SAND2016-1634C

Finite Element Simulation of a Direct-Field Acoustic Test of a Flight System Using Acoustic Source Inversion

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ABSTRACT

Making predictions of structural response in aeroacoustic environments is desirable for many aerospace structures. First, however, the predictive capability of the structural dynamics model in that type of environment must be assessed, for example by simulating a laboratory acoustic test and comparing the model predictions to test measurements. Recently, a laboratory direct-field acoustic test was performed on a large system for the purposes of assessing a high-fidelity finite element model subject to an acoustic field. This paper will discuss the process used to simulate this laboratory test, including determination acoustic loads for the finite element model using a source inversion capability in Sandia's Sierra/SD structural dynamics code.

INTRODUCTION

Aeroacoustic environments are significant for a variety of aerospace structures. As such, understanding these environments and understanding how aerospace structures respond in these environments is important. To make finite element model response predictions for structures in aeroacoustic environments, the loading needs to be defined in a method useful to the structural analyst and the performance of the model in this type of environment needs to be understood. Typically, structural dynamics finite element models are developed and assessed for point force or base excitation vibration or shock type inputs and not for acoustic inputs. To allow for assessment of a structural dynamics finite element model under acoustic loading, a method was developed and trialed using data from a laboratory acoustic test of a representative aerospace structure.

This method aims to replicate the as-tested acoustic loads on the wetted surface of the test article using a source inversion simulation with a finite element model of the test acoustic domain. With the as-tested acoustic field estimated, the wetted surface pressures, which are the loads on the test article, can be extracted and applied to a structural finite element model of the test article for response predictions and comparison to the test responses. This method is uncoupled, meaning it is assumed that the acoustic field is not strongly affected by motion of the structure and also that the structure's motion is not greatly affected by the presence of the air. The method workflow is shown in Figure 1.

[1] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy National Nuclear Security Administration under Contract DE-AC04-94AL85000.

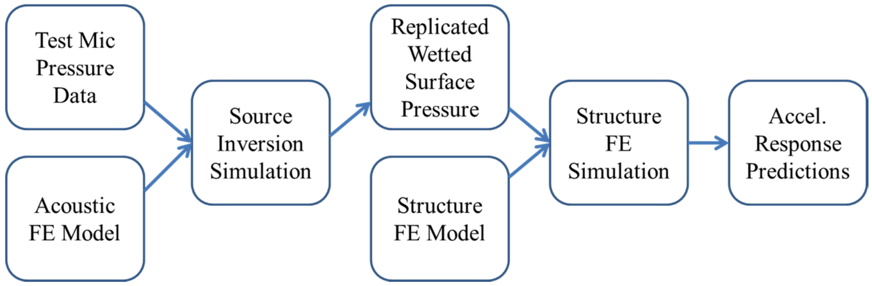

Figure 1: Workflow of the acoustic and structural simulation method.

LABORATORY ACOUSTIC TEST DESCRIPTION

The laboratory acoustic test simulated here consists of an accelerometer-instrumented test article suspended inside an octagonal stack of full range loudspeakers and subwoofers, a technique known as Direct Field Acoustic Testing [1]. Between loudspeaker cabinets, wood panels are placed to increase the overall levels and allow reflections to even out the acoustic field in the angular direction. The speakers are controlled with a multiple input-multiple output (MIMO) control system. This MIMO control system uses six control microphones to control six individual control circuits, and each circuit controls two sets of full range cabinets and provides low-frequency input to a pair of subwoofers. These control microphones are spatially distributed about the octagonal stack at various axial, radial, and angular locations around the test article. In addition to control microphones, twelve response microphones are similarly distributed around the test article. Figure 2 shows an overhead view of the test setup. The control mic pressures are specified in terms of desired sound pressure level at each microphone over some frequency range using a table of breakpoints. In addition to level, the coherence between control microphones is a user-specified control parameter. Now, the achievable level and coherence is a function of the output of the amplifiers and loudspeakers but also of the physical configuration and boundary conditions of the setup. That is, the test setup may allow for the desired level and coherence to be achieved or not. For example, one could imagine that it is impossible to achieve very large differences in sound pressure level at control microphones that are very closely spaced or similarly that it would be difficult to achieve specified high or low coherence for certain speaker and microphone configurations. Accelerometers on the test article measure the dynamic response to this acoustic environment and are the responses of interest for predicting with the structural finite element model for model assessment. A test consists of approaching full level incrementally, then running at full level for 40 seconds and recording time history data at each microphone and accelerometer location. A data collection sample rate was chosen to obtain data at least to 2000 Hz. These time histories are then processed for use with the finite element simulation method described in the next section.

