Measurement-Based Circuit Modeling of Conducted and Radiated Automotive Immunity Test Setups

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Abstract — **Simulations of automotive immunity test setups are often used to analyze the systems at early design stages and therefore to predict and to avoid failures in advance. Accurate models for different setup structures are needed to evaluate the RF coupling levels to DUTs.**

In this work an accurate measurement based approach to build models for passive test setup structures is proposed. These models are applied to estimate the interfering RF current levels at DUT inputs. A measurement-based modeling procedure for BCI coupling to a cable harness and for incident field coupling to a cable harness is presented. The proposed methods reproduce the existing test setups in a simulation environment and therefore accelerate and simplify further investigations. In order to ascertain the validity of the approach, simple test structures with different termination impedances are investigated.

Keywords— BCI, ALSE, network S-, Y-, Z-parameters, TL, per-unit-length parameters

I. INTRODUCTION

The behavioral modeling of system-level EMC setups based on ISO 11452-2 (Absorber Line Shielded Enclosure, ALSE, [1]) and ISO 11452-4 (Bulk Current Injection, BCI, [2]) was investigated by many research groups, e.g. [3-7]. Different approaches are proposed to model the setups and methods, to make it possible to predict the test results for DUTs in advance and therefore to avoid device redesign loops. The modelling of system level tests involving floating (ungrounded) multiport DUTs (e.g. [5]) has high practical relevance. Another goal of such modeling is to analyze the methods correlation and to transfer the results between different test methods [4-7].

In this paper a fast and accurate method to extract models for immunity test setup structures is presented. The models are applied for estimating the interfering RF current levels in terminating networks under RF injection. The modeling procedure takes into account the signal transmission along the cable harness, coupling of injection and current sensing probes, incident field excitation, and the termination networks.

The entire procedure was performed in Matlab using the RF Toolbox and is based on linear network parameter datasets (S, Y, Z) of the passive structures extracted from Vector Network Analyzer (VNA) measurements or circuit models. Termination models can be attached and the currents and voltages can be calculated for any specified input RF signal.

The proposed approaches are initially implemented in the frequency domain but can also be adapted for time domain simulations using Vector Fitting [8,9]. Furthermore extension to complex multiple-wire cable harness is possible. Extracted models are all validated with measurements.

The structure of this paper is as follows. Section II contains a general description of the modeling procedure and its application to a single wire cable harness, BCI coupling, and field excitation with an antenna. Transmission line theory is concerned herein to extract per-unit-parameters of the cable harness from measured S-parameter datasets. In section III the models are validated for different test setups and termination networks. Section IV shows the application of the approach for estimation of the RF currents injected into dummy DUT inputs in test setups according to ISO 11452-2 and ISO 11452-4.

II. MODELING PROCEDURE

A. General considerations on modeling procedure

The passive structures are initially characterized in terms of network S-parameters from 10 or 300 kHz to 1 GHz with VNA measurements and deembedding. The circuit or field theory can also be used to calculate the S-parameters.

The operations like e.g. connection of devices together to form a larger system or attachment of termination networks to the system ports can be performed by operations on network parameters in S, Y, Z or other representations. Mathematically each such action corresponds to introducing new equations or constraints to the main linear equation system and solving it for new relevant variables. In practice this is performed with simple matrix manipulations using Matlab RF toolbox.

A sample equation set for attaching a single termination to a device is shown below. The original three-port device is described in terms of S-parameters:

$$\begin{cases} b_1 = S_{11} \cdot a_1 + S_{12} \cdot a_2 + S_{13} \cdot a_3 \\ b_2 = S_{21} \cdot a_1 + S_{22} \cdot a_2 + S_{23} \cdot a_3 \\ b_3 = S_{31} \cdot a_1 + S_{32} \cdot a_2 + S_{33} \cdot a_3 \end{cases}$$

A passive termination impedance Z_T attached to e.g. port 3 reflects the scattered wave b_3 back into the device as a new incident wave a_3, providing an additional equation:

$$a_3 = \Gamma_T \cdot b_3$$

where Γ_T is the wave reflection coefficient (S_{11}) of the termination impedance in the 50 Ω system. The fourth equation allows solving the original system for new $b'_{1,2}$ waves in terms of $a_{1,2}$ stimuli:

$$\begin{cases} b_1' = \left(S_{11} + \dfrac{S_{13} \cdot S_{31} \cdot \Gamma_T}{1 - \Gamma_T \cdot S_{33}}\right) \cdot a_1 + \left(S_{12} + \dfrac{S_{13} \cdot S_{32} \cdot \Gamma_T}{1 - \Gamma_T \cdot S_{33}}\right) \cdot a_2 \\ b_2' = \left(S_{21} + \dfrac{S_{23} \cdot S_{31} \cdot \Gamma_T}{1 - \Gamma_T \cdot S_{33}}\right) \cdot a_1 + \left(S_{22} + \dfrac{S_{23} \cdot S_{32} \cdot \Gamma_T}{1 - \Gamma_T \cdot S_{33}}\right) \cdot a_2 \end{cases}$$

