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Vibroacoustic Response of the NASA ACTS Spacecraft Antenna to Launch Acoustic Excitation

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Abstract

The Advanced Communications Technology Satellite was an experimental NASA satellite launched from the Space Shuttle Discovery. As part of the ground test program, the satellite's large, parabolic reflector antennas were exposed to a reverberant acoustic loading to simulate the launch acoustics in the Shuttle payload bay.

This paper describes the modelling and analysis of the dynamic response of these large, composite spacecraft antenna structure subjected to a diffuse acoustic field excitation. Due to the broad frequency range of the excitation, different models were created to make predictions in the various frequency regimes of interest: a statistical energy analysis (SEA) model to capture the high frequency response and a hybrid finite element-statistical energy (hybrid FE-SEA) model for the low to mid-frequency responses.

The strengths and limitations of each of the analytical techniques are discussed. The predictions are then compared to the measured acoustic test data and to a boundary element (BEM) model to evaluate the performance of the hybrid techniques.

Introduction

The Advanced Communications Technology Satellite (ACTS) was the first high speed, all digital satellite (fig. 1). It was an experimental satellite that provided for the development and flight test of high-risk advanced communications satellite technology including: utilization of the Ka-band spectrum, use of multiple hopping narrow-band antennas, microwave switch matrix, and adaptive rainfade compensation.

The NASA Glenn Research Center (GRC) was responsible for the development, management and operations of ACTS. ACTS was launched onboard Space Shuttle mission STS-51 in September, 1993. Although it was designed for a 4 year lifespan, ACTS performed flawlessly for a total of 10+ years and was finally retired in April 2004.

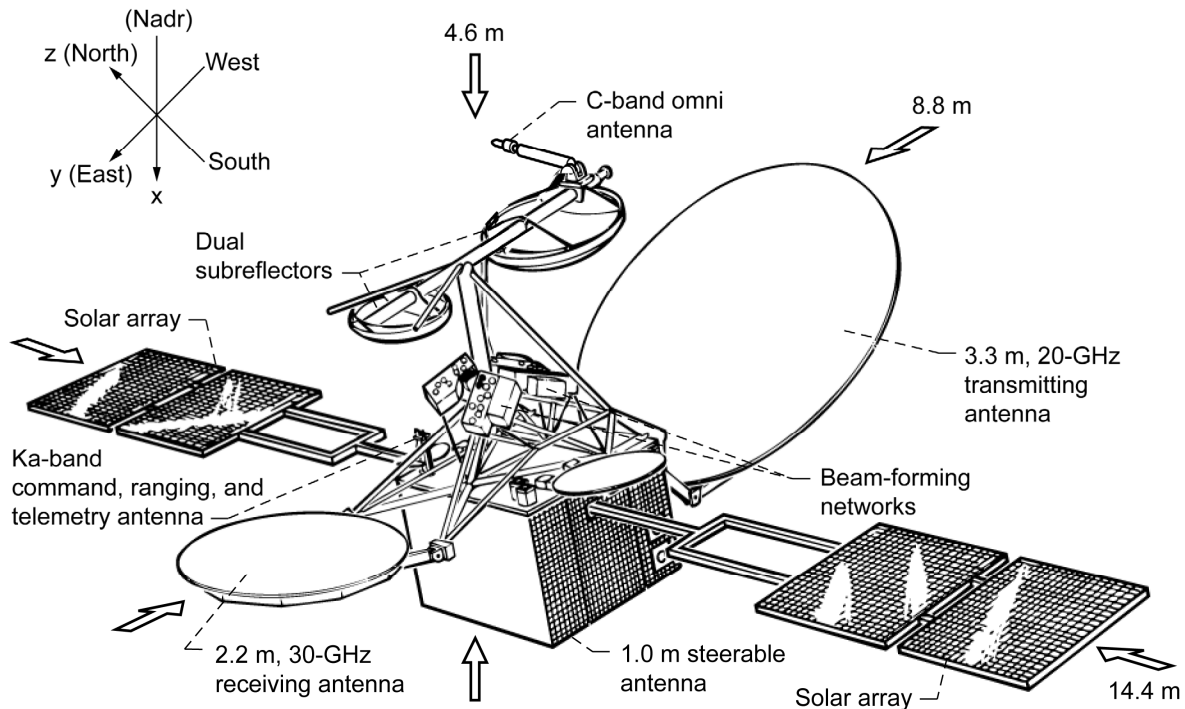


Figure 1.—Advanced Communications Technology Satellite (ACTS).

