Model to Test Electric Field Comparisons in a Composite Fairing Cavity

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Abstract: Evaluating the impact of radio frequency transmission in vehicle fairings is important to sensitive spacecraft. This study shows cumulative distribution function (CDF) comparisons of composite a fairing electromagnetic field data obtained by computational electromagnetic 3D full wave modeling and laboratory testing. This work is an extension of the bare aluminum fairing perfect electric conductor (PEC) model. Test and model data correlation is shown.

Keywords: Resonant Cavity, CDF, MLFMM, MoM

1. Introduction

An accurate determination of a spacecraft's radio frequency electromagnetic field environment is critical for mission success. Typical fairing structures consist of a parabolic nose and a cylindrical core with diameters of 1 to 5 meters resulting in electrically large dimensions for typical operational sources at S, C and X band where the free space wavelength varies from 0.15 m to 0.03 m. These complex and electrically large structures have internal fairing electromagnetic field evaluation that is typically limited to general approximation methods based on cavity Q, power balance, and some test data [1]. Though many of today's computational electromagnetic tools can model increasingly complex and large structures, field determination in large cavity structures presents challenges.

Recent test based studies have been done to evaluate these fields with applied power balance approach [2] and with full wave modeling [3]. Because some limitations existed in [3] with regard to measurement location, another study was undertaken to examine the distribution of the fields within the fairing and to evaluate the degree to which correlation could be made between the test case and a full wave model. In addition, statistical theory is applied for comparison of fields.

2. Fairing Test Fixture

A launch vehicle representative fairing fixture was used in all simulations performed in this work [4]. The 1.8 m by 0.6 m fairing fixture is made of two composite fairing halves with tabs at the edges for clamping the fairing enclosure. The composite shell is constructed with two 1 mm 4 ply layers of carbon composite material sandwiching a 6.35 mm Rohacell®WF foam core. Multiple locations were measured within the cavity with a small transmit antenna. Small receive sensors with respect to the double ridge guide horn were also used in previous tests to decrease interactions of these devices with the cavity structure [3]. Haigh-Farr S band, model 3106, and C band, model 3107, dipoles were used as the transmit antennas and fiber optic three axis field probes were used as the receive sensors. A fiberglass mount with 5 cm vertical steps (40 to 110 cm) was used for measurements at multiple locations as shown in Fig. 1.

The isotropic probes were positioned first at two different outer horizontal positions and moved vertically to quantify the cavity electric field distribution. The probes were then moved to more central positions and the process repeated (See Fig. 1 - inset). The horizontal probe positions were 0, 9, 16 and -25cm [5].
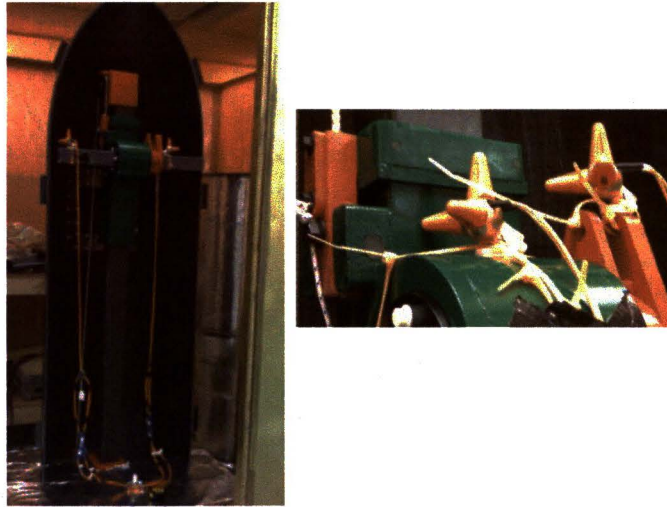
Fig. 1.   Composite fairing half test set-up with fiberglass mount and outer probe positions (inset shows inner probe placement)

