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Experimental Assessment of Over-Testing Probability in Bulk Current Injection as an Alternative Test Procedure to Radiated Susceptibility Verifications

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Abstract

The correlation between Bulk Current Injection (BCI) and radiated susceptibility (RS) test setups is investigated through the statistical characterization of a parameter called over-testing, which defines the excess of injected interference of BCI with respect to RS. Statistics takes into account lack of knowledge on the frequency response of the common-mode impedance of equipment under test. Unlike previous works which investigated this issue through theoretical modeling, a fully experimental approach is presented here. The proposed analysis confirms that BCI is a valid alternative to RS verifications, and provides a solid methodology for relating BCI test levels to equivalent RS testing conditions.

1. Introduction

Unit-level electromagnetic compatibility (EMC) verifications carried out in the aerospace industry include both conducted susceptibility (CS) and radiated susceptibility (RS) testing to demonstrate the capability of equipment to withstand harmful radio-frequency (RF) interference [1]-[2]. Below some hundreds of MHz, CS test procedures based on Bulk Current Injection (BCI) make use of an RF transformer (BCI probe) to induce noise currents in cables. Conversely, RS testing is performed above few tens of MHz by illuminating equipment and external cables via broadband antennas in an anechoic chamber. The coexistence of both test procedures in overlapping frequency ranges (e.g., 30-100 MHz in [1]) stimulates the search for possible correlation of test outcomes [3]. Actually, the possibility to avoid time-consuming RS assessments and to substitute them with faster and cheaper CS test procedures would be extremely appealing for engineers in charge for EMC qualification/certification activities. In line with this aim, an alternative CS test based on BCI and enforcing correlation with conventional RS test procedures was developed in [3], [4]. In these works, simplified models of the RS and CS test setups were used to find proper calibrating conditions of the BCI probe so to ensure statistical equivalence of the common-mode (CM) current injected in the equipment under test (EUT) with that induced by radiation. Statistics was aimed at overcoming lack of knowledge on the CM impedance of the EUT and other auxiliary equipment (AE), which is a common condition in EMC testing. Additionally, statistics took into account random positioning of the BCI probe clamped on the cable under test. This was foreseen in order to move the standing wave of the current distribution along the cable, thus avoiding deterministic constraints related to the frequency response of the specific test setup (e.g., minima and maxima of the injected current). Actually, the theoretical analysis presented in [3], [4] allows finding suitable calibrating conditions for the BCI probe, which enforce a conservative CS test procedure, that is to say, injection via BCI of an interference level which strictly bounds the maximum noise induced in conventional RS test setups. The excess of injected interference is referred to as *over-testing* (*OT*) and characterized in statistical terms through numerical estimation of its cumulative distribution function (cdf).

In this work, an experimental test setup involving a balanced twisted-wire pair (TWP) interconnection is designed to validate the theoretical derivations proposed in [3], [4]. In particular, the cdf of *OT* is obtained by processing measured scattering (S)-parameters in order to account for different random loading conditions occurring at suitable terminal ports representing EUT and AE.

2. BCI Test Levels Related to RS Effects

According to standard layouts of test setups [1], [2], the system under analysis involves two terminal units interconnected by an external cable with length $\mathscr{L}$, running at height h above a metallic ground plane. Since only the propagation of CM currents is of interest here, the simple model reported in Fig. 1 represents the cable above ground as a two-conductor transmission line, with terminal CM impedances. Without loss of generality, the EUT is represented by the right terminal impedance Z_R, whereas the AE is represented by the left terminal impedance Z_L. The incident field generated by the antenna used for RS testing in an anechoic chamber is approximated by a plane-wave with field strength E_0, broadside incidence and vertical (VP) or horizontal polarization (HP). Namely, the azimuth angle in Fig. 1 is ψ=90° whereas the polarization angle is either η=0° (VP) or η=90° (HP). The elevation angle ϑ is a free parameter, though practical values usually belong to [70°-75°].