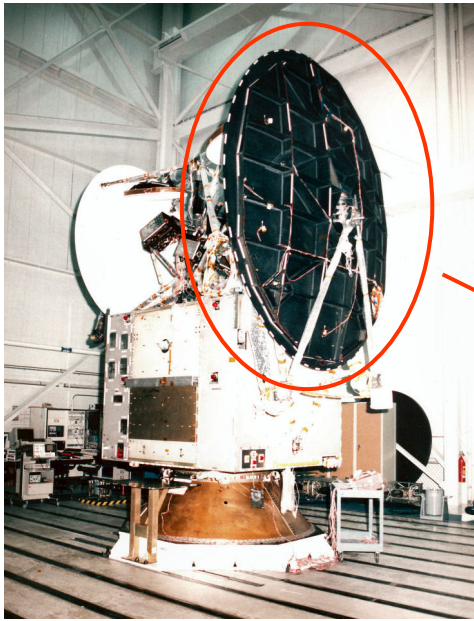
In March of 1992, the prime contractor for ACTS performed separate reverberant acoustic tests on the spacecraft system and antenna structures. GRC engineers retained the ACTS finite element models (FEM) and acoustic test data from these chamber tests. The 3.3 meter transmit antenna provided an ideal candidate for acoustic analysis and benchmarking predictions due to the fact that the structure was a typical large, lightweight, composite aerospace structure.

Using the transmit antenna data and models, GRC beta-tested the recently developed Hybrid FE-SEA (refs. 1 and 2) capability in VA One, and ESI continued the correlation with the SEA (ref. 3) and Boundary Element Model (BEM) techniques.

Modeling the Structure and Excitations

A NASTRAN bulk data deck describing the transmit antenna had been archived and was available for use in this study. The mesh was fairly coarse and a quick comparison of the acoustic free wavelength with the element length showed that the model was valid no higher than approximately 160 Hz for a vibroacoustic analysis (the element length is typically 0.6 m, acoustic wavelength at 160 Hz is about 2 m). In addition, a modal analysis showed that there are about 50 modes below 300 Hz, and it might thus be expected that a narrowband FE prediction of the response is unlikely to be accurate above this frequency.

It was consequently decided to create two models of the structure in order to cover the whole frequency range of interest from 25 to 2000 Hz. The commercial vibroacoustic analysis software VA One was used (ref. 4). The first model is a standard SEA model where both the structure and the fluid are described with SEA subsystems; this is expected to be accurate in the highest part of the investigated spectrum. The second model is dedicated to the low frequencies where the FE description of the structure is valid and captures the details of the structural response. The effect of the surrounding fluid will be described by an SEA fluid through a Hybrid FE-SEA area junction.



Curved Shell:

Kevlar-Graphite composite
 ~7.1 mm thick
 3.3 m diameter
 8.2 m curvature radius

Ribs:

Kevlar-Graphite composite
 ~7.1 mm thick
 Two closeouts along sides
 From 76 to 176 mm height

FE Model

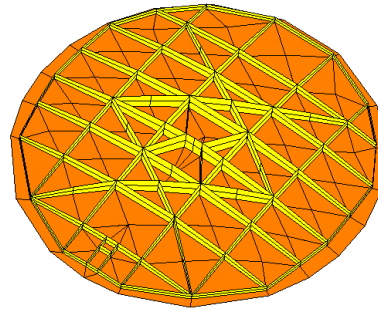


Figure 2.—ACTS transmit antenna: Characteristics and FE model.

Finally, a BEM model of the fluid was connected to the FE model of the structure (replacing the SEA model of semi-infinite fluid) to compare the Hybrid FE-SEA and the “exact” BEM-FEM prediction over the lowest part of the frequency range.