The S-parameter dataset for the new two-port device (here consisting of the initial three-port device with termination Z_T at port 3) can be recognized from the latter equation set. The solution is then implemented in a generalized form (for an arbitrary dataset size and port index) in Matlab and used for datasets processing. Using a similar approach the devices described in terms of S- or Y-parameter datasets can be connected together in arbitrary configurations, and the RF signal levels at any port of the system can be calculated for any RF stimulus at any port. Such steps are plain and very simple, but the corresponding equation sets are quite bulky and therefore not shown here.

If a transient simulation should be performed on the final structure, the final S-parameter dataset can be processed with Vector Fitting [8] to approximate the frequency-dependent behavior of the final system to a state-space model. The circuit generation procedure can then be used to produce a SPICE- or VHDL-AMS-compatible macromodel in S-, Y- or Z-parameter form [9]. Such macromodels can be used in any type of circuit simulation, also involving non-linear DUT circuits.

B. Cable over ground plane

The cable harness considered in current work consists of a single straight wire spanned within metal test fixtures in 50 mm height over a copper ground plane (Fig. 1). The harness is a passive structure and therefore can be characterized in terms of network scattering parameters.

Performing separate VNA measurements for each test-case-dependent setup length is ineffective. The signal propagation along the cable is commonly considered as a TEM mode, and therefore can be described with transmission line theory. The S-parameters for the cable harness can be generated based on TL models. The simplest approach is to use the RLCG-parameter-based models. Multiple procedures for theoretical estimation or measurement-based extraction of RLCG TL parameters exist. In current work a measurement-based approach based on [10] is used.

The influence of the fixtures cannot be neglected if higher accuracy is required, especially if the network parameters have to be predicted later for the harnesses of different lengths.

The effect of SMA connector at the test fixture can be represented with a short lossless 50 Ω TL. The connector has to be pre-characterized with an open-circuit measurement (here: Z_0=50 Ω, T_D≈60 ps) and either deembedded from the raw measurement data or appended to the final model.

Moreover, a cable harness close to fixtures (within a short distance of some cm) cannot be considered homogenous due to stray fields from the cable to the fixtures. The effect can be considered as a constant offset in RLCG parameter values for this short cable part. This offset is extracted by analysis of the RLCG parameters for several setup lengths (here 20, 40, 60 and 80 cm), fitting the frequency dependencies with simplified approximations (R_0, L_0, C_0, G_0, R_S and G_D [11]) and linear
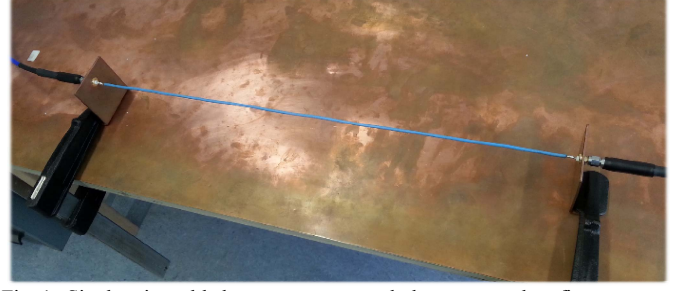

Fig. 1 Single-wire cable harness over ground plane mounted on fixtures
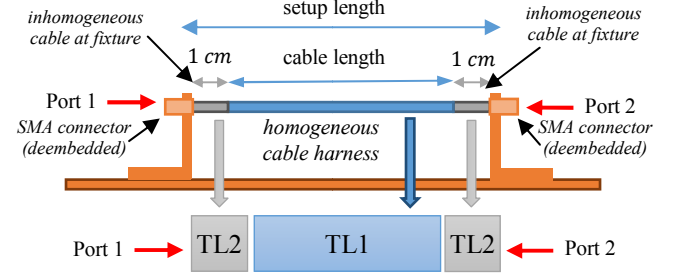

