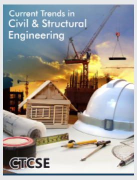

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Operational Modal Analysis and Structure Health Monitoring

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Abstract

Modal parameters are able to characterize any structure uniquely. All the structural elements and the respective boundary conditions have a direct impact in all of the modal parameters (natural frequencies, damping ratios and mode shapes), making them suitable to detect damage along the structure. To this end, experimental identification of the modal parameters is necessary and must be conducted periodically. In the last decade, operational modal analysis has been developed to this purpose. It allows the identification of the modal parameter with the structures in operational conditions and using ambient excitation. Several improvements in the field were recently made with the computation of modal parameters uncertainties and with the automation in the identification process. Therefore, vibration-base structural health monitoring system is getting popular for critical civil structures such as bridges, high buildings and old constructions.

Keywords: Operational modal analysis; Structure health monitoring; Uncertainty quantification; Stochastic modeling; Linear time-invariant systems; Identification

Introduction

Operational Modal Analysis (OMA) consists in finding the dynamic characteristics of a structure through its modal parameters using output-only measurements and ambient excitation. Differently from the classical approach of Experimental Modal Analysis (EMA), where the excitation in the structure is controlled and measured, OMA only uses hypothesis of the stochastic nature of the inputs. This fact allows the identification of systems under circumstances where EMA is limited. Large and heavy structures, commonly found in civil engineering, are good examples where OMA is more suitable than EMA. A controlled input in those structures is in general hard to apply or expensive. Also, to bring them into laboratory conditions, where the perturbations from the ambient are minimized, is usually impossible. One cannot avoid the action of ambient excitations, like the wind, nearby traffic, seismic activities, etc., on those structures. Another example where OMA becomes necessary is when a structure is too small and has a high flexibility. The small size of the structure restricts the use of an electromagnetic shaker since it adds significant mass to the system. On the other hand, the high flexibility restricts the use of a modal hammer since a clean single impact becomes hard to apply [1]. In those cases, it is better to use the ambient excitation as the only excitation for the identification process. This opens a good opportunity to periodically identify the modal parameter of the structure and assess its integrity.

Discussion

From the linear theory for time-invariant systems, the relationship between the excitation and the response of any structure is given by the impulse response function (IRF) or the frequency response function (FRF), depending on which domain (time or frequency) has been considered. Such functions

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characterize the structure uniquely and can be easily decomposed in terms of the modal parameter [2]. Therefore, the identification procedure in EMA corresponds first in estimating the IFR or FRF using the input and output signals and latter applying a dedicated curve fitting method to extract the values of modal parameters [3,4]. Since the input signal is no longer available in OMA, neither the IRF nor the FRF can be estimated from the experimental data. Nevertheless, under the special and idealistic consideration of white noise excitation, it is possible to show that the correlation functions and power spectral densities (PSD) of the systems responses can also be decomposed in terms of modal parameters [5]. This modal decomposition maintains a similar mathematical structure found in the IRF and FRF decomposition. Therefore, it is possible to apply most of the identification methods developed for EMA in OMA. The only difference is that IRFs are replaced by correlation functions and FRFs by PSDs. Although a white noise excitation is not realizable, such model is still valid because one can always consider a loading filter that transform the hypothetical white noise excitation into the actual one. The identification of the system un- der this white noise excitation hypothesis is then the identification of the loading force filter together with the actual structure. A discernment between the modal parameters related to the structure from those related to the loading filter is usually possible by examining the identified modal parameters and stabilization diagrams. In summary, to be able to perform OMA, the ambient forces must be at least random, stationary, and have a broadband spectrum to excite all the modes in the frequency band of study.

Most of the modal identification methods were developed for EMA in the second half of the twentieth century and were motivated by the aerospace and automotive industry [4]. During the 1990s, new output-only identification techniques helped in the popularization of OMA [6,7], especially in the civil engineering community. In particular, the stochastic subspace identification method became the standard identification method in the beginning of this millennium thanks to an extensive literature and its user-friendly implementation in commercially software. When compared to EMA, the main drawback of OMA is the fact that the excitation quality signal can no longer be guaranteed. The excitation level at some frequencies can become particularly low, reducing the signal-to- noise ratio significantly. The understanding of how such measurement noise affects some statistical functions were done recently to improving the robustness of identification methods [8]. The measurement error also motivated the scientific community to develop identification methods that allow the uncertainty quantification of the modal parameters [9]. The developed methods can be divided in two groups depending on the definition of uncertainty: from a frequentist point of view or from a Bayesian one. In the former, the uncertainty is the reflection of the variability of the modal parameters identified from different data sets of equal events. Perturbation techniques were implemented to evaluate the first order sensitivity of the modal parameters due to the variability of the data [10]. In a Bayesian point of view, the modal parameters are considered random variables with probability distributions that depends on the available information. The uncertainty is then related to the spread of the probability distribution nearby its maximum value, usually quantified with a Gaussian approximation. The Bayesian methods were already formulated using time domain data, power spectral density and the Fast Fourier Transform of the data [11]. Computational algorithms were latter developed [12] and field examples are currently emerging [13].

Perhaps the vibration-based structure health monitoring (SHM) is the engineer field that has been benefit- ing the most with the developments of OMA. This statement is reinforced by the large number of publications on the subject in the past few years. A quick examination on the latest proceedings of the International Operational Modal Analysis Conference (IOMAC) will prove just that [14]. Many new extremely tall buildings and long bridges have been constructed with integrated sensor for a SHM system [15]. Some of those systems have also been used to guarantee the structure quality during the construction [16]. Beside civil structure, offshore oil rigs and wind turbine farms have also been widely instrumented with SHM systems. In essence, the vibration-based SHM evaluates the integrity of a structure by analyzing the trends on the modal parameters along the time. Such variations on the modal parameters can happen slowly (from the degradation of the structure) or suddenly (cause by damage after a cataclysmic event). A good SHM system should be able to analyze the slow trends compensating and influence of the ambient (temperature, humidity etc.) on the modal parameters [17]. Also, the SHM system should be able to assess if the structure still safe after been exposed to sever conditions. A great challenge in the field of vibration based SHM is how to perform a fully automatic OMA that enables the modal characterization of a structure in an online, unassisted and robust way. Also, it must deal with transmission, storage, and analysis of this large amount of data. A recent field where OMA is now been applied is in the characterization of nonlinear systems through lin- ear approximations. OMA is a technique that is restricted to linear time-invariant systems, so any attempt to describe nonlinear systems with this technique leads, at best, to good approximation. Nevertheless, it is still a convenient task to perform since linear model are well understood and can be interesting for structure control, model reduction and also to obtain physical insights. Nonlinear systems are energy dependent, so the linearization is not unique and should be conducted at different energy levels. Researches have already been made in the identification of orthogonal modes with the usage of the proper-orthogonal (Karhunen-Loève) decomposition. This technique leads to optimized representation of the system in terms of energy and is excellent for model reduction. To extract also information regarding fundamental oscillations of the modes, an extension of the proper-orthogonal decomposition was also proposed and is known as smooth orthogonal decomposition [18,19].

Conclusion

After almost 30 years of its popularization, OMA can be considered a mature research field. Nevertheless, it is still an active one. Identification's techniques can be considered well established but improvements have still been published. From the knowledge provided by OMA about a structure, new applications are emerging every day and considerable enhancements are still needed on those areas.

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Conflict of Interest

No Conflict of interest.

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