Design and Performance Evaluation of DUT Support Equipment for Automotive EMC Testing

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Abstract—Quality EMC testing involves not only having the RF test equipment setup properly and calibrated, but to also have the Device Under Test (DUT) support equipment designed well enough so that it does not interfere with the test results. The support equipment can be very complex, and have stringent requirements to stimulate, and monitor the DUT. This complexity can create significant challenges in designing it to be functional and to be unobtrusive in testing. In this paper two testers of varying complexity are evaluated. Both conventional and advanced filtering approaches are considered to bring necessary improvements in support equipment's performance. (Abstract)

Keywords- support equipment; EMC test box; equipment filtering; component filtering; test integrity, load box, EMC test, automotive EMC, X2Y filter, traditional filter, load simulator;

I. INTRODUCTION

Before product certification testing begins, an EMC test plan is authored. The process of developing a test plan involves defining the test conditions, monitoring scheme, and product functionality that will be exercised and evaluated. The test plan will also address how the test box will be configured inside the EMC chamber. It will define grounding connections, spacing above the ground plane, if one is used, as well as connection points to the DUT. It specifies whether the tester should be located outside of the chamber, or inside, along with the method(s) that will be used to carry signals and power through the chamber wall. Fiber optics is a preferred choice, but a filtered bulkhead may be permissible. It is preferred not to use a filtered bulkhead as it introduces inductive and capacitive loading that would otherwise not be found in the product's final application.

Today's automotive EMC specifications require that product performance be approximately 12-20dBuV/m for radiated emissions, 40dBuV for conducted emissions [9], 200-300mA of injected current, and up to a 200V/m field strength. The support equipment used to stimulate and load the product during testing is required to perform 6dB better for emissions [6], and equal or better performance on immunity. If the support equipment does not achieve this level of performance, it can be very difficult to determine if the product or the tester design is flawed. When this occurs, the integrity of testing is compromised and can lead to errors in results that could cause design changes to products that may not be necessary. When program timing is short, these kinds of delays may be unacceptable.

The goal is to find an appropriate balance between providing sufficient hardening of the test box but also properly stimulate and load the product being tested.

II. CHARACTERISTICS OF TEST BOXES

Two load/simulator box (test box) categories are prevalent: custom-built and off-the-shelf solutions:

Off-the-shelf solutions are often built to serve specific functions, for example CAN, GMLAN, J1850, or other communication schemes. As a result these devices are easy to implement. Some of the solutions are built to conform to EMC standards. Many are certified according to the FCC or CE mark approval processes, which can dramatically reduce development time. For these reasons, this kind of solution tends to cost more.

Custom-built test boxes are designed to accommodate unique applications that are not always available from off-the-shelf vendors. To adequately test the DUT and appropriately simulate real world automotive conditions, more than bus communication is required. The DUTs normally contain multiple input and output lines that need to be either controlled for functionality or properly loaded. Compared to off-the-shelf solutions, more development time and resources are required to build and prove out a custom-built solution. Additionally, a dedicated owner or team is required to document, and maintain the custom-built solution. Often, the final solution contains a combination of both custom-built and off-the-shelf solutions. Choosing the right design of custom parts or deciding how they should be built and integrated can be a daunting task.

A test box can be as simple as resistive terminations or as complex as high-speed data converters and radio frequency communications. A simple solution where the test box is composed of mostly passive devices may not require remote control. A more complex solution, however, may require remote control using stand-alone software via a PC external to the test chamber, as seen in Figure 1. In most cases, fiber optic converters will be used to communicate data from the support equipment to and from the controller located outside the chamber. The fiber optic systems do not directly address the potential for the support equipment to either generate noise, or be susceptible during immunity testing. They do, however, maintain the shielding effectiveness of the chamber or other type of enclosure.