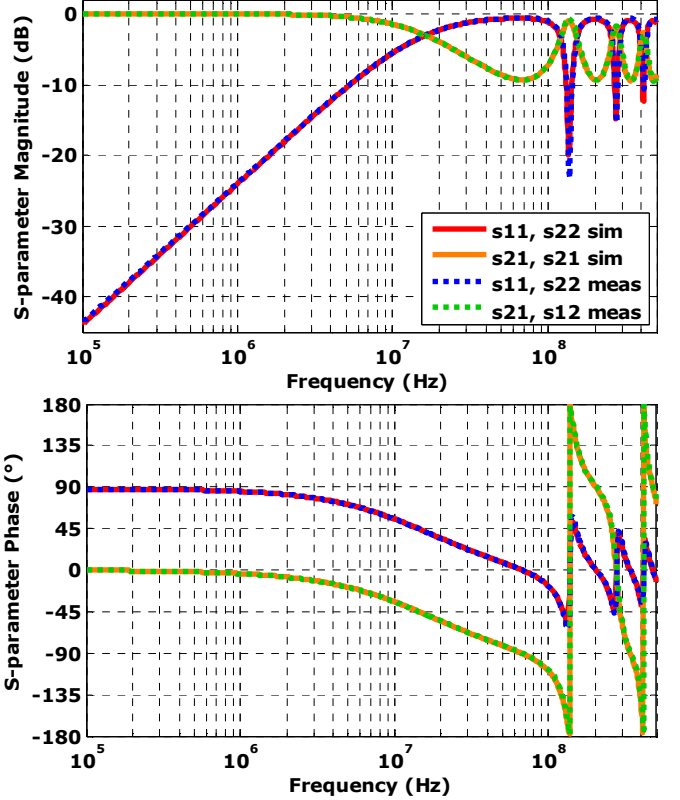Fig. 2 Cable harness in test fixtures: physical setup and model structure

Fig. 3 S-parameters of 1 m cable harness cable within fixtures, measurement and reconstruction based on the per-unit-length RLCG TL parameters

TABLE I Extracted RLCG parameters of fixtures (a) and cable harness (b)

	Ro	Rs	Lo	Co	Go	Gd
a	1.687e-02	6.759e-04	1.991e-06	3.981e-11	1.369e-06	2.334e-12
b	4.540e-03	7.34e-05	9.942e-07	1.26e-11	2.13e-07	1.964e-12

extrapolation of the RLCG values to zero cable length. Such procedure returns the per-unit-length parameters for both main homogenous cable harness outside fixture influence (a) and also for the mentioned short cable harness parts close to the fixtures, where stray field effects are involved (b).

The resistance, inductance, capacitance and skin effect values can be extracted with very high accuracy. The shunt conductance component mostly lies outside the VNA dynamic impedance measurement range, and hence cannot be extracted accurately. Due to its extremely low value it does not introduce any significant influence into the cable harness properties, and therefore can be neglected for current modeling purposes.

To confirm the validity of the cable model and to illustrate the capability to estimate the behavior for various setup lengths, the S-parameters for a new setup length of 1 m are reconstructed with TL models (Fig. 2) and compared to measurement data. The results show that the S-parameters are reconstructed with high accuracy in terms of both magnitude and phase (Fig. 3).

C. BCI coupling to a cable harness

The coupling to the cable harness using a BCI clamp under certain assumptions can be considered as a passive linear transfer function, and hence may also be described in terms of S-parameters. A three-port-measurement can be performed with a VNA. The setup is illustrated in Fig. 4. The goal is the generation of a dataset, which represents the behavior of the BCI clamp plus a short clamped piece of cable (7 cm).

All investigations were done with a Fischer FCC-F140 BCI clamp. The setup is composed of a 20 cm cable within the above mentioned test fixtures. The setup can be interpreted as five separate modules: two two-port circuits on the left (cable with fixture stray effects and main cable), a three-port central module (coupling dataset), and two two-port circuits on the right. The cable harness was characterized in the previous steps, and therefore can be deembedded from the measurement data. The remaining three-port dataset belongs to the coupling from the RF port of the BCI clamp to the clamped cable part.

The model is verified with a VNA measurement in a similar setup of larger length (here: 1 m). The coupling from RF-port at BCI clamp to the fixture ports is measured in terms of S-parameters. The same setup is reconstructed by port-to-port cascaded connection of several involved modules. Since the BCI coupling dataset contains a side port (clamp RF port), which is not directly involved in the cascaded connection, the commonly used dataset cascading by matrix multiplication of the scattering chain parameters cannot be used. The assembly is performed in terms of Y-Parameters with an approach similar to one shown in the section II.A. As demonstrated in Fig. 5, the reconstructed signal transfer shows a very good correlation to measurement data.

