an iterative process is presented to predict the stress components of an structure under a harmonic loading. Modal analysis and Fourier Series expansion are used in their work to identify the dynamic response of the structure. Although the method presented by Chierichetti et al. solves some of the aforementioned issues about health monitoring approaches, it is only applicable to the systems with harmonic loading conditions.

In this paper, the Extended Load Confluence Algorithm (ELCA) is presented to reconstruct the dynamic response of a structure under general loading conditions based on a simplified numerical model and a few experimental measurements, when there is no or little information about the loads acting on the structure. In the presented algorithm, while the real applied loads on the system are unknown both in terms of distribution and frequency bandwidth, ELCA starts with an initial guess for the applied loads, and according to this guess, it solves the system's equations to find the corresponding dynamic response of the system. This numerically calculated response is then compared with the experimental measurements collected from a few sensors installed on the structure, and based on their difference, the initial guess for the applied loads is modified. The algorithm iterates until a final equivalent loading is found that corresponds to accurate estimate of the dynamic response of the system in the entire domain of interest.

Following this introduction, the concept of ELCA will be described, as well as its mathematical formulation. Numerical and experimental examples on a three-dimensional (3D) structure and a cantilever beam will demonstrate the capabilities and advantages offered by the proposed approach. In all presented cases, it will be shown that the dynamic response of the system can be accurately and effectively predicted for the entire domain of the structure.

2. The proposed method: ELCA

2.1. Concept

The Extended Load Confluence Algorithm (ELCA) is an iterative algorithm which aims to improve the accuracy in the modeling of the dynamics of a flexible structural system under general loading conditions. This is achieved by comparing the numerical predictions with experimental measurements, and by updating the numerical model based on their difference in the frequency, time, and modal domains. This updating process is schematically depicted in Fig. 1, which shows how the dynamic response of the structure is corrected in an iterative process by comparing the numerical response to the experimental measurements in a few locations. To elaborate more, this updating process is performed through three major cores in ELCA, namely numerical, experimental, and mapping cores, as depicted in Fig. 2. The numerical core of the algorithm generates a model of the structure; in this paper the focus is on Finite Element Models (FEM). From an initial guess of the applied loads (input), the dynamic response of the structure is estimated at each time instant. The experimental core represents the real system during operations, and outputs the measured data at the locations of interest. The mapping core bridges the numerical and experimental cores. Based on the difference between the numerical and the experimental response at the sensor locations, it evaluates corrections to the applied load so that the dynamic response is improved. First, it converts all the data into frequency domain with a Fast Fourier Transform (FFT) method, then it generates a correction to the force vector of the numerical core based on modal expansion of the equations of motion.

Since the applied loads of the system are assumed to be unknown, the numerical core starts with an initial guess for the applied loads and estimates the dynamic response of the structure. These numerical responses are then compared to the measurements in the mapping core of the algorithm, and a corrected force vector is generated for each iteration. The algorithm iterates until the difference between the experimental measurements and numerical predictions is less than a user-defined tolerance.

When this condition is satisfied, the model of the structure accurately represents the operating system, not only in the sensors locations but also in the entire domain of the structure. The iterative process of the algorithm is described through the following steps.

(1) The response is measured at the desired time instant at the sensors' location.
(2) The inputs to the algorithm are the experimental data $\boldsymbol{e}_e$ and an initial guess $\boldsymbol{F}_0$ for the applied load.