Testing of full up spacecraft loaded structures is difficult because of schedule, space, and contamination constraints. Because of this problem, we evaluate the degree to which model data can be used to estimate the fields in a payload fairing cavity. However, ensuring accurate measurements within a cavity presents challenges because small changes in boundary conditions within the fairing contribute to large changes in fields [6].   In addition, test antennas and probes must be recalibrated to provide an effective response for measurements inside a conducting cavity as capacitance to conducting walls will influence these factors. Fig. 2, for example, shows a significant reduction in output when antennas are in a reflective cavity, requiring careful recalibration for cavity tests. Another challenge in predicting these fields is that there is uncertainty often about the exact materials found in spacecraft applications where the inability to know the exact location of dielectric materials such as thermal blankets exists. Hence, a process that can provide effective bounds computationally is desired.
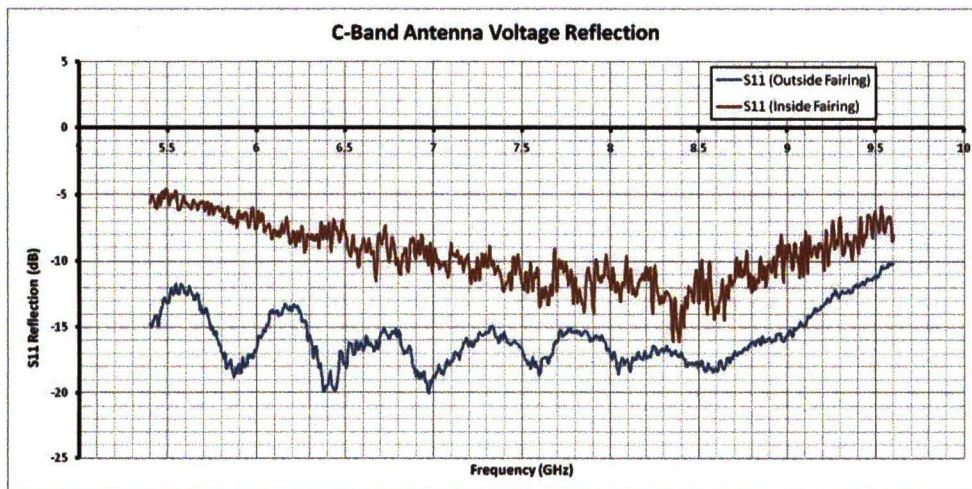

Fig. 2. Reflection coefficient for C-Band button antenna in free space and in the fairing cavity.

An example of significant variation in field strength for a given frequency and similar variation at a particular position for varying frequencies in this test is shown in Fig. 3.   It also suggests that fairly consistent peaks and averages exist over a range of frequencies and measurement locations. Hence, it is unsatisfying to evaluate the system at only one configuration and frequency, even if a single frequency response is required.
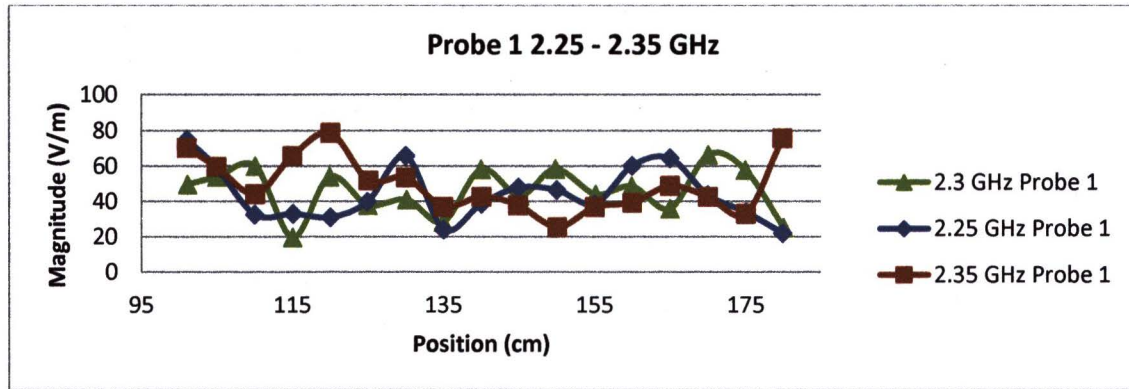

Fig. 3. Field variation with a vertical pass at multiple frequencies.

3. Computational Model and Simulations

Because of sensitivity to boundary conditions on the probe and antenna factors just discussed, model to test comparisons can be difficult. The model data points were selected as close as possible to the test points. Single axis data was used for comparison to reduce the difference of the model point evaluation of the field versus the probe averaging over its 7 cm length.   In the test, the measurement locations were reported precisely by the probe mount device, but could change slightly with each pass, leading to some difficulty in correlating the exact model and test points. The fiberglass fixture was modeled at s-band, but was not included in the results for c-band model due to the computational limitations. This deletion contributed to some difference between the model and test data, however, since the probe location changed for each measurement, a single accurate model was not feasible for multiple probe locations.

1.1.1   Composite Impedance Model

The composite material was modeled as in [3] using waveguide S-parameters measurements and a Nicholson Ross Weir (NRW) based algorithm to determine the equivalent permittivity of the complex layered structure that would otherwise be computationally prohibitive to model in this size structure. Using (1) with the relative permeability, μ_r, set to one, the resulting permittivities were calculated. When μ_r was not set to one, unrealistic material property and impedance values resulted.