In [3], [4], a BCI test is proposed which ensures the injection of a noise current (flowing in the EUT CM

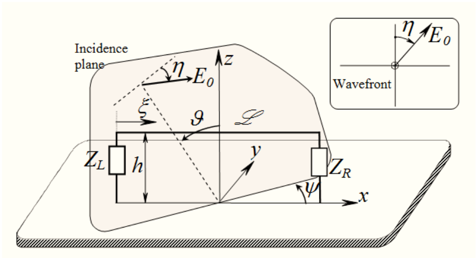


Figure 1. Symplified model of the RS test setup.

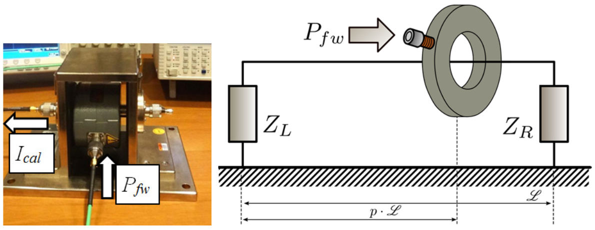
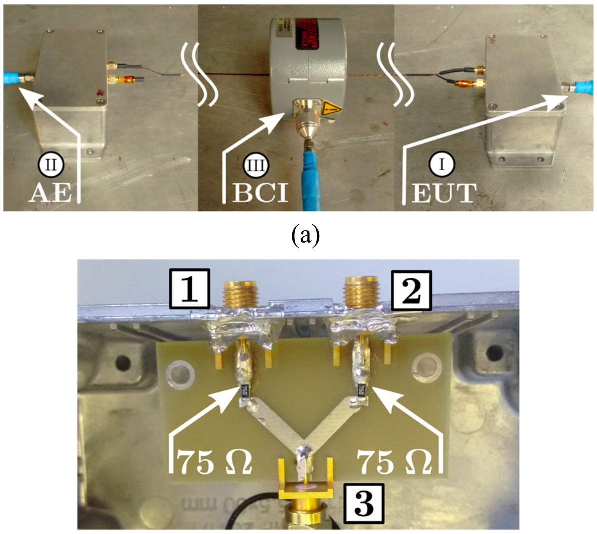


Figure 2. BCI test procedure (left: calibration, right: testing)



(a)

(b)

Figure 3. (a) BCI Test Setup (b) Terminations

impedance Z_R) greater than or equal to the corresponding current induced in an RS test setup. The proposed CS test conforms with the two-step procedure of BCI testing (see Fig. 2). Namely, the BCI probe is preliminarily calibrated using its standard calibration fixture (Fig. 2, left), so to determine the forward power P_{fw} needed to inject a certain calibration current I_{cal} in a 50 Ω terminal load [5]. Afterwards, the CS test is carried out by clamping the BCI probe on the cable (Fig. 2, right), and by feeding the probe with P_{fw}. The position of the probe, expressed as $p\mathscr{L}$ ($0 \le p \le 1$) is randomly changed (at each discrete frequency step) such that $p \in [0.6,1]$. Reference test levels (RTLs) expressed as piecewise-linear profiles of I_{cal}, have been developed in [3], [4] with respect to typical setup parameters (see Tab. 1). Namely, RTLs are expressed in dBμA, differentiated for VP and HP, and composed of (a) a linearly increasing segment (+20 dB/decade slope) for electrically-short lines (ESL), below frequency f_s, and (b) a constant segment for electrically-long lines (ELL) above frequency f_s. For test setups characterized by different geometrical and electrical parameters, RTLs can be rescaled by using simple rules in Tab. 2.

Tab. 1. RTLs for BCI (Probe Calibration Current I_{cal})
(Reference test setup: E_0=1 V/m, ϑ=73°, h=5 cm, $\mathscr{L}$=2m)

	VP	HP
ESL [dBμA]	$42+20\log_{10}[f/(300\cdot 10^3)]$	$11+20\log_{10}[f/(300\cdot 10^3)]$
ELL [dBμA]	80	72
f_s [Hz]	$24\cdot 10^6$	$24\cdot 10^6$