SEA Model

The ACTS antenna is a ribbed curved structure (fig. 2). A quick analysis of the waves propagating in the skin of the antenna showed that in the frequency range of interest, there were not many free wavelengths within the 30 cm minimum mean rib spacing (wavelength in the structure at 1000 Hz is approximately 23 cm). This suggests that the structure should not be split into several subsystems (one per bay), but rather should be described as one single SEA subsystem.

The available NASTRAN FE model of the antenna was imported into VA One and used to define the subsystem geometry. The ribbed-panel formulation was used to describe the physical properties of the structure: the skin was modelled as a doubly-curved shell, with a 0.4 by 6.35 by 0.4 mm graphite-Kevlar honeycomb-graphite sandwich material described by a VA One composite material.

In the ribbed-panel formulation, the ribs dynamics are described by the mean spacing in two directions, and by the mean properties of the ribs modelled in terms of beams. The rib mean spacing was obtained from geometry measurements. Although the ribs do not form a regular grid, the mean parameter are only needed, and the average spacing between ribs was taken to be about 30 cm in one direction, and 60 cm in the other.

Similarly, the ribs are not of uniform properties along the structure, and the averaged properties were obtained from geometrical measurements. All ribs have the same composite sandwich structure as the shell. The height of the ribs increases from the edges to the center of the antenna, ranging from about 7.6 to 17.8 cm. Based on the length and height of the ribs, the averaged height was taken to be 9 cm. Since the beam properties were estimated at the neutral axis of the beam, an offset of half the beam’s height was introduced in the ribbed panel description, so that the ribs are modelled as being only on one side of the shell.

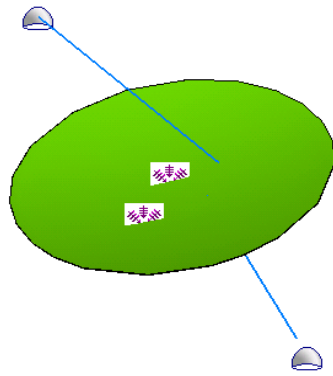


Figure 3.—SEA model of the antenna.

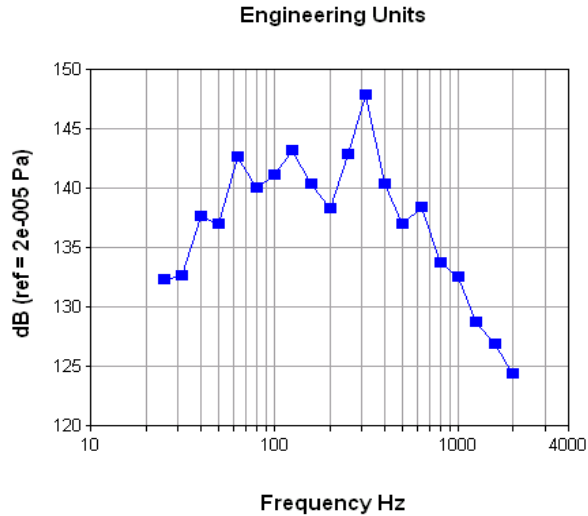


Figure 4.—Experimental chamber SPL.

The SEA model of the antenna was connected to an SEA semi-infinite fluid on each side in order to describe the fluid loading on the structure and to provide a dissipative sink. Similarly, a diffuse acoustic field loading was applied to both faces, as the structure is surrounded by fluid (fig. 3). The experimental sound pressure level (SPL) in the reverberant chamber used to define the diffuse acoustic field is shown in figure 4.

Hybrid FE-SEA Model

Starting with the same NASTRAN bulk data deck used to create the SEA model, the antenna FE subsystems were created by first importing the FE file and then simply selecting the imported FE objects needed to define the FE subsystems. In order to facilitate the diffuse-field analysis, it is useful to have a single FE face describing the coupling (acoustic radiation and loading) with the acoustic medium. For the ACTS antenna analysis, the shell and ribs were created as two distinct FE subsystems, so the coupling surface could easily be defined as the shell. The fact that the shell elements and the rib elements referenced two different property IDs allowed the FE objects to be grouped easily and the two FE subsystems created.