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right]^2\right)$$

(1)

Where, λ_0 is and λ_c, are the free-space and waveguide cut-off wavelengths, L is the sample length, and T is the transmission coefficient determined by the measured S-parameters (7).

The permittivities and sample thickness values were in turn used to calculate the equivalent surface resistance of the material. The resulting impedances are provided in Table 1.

Table 1: Complex Impedance

Frequency	Sample Impedance.
S-Band	8.37 – j5.54
C-Band	4.71 – j8.76

The impedance parameters in Table 1 are used to model the cavity walls in two computational electromagnetic models. The first is a higher order method of moments model using WIPL-D. The second is a Multilevel Fast Multipole Method (MLFMM) model using FEKO. Both models were implemented with a single layer impedance model. Although each ply of composite material is complex, multiple ply configurations tend to cancel the directionality of the composite layer conductivity allowing a simpler representation of the structure when bounding effects are desired. Fig. 4 shows the comparison of field distributions using these impedance models at a single frequency with similar results.
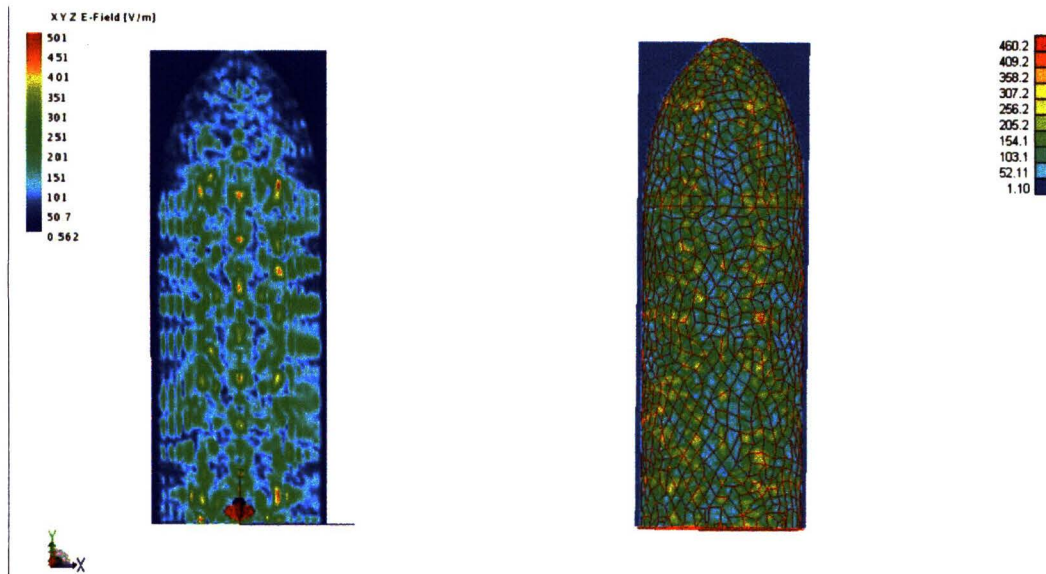

Fig. 4. Field distribution of lossless fairing at 5.65 GHz – MLFMM and MoM.

Fig. 5 shows a test to model comparison of the electric field vertical component at C-band using the MoM model. Similar results were achieved for the MLFMM models. It can be seen that the test and model data have relatively the same magnitude, but peaks are often offset in position as discussed. This result is expected due to features that are not easily modeled such as the complex shape of the fiberglass mount that changes the horizontal bar location for each position, as well as the measurement factors previously discussed. This result emphasizes the need to evaluate models over a range of frequencies around the frequency of interest. A statistical comparison of this data is evaluated in the following section.
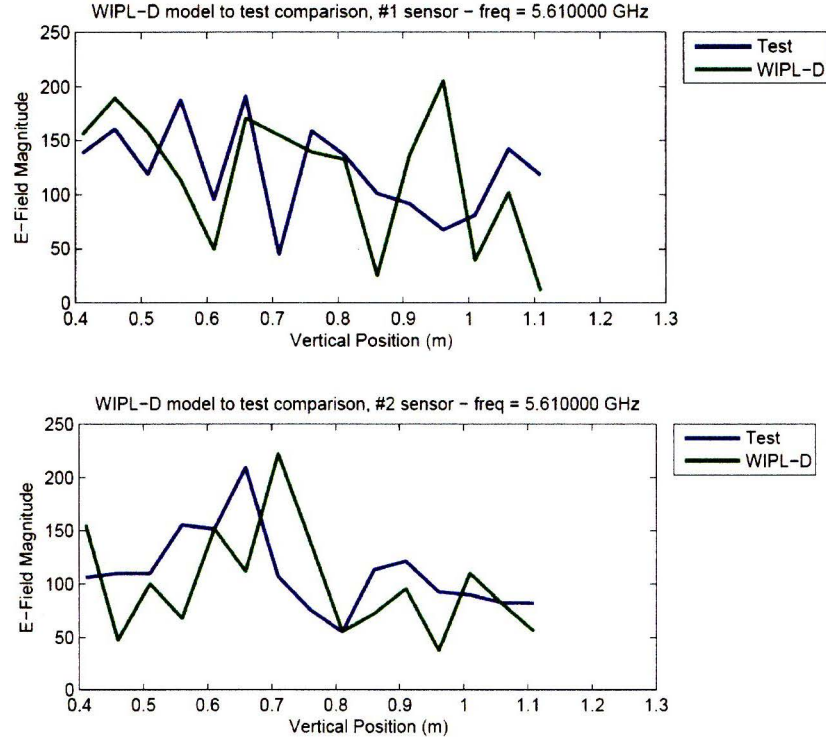
Fig. 5. C-Band single layer (outer probes) verticle component.