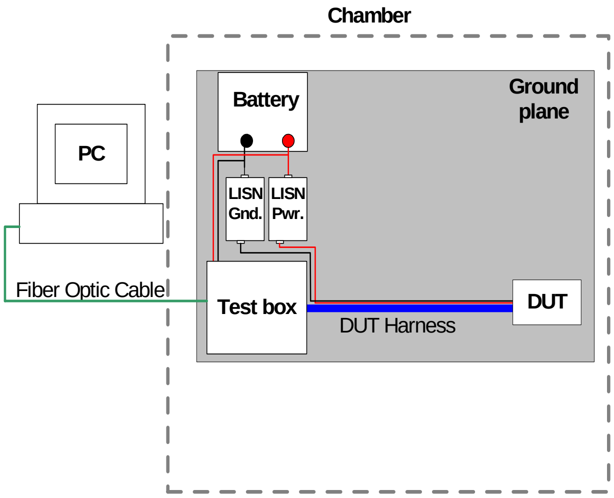


Figure 1. Generic test setup for EMC testing

The test box can be separated into two sections: the filter/passive section and the active section. The former contains the interface from the harness connector, inputs from the fiber optic lines, and ports for powering/grounding. The latter contains the active electronics used to simulate communications and loading conditions. By separating the two, filtering of the signal and power lines can be achieved while maintaining the metallic enclosure's shielding effectiveness.

III. Initial EMC Performance of Loads Boxes

For the purpose of this study, two custom-built test boxes are evaluated for radiated emissions performance.

A. Simple Test Box

A lighting test box was designed to actuate a series of LEDs on a user-interface DUT. This is accomplished by simulating the Binary Coded Decimal (BCD) output of the user switch. A continuous pattern representing all the user positions is cycled.

This test box is an entirely custom-built solution consisting of an isolated 5VDC linear power supply, a basic CMOS micro-controller, and output driver circuitry. The micro-controller is operated at a clock frequency of 20 MHz. Four of the micro-controller I/O ports are cycled in such a way to produce a recurring series of pulses that match the output of the user switch. This recurring signal simulates the user moving through each possible position of the switch. The four I/O ports output signals are fed to open collector transistors that supply the DUT. The open collector transistor circuitry is identical to the load the DUT will see in application. This allows for a test setup that is very close to the "real world" application.

A baseline radiated emissions measurement was performed and the data gathered. Figure 2 shows the circuit board used for the lighting test box as well as the radiated emissions results. Numerous narrowband failures are exhibited for the lighting test box in the 4 meter, FM, and 2 meter bands (45 MHz-176MHz).

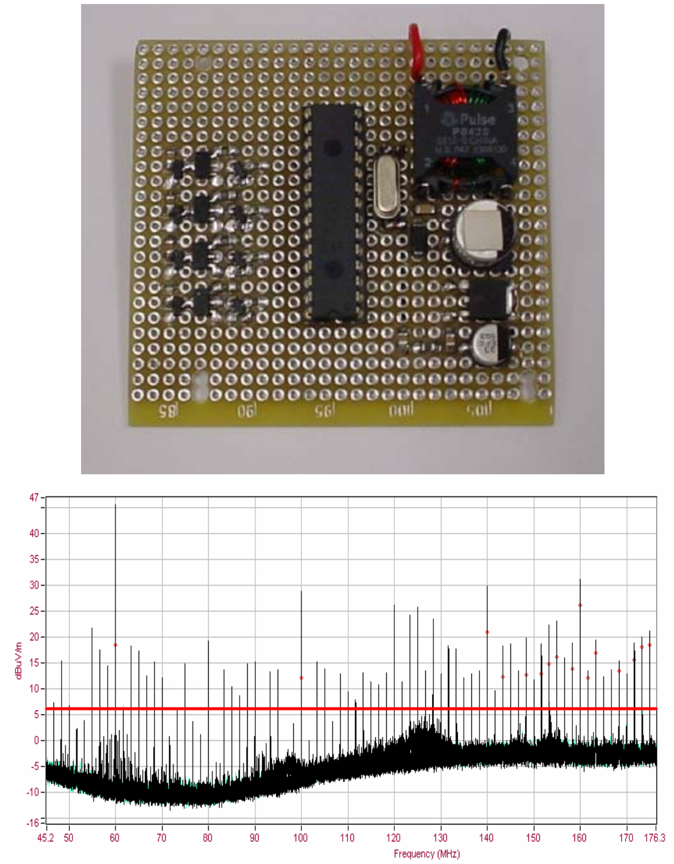


Figure 2. Lighting Test box – without filtering & CISPR 25 Radiated Emissions results for the unmodified lighting test box

