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Worst-Case Electromagnetic Coupling to an Accelerometer using an Equivalent Circuit and Experimental Co-Characterization Methodology

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***Abstract*—Worst-case coupling estimation to a complex Printed Circuit Board (PCB) system typically requires an expensive computational and/or experimental approach. Therefore, there is a strong need for a deterministic approach that can accurately predict the worst-case coupling with the least computational and experimental cost. This work uses a hybrid equivalent circuit approach coupled with experimental measurements to simplify predicting the worst-case coupling to an accelerometer board. The predictions of the proposed methodology are validated using experimental measurements with excellent agreement.**

I. Introduction

The computational and experimental prediction of the worst-case electromagnetic coupling to a wide range of systems has been investigated by several authors. For example, a computationally efficient approach for finding the worst-case waveform excitation that maximizes either the induced peak voltage or the energy across a transmission line (TL) system has been recently reported [1]-[2]. However, most reported studies only considered simple systems with a limited number of wires/traces and highly simplified components. In this work, we extend the Thévenin equivalent circuit modeling approach to predict the optimum waveform to maximize electromagnetic coupling to a practical device, an accelerometer, with a moderately complex PCB network and several Integrated Circuits (ICs) and circuit components. The modeling predictions are also validated using experimental measurements.

II. Thévenin Equivalent Circuit Modeling Approach

The Thévenin equivalent circuit modeling approach is based on the fact that coupling to a linear wiring/trace system can be replaced by an equivalent circuit that has two main components: (*i*) the open-circuit voltage (V_{oc}) and (*ii*) the input impedance/admittance (Z_{in}/Y_{in}), both defined at the load port of interest [3]. These two parameters are calculated using full-wave simulations and can be used to determine the optimum frequencies to maximize the coupling to the system when different loads are attached to the port of interest.

The transfer ratio (TR) between the voltage induced across port loads and the incident field can be estimated by applying a voltage divider between the system impedance, Zin, and the load impedance as follows:

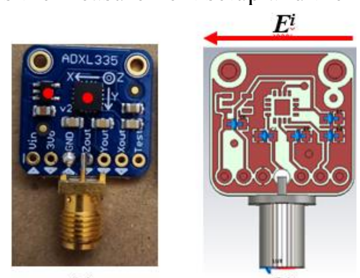
$$TR = V_{oc} * \frac{Z_{load}}{Z_{load} + Z_{in}} \tag{1}$$

where V_{oc} is the open circuit, Z_{in} is the input impedance, both defined at the port of interest, and Z_{load} is the load impedance [3]. In the next section, the device under test is introduced.

III. Device Under Test (DUT)

An accelerometer sensor is used in many electronic devices and vehicles that need speed and/or orientation control [4]. In this work, we selected the ADXL335 board, which is an analog triple-axis accelerometer (see Fig. 1), to demonstrate the versatility of the proposed methodology in predicting the worst-case waveform that maximizes electromagnetic coupling to a practical device. The red dots in Fig. 1(a) indicate the board ICs: (*i*) an LP298XS fixed-output voltage regulator and (*ii*) an ADXL335 chip. In addition, an SMA connector is connected at the Z_{out} port to measure the induced voltage at this port due to external excitation.

The board's ICs must be accurately modeled to calculate Z_{in} and V_{oc} at the port marked "Z_{out}", which measures the acceleration in the *z*-axis as shown in Fig. 1a . However, to the best of our knowledge, there are no SPICE models of the mounted ICs. Therefore, we developed the IC model experimentally, as discussed in the following section. In this work, we tested the Accelerometer with no external sources connected, and therefore, any measured voltage at the Z_{out} port is due to coupling from the incident field. As a starting point, we also assumed that the incident field levels do not induce high enough voltages to trigger the nonlinearities of the ICs. The next section discusses the measurement setup and the results.



(a) (b)

Figure 1. (a) the model of the ADXL335 accelerometer board. (b) The simulated design in CST Microwave Studio.