4. CDF Comparisons

One of the goals of this research is to provide a method to predict fields in the fairing of very complex structures. The selected distributions to be used for comparison are based on those used for reverberation chamber testing, which have shown that reverberation chamber test data correlates well with statistical distributions [8]. Given that reverberation chamber mode stirring with a paddle wheel was not feasible in the laboratory fairing, a variation of mode stirring inspired by the shipboard community's random walk method was utilized [9]. The data points were derived by variation in position and frequency variation in the measurements and model. The mean normalized CDF for the Chi distribution with two degrees of freedom (representing the electric field magnitude and phase of a single component) is shown in (2).

$$F(x) = 1 - exp\left(-\frac{\pi}{4}x^2\right)$$

(2)

Figure 6 shows the model data follows the Chi two degree of freedom CDFs, similar to the test data. When results over a series of positions and/or frequencies are considered the model is effective at simulating test results. This is an important result to show that modeling with statistical correlation is useful to evaluate the effect on expected electromagnetic fields from variation in parameters within the fairing cavity.
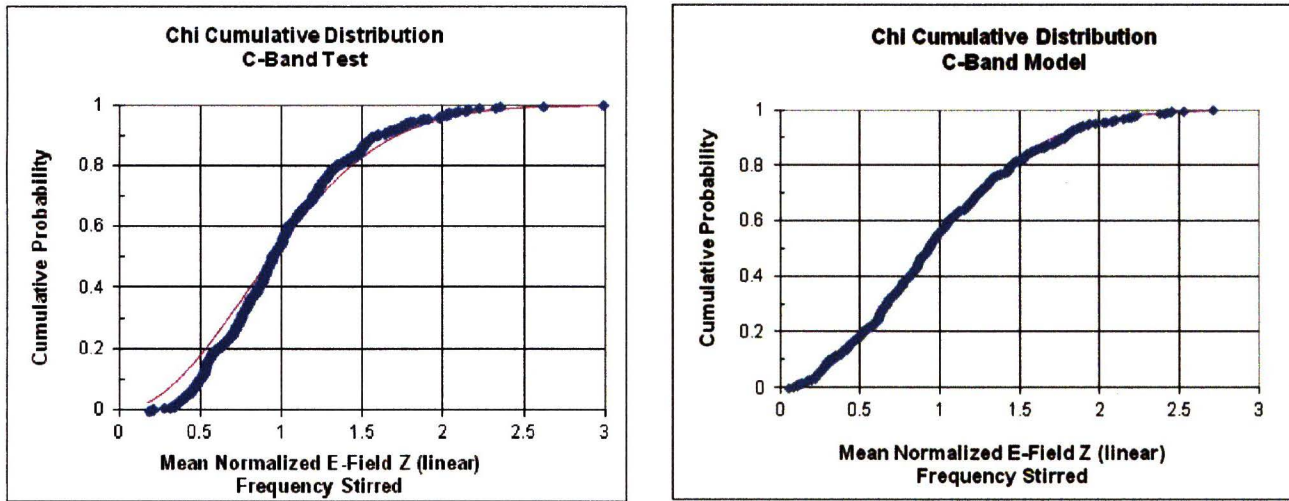
Figure 6. C-Band composite fairing position and frequency stirring test and model data following Chi distribution.

5. Conclusions

Test and model comparisons can be made as both are deterministic, but measurement compensation and model constraints limit this comparison. A test to model comparison using statistics similar to that used by the reverberation chamber community has been shown to be useful to evaluate the payload fairing cavity electromagnetic fields. This comparison is valuable in evaluating multiple configuration bounds that are not be fully modeled or tested, such as a payload fairing fully loaded with a spacecraft.

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