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Output-only full-field modal testing

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Abstract

Operational modal analysis has become the focus of much research attention in the last two decades. Instead of an artificial force, the ambient excitation is considered as white-noise input to the structure and modal properties are calculated only from measured responses. In terms of the measurement technique, full-field optical methods, for example: electronic speckle pattern interferometry and digital image correlation have become popular and there is now much interest in applying these methods in structural dynamics. In this case the generated data is a full displacement map of the object, therefore there is no necessity to select specific measurement locations in order to visualise the deformation. However, there are generally large volumes of data to be processed, which makes the computation expensive and time-consuming, especially for engineering structures with large surface areas. Thanks to image decomposition techniques, huge amounts of data can be compressed into tens of *shape descriptors* with acceptably small distortion. In this paper, operational modal analysis and full-field methods are combined together, and the analysis is done in the shape descriptor domain to reduce the required computation time. Simulated responses from a finite element model of a clamped plate (under random excitation) serve to illustrate the methodology. Several different operational modal analysis methods are applied to analyse the data, and results are provided for purposes of comparison.

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Keywords: Operational modal analysis; Full-field measurement; Image decomposition.

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1. Introduction

Experimental modal analysis (EMA) [1] is a tool that allows engineers to understand the dynamic performance of structures from vibration tests. It is regularly used for the verification and validation of mathematical (e.g. finite element) models used in engineering design. When in-situ, boundary conditions and loads might be quite different from the ideal conditions assumed in design, and for that reason it is often necessary to carry out modal tests under operating conditions. The use of artificial excitation (e.g. using electromagnetic shakers) is often impractical as well as involving an unnecessary expense. Instead, modern techniques are now available that make use of the ambient excitation due for example to wind loads or passing traffic. Such methods, often referred to as operational modal analysis (OMA), inevitably make assumptions on the character of the noise, the principal assumption being that it can be treated as Gaussian white noise. A tutorial review of OMA techniques is given by Magalhaes and Cunha [2].

The use of optical methods, such as digital image correlation (DIC) [3], in vibration testing has become a prominent research topic in recent years and offers potentially significant advantages over traditional accelerometer-based measurements. These include measurement across the complete field of view entirely without added-mass effects, which can be significant especially for close modes when measurement are made with accelerometers. Wang and Mottershead [4] proposed the use of image decomposition to reduce the large volume of pixelated output data to an acceptably small volume of features, or shape descriptors (SD), for efficient processing of full-field measurements.

The purpose of this paper is to demonstrate the application of full-field operational modal testing using outputs in the SD domain. Sections 2 and 3 provide brief overviews of OMA and SD techniques. This is followed in Section 4 by a numerical example to illustrate the performance of several OMA/SD techniques. Finally the work is concluded with statements on effectiveness of the proposed combined approach.

2. Brief overview of operational modal analysis

There are now numerous OMA methods developed from the well-established EMA theories. One of the earliest was the Ibrahim time domain method [5], originally used to calculate the modal properties from free responses. In order to create the required free decay signal for the processing, the covariance or random decrement techniques were applied to measured data. The resulting signals were proven to have the characteristic of free response [6].

The well-known stochastic subspace identification (SSI) method was described in detail by Peeters and De Roeck [7]. Using time series methods and the discrete stochastic state-space, the data were arranged in a Hankel matrix divided into two parts corresponding to shifted 'past' and the 'future' measurements referred to the i^{th} time increment. In theory the Hankel matrix should have an infinite number of rows, whereas in practice it is assumed that the data is sufficiently plentiful to obtain modal estimates of sufficient accuracy. The covariance-driven SSI makes use of the properties of the Toeplitz matrix of covariance terms, whereas the data-driven SSI is based on QR factorization of the block Hankel matrix to project the row space of future outputs on the row space of past reference outputs. Determination of the state-space system matrices is achieved (a) by the covariance-driven SSI, using singular value decomposition of the Toepliz matrix, which leads to the determination of the observabilty and controllability matrices; and (b) by the data-driven SSI, which requires a further projection at time increment i+1. A stabilization diagram may be drawn in order to visually identify the stable modes.

The frequency-domain decomposition (FDD) method [8] applies singular value decomposition (SVD) to the spectrum matrix of auto- and cross-spectra, thereby producing the maximum singular value spectrum for the extraction of modes by peak-picking (PP). An alternative method using transmissibility [9, 10] may also applied to establish frequency spectrum by SVD, based on the principle that the difference between two transmissibility functions, with the same output but different inputs, vanishes at the poles of the system.

The poly-reference least square complex frequency-domain (P-LSCF) method [11], known commercially as *PolyMax*, is based upon the minimization of a cost function, the difference between the measured transfer function and the theoretical right matrix fraction model expressed in terms of polynomial matrices. Natural frequencies, damping ratios and mode shapes may be determined from state-space system matrices via the estimated polynomial matrices.

An early example of the frequency-domain Bayesian approach to OMA is described by Yuen and Katafygiotis [12], later modified to improve the computation efficiency by Au [13]. The method is based upon the application of Bayes rule with the posterior estimate of the PDF of modal parameters given (within a constant of proportionality)