This modelling is actually neglecting the direct radiation from the ribs which was expected to be small since (1) the rib usually undergo less motion than the skin, (2) their area is small when compared to the skin, and (3) both sides of them radiate in the same fluid, making them radiate inefficiently like a dipole.

As with the full SEA model, once the proper coupling face had been created, it was connected to an SEA semi-infinite fluid and diffuse acoustic field on both sides of the structure (see fig. 5). By assuming the structure is baffled and with a large radius of curvature when compared to the acoustic wavelength, the Hybrid area junction provides a quick way of estimating the radiation properties of a structure (as well as the force exerted on the structure by a diffuse acoustic field).

Engineering unit responses at discrete node locations on the FE subsystems can be obtained by using VA One's "virtual sensors". As shown in the schematic of the experimental set up in figure 6, some virtual sensors were located at the nodes of the model corresponding to the points # 2, 3, 4, 5, 7, 8, 13, 14, and 15 where accelerometer test data was available. All sensors are located on the skin. The structural modes of the structure are needed in order to perform the Hybrid diffuse-field analysis. There are two ways to get those modes. The modes can be computed directly from the model, either by exporting a generated deck to NASTRAN or by using the built-in COSMIC NASTRAN solver within VA One. For this study, both methods were use to exercise the functionality.

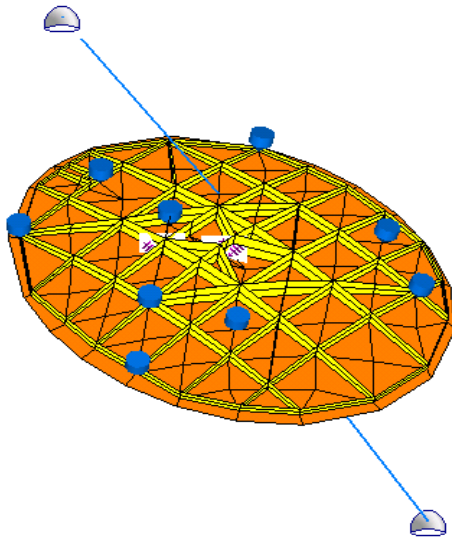


Figure 5.—FE-SEA hybrid model with virtual sensor (blue).

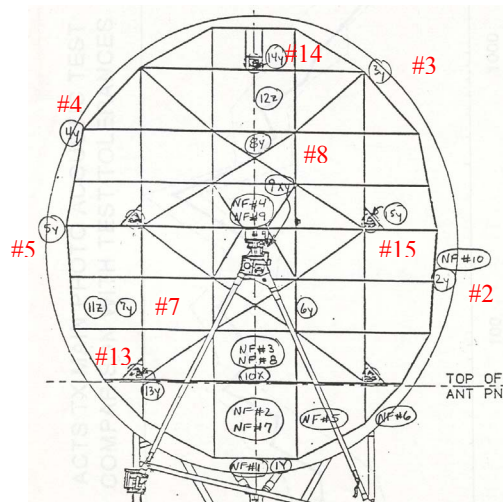


Figure 6.—Antenna schematic showing of accelerometer locations (red).

FE-BEM Model

For the BEM analysis, the same FE subsystems (and modes) were used. Instead of connecting the shell FE face to the SEA semi-infinite fluid, the face was connected to a single BEM fluid, and both sides of the face were set to be wetted (so that an indirect BEM analysis was performed). While the Hybrid area junction assumes a baffled structure, the BEM analysis computes the response of the unbaffled configuration (a baffle could be easily specified in the BEM analysis, but interest here lies in assessing the importance of the acoustic baffling on the structural response).

Results and Discussion

SEA Model Predictions

Before comparing the predictions from the SEA model to the test data, it is interesting to see over which frequency range the Hybrid and SEA models might overlap. The modes in the 1/3rd octave bands as computed by FE and by SEA are shown in figure 7. It can be seen that the SEA model seems fairly accurate over most of the frequency range. This result suggests the SEA model could be accurate even below 100 Hz, which is a good result considering that the structure is curved, ribbed and made out of composite material.