The root cause of the radiated emissions for the lighting test box was found to be the micro-controller crystal harmonics and switching noise from the I/O ports radiating via the tester harness. Determination of the root cause consisted performing a radiated measurement of the lighting box without harness and then isolating each portion of the test box until the failures were removed.

B. Complex Test box

The second test box is a more complex test box. It is designed to actuate a Telematics DUT and perform the following functions:

- Supply power to DUT, internal hardware and fiber optic converters
- Simulate phone calls by end user and support audio in and audio out.
- Transmit and receive Bluetooth communications from a cellular phone
- Support communication schemes including low speed fault tolerant CAN, medium speed CAN, J1850, RS485 and SCI Debug
- Simulate audio arbitration by head unit/Navigation unit.
- Simulate button interface by end user

This test box solution consisted of several off-the-shelf devices integrated with custom-built solutions. Some of the off-the-shelf devices used were:

- CB-COMs to control state changes.
- NEO-Vi to simulate CAN and J1850 Communication.
- Fiber optic converters for audio and 485 communication.
- USB to serial converters.
- Bluetooth development kit.
- EMC hardened shielded enclosure.

A baseline radiated emissions measurement was performed and the data gathered. Figure 3 shows the Telematics test box and its radiated emissions performance from 30MHz to 200MHz. The emissions are significantly higher than the ambient limit.

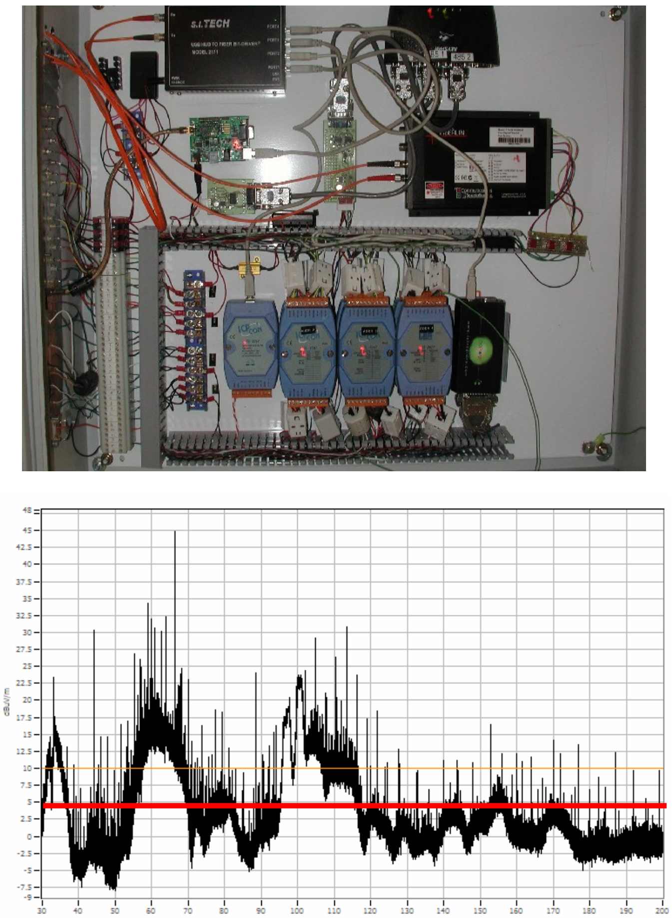


Figure 3. Telematics Test Box & CISPR 25 Radiated Emissions results for the unmodified Telematics test box.

