Radiated Immunity Test Involving Crosstalk and Enforcing Equivalence With Field-to-Wire Coupling

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Abstract—In this study, a novel test procedure aimed at assessing the radiated immunity of units and subsystems interconnected by wiring harnesses is proposed and experimentally validated. The procedure is based on crosstalk and allows inducing at the terminations of the wiring structure under test the same disturbance that would be induced by field-to-wire coupling, without requiring large and expensive test facilities. This is made possible by resorting to a generator circuit laid parallel and in proximity of the cable under test and fed at the terminations by two RF voltage sources, whose phase shift is suitably controlled. The proposed scheme of equivalence is very general, holding for any direction of incidence and polarization of the impinging electromagnetic field. Also, it involves feeding conditions of the two RF sources that do not depend on the specific terminations of the circuit under test. Accuracy of the proposed equivalence scheme is assessed by resorting to an automatically controlled test setup involving a simple wiring structure and terminal networks. Eventually, feasibility and practicality of the associated test procedure are discussed.

Index Terms—Crosstalk, field-to-wire coupling, radiated immunity.

I. INTRODUCTION

D ESIGN and development of complex systems (such as those found in the transportation sector, e.g., cars, trains, aircrafts and spacecrafts, etc.) satisfying electromagnetic compatibility (EMC) requirements usually pass through a large number of intermediate unit-level tests, aimed at assuring compliance of every single subsystem before it is assembled in the vehicle. Particularly, a great deal of effort is put on testing the immunity of units and subsystems to the harsh electromagnetic (EM) environment expected within the vehicle. In this framework, a critical aspect is usually related to the radiated susceptibility (RS) of interconnecting cables, i.e., to harness ability to pick-up EM disturbance and to carry it at the input of the terminal units. To this end, traditional RS procedures foreseen by International Standards resort to quite large and expensive test facilities (such as anechoic chambers, TEM, and GTEM cells), whose use—although justified for full-compliance verification—is often not acceptable in terms of time and costs as far as precompliance testing is the target. As a matter of fact, in this context, preliminary bench testing is more desirable. For this reason, several authors have recently investigated alternative RS procedures. Among these, particular attention was devoted to test procedures involving bulk current injection (BCI) probes. This was first investigated from the theoretical and experimental viewpoints in [1] and [2], respectively. Subsequently, in [3], the possibility to reproduce the noise induced by field-to-wire coupling (FC) at the terminal networks of a multi-wire structure by the use of two BCI probes (instead of only one) was theoretically proven. This led to the so-called double-BCI (DBCI) test procedure, practical implementations of which are described in [4]–[6].

A general limitation of the above procedures is strictly related to the nonnegligible effect of loading the coupling device exerts on the victim circuit. As a matter of fact, the presence of the coupler modifies the electrical characteristics of the circuit under test and may impair the scheme of equivalence. No wonder the feeding conditions involved by the aforementioned equivalence schemes are derived starting from an a priori knowledge (either from measurement or prediction) of the current/voltage induced by FC at the terminations of the harness under test. As a consequence, such conditions of equivalence necessary depend on 1) electrical/geometrical characteristics and 2) the specific terminal networks of the wiring structure to be tested. This introduces a twofold drawback. First, new feeding conditions have to be determined from time to time depending on the specific harness to be tested and on its terminal networks. Second, accurate knowledge of the victim circuit (i.e., cable harness and terminal units) is required in order to get accurate reproduction of FC effects.

To overcome the above limitations, this study proposes an alternative RS procedure based on crosstalk (XT), [7], [8]. Such a procedure resorts to a properly fed generator circuit placed in closed proximity and parallel to the wiring harness under test and is able to induce into the terminations of the victim circuit the same interference that would be theoretically induced by FC. Actually, a few examples of setups exploiting XT can be found in the literature (mainly in the automotive

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sector). One of these is the parallel-wire fixture foreseen by Ford Standards [9], which is used for testing the immunity of single wires or twisted pairs against wire-to-wire coupling of undesired transient (RI-130 test) and continuous (RI-150 test) disturbance. Another example is described in [10], where an additional conductor is used to test the immunity to XT of the electronic circuitry connected at the terminations of the cable harness in a typical configuration of automotive equipment.

