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Estimating effective contact resistance of resonant cavity joints using near-field scanning

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***Abstract*—The possibility of estimating the effective resistance at contact points along a seam in a cylindrical vessel is investigated. The vessel is formed from two top-hat structures bolted together at a flange. Aluminum shims at the bolt locations ensure a nearly constant 5-mil gap or slot between the flanges. Cavity modes are excited with a short monopole antenna inside the structure, and external near fields 5 mm away from the slot are probed around the vessel circumference. Comparison of CST and FDTD simulations with measurements reveals that the shape of the field-vs-angle curve is strongly dependent on the contact resistance, indicating that meaningful estimates can be extracted.**

I. Introduction

Metal enclosures commonly house sensitive electronic systems in aerospace and military applications, providing shielding from unintentional or intentional electromagnetic (EM) interference. An important objective in designing and characterizing these systems is to predict the shielding effectiveness (SE) provided by the metal enclosure [1]. Nearly perfect shielding can be obtained by welding all seams and joints. However, practical enclosures are often bolted, screwed, or riveted together to provide for easier fabrication, inspection, and maintenance, inevitably leading to small gaps, referred to herein as ports of entry (POEs).

SE of an enclosure can be predicted using full-wave EM analysis of detailed three-dimensional (3D) computer-assisted design (CAD) models, but SE is very sensitive to POE parameters that may be difficult to know a priori. For example, for a bolted joint, the nominal bolt torque may be known, but the irregular gap along the POE between bolts, as well as the resistance at contact points, may be very difficult to predict.

The goal of this work is to develop measurement techniques that allow POE details such as contact resistance and gap size to be accurately estimated. Once the relevant POE parameters are known, they can be used in full wave simulations to provide high fidelity predictions of the SE of the system. In this paper we report on a first step in this effort, where the effective resistance is estimated at contact points along a bolted flange by analyzing near-field scans along the seam.

II. Measurement Setup

Fig. 1 depicts the measurement setup presented in this study. The metal enclosure consists of two top-hat like aluminum structures that are bolted together at the 0°, 90°, 180°, and 270° positions along the flange. The wall thickness of the vessel is 0.25 inches. For this study, slot dimensions between bolt locations are controlled using 5-mil thick aluminum shims at the bolt positions. The flange is 0.25 inches thick and extends 0.75 inches from the vessel surface, giving the slots a depth of 1 inch. The interior of the vessel is a cylindrical cavity with height and radius equal to 18 and 6 inches, respectively.

Traditional SE measurements are performed with a high-power external source in the far-field of the cavity, where coaxial probes on the cavity walls sense interior fields. Our

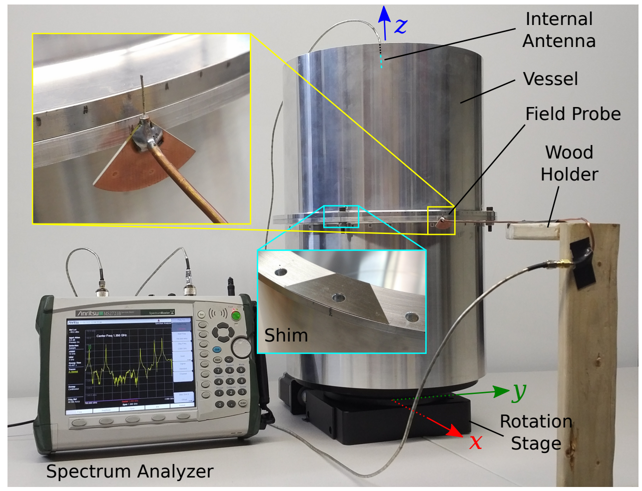

Fig. 1. Measurement setup, where an aluminum cylindrical enclosure is placed on a computer-controlled rotation stage. A spectrum analyzer with a tracking generator is used to excite an interior 1-cm antenna on the top face of the cylinder. Near fields in the vicinity of the slot are probed using a short monopole with skirt-shaped ground, as depicted in the top inset. The bottom inset provides a closeup of a bolt location when the vessel lid is removed, showing the shape of the 5-mil shims.

goal in this work is to quantify how EM fields in and around the slot change with respect to resistance at contact points. To this end, we use a reciprocal measurement strategy similar to that in [2] and depicted in Fig. 1, where a 1-cm monopole antenna at the top interior cylinder face is driven with a transmit signal, exciting cavity modes of interest. Fields in the vicinity of the slots are then measured using an external electric field probe. Given the rotational symmetry of the vessel, slot fields can be sampled along the entire circumference of the flange by placing the vessel on a computer-controlled rotation stage. A spectrum analyzer with a tracking generator is used to excite the antenna with a 0 dBm signal and measure the signal from the field probe. Although Fig. 1 shows components in the open, actual measurements were performed in a small anechoic chamber (dimensions $4\times4\times6$ ft^3).