The source for these emissions is the broadband nature of micro controller-enabled active switching relays as well as microprocessor-based CAN communications bus simulator. A “sniffer” probe was used to determine if there were any radiation directly from the enclosure and no leakage was found. Radiated emissions were caused by common mode currents on the power and signal lines causing the harness to become a radiating antenna.

In addition to emissions, the DUT connected to the Telematics test box had to meet the following radiated and conducted immunity requirements (figure 4):

- Radiated Immunity requirement of 100V/m from 200MHz to 6GHz using AM modulation and pulsed modulation from 4 – 6GHz
- Conducted Immunity requirement of 130mA from 1-800MHz with 1KHz 80% amplitude modulation at multiple probe positions using substitution method
- Conducted Immunity requirement of 130mA from 800-2000MHz with pulsed modulation at multiple probe positions using substitution method
- Conducted immunity requirement of 107mA from 1-200mA with 1KHz 80% amplitude modulation at multiple probe positions using the closed-loop method.

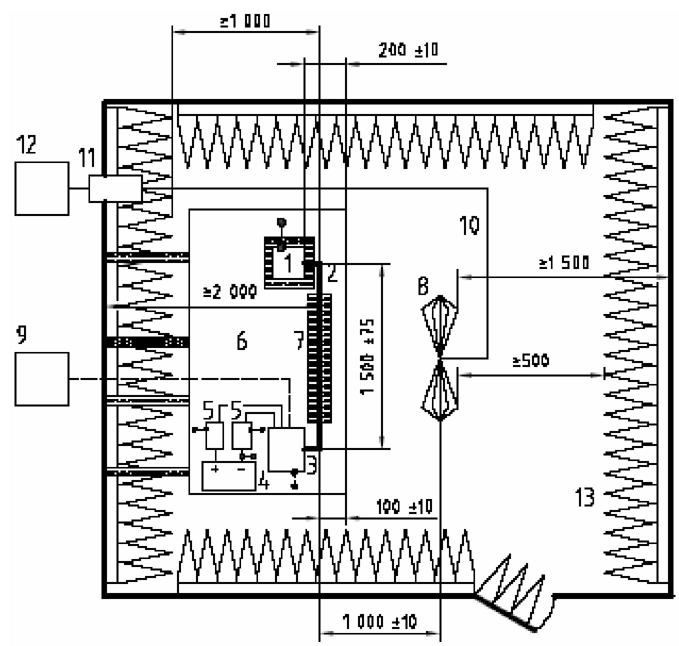
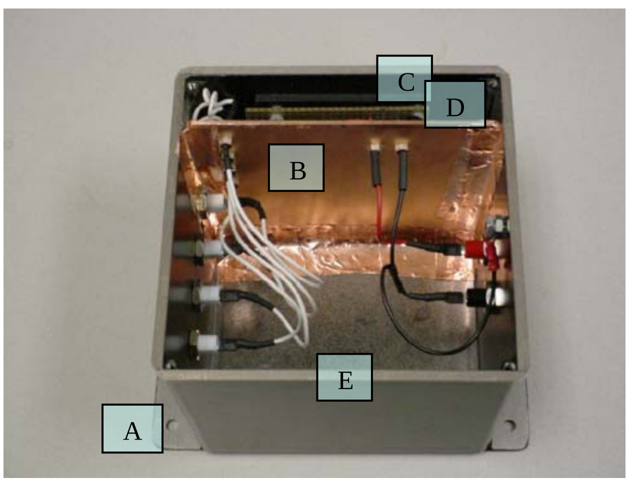


Figure 4. Conducted Immunity set-up showing substitution method above and closed loop method below

When immunity testing was performed, failures were observed at multiple frequencies. The RF caused an interruption in the functionality of communications. Initially it was not clear as to whether there was an issue with the DUT or the Telematics test box. A ferrite clamp was placed directly on the wiring of the test box to prevent RF energy from coupling into the metal enclosure through the cabling. When the test resumed, using the ferrite clamp, there were no interruptions in functionality. Through this troubleshooting it was discovered that conducted and radiated RF energy had coupled into the test box, through the impedance of the active electronic devices inside. Due to these failures, it was not possible to properly assess the immunity performance of the DUT.