D. Antenna coupling to cable harness

The coupling of an antenna to a cable harness can be measured with a VNA for fixed setup geometry. The test setup structure is shown in Fig. 6. The cable harness is mounted between the same fixtures in 50 mm height above a copper table, which is located in an anechoic chamber. A logarithmic-periodical antenna is located in 1 m distance from the table, according to [1]. The incident electromagnetic field coupling to the cable generates a current in both terminating networks.

The coupling to a cable harness can be calculated by incorporating the effects of the incident electromagnetic fields
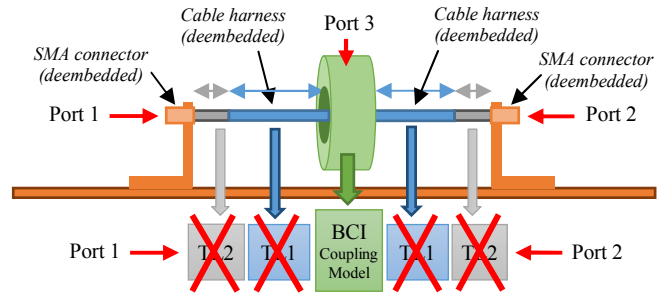

Fig. 4 Deembedding cable and test fixtures to extract BCI-coupling
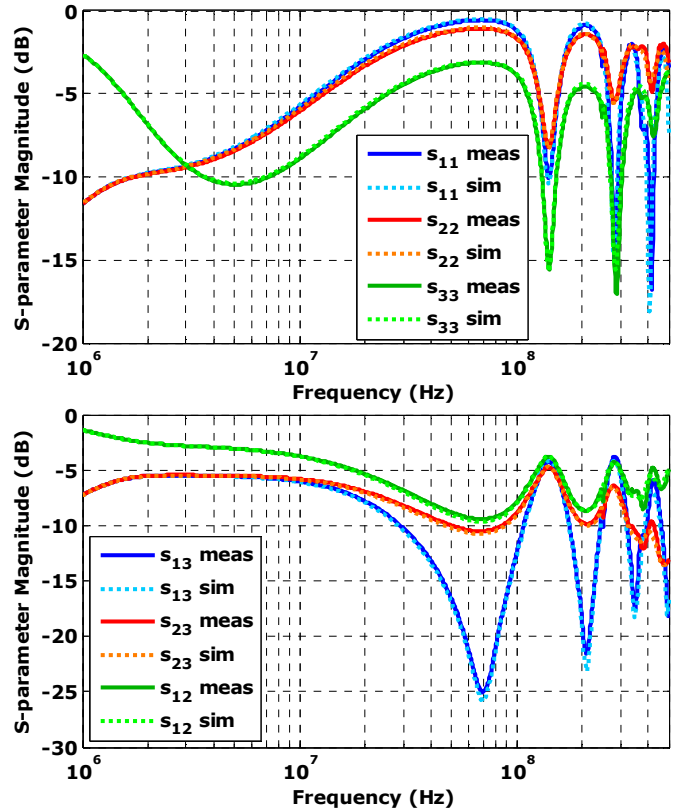

Fig. 5 Scattering parameters of BCI coupling to a 1m long cable, VNA measurement of the physical setup, and reconstruction using BCI coupling model and RLCG TL models for cable and fixtures
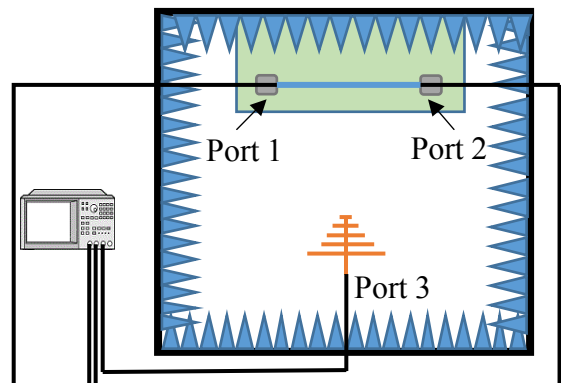

Fig. 6 Setup for the measurement of antenna coupling to a cable harness in an anechoic chamber

as distributed sources along the harness [11]. However, due to a variety of parasitic effects and non-ideal environment a real test setup in an anechoic chamber cannot be characterized with simple analytic approaches.