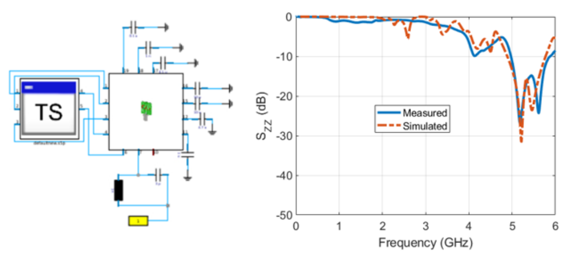
IV. Characterization Methodology and Results

A characterization kit is designed to calculate the scattering parameters of the functioning five ports of the ADXL335 IC. Using a 2-port VNA, we created 25 ". s2p", and combined them into a single ".s5p" file compatible with CST/SPICE simulations. Next, we used CST schematics to add the measured IC touchstone file to the accelerometer 3D trace model, as illustrated in Fig. 2(a). Figure 2 (b) compares the measured and the simulated S-parameter at the port marked "Z_{out}", of the complete accelerometer board. The good agreement between the simulated and the measured S-parameters at the Z_{out} port, justifies the use of the model in developing the equivalent circuit of the Accelerometer for coupling predictions.

The normalized Thévenin equivalent parameters of the accelerometer board are plotted in Fig. 3. Figure 3 indicates that for a plane wave excitation polarized as shown in Fig. 1 (b), the maximum induced energy at the "Z_{out}" port can be achieved by exciting the board with a narrowband Gaussian pulse centered at 2.1 GHz [1]. However, a wideband Gaussian pulse excitation can create a higher peak load voltage but lower total energy [1]. Additional optimizations to different loads can be achieved using the developed equivalent circuit in Fig. 3.

To further validate the computational model of the accelerometer board with the IC, we measured the coupled voltage across the Zout port experimentally and compared the results with the modeling predictions. The experimental setup, shown in Fig. 4 (a), consists of an Arbitrary Waveform Generator (AWG) connected to an amplifier and then to the TEM cell. The output port of the TEM cell is then connected to the Oscilloscope through a 40 dB attenuator.

A Gaussian sinusoidal waveform with a 2.1 GHz Center frequency and a 1 % bandwidth is then used to excite the board in the TEM cell.



(a) (b)

Figure 2. (a) A schematic of the ADXL 335 accelerometer showing the 3D trace model connected to the experimentally measured touchstone file of the IC. (b) Comparison between the measured and simulated S-parameters of the ADXL 335 Accelerometer board with the IC at the port marked "Z_{out}".

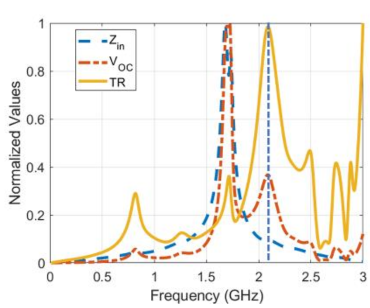


Figure 3. The Normalized Thevenin parameters of the accelerometer board.

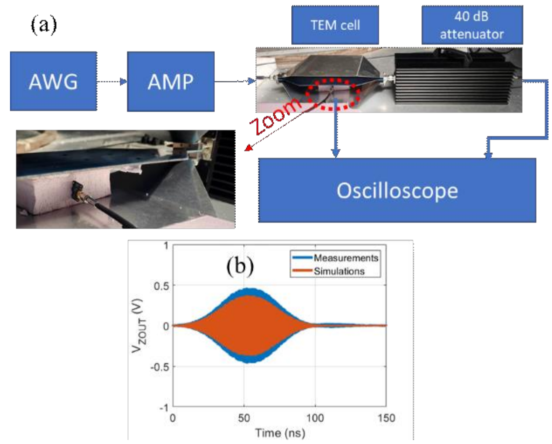


Figure 4. (a) Measurement coupling setup for the ADXL 335 Accelerometer board. (b) The comparison between the simulated and measured voltage at the Zout port of the Accelerometer.

The measured voltage at port 2 of the TEM cell is then used to estimate the incident electric field inside the TEM cell. The estimated electric field is then used in the full-wave simulation to excite the accelerometer model. Figure 4(b) compares the measured voltage at the Z_{out} of the Accelerometer versus the simulated voltage. Good agreement between the measurement and simulated induced voltage is achieved with < 20 % error in the magnitude due to several experimental approximations, such as the negligence of cable and other sources of losses in the setup.

V. Conclusion

This work illustrates how the Thévenin equivalent circuit modeling approach can identify the worst-case excitation that maximizes coupling to an accelerometer sensor with a complex network of traces connecting ICs and circuit components. Furthermore, the computational model of the accelerometer board is validated through experimental S-parameter and coupling measurements. Future work will include considering the nonlinearities of the ICs and biasing the accelerometer board with an external DC source during coupling experiments.

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