However, in these examples, the test is aimed at reproducing XT and not FC effects. Focusing the attention on the possible equivalence between FC and XT, preliminary investigations can be found in [11] and [12]. However, the conditions of equivalence with FC obtained in these works 1) are limited to specific conditions of incidence only (e.g., end-fire excitation in [11], and broadside excitation in [12]), and 2) theoretically involve a generator circuit definitely hard to manufacture [12].

Here, the possible equivalence between FC and XT is reconsidered both from the theoretical and experimental viewpoints, leading to a new and more general scheme of equivalence, which allows reproducing the noise induced at the terminations of a wiring harness for whatever condition of incidence of the impinging EM field. Additionally, the proposed scheme has the potential to assure equivalence between FC and XT in spite of the specific terminations of the victim circuit, since an a priori knowledge of the current/voltage induced by FC into the terminations of the victim circuit is not involved in the derivation of the feeding profiles. This is achieved by resorting to a generator circuit fed from the terminations by two RF generators, whose amplitude and phase shift is automatically controlled by a LabView software run by a computer. Accuracy of the proposed scheme of equivalence is preliminary investigated by simulation and subsequently validated by measurement on a simplified test setup.

The rest of the paper is organized as follows. In Section II, the proposed scheme of equivalence between FC and XT is derived, and the need for the use of two generators to manage whatever incidence condition is proven. In Section III, frequency characteristics of the feeding profiles obtained for the two generators are discussed through simulation with focus on the typical incidence conditions foreseen by the Standards. Implementation and experimental validation of the proposed XT-based procedure are presented in Section IV. Finally, conclusions are drawn in Section V.

II. EQUIVALENCE SCHEME

In this section, theoretical conditions assuring equivalence between FC and XT in terms of noise induced at the terminations of the cable harness undergoing the RS test are derived. To this end, a canonical wiring structure conceived as a single-ended interconnection above ground is considered as the circuit victim of radiated interference, and suitable feeding conditions for the circuit used to generate XT (i.e., generator circuit) are derived by enforcing equivalence with FC.

A. FC Model

The wiring structure victim of radiated interference is composed of a bare wire of length \( \mathcal{L} \) and radius \( r_w \) running parallel to and at a height \( h \) above a metallic ground plane.

The line is terminated in either linear or nonlinear loads and is illuminated by a uniform plane-wave field characterized by strength of electric field vector \( \mathbf{E}_0 \) and arbitrary incidence \((\theta, \psi)\) and polarization \((\eta)\) angles, as shown in Fig. 1.

To predict the noise induced at the terminations of the wiring structure under analysis, several models are available in the literature [13]–[18], which are based on a circuit representation of FC in terms of voltage and current sources induced in the victim circuit and lumped at its terminations. As far as prediction at the external ports is the target, these formulations lead equivalent models of the victim circuit as the one shown in Fig. 2. In this model, the wiring structure victim of interference is modeled as a uniform and lossless two-conductor transmission line (TL)—with characteristic impedance \( Z_v \) and propagation constant \( \gamma_0 = j\omega/v_0, v_0 \) denoting the light speed in free space—driven from the terminations by two lumped voltage sources \( V_{FC,L} \), \( V_{FC,R} \) representative for FC effects. Derivation of analytical expressions for the involved sources \( V_{FC,L}, V_{FC,R} \) (here omitted for the sake of brevity) is thoroughly reported in [3] and yields

\[
V_{FC,L} = 2E_0 h \left\{ \frac{\gamma_0 e^{-\gamma_0 L} - \gamma_0 \cos\theta (\gamma_0 L) + \gamma_0 \sin\psi (\gamma_0 L)}{\gamma_0 \sin\theta (\gamma_0 L)} - G \right\} \tag{1}
\]

\[
V_{FC,R} = V_{FC,L} e^{-\gamma_0 L} \tag{2}
\]
where $V_{FC,L}^*$ denotes the conjugate of $V_{FC,L}$, whereas $F$, $G$, and $\gamma_0$ are functions of the wave angles as

$$F = \frac{\cos(\phi_0/\cos\theta_0\cos\eta + \sin\psi/\sin\eta)}{1 - \sin^2\theta_0\cos^2\psi},$$

$$G = \sin\theta_0\cos\eta,$$

$$\gamma_0 = \gamma_0\sin\theta_0\cos\psi.$$

By virtue of this formulation, voltages (i.e., $V_L$, $V_R$) and currents (i.e., $I_L$, $I_R$) induced at line terminals by the impinging EM field are related by the open-ended representation (gray block in Fig. 2) of the wiring harness, that is