The structure can be characterized with a VNA as a three-port network S-parameter dataset. The S-parameters of the structure are sufficient to calculate the currents in any passive termination attached to the cable. Full system model can be obtained by cascading the arbitrary termination impedance networks to the main three-port.

III. EXPERIMENTAL, RESULTS AND DISCUSSIONS

A. General procedure overview

The simplicity and accuracy of proposed methods in Section II.C and D are confirmed with test setups based on [1] and [2]. The models extracted from S-parameter measurements are used to calculate RF currents coupled to passive terminations attached to the harness for specified signal levels of injected into the BCI clamp or antenna port.

The terminations are composed of small PCBs with SMD resistors (see Fig. 7). The terminations are placed on grounded metal mounts and attached to the cable instead of test fixtures.

Tested systems often contain a low-ohmic signal source and a high-ohmic receiver. The termination resistances were correspondingly selected as 10 Ω (low-ohmic side) and 1 kΩ (high-ohmic side). The termination impedance models are created in terms of S-parameters by VNA measurements to include all the characteristics and parasitic effects.

For model verification purposes a constant RF forward power of specified amplitude (10 dBm) is injected into each setup. The measurement of current at the termination networks is performed using current probe FCC F-65 clamped over cable harness in 5 mm distance from the termination PCB edge. The characterization of the current probe and extraction of transfer impedance is performed in a similar way as for the BCI injection clamp (see section II.C). The measured termination currents are extracted from the signal at the current clamp port and the pre-characterized transfer impedance of the clamp.

The models for the entire setups are assembled in Matlab from the S-parameters of individual setup components. The termination currents are calculated for a given forward power level at the RF port of the BCI injection clamp or antenna.

Finally, the calibration of RF forward power according to both standards is performed with available simulation models and specifications. The RF currents are calculated for this calibrated forward power and verified with measurement data.

B. BCI setup

The structure of the BCI setup is shown in Fig. 8. A cable of 1.5 m length was used and the clamp was located in 150 mm from the termination PCB with 1 kΩ SMD resistor.

A constant RF power of 10 dBm was injected into the BCI clamp and the currents were measured with a current clamp at both terminations as described before.

The model of the entire setup is assembled by cascading the individual S-parameter blocks extracted in sections II.B and C. The final modular dataset structure containing the entire setup
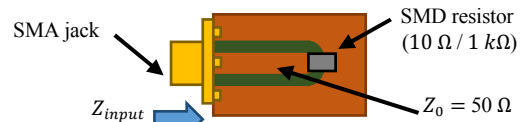

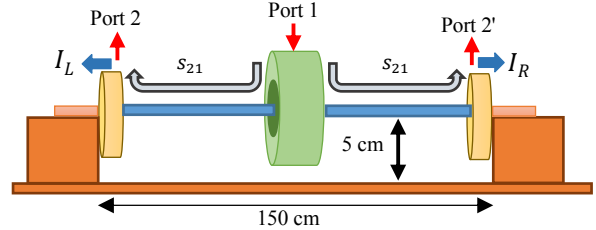Fig. 7 Structure of a dummy termination: test PCB with SMD resistor

Fig. 8 Measurement of the RF currents coupled to termination impedances (10 Ω, 1 kΩ) in a BCI setup with 1.5 m cable
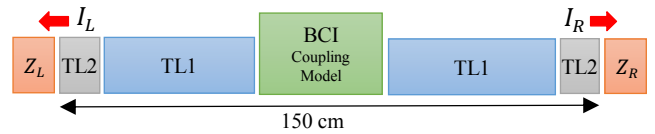