Various near-field probes have been considered for this work, but the results here use the probe shown in the inset of Fig. 1, placed 5 mm from the slotted flange surface. The probe consists of a short 1-cm monopole with a flat ground skirt, which was fabricated with semi-rigid 0.086-inch outer-diameter cable for the feed line and monopole, and 32-mil thick copper-clad Rogers 4003C substrate for the ground skirt. The thin semi-rigid feed line and the flat skirt allow the monopole to be positioned as close as 1 mm away from the flange surface. By using a feed section of semi-rigid line and a 90° bend at the probe, cables, connectors, and supports can be kept relatively far from the probe and vessel. Operation of

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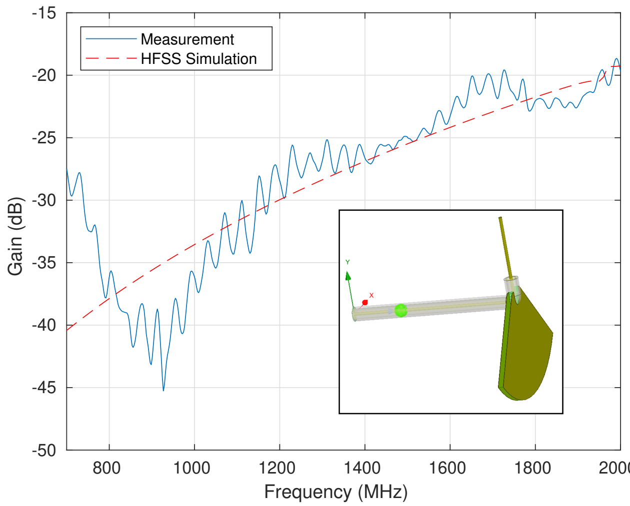

Fig. 2. Measured and simulated gain of the 1-cm monopole with skirt-shaped ground. Inset shows the model used in HFSS.

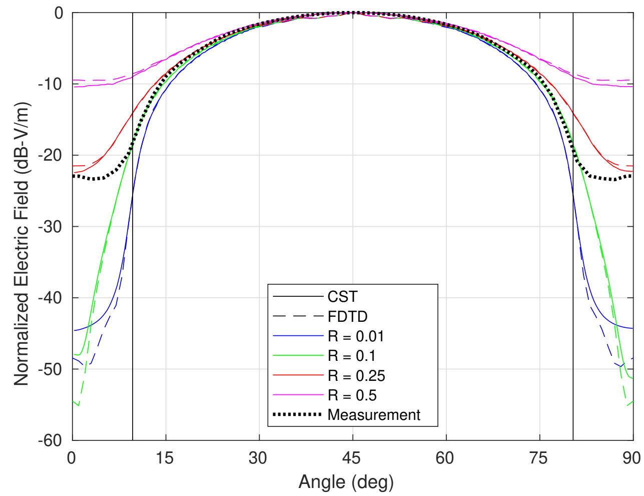

Fig. 3. Simulated and measured near fields 5 mm from the flange slot. The noise floor of the spectrum analyzer measurement is -120 dBm, giving an effective noise floor of -43 dB-V/m in this plot.

the probe was checked by performing HFSS simulations of realized probe gain (Z_0=50 ohm) and comparing with direct measurement in an anechoic chamber, as plotted in Fig. 2. Good agreement is seen in the gain except at frequencies below 900 MHz where the compact chamber size is likely inadequate.

III. Contact Resistance Estimation

Effective contact resistance at the shim/bolt contact points is estimated using a simple procedure. Full-wave simulations of the POE geometry are performed, where the bolt/shim region is filled with resistive material. Resulting near fields in the plane of the slot are stored for different values of conductivity of the resistive material. A field measurement near the POE can then be compared to this set of simulations, allowing a best-fit value for the contact resistance to be identified.

We can relate effective contact resistance to the shim material conductivity by approximating the shim to be a rectangular box with depth $d = 1$ inch, height $h = 5$ mil, and conductivity σ. We expect fields to penetrate according to the skin effect, where $\delta = \sqrt{2/(\omega\mu_0\sigma)}$ is the skin depth, ω is the circular excitation frequency, and μ_0 is the free-space permeability. The resistance of the slab at the slot edge is defined as

$$R = \frac{1}{\sigma}\frac{h}{\delta d} = \sqrt{\frac{\omega\mu}{2\sigma}}\frac{h}{d}. \tag{1}$$

Fields near the POE were analyzed at 754 MHz, which corresponds to the lowest-order transverse magnetic mode of the cavity. Simulations were first performed with CST Microwave Studio for the complete 3D vessel, where the air regions inside and just outside the slots required fine explicitly controlled meshing for good results. Second, simulations were performed with a lower complexity 2.5D finite-difference time-domain (FDTD) approach, where only a small 0.125-inch slice of the vessel about the slot plane was simulated. The FDTD simulations used a uniform cell size of 5-mil along z, and 1×1 mm^2 in the xy plane.

IV. Results

Fig. 3 plots simulated z-directed electric field 5 mm away from the flange for the two simulation approaches for different contact resistances. Note that each curve is normalized with respect to the peak field amplitude at the middle of the slot. Good agreement is seen between the detailed CST and simplified FDTD simulation approaches. The plot also shows measured near fields with bolts torqued to 80 inch-pounds.

It is interesting that in the slot region, the shape of the measured field amplitude closely follows the 0.1-ohm simulated curve. However, in the shim region, the measured shape conforms more closely to the shape of the higher contact resistance of 0.25 ohm. This discrepancy suggests that the uniform resistive material model is too simple to capture the complete behavior of a torqued bolt and shim. A more detailed bolt/shim model will be analyzed in future work. Another possible deficiency is that since the probe does not strictly measure fields at a point, a deep and narrow null cannot be measured. This latter possibility suggests the need for more careful consideration of probe spatial resolution, which we also plan to investigate.

V. Acknowledgment

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