$$\begin{bmatrix} V_R \\ I_R \end{bmatrix} = \Phi_v(\mathcal{L}) \cdot \begin{bmatrix} V_L \\ I_L \end{bmatrix} + \begin{bmatrix} V_{FC,R} - \cosh(\gamma_0\mathcal{L})V_{FC,L} \\ \sinh(\gamma_0\mathcal{L})Z_v^{-1}V_{FC,L} \end{bmatrix},$$

where

$$\Phi_v(\mathcal{L}) = \begin{bmatrix} \cosh(\gamma_0\mathcal{L}) & -\sinh(\gamma_0\mathcal{L})Z_v^{-1} \\ -\sinh(\gamma_0\mathcal{L})Z_v^{-1} & \cosh(\gamma_0\mathcal{L}) \end{bmatrix}.$$

### B. XT Model

To reproduce by XT the same voltages and currents induced by FC at the terminations of the victim circuit, a generator circuit is placed at a distance $\Delta$ and parallel to the wiring harness under test, as schematically shown in Fig. 3. The left termination of the generator circuit is fed by an RF voltage source with internal impedance $Z_{GL}$, whereas the right end is terminated by the load impedance $Z_{GR}$. Without loss of generality, geometrical characteristics (i.e., radius, length, and height above ground) of such an additional wiring structure are hereinafter assumed to be the same of the victim circuit.

For the obtained wiring structure (three-conductor TL above ground), possible conditions of equivalence between FC and XT are investigated by resorting to the port-reduction technique in [19]. In line with this approach, and as long as prediction of currents and voltages at line terminals is the target, the near-field interference due to the generator circuit can be included into the TL model of the victim circuit as shown in Fig. 4 [12]. By virtue of this equivalent representation, the twofold effect exerted by XT onto the victim circuit can be readily appreciated. Namely, likewise FC, circuit representation of XT involves induced voltage/current sources lumped at the terminations of the victim circuit (here, a representation based on voltage sources only is considered on the analogy of the FC model in Fig. 2).

Additionally, since XT is inherently a near-field phenomenon of coupling, the presence of a second wiring structure in close proximity of the victim circuit may also induce a perturbation of the per-unit-length (p.u.l.) parameters of the circuit under test, which is accounted for in Fig. 4 by matrix $\Phi_{XT}(\mathcal{L})$. However, such a perturbation was proven to have a negligible influence on voltages and currents induced at the terminations of the victim circuit as long as the following two conditions are satisfied [19]. First, the two circuits shall be weakly coupled [20], [21]. Second, the generator circuit shall be matched at both terminations, i.e., $Z_{GL} = Z_{GR} = Z_G$, where $Z_G$ denotes the characteristic impedance of the generator circuit, which does not depend on the presence of the victim circuit as long as the weak-coupling assumption is satisfied [20], [21].

Under the aforementioned assumptions, the contribution due to matrix $\Phi_{XT}(\mathcal{L})$ can be neglected, and the induced voltage sources $V_{XT,L}$, $V_{XT,R}$ can be cast in closed form as

$$V_{XT,L} = \alpha V_S, \quad V_{XT,R} = V_{XT,L}e^{-\gamma_0\mathcal{L}},$$

where $V_S$ denotes the open-ended voltage of the RF generator feeding the generator circuit, whereas the dimensionless and frequency-independent coefficient $\alpha$, i.e.,

$$\alpha = \ell_m/(2\ell_G),$$

is proportional to the ratio between the mutual p.u.l. inductance between the two wires above ground ($\ell_m$) and the p.u.l. self-inductance of the generator circuit ($\ell_G$).

### C. Equivalence Between FC and XT

Thanks to port-reduction and to the assumptions of weak coupling and matching of the generator circuit, the previous section has proved that the relationship between voltages and currents at the terminations of circuit victim of XT can be written as

$$\begin{bmatrix} V_R \\ I_R \end{bmatrix} = \Phi_v(\mathcal{L}) \cdot \begin{bmatrix} V_L \\ I_L \end{bmatrix} + \begin{bmatrix} V_{XT,R} - \cosh(\gamma_0\mathcal{L})V_{XT,L} \\ \sinh(\gamma_0\mathcal{L})Z_v^{-1}V_{XT,L} \end{bmatrix},$$

which would be identical to (6) if the involved sources were equal, that is, if $V_{FC,L} = V_{XT,L}$ and $V_{FC,R} = V_{XT,R}$. If these equalities were satisfied, the equivalence between FC and XT...
could be enforced in spite of the specific loads (either linear or not linear) connected at the terminations of the victim circuit.

