Mechanical Systems and Signal Processing 41 (2013) 196–225

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Optimal reference sensor positions using output-only vibration test data

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ARTICLE INFO

Article history:
Received 26 November 2010
Received in revised form
13 June 2013
Accepted 14 June 2013
Available online 13 August 2013

Keywords:
Optimal sensor position
Reference sensor
Roving setup configuration
Model updating
Random vibration analysis
Output-only modal identification

ABSTRACT

In the context of finite element model updating, experimentally obtained features are used to improve the quality of an initial finite element model. Using vibration tests, features like natural frequency, mode shapes, and modal damping ratios can be extracted from measured data. One possibility to perform such tests is a roving setup configuration that requires defining the positions of reference sensors to merge the information of all setups. Therefore, the determination of reference sensor positions is very important for reliable results.

The presented research is concentrated on the determination of optimal reference sensor positions assuming random excitations within a weakly stationary process. Predicted power spectral amplitudes and an initial finite element model are the basis to define the validation criterion of possible sensor positions. In combination with geometrically based design variables, which define the sensor positions, a genetic algorithm is applied to avoid the assessment of all possible combinations of reference sensor positions.

The applicability of the proposed approach is demonstrated on a numerical benchmark study of a simply supported beam and a case study of a real test specimen. Furthermore, the theory of determining the expected power spectral amplitudes is compared with results of vibration tests. It can be concluded that the proposed approach is suitable to determine optimal reference sensor positions as long as the initial finite element model has a sufficient accuracy.

1. Introduction

1.1. Problem description

Finite element model updating [23] is a frequently applied tool to correlate a numerical model with measured quantities. Of course, the success of this procedure depends on both, the numerical challenges and the quality of measured values. The numerical aspects include the accuracy of the numerical model and the updating algorithm. A pretest analysis based on an initial numerical model will be typically performed to optimize the measurement configuration with respect to the features used for model updating. The basic principles of a pretest analysis used for optimizing vibration measurement configurations are explained, for example, in [22]. The modal properties (i.e., natural frequencies, mode shapes, and damping ratios) of a system, as one class of features, are extracted from vibration test data. In many cases, the modal

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http://dx.doi.org/10.1016/j.ymssp.2013.06.039

identification is performed based on response vibration measurements only. An introduction to output-only modal testing can be found in [18,10,63]. The most widely used identification algorithms are the stochastic subspace identification (SSI) [61], the enhanced frequency domain decomposition (EFDD) [11], and the poly-reference least squares complex frequency domain method (p-LSCF) [13].

Consequently, the main task of a pretest analysis in the field of experimental modal analysis is the optimal placement of sensors. Two main sensor setup configurations are possible. First, all sensors are fixed at certain positions during all measurements. Such a single setup configuration is appropriate, if the sensor positions at the structure are difficult to access and if the number of sensors is sufficient to get a certain spatial resolution of information about the structure. Second, at least one sensor is fixed during all measurements and at least one sensor is moved across the structure. This roving sensor setup configuration is applied, if the number of available sensors or channels is not sufficient to get the necessary resolution of information in space at the structure. The fixed sensors are called reference sensors, which will be used to merge all different setups. It is obvious that the success of this merging approach strongly depends on the signal quality and frequency content of the reference sensors.

This paper is focused on the determination of optimal reference sensor positions within a roving sensor vibration test to be used as a basis for updating an initial finite element model. An output-only vibration measurement with random excitation is assumed that can be interpreted as a weakly stationary process.

1.2. *Literature review*

As this specific topic of the optimal placement of reference sensors is almost neglected in the literature, pretest approaches with respect to single setup configurations are reviewed additionally. Furthermore, the search strategies available in the literature will be discussed. Most of the reviewed criteria are related to the mode shapes of a numerical model in the pretest phase.

The research activities on optimal sensor placement problems started already in 1978, with the publication of [66], in which a sensor placement technique to identify dynamic system parameters, such as column stiffnesses, has been proposed. Since this initial work, many other research activities could be recognized. One common measure to judge the suitability of sensor positions in single setup configurations is the Fisher information matrix using mode shapes of the structure, which leads to the D-optimal design criterion. By maximizing the determinant of the Fisher information matrix (e.g., [30–32,76,42,35,70,71,8]), by maximizing the smallest eigenvalue of the Fisher information matrix (e.g., [64]), by minimizing the trace of inverse of the Fisher information matrix (e.g., [28]), by maximizing the norm of the Fisher information matrix (e.g., [73,68,28]), or by minimizing the condition number of the Fisher information matrix (e.g., [34]), it is assumed that a least linear dependent set of sensor positions can be found. Of course, this approach assumes that the number of sensors is at least as big as the number of target modes that should be identified [41]. Otherwise, the independency of modes cannot be guaranteed. By considering different noise levels, [36] compared several measures related to the Fisher information matrix. Garvey [24] enhanced the original criterion by a Guyan reduced mass weighting scheme.

Another criterion to judge combinations of sensor positions within single setup configurations is the modal kinetic energy, proposed by [32] and applied by [58,41]. It is assumed that large response amplitudes at a certain position are related to high modal kinetic energy. With this criterion, it should be possible to increase the signal to noise ratio. This is essential if notable measurement noise is expected. The drawback of this method is the high dependency on the element mesh size [58]. Therefore, the method tends to choose regions with large element sizes where the mass is concentrated. This can lead to unsatisfying results. As the kinetic energy is only a mass weighted version of the Fisher information matrix, the connection to the effective independence method (e.g., [32,26,40]) is obvious. This has been investigated in detail by [41]. Tuttle [72] proposed the application of the iterative residual kinetic energy method and the mass weighted effective independence method. These methods are modifications of the modal kinetic energy method and the effective independence method, respectively.

Several other objectives and assessment criteria for optimal sensor positions within single setup configurations have been proposed. One set of criteria is derived from the modal assurance criterion (MAC) originally introduced by [3], whereas the off diagonal terms of the MAC matrix need to be minimized (e.g., [47]). This typically leads to uncorrelated mode shapes. The MAC and the mass weighted MAC were proposed as validation criterion, for example, by [62]. Modal strain energy based criteria were proposed by [47,64]. An efficient backward elimination technique based on variances of the estimates derived from a perturbation analysis was suggested by [45]. In [16], an analytical formulation of the singular value decomposition for a candidate-block Hankel matrix using subspace correlation techniques for the purpose of determining the optimal sensor positions was tested. A probabilistic approach to identify optimal number and location of sensors was recommended by [7]. In this work, the criterion of the probability of detection according to [15] was efficiently evaluated by utilizing the weights of a neural network description. Moreover, an information entropy based criterion was introduced by [57,56,53]. In [55], spatially correlated prediction errors were considered in addition. The minimization of the information entropy based on spectral densities as a measure of uncertainty in the model parameter was introduced by [77] to define a criterion for the best sensor placement configuration. However, [54] concluded that the information entropy is related to the determinant of the Fisher information matrix.