Tab. 2. Rescaling of RTLs for arbitrary setup parameters

	VP	HP
Field Strength	$+20\log_{10}(E_0/1)$	$+20\log_{10}(E_0/1)$
Elevation Angle	$+20\log_{10}(\sin\vartheta/\sin 73°)$	$+20\log_{10}(\cos\vartheta/\cos 73°)$
Line Height	$+20\log_{10}(h/0.05)$	$+20\log_{10}(h/0.05)$
Line Length (ESL)	$+20\log_{10}(\mathscr{L}/2)$	$+20\log_{10}(\mathscr{L}/2)$
" " (ELL)	no changes	no changes
" " (f_s)	$\times 2/\mathscr{L}$	$\times 2/\mathscr{L}$

3. Experimental Test Setup

The experimental setup shown in Fig. 3(a) has been designed and constructed to assess the effectiveness of the proposed BCI test in reproducing worst-case RS effect. The cable under test is a TWP (AWG-28), with length $\mathscr{L}$ =1.51 m and height h=4.5 cm. At each cable end, wires are singly terminated in separate SMA male connectors, screwed to SMA female connectors mounted on the metallic frame of terminal units. As shown in Fig. 3(b), each terminal unit contains a double-sided printed-circuit board (bottom ground plane and upper traces) which implements a balanced load matching the 150 Ω TWP differential-mode (DM) characteristic impedance (i.e., two 75 Ω resistors connected at ports 1 and 2), and a center-tap connection to drain the CM current into port 3 [6, Ch. 9.8.4]. As a result, the whole test setup presents three external ports renumbered with roman numbers in Fig. 3(a), that is, port I (i.e., port 3 of the left terminal unit, representing the EUT), port II (i.e., port 3 of the right terminal unit, representing the AE), and port III (input connector of an FCC F-130 BCI probe).

By measuring the 3×3 S-parameter matrix $\boldsymbol{S}_3$ of the test setup via a vector network analyzer (for each specified probe position) one obtains a behavioral model which can be used to investigate the operation of the proposed BCI test with variable loading conditions occurring at EUT and AE ports. As shown in Fig. 4(a), port III is fed by the forward power P_{fw} corresponding to calibration current I_{cal} in Tab. 1 rescaled for a different $\mathscr{L}$ and h according to Tab. 2. To this aim, if linearity is assumed, the forward power (in dBm) can be cast as $P_{fw}=I_{cal}-IL-73$, where IL is the insertion loss of the BCI probe (in dB) measured via the standard calibration fixture [7]. Without loss of generality, RTLs for VP (E_0=1 V/m, ϑ=73°) are considered for exemplification in the remainder of this paper. Two generic terminal impedances $Z_{3,EUT}$ and $Z_{3,AE}$ are supposed to be connected to ports I and II,

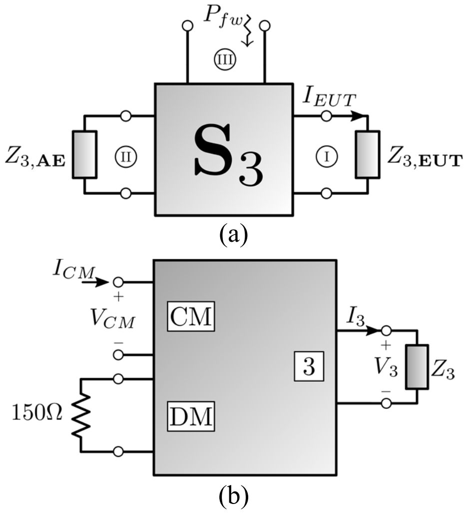


Figure 4. (a) Experimental characterization of (a) test setup; (b) terminal units.

respectively, and S-parameters $\boldsymbol{S_3}$ are processed to evaluate the current I_{EUT} flowing in $Z_{3,EUT}$. As an illustrative example, Fig. 5 shows the frequency response of I_{EUT} for three different loads ($Z_{3,EUT}$=$Z_{3,AE}$=1 kΩ, 300 Ω, 50 Ω) and two probe positions (p=0.6, 0.9). It is worth observing the large sensitivity of I_{EUT} to terminal AE/EUT loads. Such an observation is particularly meaningful in the light of full lack of knowledge about CM impedances, which is a common operating condition in real-world EMC testing. Moreover, in Fig. 5 one can appreciate the positive impact of setting a different probe position for ELL (i.e., above frequency f_s), as mentioned in Sec. 1.

