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Optimal selection of artificial boundary conditions for model update and damage detection

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ABSTRACT

Sensitivity-based model error localization and damage detection is hindered by the relative differences in modal sensitivity magnitude among updating parameters. The method of artificial boundary conditions is shown to directly address this limitation, resulting in the increase of the number of updating parameters at which errors can be accurately localized. Using a single set of FRF data collected from a modal test, the artificial boundary conditions (ABC) method identifies experimentally the natural frequencies of a structure under test for a variety of different boundary conditions, without having to physically apply the boundary conditions, hence the term "artificial". The parameter-specific optimal ABC sets applied to the finite element model will produce increased sensitivities in the updating parameter, yielding accurate error localization and damage detection solutions. A method is developed for identifying the parameter-specific optimal ABC sets for updating or damage detection, and is based on the QR decomposition with column pivoting. Updating solution residuals, such as magnitude error and false error location, are shown to be minimized when the updating parameter set is limited to those corresponding to the QR pivot columns. The existence of an optimal ABC set for a given updating parameter is shown to be dependent on the number of modes used, and hence the method developed provides a systematic determination of the minimum number of modes required for localization in a given updating parameter. These various concepts are demonstrated on a simple model with simulated test data.

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1. Introduction

In sensitivity-based finite element (FE) model updating and damage detection (here, collectively referred to as "updating"), there are typically a large number of physical parameters which need to be identified, either as "corrections" to the FEM in model updating, or as "flags" for potential damage in the test article in damage detection. The number of these updating parameters frequently exceeds the number of measured modes available for use in the updating process. This disparity between the number of available modes and the number of updating parameters has motivated much prior and current research into ways to increase the size of the available measured data set. An increase in the size of the data set, however valuable, does not directly address a fundamental limitation in the sensitivity-based approach to model

Abbreviations: ABC, artificial boundary condition(s); OCS, omitted coordinate system(s); RME, relative magnitude error; MFA, maximum false alarm; QRB, QR basis.

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updating. The updating solution for each parameter is dependent on the relative magnitude of its modal sensitivities, calculated from the FE model. Given the limited bandwidth of a modal test, the modal sensitivities calculated for the various updating parameters are of different magnitudes, and hence updating solutions are biased towards those parameters associated with higher sensitivity values. A low relative modal sensitivity of a given updating parameter will prevent the updating solution from localizing an error in this parameter, and prevent the estimation of the true error magnitude. In fact, without an accurate localization, it is in general not possible to accurately estimate the error magnitude. As has been noted previously [1], accurate localization is critical, as once the parameters in error have been identified, the updating can be carried out and the updating solution residual (however defined) between measured and calculated response minimized, or even driven to zero. This minimization can occur regardless of whether or not a "correct" selection of updating parameters (i.e. localization) has been made. A clear reminder is given in [2] that in sensitivity-based updating, a low sensitivity value does not imply that a parameter is not in error, but can impede both localization and estimation.

The use of artificial boundary conditions (ABC) addresses this fundamental limitation. Through the application of selected sets of ABC to the FRF data normally collected in a modal test, an accurate localization solution for a greater number of, and possibly all, individual updating parameters can be obtained. When the measured FRF are insufficient, either in spatial completeness and/or bandwidth, to localize the error in a given parameter, the method clearly indicates this insufficiency, for each updating parameter. As will be shown, this is accomplished through the application of multiple ABC sets, where a large number of alternative sensitivity matrices are generated, and these alternative sensitivity matrices are queried as to whether or not the localization of each updating parameter is possible. This large number of alternative sensitivity matrices made available by the method substantially increases the possibility of generating an accurate localization solution for each updating parameter. This application of multiple ABC sets also relaxes the demand on test bandwidth required (i.e. number of modes) for accurate localization.

2. Background

In a modal test of a structure, a single set of boundary conditions are typically used, due to the prohibitive demands in time, cost, and practicality of physically altering the boundary conditions and retesting the structure. The modal test yields spatially incomplete frequency response function (FRF) data at each frequency point in the measurement bandwidth. From this FRF data, the modal parameters of the structure can be identified. These parameters include a single set of natural frequencies and the associated mode shapes and damping ratios, and are specific to the "as-tested" configuration (e.g. boundary conditions) of the test article. Given the typically large number of physical parameters for which errors or damage need to be identified (updating parameters), the use of natural frequencies alone can therefore result in an underdetermined system of updating equations in the unknown parameters. A basic solution to an underdetermined problem is non-unique, while a least-norm solution tends to smear the identified location of errors, in that falsely non-zero values are produced for parameters other than those truly in error. One strategy for increasing the number of equations in the updating system is by the inclusion of mode shape sensitivity data, which can provide a sufficient number of additional equations such that the problem is rendered overdetermined. For an overdetermined problem, the least-squares solution again tends to smear error location. For brevity, we will refer collectively to FEM updating and damage detection as "updating", and to the solution of either problem as "errors" in the updating parameters.

The advantages of the use of natural frequencies only (excluding mode shape data) as a response metric are well known. These advantages include the higher accuracy with which natural frequencies can be identified as compared to mode shape data, the elimination of both the mode shape estimation process and the identification of real mode shapes from complex shapes. Despite the relative quality of the natural frequencies in the updating process, the limited number of measured natural frequencies can restrict the effectiveness of updating.

Another strategy for enlarging the measured data set is by the direct use of FRF data, due to the large amount of potentially useful data contained therein. This advantage is mitigated by the realization that not all FRF frequency points are of value, and a frequency selection algorithm is therefore needed. The use of antiresonance frequencies in addition to (or in place of) natural frequencies has also been explored; see for example [2–6]. Antiresonances are a potent response quantity for updating due to their being functions both of the (global) natural frequencies and the (local) mode shape elements specific to the excitation and response coordinates of the FRF. However, antiresonances are not without their peculiar limitations; it has been shown that antiresonances of transfer FRF are very sensitive to small changes in a structural model and excitation location, and that the robustness of the updating process is improved if restricted to the use of antiresonances from driving point FRF [4]. However, in a standard single-input modal test, only a single point FRF is measured. Other point FRF can be synthesized using the (incomplete) identified modes, and the resulting error in antiresonance locations (along the frequency axis) compensated for by the inclusion of low and high frequency residuals calculated from the model [6]. Furthermore, antiresonance sensitivities have been shown to be linear combinations of eigenvalue and mode shape sensitivities, and hence antiresonance data can replace, but not augment, mode shape data [3]. The overall performance of updating has been compared when using resonances versus using resonances along with some antiresonances. It was concluded that the improvement of the updating results upon inclusion of the antiresonances is dependent on the updating parameters selected as well as the location of the errors [7].