Fig. 9 Reconstruction of the BCI test setup transfer function using pre-characterized S-parameter blocks for individual setup components
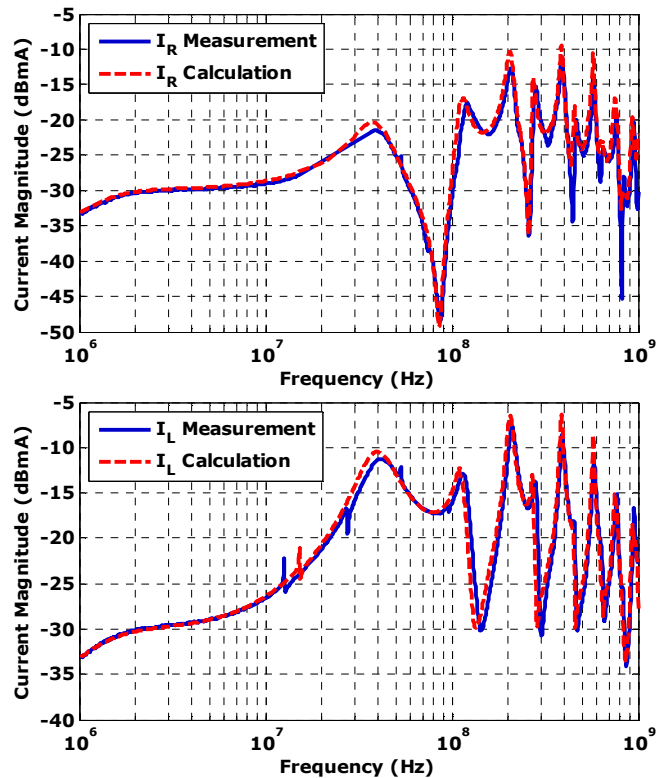

Fig. 10 Current magnitudes at the cable terminations ($Z_R = 1$ kΩ, $Z_L = 10$ Ω) under input forward power of 10 dBm injected into the BCI clamp, measurement vs. calculation

including the passive terminations is shown in Fig. 9.

The current produced at both passive terminations is calculated using the given level of input forward power and the S-parameter data. The comparison between measured and calculated data in Fig. 10 shows a very good matching even for the frequencies above 400 MHz for both terminating networks.

C. Antenna setup

The same procedure is repeated for the currents in a setup with antenna coupling to the harness. The setup structure used for current measurement is shown in Fig. 11. The current probe is placed again at two locations close to terminations. The currents through the terminations produced by the coupling of antenna radiation to the cable harness are measured.

The model incorporating the entire structure is assembled in the same way on modular basis. The model structure is shown in Fig. 12. A good congruence of the calculated and measured values can be observed in Fig. 13.

IV. APPLICATION EXAMPLE

The termination currents corresponding to BCI and ALSE realistic severity levels according to ISO-11452 are calculated using the developed models.

For the BCI setup, the power is calibrated using a model of a short setup consisting of the BCI clamp over a short 10 cm cable within the same test fixtures. The model is assembled from the same discrete S-parameter blocks. Both fixture ports are terminated with ideal 50 Ω impedances. The RF power necessary to produce a 100 mA current is determined.

The forward power necessary to reach the severity level of $100\ V/m$ in an ALSE setup is extracted from the datasheet of the antenna [12]. The datasheet specifies the RF forward power to obtain a field magnitude of $10\ V/m$ in a 3 m distance from the antenna. This RF power level is scaled correspondingly to the required E-field value and to the required distance from the antenna to the cable harness in current configuration.

The calibrated RF forward power levels (Fig. 14) are then virtually injected into BCI and ALSE setup models and the RF currents in both terminating networks are calculated (Fig. 15).

Due to strong inductive coupling between BCI probe and cable harness the amount of power injected into the input port to reach 100 mA is much less than the injected power to reach the severity level of 100 V/m by ALSE.

The different coupling mechanism of both procedures results in significantly different current patterns injected into both terminations for the calibrated RF input power level.

The entire procedure can be summarized as following:

- Characterize setup components with VNA
- Process the setup or component S-parameter datasets
  - Deembed fixtures to obtain component datasets
  - Connect the modules together into a system setup
  - Attach DUT or termination models
- Define the forward power to be injected into setup
- Calculate RF levels at the DUT ports for this power

The S-parameter datasets can be processed with Vector Fitting [8,9] to obtain the state-space macromodels, which can be used for non-linear time domain simulations in many circuit simulators. This procedure can be summarized as following:

- Apply Vectfit approximation to a S-parameter dataset to produce a state-space model and its equivalent circuit
- Attach nonlinear DUT models in the circuit simulator
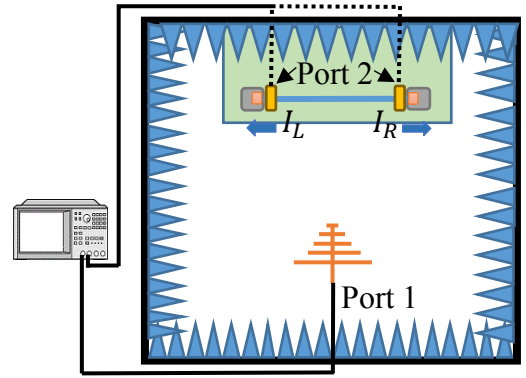- Simulate the DUT response in time domain