4. Experimental Assessment of the Correlation Between BCI and RS Testing

4.1 Setting a Controlled CM Impedance

According to [3], a significant assessment of the operation of a BCI test setup with different loading conditions must properly consider the ratio k=Z_{CM} /Z_C between the CM impedance Z_{CM} seen by the cable under test, and the CM characteristic impedance Z_C of the cable above ground (here, about 330 Ω). Since terminal units [see Fig. 3(b)] allow connecting arbitrary impedances Z_3 only at port 3, it is necessary to find the relationship between Z_3 and the resulting CM impedance seen by TWP terminals. To this aim, each terminal unit has been characterized by measuring its mixed-mode scattering parameters. As shown in Fig. 4(b), ports 1 and 2 are transformed into CM and DM ports, while port 3 remains unaltered. The DM port is connected to a matching 150 Ω load, and the following transmission representation between port CM and port 3 is retrieved by processing S-parameters:

$$\begin{bmatrix} V_{CM} \\ I_{CM} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V_3 \\ I_3 \end{bmatrix}. \qquad (1)$$

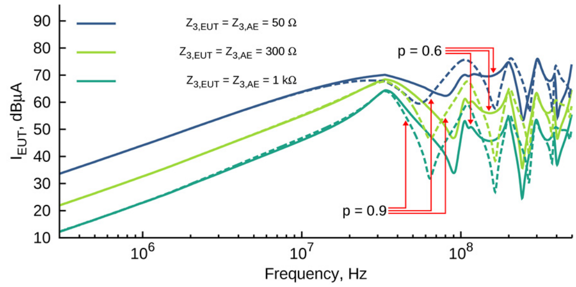


Figure 5. Current injected by BCI in the EUT (port I) for different loading conditions and two probe positions.

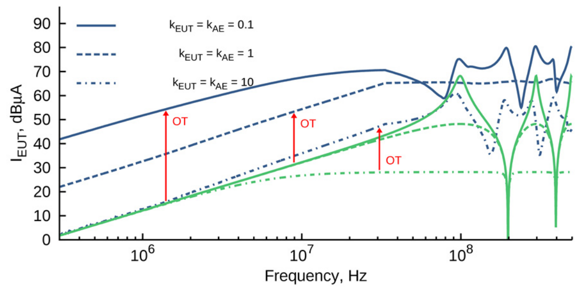


Figure 6. Comparison of currents injected by BCI (blue) and induced by RS-VP (green). Arrows define Over-Testing (OT) as the excess of injected current.

By imposing the terminal condition V_3=$Z_3 I_3$ and the definition Z_{CM}=V_{CM} /I_{CM} in (1), one readily obtains

$$Z_{CM} = \frac{A \cdot Z_3 + B}{C \cdot Z_3 + D},\ Z_3 = \frac{B - D \cdot Z_{CM}}{C \cdot Z_{CM} - A}. \qquad (2)$$

4.2 Evaluation of Over-Testing

The characterization of terminal units in (1)-(2) allows simulating the operation of the BCI test setup with controlled CM loading conditions seen by TWP terminals. Indeed, for any desired CM impedance Z_{CM} one can preliminarily compute the termination impedance Z_3 to be connected to port 3. By connecting such impedances to ports I and II of the test setup in Fig. 4(a), and processing S-parameters $\boldsymbol{S_3}$, one can compute the current I_{EUT} at port I, which is the target of the proposed analysis. As a specific example, Fig. 6 shows the current injected by BCI for three different loading conditions k=0.1, 1, 10 (probe position p=0.6) occurring both at AE and EUT ports. The same current induced by an RS-VP test in similar loading conditions is also reported in Fig. 6, as evaluated through prediction models [3]. One can observe that currents injected by BCI bound currents injected by RS in the whole frequency range, regardless of loading conditions, thus confirming the correct derivation of RTLs in Tabs. 1-2. The difference (in dB) between BCI and RS currents (red arrows in Fig. 6) is called over-testing (OT), and quantifies frequency by frequency the excess of injected interference.

