Electromagnetic Launch Vehicle Fairing and Acoustic Blanket Model of Received Power using FEKO

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***Abstract*─** Evaluating the impact of radio frequency transmission in vehicle fairings is important to electromagnetically sensitive spacecraft. This study employs the multilevel fast multipole method (MLFMM) from a commercial electromagnetic tool, FEKO, to model the fairing electromagnetic environment in the presence of an internal transmitter with improved accuracy over industry applied techniques. This fairing model includes material properties representative of acoustic blanketing commonly used in vehicles. Equivalent surface material models within FEKO were successfully applied to simulate the test case. Finally, a simplified model is presented using the Nicholson Ross Weir derived blanket material properties. These properties are implemented with the coated metal option to reduce the model to one layer within the accuracy of the original three layer simulation.

***Index Terms* ─** FEKO, MLFMM, Nicholson Ross Weir, resonant cavity.

I. INTRODUCTION

With multiple contributions from the range and surrounding radio frequency (rf) emitters, defining the electromagnetic environment for spacecraft can be a daunting task [1]. Determining the environment inside the vehicle fairing presents further challenges as field distribution within the cavity is influenced by resonances which require a full wave solution to achieve a desired accuracy. An added concern is that most spacecraft transmitters are in the GHz frequency range making the structures electrically large and memory requirements a constraint for many of the 3D electromagnetic simulation tools available. Recent research with hybrid physical optics and near-field to far-field transformations, as well as the use of parallelized fast multilevel codes with non-uniform rational B-spline surfaces, have had demonstrated success in modeling complex, electrically large structures [2-3]. This study is focused on solutions to electrically large internal cavity problems related to structures with layers of acoustic blanketing.

In this paper, two structural cases are evaluated: a three layer model, and a one layer model. The three layer model of a vehicle fairing with layered acoustic blanketing materials characterized by thin surface approximations is first presented [4]. For comparison and validation purposes the test case from [5] is summarized here and used as the evaluation data. Next, an equivalent one-layer model is developed using material properties predicted with S-parameters measurement and implemented into the FEKO standard coating option.

II. FAIRING FIXTURE

A fairing test fixture is shown in Figure 1. It is a scaled version with a height of 2 meters and a diameter of 0.6 meters and with industry grade

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aluminum foil lining on the Lexan outer shell [6]. This fixture is representative of typical launch vehicles. The fairing has three sections bolted together and a metal frame outer support structure. Double ridge guide horns were used for transmit and receive and were placed at the bottom and top of the fairing fixture, respectively [7].

Lining materials were added to the inside of the test fixture to simulate typical acoustic blankets inside vehicle fairings. Kapton is commonly used in space applications for its favorable thermal insulating properties. DuPont's Kapton 160XC, designed to maintain a surface resistance of 377 ohms with inherent RF absorption properties, is utilized as the outer blanket layers while standard ½ inch foam is used as the internal layer.

The test results from this fairing fixture with acoustic blanketing are used for comparison with the three layer and one layer computational models presented here. The goal is to obtain an equivalent one layer model that has similar test data correlation as the three layer model.

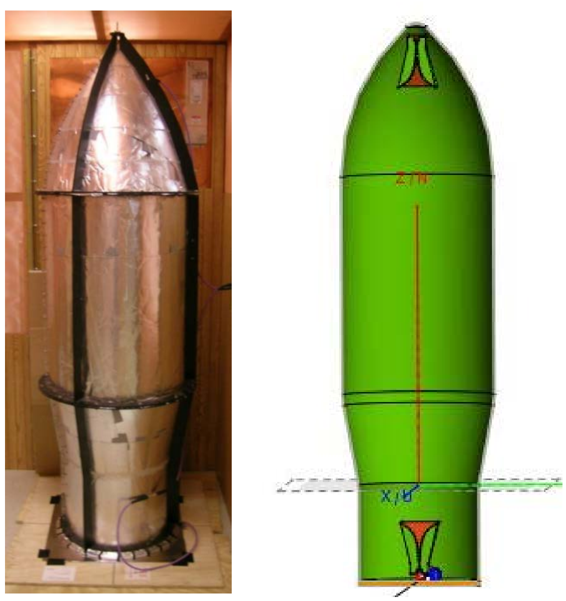

Fig. 1. Test fixture with CAD model.