However, comparison between the induced voltage sources in (1), (2), and (8) puts in evidence that $V_{XT,L}$ and $V_{XT,R}$ cannot be generally made equivalent to $V_{FC,L}$ and $V_{FC,R}$ unless specific conditions of incidence of the incoming plane-wave field are considered (due to the presence in (2) of the conjugate operator and of $\hat{\gamma}_0$, which is function of wave angles). As a matter of fact, this happens only in the specific case of end-fire line excitation (i.e., $\theta = 90^\circ$, $\psi = 0^\circ$, $180^\circ$) with electric field in vertical polarization (i.e., $\eta = 0^\circ$), as considered in [11].

In order to overcome this limitation and to develop an equivalence scheme valid for whatever condition of incidence of the incoming wave, the idea here proposed is to replace the generator circuit in Fig. 3 with a new generator circuit fed from both terminations by two RF sources. A principle drawing is shown in Fig. 5, where $V_{S1}$ and $V_{S2}$ denote the open-ended voltages of the two RF generators, and $Z_{GL} = Z_{GR}$ their internal impedances.

In this new configuration, the induced voltage sources in (8) result from the superposition of contributions from each generator, i.e.,

$$ V_{XT,L} = f_L(V_{S1}, V_{S2}), \quad V_{XT,R} = f_R(V_{S1}, V_{S2}) $$

(11)

where

$$ f_L = \alpha \left( V_{S1} + e^{-\gamma_0 L} V_{S2} \right), \quad f_R = \alpha \left( V_{S2} + e^{-\gamma_0 L} V_{S1} \right) $$

(12)

and can be made equivalent to the sources in (1), (2) without any assumption on wave angles. Particularly, if weak coupling and matching at the terminations of the generator circuit are assumed, some algebra (here omitted for the sake of brevity) yields the following expressions for the voltage sources $V_{S1}$ and $V_{S2}$ assuring equivalence with FC:

$$ V_{S1} = \frac{1}{\alpha(1 - e^{-2\gamma_0 L})} \left[ V_{FC,L} - V_{FC,R} e^{-\gamma_0 L} \right] $$

(13)

$$ V_{S2} = \frac{1}{\alpha(1 - e^{-2\gamma_0 L})} \left[ V_{FC,R} - V_{FC,L} e^{-\gamma_0 L} \right] $$

(14)

where $\alpha$, $V_{FC,L}$, and $V_{FC,R}$ take the expressions in (9), (1), and (2), respectively.

III. FEEDING CONDITIONS

In this section, main characteristics and feasibility of the feeding profiles in (13) and (14) are investigated with specific focus on the incidence conditions foreseen by International Standards for RS testing.

In order to investigate the frequency behavior of the feeding profiles in (13) and (14), simulations were carried out for different (random) combinations of the angles $\theta$, $\psi$, $\eta$ characterizing the interfering EM field. With the exception of a few cases—that will be commented in detail in the next subsection—numerical simulations confirmed the possibility to reproduce whatever condition of incidence by the use of two RF generators properly controlled in magnitude and phase. Concerning the magnitude, explicative examples of feeding profiles are shown in Fig. 6 for the sets of wave angles reported in Table I. In these simulations, $r_w = 0.3$ mm, $\Delta = 14$ mm, $h = 20$ mm, $L = 1$ m, and $E_0 = 1$ V/m.