The predicted and experimentally measured space-averaged modulus squared accelerations (Engineering Units) are shown in figure 8 as functions of frequency. The test result was obtained by averaging the test data from all nine available sensors. It can be seen that the SEA model predicts the overall trend of the response, even at low frequencies. It however under-predicts the response level at higher frequencies by about 3 dB. Below 100 Hz, the SEA model is shown to over-estimate the response and produces a zero value at 40 Hz, as no modes are present in the subsystem at this frequency.

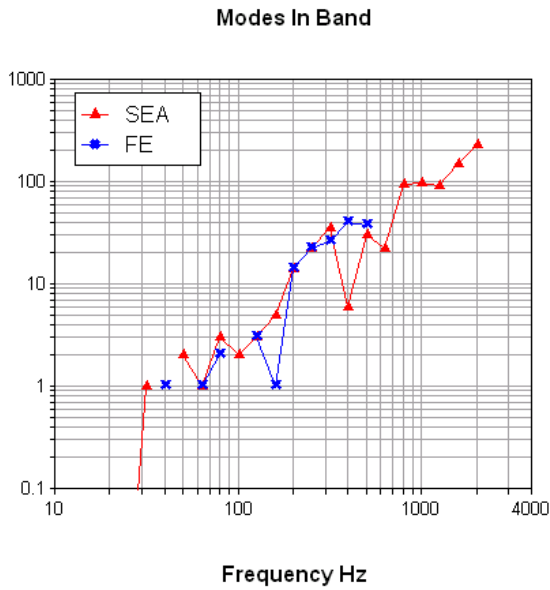


Figure 7.—Number of modes in 3rd octave bands.

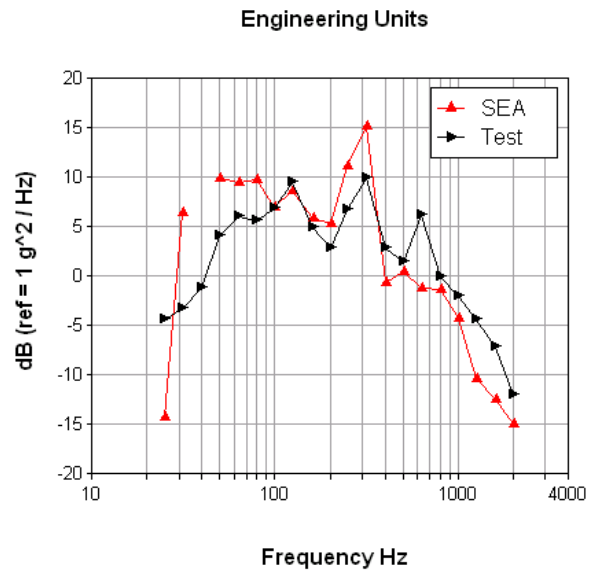


Figure 8.—Space-averaged response.

Hybrid FE-SEA Model Predictions

A comparison of responses from the Hybrid FE-SEA model virtual sensors and test data showed two trends: of the 9 sensor locations, 6 showed very good correlation and 3 correlated poorly with test data. In figure 9, sensors 2, 4, 8 are a representative sampling of the good correlations; sensor 13 reflects typical poor correlation.

Although 3 of the 9 sensors correlated poorly with the test data, the predictions were conservative. The discrepancy with test data for 2 of the 3 poorly correlated sensors is thought to be caused by the fact that the test accelerometers were located on or near very complex local structure. For all other 6 sensors, the prediction almost always agrees with the test results as to the frequency of the various peaks in the responses and the trend across the frequency domain. This correlation is extremely good considering that these are responses at discrete points and not a typical SEA spatial average.

The response at very low frequency (at 25 Hz) seems to be consistently underestimated, and this is traced to the fact that the acoustic field is not diffuse at very low frequencies: the volume of the reverberant room used in the test was 1700 m³, which according to Beranek (ref. 5) yields a lower frequency limit of 50 Hz. Below that frequency, the acoustic field cannot be considered as diffuse, and a correct model would need to account for the modes of the room rather than using a diffuse field excitation.