IV. TRADITIONAL FILTERING APPROACH

After preliminary testing, both test boxes were found to be unacceptable for use in emissions testing for product certification. The Telematics test box required approximately 40dB of improvement in emissions between 20MHz – 200MHz (figure 3) while the lighting test box required nearly 15 db of improvement from 45MHz – 176MHz (figure 2). In the baseline design configuration both test boxes required significant improvements before they could be used in emissions testing.



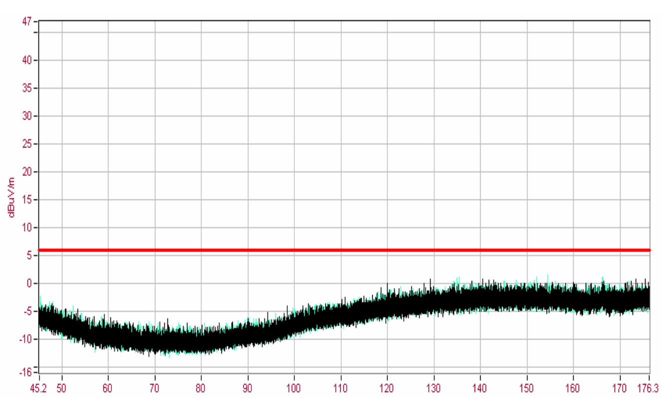
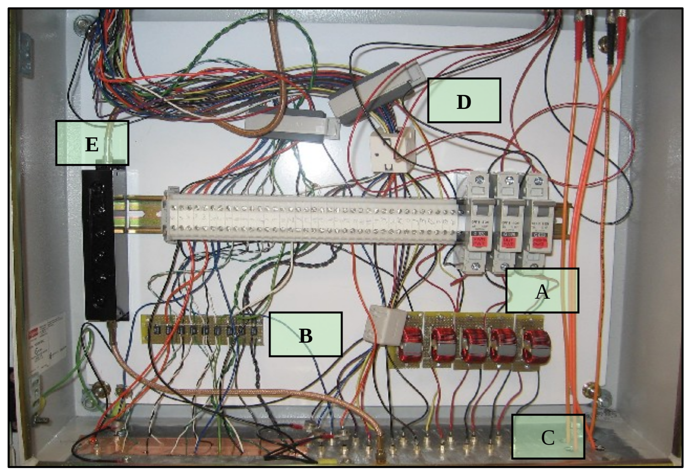


Figure 5. Simple lighting test box with traditional filtering & improved radiated emissions performance.

For the lighting test box, the following approaches were utilized in an attempt to improve the emissions (figure 5).

- Implementation of a metal enclosure that is bonded to the ground plane during radiated emissions testing [6] (A).
- Use of feed-through PI filters on all discrete signal lines (B).
- Common mode chokes on power and ground lines [7] (C).
- Low ESR capacitors on the test box power supply output (D).
- EMI gasket material on metal enclosure lid (E).

When comparing figure 2 and figure 5, a reduction of approximately 20dB is shown. The combination of a metal enclosure and filtered bulkhead brought most of improvements in emissions. The PI filters reduced differential and common-mode noise from I/O and power lines, while the common-mode choke focused on reducing common-mode noise from the power lines.



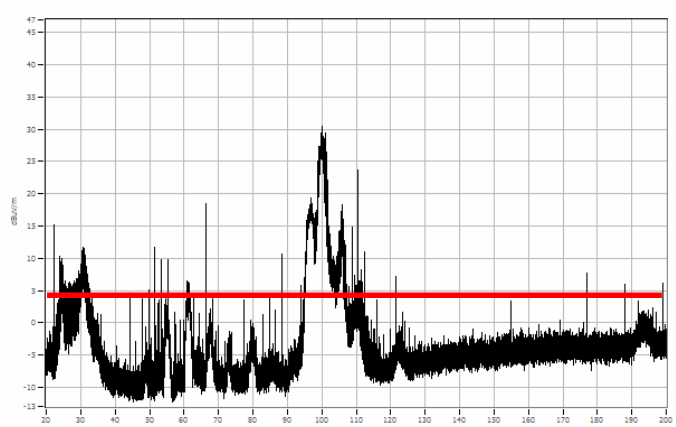


Figure 6. Complex Telematics tester with traditional filtering & moderately improved radiated emissions performance