Fig. 11 Measurement of the RF currents coupled to dummy terminations (10 Ω, 1kΩ) in an antenna setup with 1.5 m cable
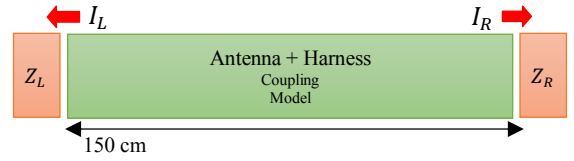

Fig. 12 Structure of final model used for current calculation, containing the antenna coupling model and termination network impedances
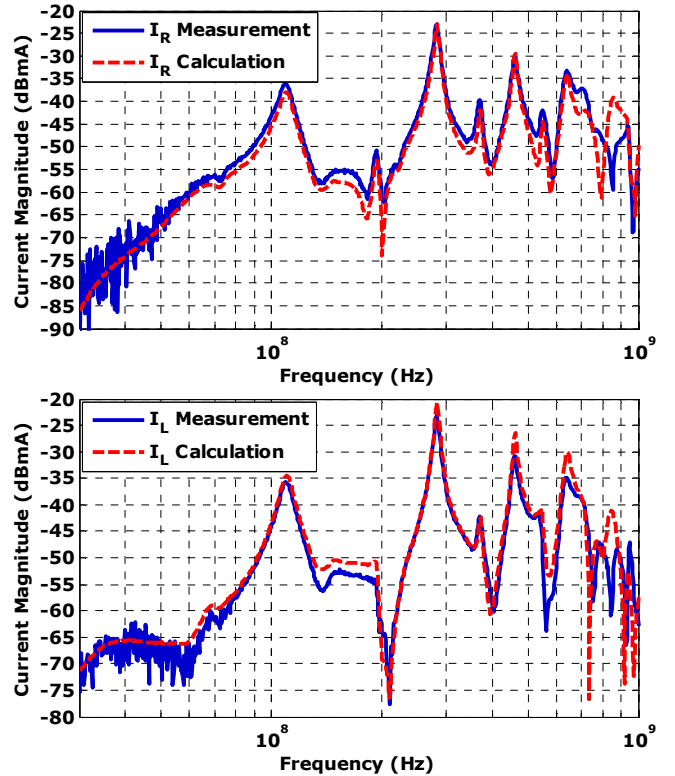

Fig. 13 Current magnitudes at the cable terminations ($Z_R = 1\ k\Omega$, $Z_L = 10\ \Omega$) under a forward power of 10 dBm injected into the antenna RF port, measurement vs. calculation
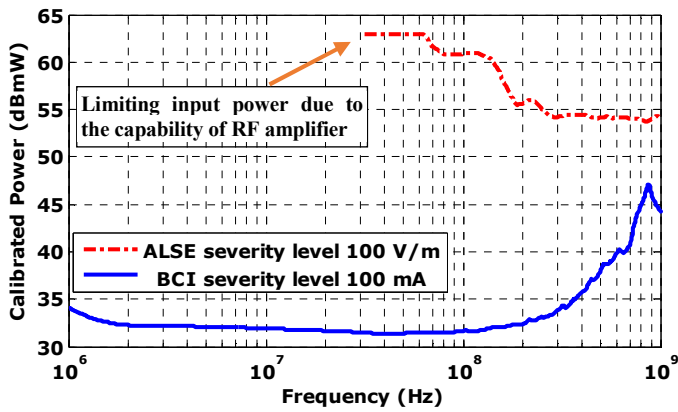
Fig. 14 Calibrated forward power level required for performing real BCI and ALSE tests with normed severity levels based on [1] and [2]
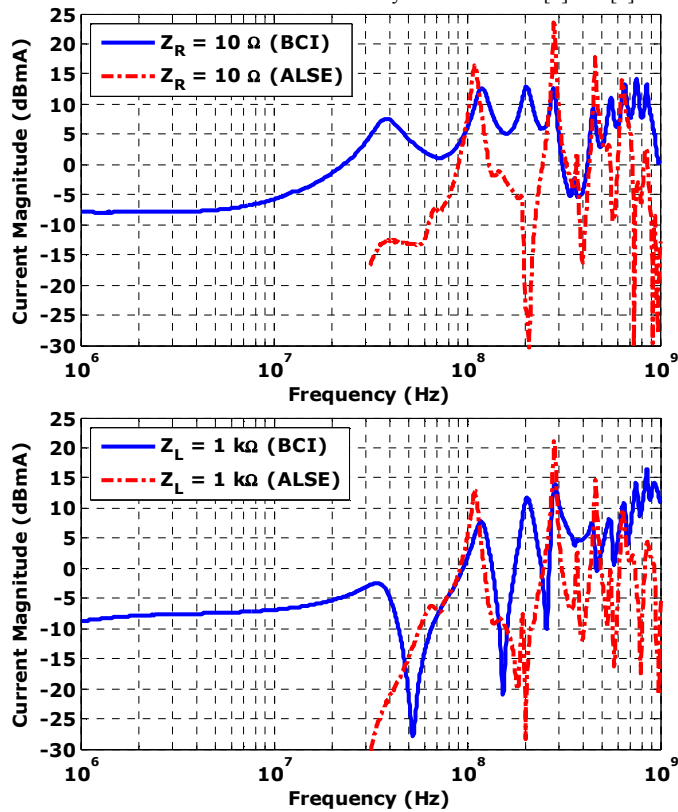