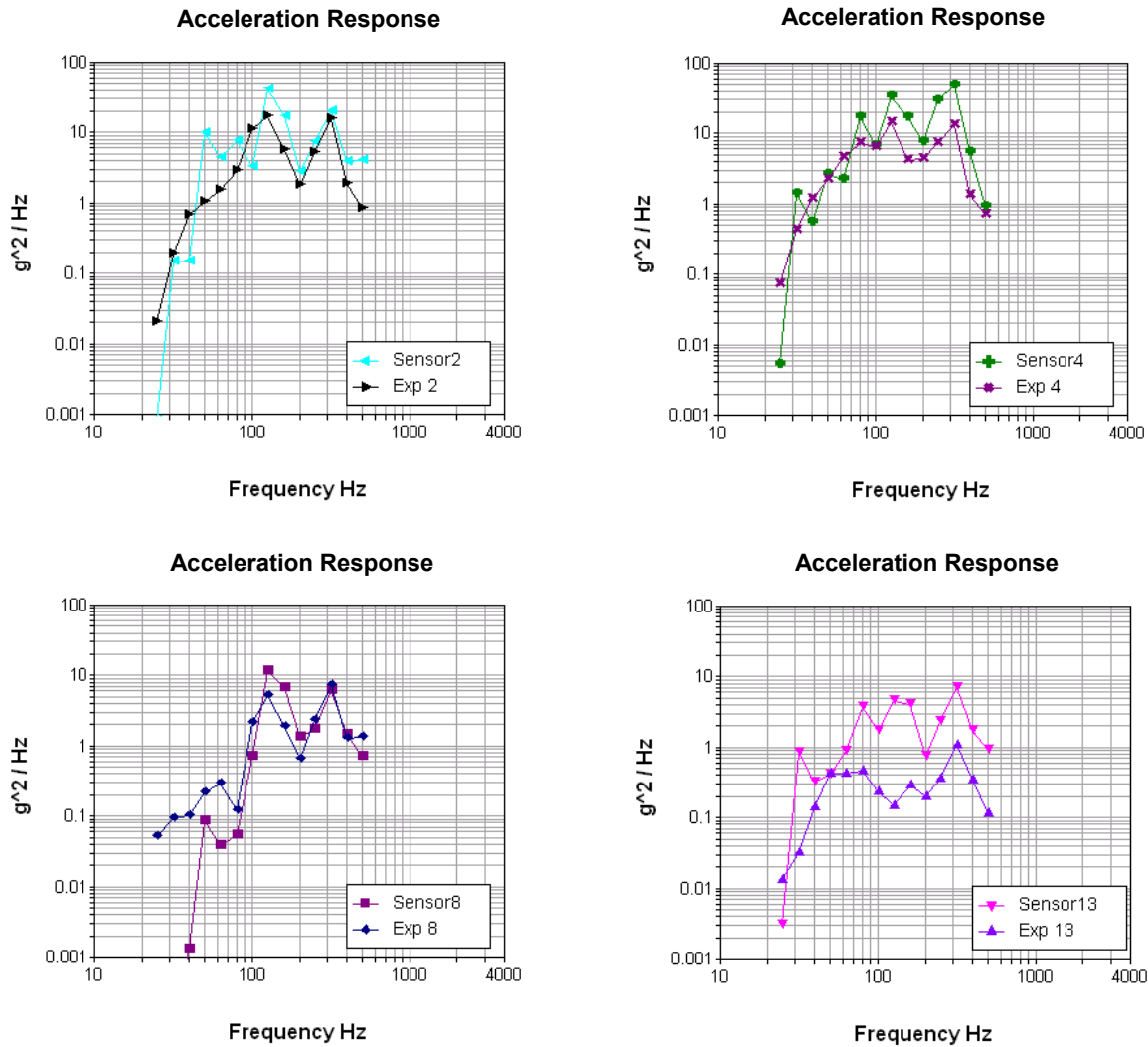


Figure 9.—Typical response comparison between Hybrid FE-SEA predictions and test data.