The Telematics test box was also modified to accommodate traditional filtering. In order to achieve the filtering while maintaining the shielding integrity of the test box, a separate enclosure was used to provide all the filtering components. The two enclosures were bonded to provide a common ground. All power and ground lines and signal lines that could tolerate an in-line pi-filter were fed to the filter box using feed-through filters, grounded to both enclosures.

The filtering scheme employed on the Telematics test box is summarized below:

- Common mode chokes on power and ground lines (A).
- Special filters for CAN bus, RS485, SCI and other communication lines (B).
- Feed through PI filters on all discrete signal lines (C).
- Multiple ferrite clamps on signal lines (D).
- Special filter for Bluetooth Communication (E).

Figure 6 shows the traditional filters that were implemented along with the radiated emissions. As seen from the plot, the traditional filtering provided improvements in some areas. In other areas, however, the emissions were higher than baseline. The differential filters provided no filtering of common mode current on the lines. The common mode chokes on the power lines were ineffective at the higher frequencies. When comparing figure 3 and figure 6 it can be seen that the traditional filters provided about 6-8dB of improvement in some areas, but caused an increase between 90 – 110MHz.

The traditional filter approach improved the immunity performance of the test box. There were no tester abnormalities observed during radiated immunity testing. When conducted immunity testing was performed, there were no issues found in the substitution method. However, the closed loop method had a similar loss of communication as without traditional filtering applied. The failure occurred at 1MHz with an injection current of about 1.3dBmA. Further examination of the closed loop test set up showed that it operated at 6 times more power from the amplifier into the injection probe, as compared to substitution method. As a result, an alternate filtering approach was required.

V. Comparison of Traditional Filtering Approach vs. X2Y® Technology Approach

Traditional approaches to EMC filtering usually use discrete passive components in combinations that create multiple stage broadband filter networks. A simple example of this would be a "PI" filter made up of inductors and capacitors. Individual discrete passive components mainly provide a "brute force" filtering approach. For example, inductors "block" noise currents and capacitors "shunt" unwanted noise voltage. But these components have limitations; they are not perfectly broadband in frequency response. They also have packaging and mounting considerations that affect they way they perform in the circuit.

There are several factors in building/implementing an EMC filter network. An ideal filter network would consist of a single element that would have a broad effective range of frequencies with minimized parasitics [8]. The location of the filter would ideally be positioned at the signal/power line entrance or exit point of a shielded enclosure. It would maintain or induce balance between lines for maximum filtering benefits.

In passive component technology, few components fully address the ideal filter network characteristics. Considering all of the options, a primary candidate is the X2Y Technology. The X2Y chip component is a 4-terminal capacitive circuit integrated into standard surface mounted packages.

Package sizes such as 0603 and 0402 allow for implementation into connectors that mount onto enclosures. Another consideration in this application would be other four-terminal technologies such as chip feed-through capacitors. They are single-ended and unbalanced series elements and as a result would not achieve the same performance level as a dual-ended parallel filter that operate in bypass [1]. The X2Y chips are balanced and the structure allows for both single-ended (circuit 2) and dual-ended (circuit 1) filter applications.