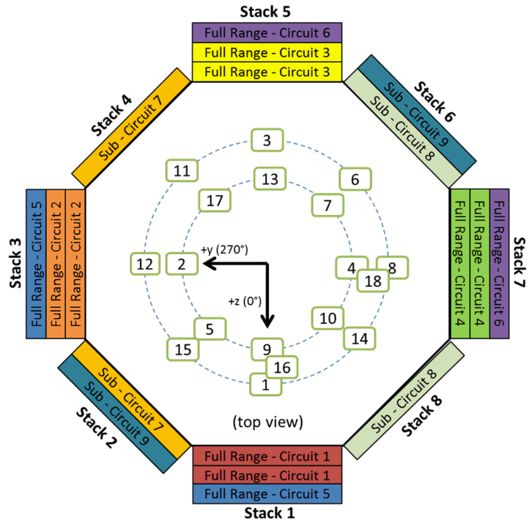

Figure 2: Diagram of the test setup with octagonal speaker stacks and microphones around a centered test item.

FINITE ELEMENT SIMULATION OF THE AS-TESTED ACOUSTIC FIELD

Applying the as-tested acoustic pressures to the surface of the finite element model requires some effort as pressures in a typical acoustic test are not measured at the wetted surface. Instead, microphones are located at some distance from the structure. Additionally, there are not sufficient microphones available to fully resolve all but trivially-shaped acoustic fields. Test-based methods for direct measurement of wetted surface pressure would be ideal, but have drawbacks including cost and installation on or in the structure's surface [2, 3, 4].As such, a method was developed and employed here to take data from a small number of microphones and generate acoustic loads that can be applied to the structural dynamics finite element model of the structure under test. This method utilizes a source inversion capability in Sandia National Laboratory's Sierra/SD finite element software [5]. This source inversion capability utilizes optimization algorithms from the Rapid Optimization Library (ROL) to iteratively modify acoustic loads on an acoustic finite element model with the objective of matching some user provided acoustic pressures at specific nodes in model [6]. Here, these nodes are at the test microphone locations and the user provided data is the test-measured microphone pressure spectra. Generally, the process can be described as follows. First the user processes the microphone test data into real and imaginary components of the pressure linear spectrum. This data serves as the "target data" for the optimization routine; that is, the data that the optimization routine will try to replicate by choosing an appropriate set of loads. The acoustic loads in this case are acoustic acceleration linear spectra at surfaces on the boundary of the acoustic finite element model. A user must specify an initial guess for these loads and here an initial guess of zero was used as there is not a convenient method for determining complex acoustic acceleration spectra estimates. Then, the optimization routine iteratively updates the acoustic accelerations (loads) to minimize objective function value. Here, the objective function is the difference between the target pressure data and the pressures at those target nodes in the model. When this objective function is sufficiently small, the optimization is stopped and the acoustic field resulting from the determined loads is saved. This acoustic field is the best replication of the as-tested acoustic field given the available target data.

ACOUSTIC FINITE ELEMENT MODEL DESCRIPTION

For the acoustic test in question, the physical size of the loudspeaker stack is an octagon with walls of four feet and a height of approximately eleven feet. Creating a finite element model of that entire air volume with element size sufficient to represent waves up to 2000 Hz would require a very large number of degrees of freedom. As a rule of thumb, six to ten elements per wavelength are required to avoid dispersion errors and correctly represent the wave speed [7]. At 2000 Hz, this would mean an element size of around 0.8 inches, and to mesh that octagonal volume with linear tetrahedral elements the degree of freedom count would be around 5.5 million. To reduce the degree of freedom count significantly, a different approach was taken wherein only a portion of the acoustic volume was modeled and then the exterior of this subdomain is covered with small source surfaces, as seen in Figure 3. The rationale behind this approach is that by allowing many possible sources on the outside of this subdomain, the acoustic field may be replicated so long as the inverse optimization method determines the source spectra that replicate the target pressure data. This subdomain has the advantages of being much smaller, at around 2.6 million degrees of freedom, and also all features of the test setup (loudspeakers, cabinets, floors, etc.) are eliminated because the subdomain only includes the air around the test article and not any of the other setup hardware. As such, the modeling is greatly simplified and the acoustic impedance boundary conditions for the various test setup hardware does not need to be estimated. That said, this choice of modeling technique does make assumptions in terms of the necessary subdomain size and number of sources on the exterior.