FE-BEM Model Predictions

A comparison of the Hybrid FE-SEA and the BEM analyses was performed over the lowest part of the frequency range (below 500 Hz) to assess the impact of the theory underlying the hybrid area junction.

The predicted radiation efficiency (normalized ratio of power radiated by the structure over the mean square velocity) is plotted in figure 10. A typical response is plotted in figure 11. The predictions by Hybrid FE-SEA and the BEM model are very similar. In particular, it was observed that the (more exact) BEM analysis does not improve the prediction of the response at the sensors where discrepancies were seen (nor does it improve the prediction at very low frequencies, which was expected since the issue here is with the assumption of the diffuse acoustic field).

In the actual test set up, the antenna was not baffled, and it was thus expected that a BEM analysis would improve some of the predictions. However, the physical phenomena dominating the acoustic coupling is related to the stiffening effects of both the ribs and the curvature of the skin, so that the impact of the baffling condition mainly impacting the edge radiation is small (note that the ribs do not radiated directly, but enhance radiation by stiffening the skin).

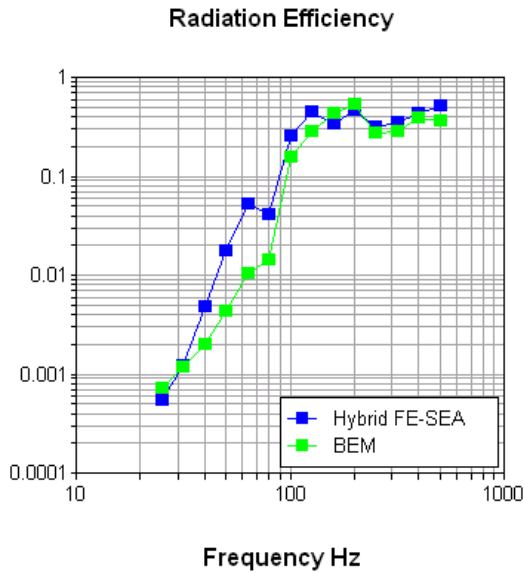


Figure 10.—Hybrid FE-SEA and FE-BEM prediction of the radiation efficiency.

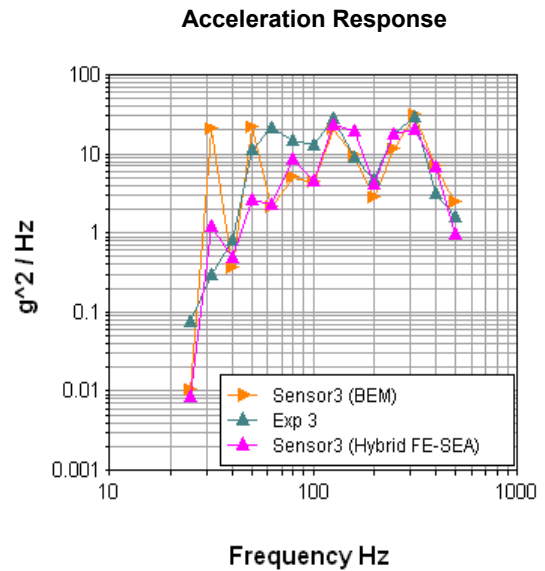


Figure 11.—Hybrid FE-SEA and FE-BEM prediction of the response of a sensor.

Summary and Conclusions

- The ACTS transmit reflector FE model and acoustic test data were used to beta-test and correlate the VA One Hybrid FE-SEA technique.
- At the majority of specific spatial locations, the Hybrid model predictions matched test accelerometer data very well. The Hybrid predictions were conservative at the few locations where the comparison was not as good.
- For the antenna structure studied, the Hybrid FE-SEA predictions matched the test data as well as the FE-BEM predictions, with the benefit of considerable computation time savings.
- SEA is still necessary to predict the responses at high frequencies due to limitations from FEM in capturing high-frequency modes.
- A combination of Hybrid and SEA methods could be used to cover the entire frequency range of interest for this and other problems.

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