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# Minimum condition number by orthogonal projection row selection of artificial boundary conditions for finite element model update and damage detection

Joshua H. Gordis [a,*], Jae-Cheol Shin [b], Matthew D. Bouwense [c]

[a] *Room 313, Watkins Hall, Department of Mechanical and Aerospace Engineering, Naval Postgraduate School, 1 University Circle, Monterey, CA, 93943, USA*
[b] *The 1st R&D Institute-2, Agency for Defense Development, P.O. Box 35, Yuseong, Daejeon, 305-600, South Korea*
[c] *18 Atlantic Avenue, Groton, CT, 06340, USA*

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The method of artificial boundary conditions provides a way of significantly expanding the amount of useable data for performing model update or damage detection. It accomplishes this by artificially applying boundary conditions directly to the measured frequency response functions, which can then be curve fit to obtain the modal parameters. A critical task in the application of this method is the selection of modes from a large available set of candidate modes generated by the application of various artificial boundary conditions. An orthogonal projection procedure is used to select modes from which to build a composite sensitivity matrix of minimum condition number for update and damage detection. Both simulation and experiment are used to investigate this method. The experimental study makes use of two beams, identical except for damage installed in one beam. Issues regarding the number and type of artificial boundary conditions, the synthesis of boundary conditions, and test frequency resolution are studied. Both the simulation and the experiment reveal that model updating and damage detection can be accomplished with high accuracy.

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## 1. Introduction

The problems of finite element model updating and structural damage detection can be seen as two versions of the same fundamental problem. Given two models of a structural dynamic system, one analytic (i.e. finite element model) and the other, measured (frequency response functions), the goal is to identify the location of differences between the two models, and the magnitude of those differences. Over the last five decades, much has been written about both problems. Within this large literature, a class of methods exists which seek to generate additional information from the FRF gathered in a single modal test. This additional information can consist of natural frequencies and mode shapes for the tested structure under a variety of artificially applied boundary conditions or structural modifications. 'Artificial' boundary conditions are, at a fundamental level, a byproduct of the secondary dynamic system which is implicitly defined by spatially incomplete dynamics models [1]. The application of artificial boundary conditions (ABC) can be accomplished in two ways. The first being

* Corresponding author.
*E-mail addresses:* jgordis@nps.edu (J.H. Gordis), jcshin@add.re.kr (J.-C. Shin), mdbouwense@gmail.com (M.D. Bouwense).

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the recognition of the relationship of the natural frequencies of the artificially constrained structure to the zeros (anti-resonances) of the structure in its original configuration. In Refs. [2–4], antiresonance eigensolutions are calculated from the FRF data yielding natural frequencies for the structure under a variety of artificially applied constraints to ground at combinations of the transducer locations. The second way to apply ABC is by transformation of the FRF measured from the structure in its original configuration, yielding the FRF of the structure with artificial boundary conditions (pins) applied at the combinations of the transducer locations [5–10]. An experimental study of model updating using anti-resonances and 'virtual' antiresonances was described in Refs. [11–13]. The sensitivities of the zeros of the FRF were developed in Ref. [14], and the sensitivities of the natural frequencies of a structure with artificial boundary conditions were developed in Ref. [10].

The application of artificial structural modifications has also been explored. In Ref. [15], artificial stiffness modifications were used to separate closely spaced modes for updating. Similarly, in Ref. [16], an 'imagined' stiffness is used in model updating. The use of both 'fictitious' grounded springs and lumped masses are used in the updating of cyclically symmetric and axisymmetric structures [17].

## 2. Additional natural frequencies provided by artificial boundary conditions

The use of artificial boundary conditions (ABC) is a unique approach to the problems of model update and damage detection in that the amount of useable measured dynamic data is greatly expanded without conducting additional modal tests. In this test, frequency response functions (FRF) are measured and modal parameters identified. The implementation of the ABC in the present work is that the measured FRF are transformed into additional FRF that represent the system under test with alternative boundary conditions, without having to physically apply these alternative boundary conditions.

The synthesis transformation will be described in what follows. Once the measured FRF are transformed, the modal frequencies are identified using a single degree-of-freedom curve fitter. The ABC can then be applied in the usual manner to the finite element model (FEM) and the corresponding analytic natural frequencies and modal sensitivities calculated. This strategy produces additional natural frequency data for sensitivity-based FEM updating and structural damage detection.

That this approach generates a large amount of additional data is illustrated in Figs. 1 and 2, where the interlacing property of the natural frequencies [18] with one additional constraint is clear. These figures were produced using only the experimentally obtained data to be described in detail in what follows – no simulation data was used. In Fig. 1, the natural frequencies for a single pin, artificially applied successively to all 15 transducer locations on a free-free beam is shown, constituting 15 configurations. The green stars in row '0', and the green lines correspond to the finite element prediction of the natural frequencies of the free-free-beam. Between the green lines are the natural frequencies found from curve-fitting (peak picking) the transformed FRF resulting from the application of a single artificial boundary condition. For example, in row '1' are the natural frequencies found from the FRF with a single artificial pin applied at transducer #1. The measured natural frequencies of the free-free beam without artificial boundary conditions are not shown. With respect to the large

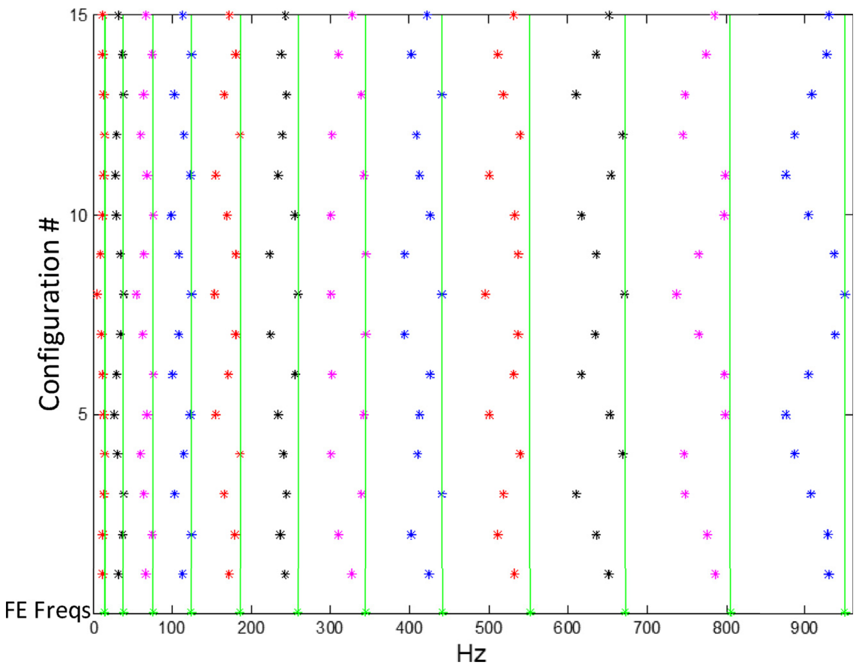


**Fig. 1.** Interlacing of natural frequencies of beam with a single artificial pin at all 15 transducer locations.