III. THREE LAYER MODEL

A commercial computational electromagnetic software tool, EM Software Systems, FEKO is utilized in this study. The multilevel fast multipole method (MLFMM) feature is implemented to extend the method of moments (MoM) technique to higher frequencies. MoM is directly implemented for near elements and iterations are used to achieve the desired overall convergence criteria. Figure 2 demonstrates the adequacy of this approach for an aluminum cavity represented by an impedance sheet using both the MoM and MLFMM techniques. The field distribution and power received at 1 GHz using a surface impedance of 0.015 ohms reveals excellent agreement.

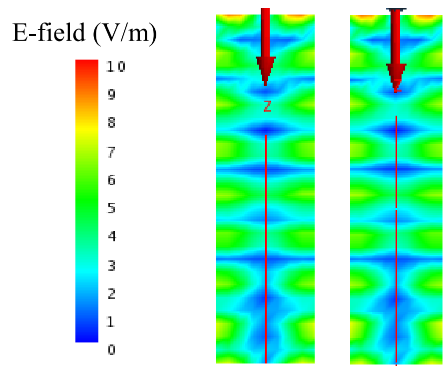

Fig. 2. Field distribution of an aluminum fairing using MLFMM (a) and MoM (b) techniques.

Comparable results were found with FEKO's lossy metal feature which has a similar implementation as the impedance sheet. FEKO evaluates the input material properties, such as permittivity and conductivity, to obtain a representative impedance term, Z_s, which is then added to the standard electric field integral equations used for perfect electric conductor (PEC) structures as in (1) [8, 9].

$$E_{s,tan} - Z_s J_s = -E_{i,tan}, \tag{1}$$

where:

$\vec{E}_i$ is the field due to an impressed source in the absence of the scatterer, $\vec{E}_s$ is the scattered field, and J_s is the equivalent current density.

The double ridge guide horns were implemented in the simulation using antenna pattern models presented in [4] of the EMCO 3115 horn developed within FEKO. Replacing the horn model with the horn pattern affords a significant savings in computational resources. In addition, parallelization of the FEKO code via pre-conditioners, such as the sparse approximate inverse, supports solutions for detailed electrically large structures as those considered here. [10].

A combined blanketing and composite fairing structure model was presented in [11]. In this paper, it is desired to first represent the layers separately for direct test comparison. Figure 3 depicts the separate test fixture layers and the composite model used within FEKO.

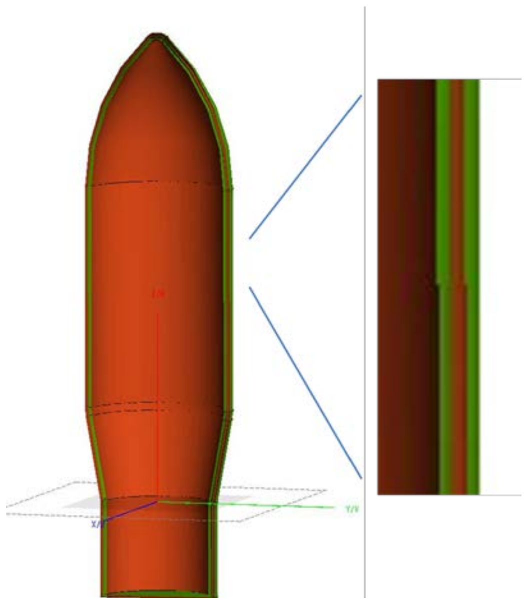

Fig. 3. FEKO model with acoustic blankets.

The aluminum foil outer layer and acoustic blanketing layers were represented within FEKO as described below:

- The fairing outer walls were represented as a single layer lossy metal with a thickness representing the industry aluminum foil that lined the prototype fairing (0.127 mm thick).
- The Kapton acoustic blanket sheets are modeled with a surface impedance based on industry data at the model frequency.
- The gaps between the impedance sheets represent the foam layer.
- Free space is required on both sides of the impedance sheet thus a thin layer of free space is implemented between the Kapton layer and the aluminum foil outer layer

Figure 4 shows a comparison of received power between the computational and the test results. The data compares well, with the average variation of 2.43 dB from test data. This is a reasonable result for a test article to model comparisons given uncaptured variations present in the test set-up. The selection of this frequency range is related to the waveguide measurements used in the equivalent one layer approach described in the following section.