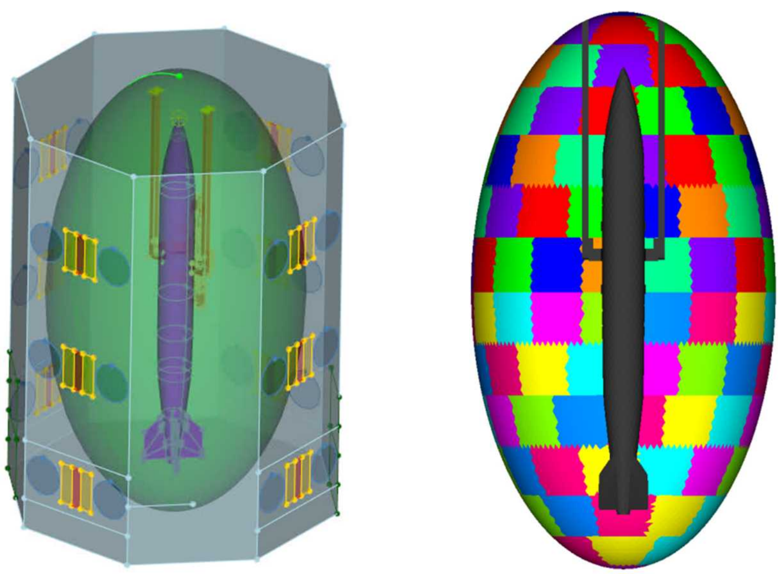

Figure 3: Left: Model of the full acoustic domain instide the octagonal speaker stack with the subdomain (green) encompassing the test article. Right: Acoustic subdomain with multiple sources (patches) on exterior surface.

DIRECT FREQUENCY RESPONSE SIMULATION USING MULTIPLE MESH SIZES

As previously mentioned, the required mesh size is a function of frequency with smaller element size (and therefore a larger model) needed for higher frequency. To save computational cost, four different meshes are created with element sizes of 4.0, 2.0, 1.0, and 0.8 inches. The coarser models are then run for lower frequency ranges and the expensive, small element size models are run only for high frequency ranges. This greatly reduces the necessary computation time to complete a broadband simulation. Table 1 shows the mesh sizes used for the various frequency ranges. A total of 470 frequency lines are simulated, though only 25 are required for the most computationally expensive model using this multiple-mesh simulation approach.

Table 1: Frequency dependent mesh scheme employed to save computational time

Mesh Size (in)	df (Hz)	Freq. min (Hz)	Freq. max (Hz)	# Lines	λ (in)	Min. Elem/λ	# kDOF	# CPU
4	1	30	150	120	90	22.5	61	2
4	2	150	400	125	34	8.4	61	2
2	4	400	800	100	17	8.4	208	4
1	8	800	1600	100	8	8.4	1349	48
0.8	16	1600	2000	25	7	8.4	2242	96

SOURCE INVERSION SIMULATION RESULTS

Results of the source inversion simulation are acoustic pressure linear spectra for the entire acoustic domain, however only pressures at the target nodes and at the wetted surface are of particular interest here. Pressures at the target nodes are compared with the test-measured target pressures to ensure the source inversion simulation is successful. An example comparison of target and replicated pressure at one of the target nodes can be seen in Figure 4. For all target nodes, the pressures are replicated nearly exactly indicating the simulated acoustic field matches the test field very well at all the microphone locations.

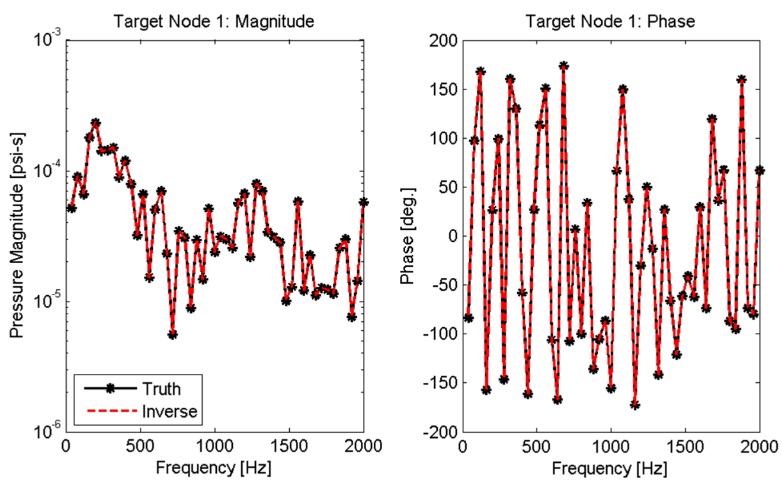

Figure 4: Test compared with simulation-replicated pressure magnitude and phase.