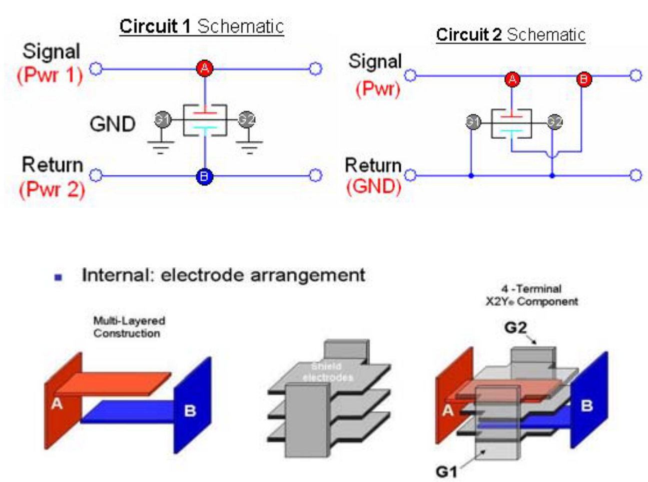


Figure 7. X2Y capacitor circuit configurations and physical structure

As figure 7 illustrates, the X2Y structure is symmetrical and thus is tightly balanced (1-3% unsorted) end-to-end. When attached in a circuit 1 configuration, imbalances between signal pairs are greatly reduced. The X2Y structure arranges noise currents coming in on the 'A' and 'B' electrodes in opposing directions (180 degrees opposites) and references them to a common "ground" reference internally. The result is maximized mutual inductive coupling and opposing fields cancel. This phenomenon means the net parasitics for X2Y components are very small and fields are contained internally, unlike other passive devices [3][4]. This allows for effective filtering performance from DC to several gigahertz in order to comply with automotive (CISPR 25) [6] and consumer electronics (FCC part 15) EMC criteria [5].

It should also be noted for the X2Y circuit 1 configuration, signal pairs do not need to be matched pairs. The only consideration should be the amount of capacitance applied so signal lines don't get overloaded.

The Telematics test box previously discussed requires ~40dB reduction in radiated emissions. Traditional filtering did not yield the required results for certification. X2Y components were chosen as the next possible candidate for addressing the issue. Since a standard metal back-shell Amphenol connector was used for the primary connection to the test box, a proposal was made to design a custom printed circuit board that would mount easily on the backside.

For performance reasons, and to reduce the total component count required, circuit 1 was the desired configuration of the X2Y components, however, there were three pins that required circuit 2. 0603 4700pF X2Y capacitors were used on all pins except sensitive communication lines such as CAN Buss, RS485, and the proprietary serial communications interface (SCI). For those lines, 0603 100pF X2Y capacitors were used. It should be noted that due to the configuration where the 3 odd pins were connected with circuit 2, the capacitance value of 4700pF is double (9400pF).

Figure 8 shows the printed circuit board containing the X2Y capacitors and provides the improved radiated emissions data for 30-200MHz. When comparing figures 6 and 8, a significant improvement (20-35dB) in emissions performance, with the use of X2Y filters, can be observed. The closed-loop conducted immunity failures attributable to the tester were also eliminated through the use of the X2Y filter approach.

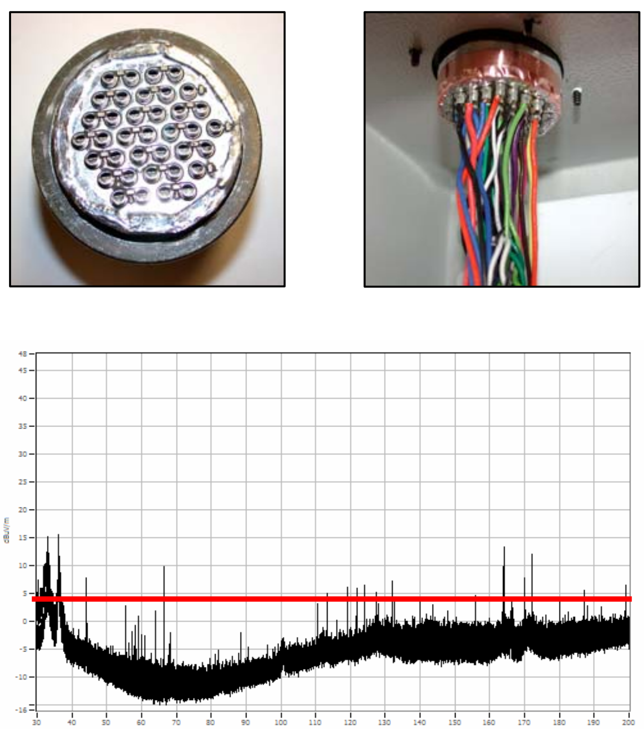


Figure 8. X2Y Filter board implemented and attached to Amphenol connector of test box. The figure below shows the improved radiated emissions performance