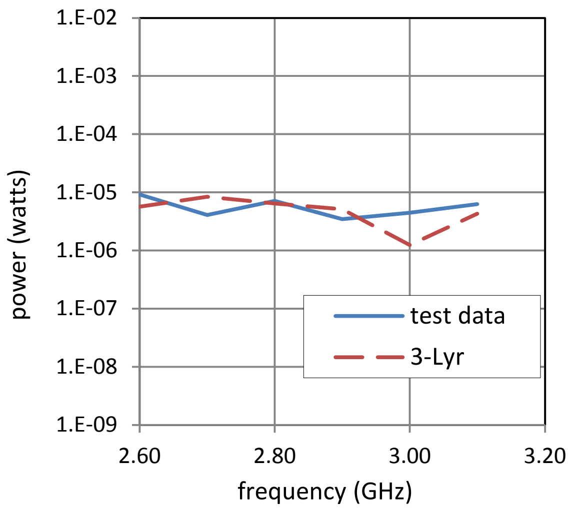

Fig. 4. Comparison of received power using computational and test results for the acoustic blanket model.

IV. EQUIVALENT ONE LAYER MODEL

It is desirable to further reduce the required computational resource and run-time requirements of the three layer structure with an electrically large cavity model and simulation by using an equivalent one layer model. Another reason to form a one layer equivalent model is the limited availability of vehicle CAD models with blanket configuration information. It should be noted that the following equivalent layer technique is not needed for simulating waveguide structures in general as there are finite element codes available that precisely model these layers and complex materials in such structures with no simplification [12-13]. This effort uses the waveguide equivalent model to later implement the layered material effects in the computationally intensive electrically large cavity structures where dimensions can be greater than 100 times the transmit wavelength and exact representation of blankets not feasible with existing software packages on available platforms.

A. Methodology selection

Truncation of the scalar Green’s function implemented with the addition theory series in MLFMM introduces an error that can be controlled in open structures, but difficult to achieve sufficiently accurate results in electrically large reflective cavities [14]. This residual error can, in effect, numerically excite the cavity. Thus, convergence is improved by using layer representations that characterize the material absorption. The absorbing impedance sheets used in the three layer model require a layer of free space on either side; consequently, the one layer model requires a different material representation that can readily be combined with the metallic outer layer. The difficulty in representing the entire vehicle in one layer is the contrast between properties of the aluminum layer and that of the acoustic blankets. Accordingly, an option was used to apply the blanket properties as a coating to the metal outer layer. Material properties of the lossy metals and dielectrics are available in the FEKO material tree. Dielectrics can then be selected as a thin dielectric sheet (TDS) with specified thickness. The coatings were selected from the TDS single layer option. The TDS is implemented within FEKO in a similar way as the impedance sheet in (1) with the Z_s term described in given by [6].

$$Z_s = \frac{1}{j\omega(\varepsilon_2 - \varepsilon_1)\mathrm{d}} \, . \tag{2}$$

A TDS is required to be geometrically or electrically thin (approximately 1/10 the smallest element or wavelength, respectively). Due to the this requirement, an inherent limitation is often encountered in the computation when the automatic mesh routine generates fine elements to accurately characterize the respective geometries. However, if the coating is geometrically small with respect to the majority of the elements, the geometrically thin constraint driven by these fine elements is effectively ignored in the model solution. A FEKO utility will perform a validate check, and will return a solution with warnings only. It is also important to note that the electrically thin constraint is relative to a wavelength in the interfacing medium, but the layer does not have to be electrically small relative to a wavelength of the layer itself [9]. Nevertheless, it is often the situation that the actual thickness of the blankets cannot be represented in a coating, and an equivalent method must always be demonstrated and evaluated.

B. Sample S-parameter measurement

The one layer coating model constraint drives the need to alternately represent the three layer blanket model in a waveguide with a one layer TDS. The Nicholson Ross Weir (NRW) technique is used to derive an equivalent permittivity of the entire layered blanket using S-parameter measurements. A blanket sample was placed in an S-Band waveguide. The S-parameters were then measured with a vector network analyzer as in Fig. 5. These parameters are used in an equation to determine the transmission coefficient and then evaluated in expression (3) to obtain an approximate value of the equivalent permittivity of a homogenous sample with the same length. As most launch vehicle blanketing materials are non-magnetic, setting the permeability, μ_r, to one simplifies the permittivity determination. Moreover, the TDS implementation requires the permeability to be continuous with the surrounding media.

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r}\left(\frac{1}{\lambda_c^2} - \left[\frac{1}{2\pi L}\ln\left(\frac{1}{T}\right)\right]^2\right), \tag{3}$$

where: λ_0 is the freespace wavelength for the desired frequency, λ_c, is the waveguide cut-off wavelength, L is the sample length, and T is the transmission coefficient determined by the measured S-parameters [15].

Fig. 5. Material sample test fixture.