A. General Characteristics of the Feeding Profiles and Validation of the Equivalence Scheme

In order to investigate the frequency behavior of the feeding profiles in (13) and (14), simulations were carried out for different (random) combinations of the angles $\theta$, $\psi$, $\eta$ characterizing the interfering EM field. With the exception of a few cases—that will be commented in detail in the next subsection—numerical simulations confirmed the possibility to reproduce whatever condition of incidence by the use of two RF generators properly controlled in magnitude and phase. Concerning the magnitude, explicative examples of feeding profiles are shown in Fig. 6 for the sets of wave angles reported in Table I. From these plots, it can be observed that the obtained feeding profiles exhibit a flat behavior in the low-frequency interval that is for frequencies at which both the generator and the victim circuits are electrically short. Conversely, they exhibit oscillations with associated peaks and notches in the standing wave region.
Although not shown here for brevity, the corresponding phase shift ($\Delta \phi$) between $V_{S1}$ and $V_{S2}$ may assume values equal to $\Delta \phi = 0^\circ$ (i.e., RF generators in-phase) or $\Delta \phi = 180^\circ$ (i.e., RF generators out of phase), except for narrow frequency intervals around the notches. More precisely, for feeding profiles with magnitude not exhibiting notches [as those shown in Fig. 6(a)], the phase shift is constant over frequency and equal to 0$^\circ$ or 180$^\circ$ depending on the specific combination of wave angles. For instance, in the specific test case in Fig. 6(a), the phase shift between $V_{S1}$ and $V_{S2}$ is constant to the value 180$^\circ$. Conversely, for feeding profiles as those shown in Fig. 6(b) and (c), where the magnitude of at least one of the two generators exhibits notches, the phase shift varies (from 0$^\circ$ to 180$^\circ$ and vice versa) in a narrow frequency interval around the notch.

The proposed scheme of equivalence is validated in Fig. 7, by comparison of the voltage induced by FC (solid curves) and XT (dotted curves) at the left termination of the victim circuit for the sets of wave angles in Table I. Particularly, the results shown in Fig. 7 were obtained for different degrees of mismatching affecting the terminations of the victim circuit, that is for different values of coefficients $\beta_L = Z_L/Z_v$ and $\beta_R = Z_R/Z_v$ (where $Z_L$, $Z_R$, and $Z_v$ denote the impedances at the left and right end of the victim circuit, respectively, and $Z_v$ its characteristic impedance). The observed good agreement between voltages induced by FC and XT proves the accuracy of the proposed scheme of equivalence despite the specific loads connected with the terminations of the victim circuit.

### B. Analysis of Specific Conditions of Incidence

In this section, specific combinations of wave angles, aimed at reproducing the testing conditions foreseen by International Standards in force in the aircraft and aerospace sectors [22]–[24], are considered. Hence, according to typical unit-level RS test setups foreseen by these standards, the analysis is here narrowed to the cases in which the antenna is positioned broadside (i.e., $\psi = 90^\circ$) to the wiring harness interconnecting the units under test, and the test is repeated for both vertical ($\eta = 0^\circ$) and horizontal ($\eta = 90^\circ$) polarization of the antenna. Additionally, for each polarization, it is worth considering different elevation angles ($\theta$), in order to reproduce wavefront orientations resulting from different heights of the antenna tip with respect to the system under test. Without loss of generality, the value $\theta = 75^\circ$ will be hereinafter assumed.

The corresponding test cases are reported in Table II: The former (i.e., case no. 1) being associated with vertical polarization of the antenna, the latter (i.e., case no. 2) referring to horizontal polarization. For these test cases, main characteristics of the required feeding profiles are summed up in Table III. Particularly, for the above test cases, the magnitude of the two RF generators $V_{S1}, V_{S2}$ is equal, with the frequency behavior shown in Fig. 8. Due to the absence of notches, the phase shift between the two RF generators is constant over frequency, taking the value $\Delta \phi = 0^\circ$ for vertical polarization of the antenna, and $\Delta \phi = 180^\circ$ for horizontal polarization. Additionally, for a given elevation angles $\theta$, the feeding profiles associated with the two polarizations results to be shifted each other by a frequency-independent factor, which is function of the specific elevation angle under analysis.
TABLE III  
CHARACTERISTICS OF THE FEEDING PROFILES

<table>
<thead>
<tr>
<th>Case</th>
<th>Shape</th>
<th>Magnitude</th>
<th>Phase Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fig. 8</td>
<td>$</td>
<td>V_{S1}</td>
</tr>
<tr>
<td>2</td>
<td>Fig. 8</td>
<td>$</td>
<td>V_{S1}</td>
</tr>
<tr>
<td>3</td>
<td>Flat</td>
<td>One generator only</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8. Feeding profiles for broadside ($\psi = 90^\circ$) incidence with the antenna in vertical ($\eta = 0^\circ$) and horizontal ($\eta = 90^\circ$) polarization for $\theta = 75^\circ$ (cases 1 and 2, respectively, in Table II). See Fig. 6 for line geometrical data.