VI. Test Box Design and Prove-Out

Through the experiences that were gained while designing and evaluating the two test boxes, it was evident that a clear plan for design and test were required for a successful implementation. It may be that the test box would require as much time and effort as a company electronic product or system would in its launch cycle. While we know that in most organizations it is not possible to spend those kind of resources on support equipment development, it is recommended to consider the following key factors when designing and planning:

- Software prove-out
- Hardware prove-out
- Functional testing prior to EMC testing
- Configuration of the tester (positioned in the product position or the tester position)
- Source of power and grounding
- Applicable EMC tests

It is recommended that validation of the tester box functionality be confirmed prior to proceeding to the EMC test facility for measurements. In some cases functional issues may need to be solved and it may be very costly to resolve these issues in the EMC facility. When filtering is applied to the design of the support equipment, a compromise is often made. The signal integrity of the inputs and outputs can be affected adversely. In the case of automotive CAN or LAN communications, attention should be paid to the kind and amount of filtering that is applied to those lines [10]. Due to the differential nature of some communication protocols, a balanced filtering scheme is needed. The amount of capacitance from side to side must be equal and balanced or the bus can become unstable.

Allowable capacitive loading on the communications bus is typically determined by the number of modules connected to the network in the in the final application. Fewer total modules allow you to use more capacitance per module for filtering. It is, however, difficult to quantify this number in the specification, especially early in product development when the vehicle architecture is experiencing significant development. A typical CAN bus filter that consists of a common-mode choke and parallel capacitance does not always protect the system from electro-static discharge (ESD). Choosing CAN enabled integrated circuits that are inherently designed to be more robust usually enhances the level of immunity performance.

A small test plan for the test box should be considered in order to identify the kinds of tests and severity levels that would be applied. In many cases, a scaled-down version of the product test plan may be used. Evaluating the performance of the test box can be done several ways: One approach is to measure the test box in its intended configuration without being connected to the DUT; this approach will work well for emissions. A second approach is to place the test box in the position normally taken by the DUT in the chamber; this method is ideal for immunity testing.

When testing is performed with both the test box and the DUT and a failure is observed, it can difficult to determine the source. One approach to determining the source would be to provide a 'stand-alone' piece of software for the product that allows it to be tested without the need for support equipment. A continued failure would indicate that the product is responsible. A second approach would be to replace the DUT or tester with an equivalent passive load. This approach would not allow functionality to be evaluated, but would provide a point of reference leading to the source of the failure. A third, and more methodical approach would be to disable various functions of the product or the tester and take measurements to evaluate for improvements.

VII. Conclusion

Two test box case studies are presented. Each design has unique features and challenges that require their own root-cause, countermeasures, and final solutions. The design and application of simpler test boxes may only require conventional filtering for acceptable EMC performance. However, as the complexity, capability and EMC requirements demand more, advanced filtering techniques may be necessary.

The process of designing, hardening and proving the two test boxes has common threads. When planning to test a product that requires support equipment, it is recommended to consider the following:

- Test box enclosure design
- Filtering of power and ground connections
- Filtering of inputs/outputs/communications
- Grounding and bonding requirements
- Complexity and number of stimuli and loading
- Test box prove-out plan
- Level of acceptable performance
- Available chamber feed-through options

It is recommended that a formal plan be developed. The plan should address the details of the design, process for prove-out, and level of acceptable performance of the test box. Generation of the product test plan can facilitate, as well as document, the proper steps in producing well-designed support equipment.

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