Determining the permittivity of a homogeneous sample using waveguide measurements and computational models has been verified as being effective in the literature [16]. In this paper, the NRW technique is used to determine a first level approximation of an equivalent permittivity that would apply to a dielectric block with the same measured S-parameters, although the sample itself is layered. Full wave analysis is then used to modify the permittivity at each frequency until a sufficiently close approximation of the S-parameters is found. This equivalent permittivity data is then used to construct the coating in the one layer model of the fairing.

C. Waveguide sample models

A three layer MoM model was first constructed in FEKO as shown in Fig. 6 to emulate the actual S parameter measurement set-up.

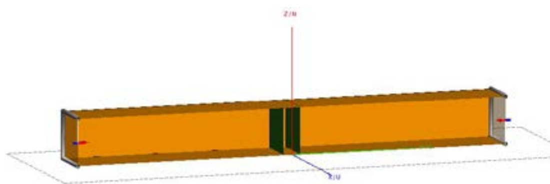

Fig 6. FEKO MoM model of a three layer fairing blanket sample.

The permittivity and conductivity of each Kapton layer was characterized as a dielectric with the thickness accounted for in the TDS implementation. The foam was represented by air as in the three layer fairing model.

It is straight forward to convert the separate layer model into a multilayer TDS which only uses one face in the geometry representation. However, the multilayer TDS cannot be represented as a coating to a metal. Hence, representation of the material in a single TDS is pursued.

The finite element method (FEM) was employed to verify that the NRW derived equivalent properties derived with (3) represent the S parameters when the waveguide is filled with a homogeneous dielectric block. The FEM model in Fig. 7 effectively reproduced the results as shown in Fig. 9 with some parameter optimization in the model. In this instance, the regions defining the boundary of the block are represented as the dielectric material and implemented with permittivity parameters with respective loss tangents.

The parameters were then implemented with a TDS single layer as shown in Fig. 8 for final implementation into the fairing fixture.

When meshing constraints require a reduced thickness in the TDS layer, a thinner layer can be established by changing the sample length in (3) to achieve a corresponding permittivity. Figure 9 shows a comparison of test, MoM separate layer model, FEM dielectric block model, and the final single layer TDS with original and reduced sample thicknesses. The material parameters can then be adjusted to provide a closer match to the original S_{21} measurements.

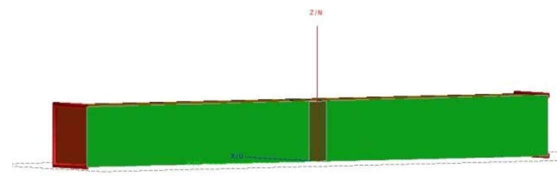

Fig. 7. Equivalent homogeneous dielectric block.

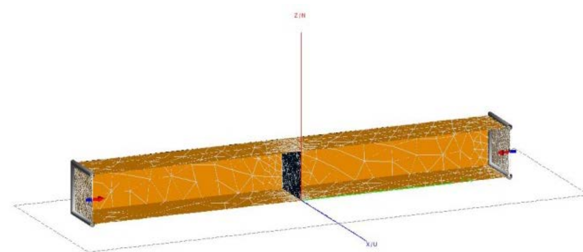

Fig. 8. TDS layer in waveguide.

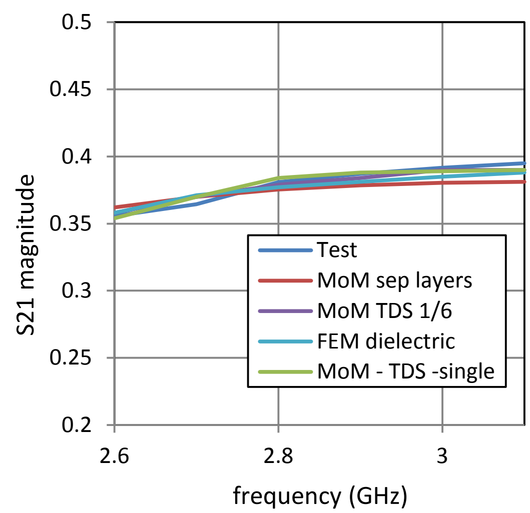

Fig. 9. Comparison of the waveguide S-parameter test data to the FEKO models.

D. Equivalent one-layer vehicle model

Results in Fig. 10 show that incorporation of the permittivity and loss tangent derived from the NRW waveguide technique into a TDS coating of a single metal layer in the vehicle model provides a reasonable correlation to the test data, as does the three layer model. First, the original sample thickness results are applied directly to the coating properties. Due to layer wavelength related constraints, however, the thickness of the coating is set at three skin depths of the Kapton layer. A closer approximation is achieved by using (3) to provide a different permittivity and loss tangent to correspond to a sample thickness adjusted to a smaller value. Results shown are for a TDS length of 1/6 of the original sample which varied from the test results an average of only 2.5 dB.