It should be noted that while there is good agreement between the test and simulation pressures at the target nodes, it cannot necessarily be said that simulated pressures match test pressures elsewhere in the acoustic domain because pressures were not measured at other points in the domain. Other studies have shown that the simulation-replicated acoustic field may not match the test pressures at non-target node points, depending on test and simulation conditions [8].

SIMULATION OF THE STRUCTURAL RESPONSE TO ACOUSTIC LOADING

With the acoustic field obtained from source inversion simulation using the acoustic finite element model, the loading for the structural finite element model can be extracted. First, the pressures at each wetted surface node are extracted from the source inversion simulation results and saved. Next, these pressures are mapped onto the mesh of the structural model. This can be done by doing a nearest-node match, but in this case it was decided to discretize the wetted surface into patches and apply a uniform pressure to each patch on the structure as seen in Figure 5. These patches were sized to be small relative to an acoustic wavelength. Note that only one patch size is used regardless of the frequency of the applied pressures and as such the patch size relative to a wavelength is not constant. The pressure on each patch was determined by finding the acoustic nodes within each patch boundary, comparing the pressures of each of these nodes to ensure the pressure is consistent over the whole patch, and then extracting the pressure from the node nearest the patch center. It was observed that the nodal pressures were very even over a patch area for frequencies up to around 1500 Hz. Above that frequency, there is some pressure variation over a patch which is expected as the patch is becoming larger relative to a wavelength at higher frequencies. A topic of further study would be to size the patches such that the pressure remains uniform up to the maximum analysis frequency. These patch pressures then act simply as loads for a modal-based frequency response simulation of the structural model. Acceleration response output from this simulation can then be compared with the response of the test article and used for assessment of the structural model in acoustic environments.

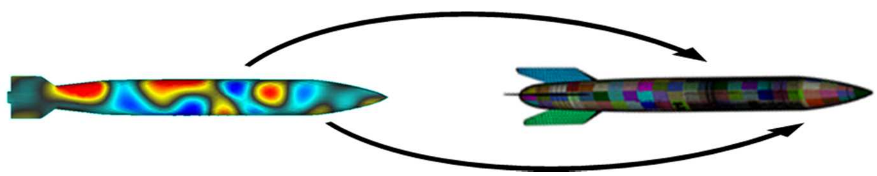

Figure 5: Notional graphic showing the mapping of wetted surface pressures from the acoustic model (left) to patches on the surface of the structural model (right).

Now, differences that arise between the simulated structural response and the test-measured response are a function of errors in the structural model's response to acoustic loads and also of errors in the determination of the as-tested acoustic loads on the structure. Isolating these sources of error is important when using this method for model validation and therefore will be the focus of future research efforts, both in testing methods and simulation techniques.

CONCLUSIONS

A method was described which allows for assessment of a structural dynamics finite element model in an acoustic environment, a first step in model assessment or validation for response simulation in aeroacoustic environments such as flight. By simulating a direct-field acoustic test on a structure, the accuracy of the structural dynamics model can be explored. This method utilizes a two-step, uncoupled simulation process where first the test acoustic loads are replicated using a source inversion simulation of an acoustic surrogate domain. Next, the acoustic loads on the structure's wetted surface are extracted from the results of that acoustic simulation and applied as pressure loads on the structural model. The response of the structural model to these pressure loads are then compared to the as-tested structural responses to allow for model assessment. Through execution of this method, some opportunities to gain better understanding of the problem at hand were uncovered including sensitivity of the source inversion simulation to modeling choices and available target data – these will be topics of further study. As structural response predictions are a function of both the accuracy of the model and the loads, understanding the influence of errors in this method for acoustic load determination is important. That said, the demonstrated method does allow for generation of acoustic inputs for finite element simulation using nothing more than far-field microphone measurements distributed throughout the test domain.

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