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Scaling of mode shapes from operational modal analysis using harmonic forces

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ABSTRACT

This paper presents a new method for scaling mode shapes obtained by means of operational modal analysis. The method is capable of scaling mode shapes on any structure, also structures with closely coupled modes, and the method can be used in the presence of ambient vibration from traffic or wind loads, etc. Harmonic excitation can be relatively easily accomplished by using general-purpose actuators, also for force levels necessary for driving large structures such as bridges and highrise buildings. The signal processing necessary for mode shape scaling by the proposed method is simple and the method can easily be implemented in most measurement systems capable of generating a sine wave output. The tests necessary to scale the modes are short compared to typical operational modal analysis test time. The proposed method is thus easy to apply and inexpensive relative to some other methods for scaling mode shapes that are available in literature. Although it is not necessary *per se*, we propose to excite the structure at, or close to, the eigenfrequencies of the modes to be scaled, since this provides better signal-to-noise ratio in the response sensors, thus permitting the use of smaller actuators. An extensive experimental activity on a real structure was carried out and the results reported demonstrate the feasibility and accuracy of the proposed method. Since the method utilizes harmonic excitation for the mode shape scaling, we propose to call the method OMAH.
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1. Introduction

Operational Modal Analysis (OMA) is a powerful tool for estimating modal parameters of large structures, as well as of systems hard to be reached (e.g. [1–6]). The technique allows to estimate modal parameters (i.e. eigenfrequencies, nondimensional damping ratios and mode shapes) by measuring the output of the structure/system and exploiting the natural forcing (e.g. wind, traffic, operating machines). This approach is attractive also because it allows for permanent monitoring of the modal properties of structures and systems without the need for providing excitation.

A common issue with OMA tests is that the obtained modal model is not scaled, due to the fact that the loads on the structure are not measured. Many efforts have been spent investigating methods for scaling mode shapes estimated by means of OMA (or to estimate the modal mass, which is synonymous). We can split these methods into four main categories:

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1. methods based on the repetition of OMA tests with several configurations of the structure, e.g. change of mass or stiffness of the structure;
2. methods based on operational modal analysis with exogenous inputs (OMAX), where the unmeasured environmental excitation is complemented with an additional measured force provided by external actuators;
3. methods relying on OMA tests with the use of specific dynamic systems (e.g. tuned mass dampers) coupled to the main structure;
4. methods relying on an accurate finite element (FE) model

The four categories are discussed one by one below.

As for the first category, Parloo et al. [7] proposed a method to scale modes computed by means of OMA by using the change of poles due to a change of the mass of the structure. Obviously, this requires to repeat the OMA test with (at least) one different layout of the structure (i.e. with another mass configuration). A sensitivity analysis about the relation between possible bias in the estimates of the eigenfrequencies and the resulting bias in the estimates of the scaled eigenvectors was also performed within the work. Subsequently, such an approach was further studied and developed by many authors. Two main issues were taken into account by several authors: the achievement of more refined formulations to describe the shift of poles due to mass changes [8–12], and the analysis of procedures able to decrease the uncertainty associated with results [8,13–15,10] (e.g. optimisation of the number of masses to be used, their locations and the mass needed). Coppotelli also showed that a change of stiffness can be used as well [15]. This kind of technique has been tested on many different systems such as bridges [16], steel beams [17] and aerospace structures [15] with good results. For some structures, however, as [9] concludes, '…, *it is evident that in some civil engineering applications the required masses may prove too large to be practical*…'.

As for OMAX-based methods (point 2 of the previous numbered list), Reynders et al. [18] demonstrated the capability of such approaches to provide high-accuracy results even on large structures such as footbridges. Recently, Cara proposed an OMAX method based on the state-space representation of the system under analysis [19]. This work explains how to scale modes using OMAX by employing invariants of the state space model of the system. In this scenario, a broadband measured force must be provided to the structure and the state space matrices are identified. Then, the invariants are calculated, as well as the modal mass values.

Other works propose to couple the structure under analysis with known dynamic systems (point 3 of the previous numbered list). The measurement of the structural output, complemented by knowledge of the added system, allows to estimate the modal masses. Hwang et al. [20] demonstrated the feasibility of coupling a tuned mass damper (TMD) to the system under analysis. Mode scaling is achieved by H-infinity optimal model reduction for the degree-of-freedom (dof) in which the TMD is installed and for the mode to which the TMD is tuned. Brownjohn and Pavic showed how to scale modes by adding people to the main system in [21]. In this work, OMA scaling of pedestrian structures was achieved by using a database of pedestrian excitation built by measuring human-induced excitations in a laboratory environment. Finally, Porras et al. [22] proposed a modal mass estimation technique relying on the addition of a single dof (SDOF) system to the main structure. The solution of the dynamics of the coupled system allows to estimate the modal mass and thus to scale OMA modes. The additional device must have its eigenfrequency close to that of the mode for which the modal mass is sought. Two algorithms were proposed; one in the frequency domain and the other in the time domain.

The fourth approach is to rely on a FE model, as proposed by [23]. With this method, the mass matrix of the FE model is used together with expanded experimental mode shapes. Apart from being sensitive to errors in the mode shape expansion, this approach is efficient and attractive in its simplicity, provided the FE model exists, of course.

The referenced approaches are all based on rather elaborate experimental procedures (e.g. mass changes) and/or set-ups, or they rely on the accuracy of a computational model, which latter must be based on an assumption. The aim of the present paper is to present an alternative method for computing modal masses, and thus scaling the OMA mode shapes, employing a fast and readily applicable experimental procedure involving the use of relatively inexpensive and general-purpose actuators as well as simple signal processing.

This paper is structured as follows: Section 2 explains the method proposed here. Section 3 describes some signal processing tools that may be applied to the purpose of estimating the harmonic components necessary for the mode shape scaling. Section 4 highlights some advantages with the proposed method, and, finally, Section 5 discusses an extensive experimental campaign carried out to demonstrate the effectiveness of the method.

2. Theory

The frequency response function (FRF) of a mechanical system between the displacement at a point p and a force applied at a point q can be expressed as [24]:

$$H_{p,q}(\mathrm{j}\omega) = \sum_{r=1}^{N_m} \frac{\psi_r^p \psi_r^q}{m_r(\mathrm{j}\omega - s_r)(\mathrm{j}\omega - s_r^*)} \tag{1}$$

where ω is the circular frequency, j is the imaginary unit, N_m is the number of modes of the structure (theoretically, of course, $N_m \to \infty$ for continuous structures), m_r is the modal mass of mode r, s_r the pole of mode r, and * denotes complex

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