The upper and lower bounds represented in Fig. 10 are based on cavity Q equations for aluminum and blanketed walls [17].

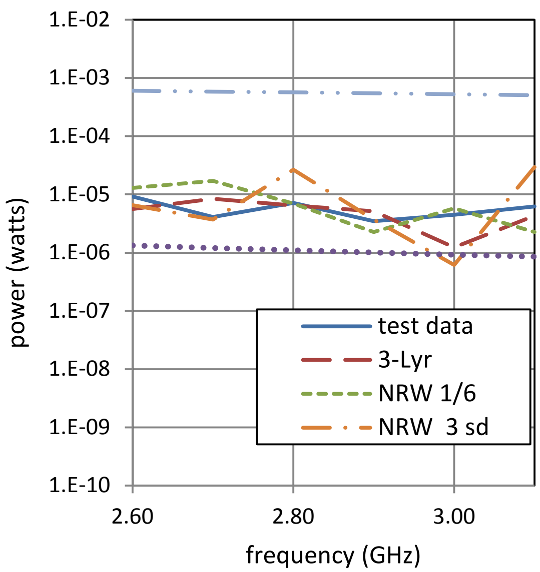

Fig. 10. Comparison of received power using the single layer and the three layer fairing models with the test data.

It is evident that the FEKO models provide significantly better results than approximation results that are generally relied upon. It should be noted that the primary intent of the Q related approximations are to evaluate chambers with very conductive walls with small absorbers present, but the application of these equations are often extended to cavities with more complex material configurations.

The efficiency benefits of using MLFMM in a three and one layer model as compared to MoM are shown in Table 1.

Table 1: Memory/run time comparison/2.6 GHz

Method	# Un - knowns	CPU Time/ process (hrs)	CPU Time total	Peak Memory (GB)
Mom 1 layer	124,377	21.2	339	115
MLFMM 3 layer	372,622	3.9	60.9	10
MLFMM 1 layer	124,377	0.066	1.1	2.2

V. CONCLUSION

This paper shows that fairing structures with complex blanketing materials can be modeled effectively with equivalent impedance techniques in a multilayer MLFMM model within the FEKO solution environment by establishing the eigenmodes within the cavity verses an average power approximation. This is important because quantifying fields due to transmission within a vehicle fairing has largely relied on general reverberation chamber average power approximation. The MLFMM more accurately depicts the actual RF energy within the cavity structure. The techniques explored here were the three layer and one layer models. From this data set, both methods appeared to have an improvement over the power approximation techniques for a launch vehicle with simulated acoustic blankets. The equivalent one-layer approach utilized a novel application of NRW formulations to derive an equivalent permittivity of the three layer configuration. Future work includes extending the frequency range beyond S-Band and the application of this technique to other layered materials such as composite vehicle structures.

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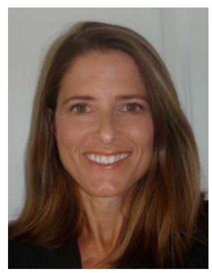

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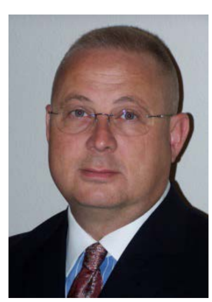
Ms. Trout has served on multiple EMC standards committees and led the development of ISO 14302, Electromagnetic Compatibility, Space Systems Standard for which she received an AIAA award.



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In 1989, Dr. Wahid was named the Tau Beta Pi Professor of the Year. She received the College of Engineering Excellence in Teaching Award in 1994 and 1999. In 1991, she received the University of Central Florida Excellence in Advising Award and in 1997, the University of Central Florida Excellence in Professional Service Award. In 2000, she was awarded the IEEE Region 3 Outstanding Engineer Educator Award and the IEEE Florida Council Outstanding Educator Award. She is a recipient of the IEEE Millennium Award. She was the Technical Program Chair for the 1999 IEEE International AP/URSI symposium and the General Chair for the 1998 IEEE Region 3 Southeastcon conference. She has served many times on the technical program committee for the IEEE AP/URSI conferences. Dr. Wahid is a Senior Member of the IEEE and a member of the Eta Kappa Nu and the Tau Beta Pi Societies.