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Estimating the modal parameters from multiple measurement setups using a joint state space model

F. Javier Cara [a,*], Jesús Juan [a], Enrique Alarcón [b]

[a] Laboratory of Statistics, ETS Ingenieros Industriales, Universidad Politécnica de Madrid, José Gutiérrez Abascal, 2, 28006 Madrid, Spain
[b] Department of Structural Mechanics, ETS Ingenieros Industriales, Universidad Politécnica de Madrid, José Gutiérrez Abascal, 2, 28006 Madrid, Spain

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ABSTRACT

Computing the modal parameters of structural systems often requires processing data from multiple non-simultaneously recorded setups of sensors. These setups share some sensors in common, the so-called reference sensors, which are fixed for all measurements, while the other sensors change their position from one setup to the next. One possibility is to process the setups separately resulting in different modal parameter estimates for each setup. Then, the reference sensors are used to merge or glue the different parts of the mode shapes to obtain global mode shapes, while the natural frequencies and damping ratios are usually averaged. In this paper we present a new state space model that processes all setups at once. The result is that the global mode shapes are obtained automatically, and only a value for the natural frequency and damping ratio of each mode is estimated. We also investigate the estimation of this model using maximum likelihood and the Expectation Maximization algorithm, and apply this technique to simulated and measured data corresponding to different structures.

1. Introduction

The modal analysis of a structural system consists of computing its vibrational modes. The experimental way to estimate these modes requires exciting the system with a measured or known input (for example, with a hammer or a shaker), and then measuring the system output at different degrees of freedom (DOFs) using sensors. When the system refers to large structures like buildings or bridges, to apply a known input (more suitable for laboratory conditions) is usually difficult and expensive, and uncontrolled disturbances are also present during the measurements. This led to the idea of performing the modal analysis using ambient vibrations, that is, the vibrations due to unmeasured inputs like wind, traffic, human action, ground vibrations, etc.

The modal parameters estimated from ambient vibration measurements comprise natural frequencies, damping ratios and mode shapes [1]. Natural frequencies and damping ratios might be computed using the data recorded by a single sensor, but the mode shapes can be only estimated at those points where a sensor is placed. When the number of available sensors is lower than the number of tested points (because the structure is large or because the resolution required in the mode shapes is high), it is common practice to perform non-simultaneous measurement setups changing the position of the

* Corresponding author at: ETS Ingenieros Industriales, Universidad Politécnica de Madrid. José Gutiérrez Abascal, 2, 28006 Madrid, Spain. Tel.: +34 913363149.
E-mail address: fjcara@etsii.upm.es (F.J. Cara).

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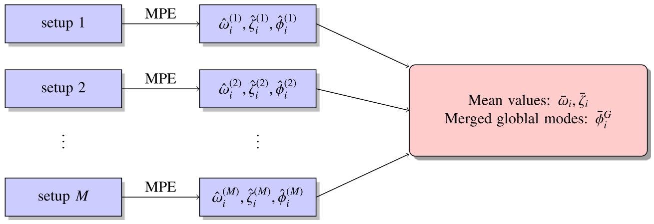

Fig. 1. Merging M individual partial mode shapes into a global mode shape (the multi-step approach). MPE means modal parameter estimation.

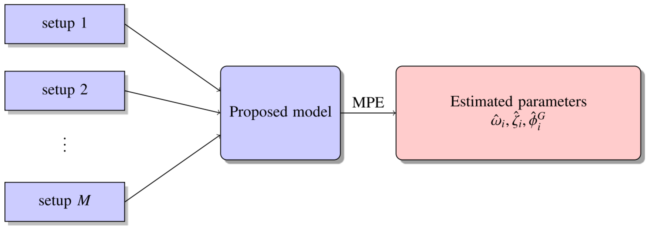

Fig. 2. Estimating the modal parameters processing M setups at the same time (the one-step approach). MPE means modal parameter estimation.

sensors among setups [2]. Since the mode shapes estimated in each setup cannot be scaled in an absolute sense (e.g. to unity modal mass), some sensors have permanent positions because these fixed or reference sensors are needed to glue or merge the mode shapes estimated at each setup (or partial mode shapes) into global mode shapes. The rest of the sensors change their position in the structure from one setup to the next, so different parts of the global mode shapes can be estimated.

The algorithms available to estimate or identify the modal parameters from ambient vibration measurements (also known as Operational Modal Analysis or OMA) were originally developed to process the measured data of one setup of sensors [1,3]. That is why it is usual to process separately the data measured in each setup and then merge the partial mode shapes to obtain global ones: the reference sensors are used to combine the different parts of the mode shapes, while the eigenfrequencies and damping ratios are averaged. This way of computing global mode shapes, which can be named as the multi-step approach, is outlined in Fig. 1. However, some drawbacks can be pointed out:

1. If the number of setups is large, this approach is tiresome, especially if the modes of interest are not well excited and therefore difficult to extract at all the setups [4–6].
2. Since the excitation cannot be controlled or measured, differences in the excitations result in the extraction of spurious or unphysical modes in some setups while these modes are not found in the other setups [4–6].
3. It is not easy to pair the corresponding mode at each setup, especially when there are modes with closely spaced natural frequencies or with similar mode shapes at the reference DOFs [4–6].
4. A lot of effort has to be made to properly merge the different parts of the mode shapes estimated in each setup, for example in a least square sense [7].

On the other hand, there is an increasing interest to process all setups at the same time because the global mode shapes are obtained automatically (the one-step approach, in contrast to the multi-step one, shown in Fig. 2): in Ref. [8] a frequency-domain maximum likelihood identification technique was used for the modal parameter estimation. A comparison was made between a non-parametric and a parametric approach, where the unwanted non-stationary effects are removed respectively before and after the system identification step; in Refs. [9–11] the Stochastic Subspace Identification (SSI) method was adapted to handle these kinds of problems. However, it is necessary to normalize the data of the different setups before to apply the algorithms because the unmeasured background excitation of each setup might be different. Finally, some of these techniques were analyzed and compared in Refs. [2,12,13].

In this work we propose a new state space model to manage multiple setups of sensors and ambient vibrations. The model, described in detail in Section 2.1, belongs to the one-step approach (Fig. 2). Its main properties are:

- The drawbacks described for the multi-step approach are overcome:
  1. All setups are processed at the same time.
  2. The model extracts the parameters that are common to the setups.
  3. Pairing modes among setups is not needed.
  4. Global mode shapes are obtained directly, without further treatment.
- The same sensor position can be measured more than one time, and all the recorded information is used by the model. The more information is recorded, the better estimate of the modes is obtained.