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Mass-weighting methods for sensor placement using sensor set expansion techniques

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Abstract

Placement of sensors is one of the most important tasks performed during pretest planning. The purpose of this work was to develop and investigate the use of an iterative Guyan expansion for mass weighting of target modes for sensor placement analogous to the common iterative Guyan reduction technique. The goal was to determine the appropriate mass-weighting approach to use in conjunction with effective independence sensor set expansion. In either sensor set expansion, or reduction, mass weighting requires a reduction of the FEM mass matrix to the current sensor set size Test-Analysis-Model (TAM). A general theory is presented for target mode mass weighting that can accommodate any type of reduction technique. The theory predicts that sensor set expansion using static mass weighting will result in sensor configurations that produce poor static TAMs. In contrast, sensor set expansion using modal mass weighting exactly reproduces the correct mass distribution during the expansion process. The results of a numerical example corroborate the theory. The modal mass sensor set expansion process produced significantly more accurate static TAMs than the static mass expansion. The modal expansion process was not quite as accurate as the iterative static reduction approach, but modal expansion was over 1600 times faster.

Keywords: Sensor placement; Modal testing; Correlation

1. Introduction

Comprehensive pretest planning is crucial to successful modal vibration testing. This is especially true when testing complex aerospace structures. Placement of sensors, usually in the form of accelerometers, is one of the more important tasks performed during pretest planning. The sensors must be distributed such that all of the required dynamic information is obtained during the course of the vibration test. At the same time, the resulting sensor configuration must be optimal in some sense to conserve testing resources. Many sensor placement techniques have been developed over the years using pretest finite element models [1,2]. In most cases, sensors are selected from a very large candidate set of several thousand locations based on a specific measure of goodness. The suitability of the final sensor configuration is often determined by its ability to

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accurately predict the target modes when the original finite element model is reduced to the sensor degrees of freedom. This reduced representation, or Test-Analysis-Model (TAM), is used in test–analysis correlation [3].

Some sensor placement methods are iterative, while others are based on a single calculation and a truncation to the desired number of sensors. The advantage of single truncation techniques is their computational efficiency. For example, modal kinetic energy [4] is a single truncation technique that is a popular choice for selecting a sensor configuration that can produce an accurate static TAM [5]. The method emphasizes a measure of target mode signal strength in the sensor data. However, it does not consider the linear independence of the target modes, which is important in modal identification and test–analysis correlation. This technique is usually applied to reduce the very large initial candidate set of sensors to a more manageable size that can be used as a starting point for a more advanced sensor placement technique. In contrast, a popular iterative technique called effective independence (*EfI*) [6] maximizes a combination of target mode signal strength and linear independence. The method starts with a large candidate sensor set, ranks all the sensors based on their contributions to the determinant of a Fisher information matrix, and then throws away the lowest ranked sensor. The new candidate sensor set is then re-ranked and the lowest ranked sensor is again discarded. In an iterative fashion, the initial candidate set is reduced to the desired number of locations. Sensor locations can either be considered individually or they can be grouped, for example, as triaxes [7].

Effective independence, applied in its original unweighted form, has been shown to produce sensor configurations that provide superior target mode identification [8] from vibration test results. This sensor placement strategy is precisely tailored for the advanced model reduction techniques that produce the modal [9] and hybrid TAMs [10]. However, because advanced TAM representations can sometimes be overly sensitive to noise and modeling errors, the aerospace industry has tended to use the static TAM as the standard for test–analysis correlation and analytical model validation. It has been shown [7] that the *EfI* approach can be generalized to include a weighting matrix that can be tailored to the desired TAM reduction technique. In the case of the static TAM, the finite element model mass matrix can be used to provide the appropriate weighting of the candidate sensor locations. Mass-weighted effective independence (*MWEfI*) has repeatedly been shown to provide superior static TAM representations [11,12]. However, the iterative nature of the method can be a drawback. If the initial candidate sensor set is large, which it generally is, significant computational cost is required to reduce the set to the desired number of locations. This is especially the case when using mass weighting of the target mode shapes and Guyan reduction [5] to update the mass matrix as each sensor is reduced from the candidate sensor set. In addition, there are often cases when the test engineer has a small set of locations that they absolutely want to be included in the final sensor configuration. The straightforward *EfI* technique provides no mechanism for retaining specific sensor locations.

The problems associated with iterative reduction and the inability to specify desired sensor locations were addressed in Ref. [11] by reformulating *EfI*. The new method, effective independence-plus (*EfI*+) differs in that it iteratively expands an initial set of sensors instead of iteratively reducing a large candidate set. In most cases, the candidate sensor set can have thousands of sensor locations. This change in approach can result in a dramatic reduction in the required computational effort. In addition, the new method allows a test engineer to specify a set of locations that they want to retain in the final sensor configuration. The initial set, perhaps as small as one sensor, is optimally expanded to the desired number of sensors. If the initial set renders the target modes linearly independent, additional sensors are added from the large candidate set based upon their contribution to the determinant of the information matrix corresponding to the current expanding sensor set. If the initial set does not render the target modes independent, the corresponding information matrix is rank deficient. Sensors from the candidate sensor set are iteratively added to the current configuration based upon their contribution to information in the candidate sensor set that is orthogonal to the information already contained in the current expanding sensor set.

Mass-weighted effective independence (*MWEfI*), in conjunction with iterative Guyan reduction of the mass matrix, has been used effectively to produce sensor configurations that result in accurate static TAMs [12]. However, no work has been done to date for determining the appropriate form of mass weighting and iterative mass expansion that should be used in conjunction with *EfI*+. The purpose of this project was to determine how the reduced mass matrix should, essentially, be unfolded during the process of sensor set expansion using the new *EfI*+ technique. As in the case of sensor set reduction using *EfI*, the goal is to produce a sensor