4.3 Statistical Characterization

A Monte Carlo approach can be used to characterize the statistics of *OT* by processing S-parameters as described above. Namely, by repeating the evaluation of *OT* for 10^3 random realizations of the dimensionless parameters k_{EUT} and k_{AE} occurring at EUT and AE, respectively, as well as 10^3 random probe positions p, one can collect a set of random *OT* samples and plot the cdf. In particular, according to [3], [4], k_{EUT} and k_{AE} are treated as independent random variables, whose decimal logarithms are uniformly distributed in the interval [0.1, 10], whereas the probe position p is uniformly distributed in [0.6, 1].

Given the piecewise-linear, two-segment shape of RTLs used to feed the BCI probe, it is significant to separately evaluate the statistics of *OT* for ESL and ELL [3], [4]. Indeed, *OT* does not depend on frequency in the very low-frequency region (see Fig. 6 below 1 MHz), therefore the set of *OT* samples for ESL can be computed with reference to any arbitrary frequency (e.g., 300 kHz). Conversely, *OT* strongly depends on frequency in the ELL case, with a sort of pseudo-periodic behavior (determined by transmission-line effects). Hence, the considered set of *OT* samples collects together all values of *OT* regardless of frequency in a range such that $\frac{1}{2} < \mathcal{L}/\lambda < (\frac{1}{2}+k)$, where k is an integer number and λ is the wavelength. For the sake of brevity, among the obtained experimental results only the cdf of *OT* for ELL is plotted in Fig. 7 and compared with the theoretical cdf predicted in [3], [4].

5. Conclusion

Several experiments were performed to investigate *OT* cdfs in different cases (VP/HP; ESL/ELL; balanced and unbalanced TWP terminations). Generally, *OT* cdfs obtained experimentally resulted to be in remarkable agreement with those predicted by numerical analysis in [3], [4], as one can appreciate in Fig. 7 with reference to the specific VP-ELL case. Quantiles of the distribution provide precise information on the severity of the performed BCI test with respect to RS. As a specific example, significant quantiles (0.95, 0.9, 0.5, 0.1) are highlighted in Fig. 7. By translating them into percentiles, one can state that the probability of over-testing up to 38 dB is 95%, up to 33 dB is 90%, up to 21 dB is 50%, and up to 15 dB is 10%. These values corroborate the conservative nature of RTLs proposed in Tabs. 1-2. In other terms, if equipment passes the proposed BCI test, it will pass the corresponding RS test as well, and this fact is rigorously demonstrated by an engineering margin quantified by *OT* quantiles.

If a less severe test level is desired, the operator can always choose to reduce the P_{fw} obtained by probe calibration by a certain quantity Δ (in dB). Consequently, the cdf of *OT* will translate along the x axis by the same quantity and all quantiles will be reduced by $-\Delta$. For

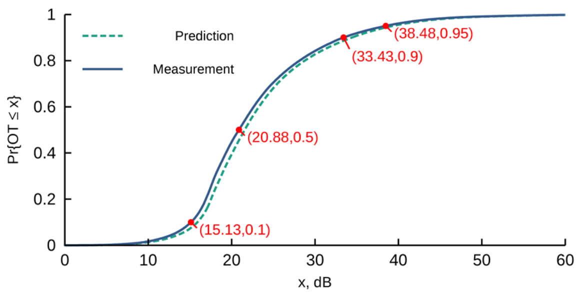


Figure 7. Cdf of *OT* for ELL. This plot rigorously quantifies in statistical terms the severity level of the proposed BCI test with respect to RS (VP-ELL case).

instance, if a reduction Δ=15 dB is applied in Fig. 7, the probability of over-testing up to 23 dB will be 95%, up to 17 dB will be 90%, up to 6 dB will be 50%. However, a non-null probability of under-testing Pr{$-15 \leq OT \leq 0$}=10% will be accepted as an unavoidable consequence of the applied test relaxation. To conclude, the CS testing method proposed in [3] and here supported by the experimental evidence definitely represents a valid alternative technique for RS verifications.

6. References

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