Fig. 15 RF current magnitudes at terminations ($Z_R = 1\ k\Omega$ and $Z_L = 10\ \Omega$) under a realistic forward power injected into the BCI clamp and antenna

V. CONCLUSIONS

Numerical EM field simulations can commonly handle neither BCI nor antenna configurations in absorber chambers with sufficient accuracy due to high complexity of the structures, while the measurement-based macromodels can produce very accurate results.

The paper proposes an efficient method to predict the RF signals excited in electronic control units (ECU) during various automotive RF immunity tests. The main benefit is the straightforward procedure to predict the RF signals at any accessible port of a test setup with VNA measurements and S-parameter dataset processing.

As EMC test setups look generally similar to each other, this method can significantly improve the quality and accelerate the analysis. The main coupling and signal propagation path in such setups is the cable harness. For preliminary analysis purposes the EM field coupling to small-size PCBs can be neglected in many cases without significant loss of accuracy.

The approach can be extended to any number of wires in the cable harness, active non-linear DUTs, and also applied to the radiated emission estimations.

ACKNOWLEDGEMENT

REFERENCES

[1] ISO 11452-2: Road vehicles - Component test methods for electrical disturbances from narrowband radiated EM energy -- Part 2: Absorber-lined shielded enclosure.

[2] ISO 11452-4: Road vehicles-component test methods for electrical disturbances from narrowband radiated EM energy, Part 4: Bulk Current Injection

[3] M. F. Sultan, „Modeling of a bulk current injection setup for susceptibility threshold measurements," IEEE Int. Symp. On Electromagn. Compat. Proceedings, pp. 188-195, 1986.

[4] S. Frei, S. Miropolsky, Modeling of Bulk Current Injection (BCI) Setups for Virtual Automotive IC Tests, EMC Europe: Wroclaw, 2010.

[5] S. Miropolsky, A. Sapadinsky, S. Frei, A Generalized Accurate Modelling Method for Automotive Bulk Current Injection (BCI) Test Setups up to 1 GHz, EMC Compo, Nara, Japan, 2013

[6] S. Pignari, F. G. Canavaro, „On the equivalence between radiation and injection in BCI testing," IEEE Int. Symp. On Electromagn. Compat. Proceedings, pp. 179- 182, May 1997.

[7] D. A. Hill, „Current Induced on Multiconductor Transmission Lines by Radiation and Injection," IEEE Trans. Electromagn. Compat, Vol 34, pp. 445-450, November 1992.

[8] B. Gustavsen and A. Semlyen, "Rational approximation of frequency domain responses by vector fitting", IEEE Trans. Power Delivery, vol. 14, no. 3, pp. 1052-1061, July 1999.

[9] S. Miropolsky, F. zur Nieden, S. Frei, „Optimierung der Makromodellierung von Übertragungsstrecken mit Vector-Fitting-Methoden durch Anpassung der Eingangsdaten." EMV-Düsseldorf, Germany, 2014

[10] Degerstrom, M.J., B.K. Gilbert, and E.S. Daniel. Accurate resistance, inductance, capacitance, and conductance from uniform transmission line measurements, IEEE-EPEP, 18th Conf., Oct. 2008, pp. 77–80.

[11] C. R. Paul, "Analysis of Multiconductor Transmission Lines", John Wiley & Sons, Inc., 1994

[12] http://www.teseq.com