Finally, the last case reported in Tables II and III refers to the special case of lateral line excitation (i.e., $\psi = 0^\circ$, 180°), with electric field in vertical polarization. Although not foreseen by the standards, this test case is included in Tables II and III because it involves worst-case voltages induced across the loads [25]. Additionally, it represents an exception to the general scheme of equivalence here proposed. Indeed, in this case, only one generator fed by a flat frequency profile is necessary in order to reproduce FC effects at the terminations of the victim circuit. Particularly, if the EM field impinges the line from the left termination (i.e., $\psi = 0$), (13) and (14) yield

$$V_{S1} = \frac{2E_0h}{\alpha}, \quad V_{S2} = 0.$$  \hspace{2cm} (15)

Vice versa, for $\psi = 180^\circ$, the role of the two generators is exchanged, and the first generator zeroes. These results are in line with those obtained in [11], where investigation of the possible equivalence between FC and XT was limited to such a specific condition of incidence.

IV. EXPERIMENTAL VALIDATION

In this section, the proposed crosstalk-based RS test is implemented in a well-controlled test setup, with the aim of validating by measurement the theoretical predictions shown in the previous sections. To this end, a generator circuit fed by two RF generators properly controlled in magnitude and phase is designed and exploited for the test.

A. Test Setup and Measurement Procedure

For practical implementation of the proposed procedure, the test setup shown in Fig. 9 was realized. For the sake of simplicity, in this specific implementation, both the generator and the receptor circuits were soldered to the same vertical metallic bulkheads through SMA connectors, as shown in Fig. 9(a).

The wires in the two circuits have length 1 m (SMA connectors excluded), radius 0.3 mm, wire distance 14 mm, and height above ground 20 mm. Hence, since for each circuit the above dimensions lead to a characteristic impedance of nearly 300 $\Omega$, matching resistors of 250 $\Omega$ were attached at the terminations of the generator circuit in order for the matching condition in Section II-C to be satisfied.

During the test, a Spectrum Analyzer Agilent E7401A 9 kHz–1.5 GHz was used to monitor the voltage induced at one termination [left termination in Fig. 9(a)] of the receptor circuit [see the blue cable on the left side of Fig. 9(a)]. To properly feed the generator circuit, an *ad hoc* system was designed, which involves two RF generators (here, Agilent MXG N5182A 100 kHz–3 GHz and Rohde & Schwarz SML03 9 kHz–3.3 GHz), sharing the same 10-MHz reference oscillator, an oscilloscope Tektronix DPO 4104-1 GHz, and two resistive power dividers JFW 50PD-133-N.

A principle drawing is shown in Fig. 10. The cables on the left-hand side (i.e., those pertaining to generator no. 1) must have exactly the same length of the corresponding cables on the right-hand side (i.e., those pertaining to generator no. 2).
Fig. 11. Experimental validation: Reconstruction of the voltage induced by FC (solid/dashed curves) at the left termination of the receptor circuit by the proposed XT-based setup (circles and squares) for different conditions of incidence of the EM field, and for different degrees of mismatching (i.e., $\beta_R = 1/6$, $\infty$) at the right termination of the victim circuit.

System operation—i.e., feeding of the generator circuit, and measurement at the monitored termination of the receptor—is automatically managed by a customized software, developed in LabView, and running on a PC controlling the generators, the oscilloscope and the spectrum analyzer through GPIB cables. A graphical user interface [see Fig. 9(b)] allows the user to assign the desired input data by a lookup table reporting frequency-by-frequency the required forward power and phase shift [see upper windows in Fig. 9(b)], and to monitor the voltage induced at one termination of the receptor circuit, while the test is still on-going [see lower window in Fig. 9(b)]. For each frequency point, the required forward power is set on the generators. Then, the two cables connecting the power dividers with the terminations of the generator circuit [see dashed lines in Fig. 10, and the green cables in Fig. 9(a)] are switched to 50-Ω loads. The actual random phase shift is read by the oscilloscope and used to correct the output phase of generator no. 1 according to the required phase shift. Then, the two cables are switched to the ports of the generator circuit, and the voltage induced across the monitored termination of the receptor is measured and stored.

B. Test Results

Measurements were carried out in the frequency interval from 1 MHz up to 1 GHz, by feeding the two RF generators through different sets of feeding profiles in order to emulate different incidence conditions of the EM field. The obtained measurement results (circles and squares) are compared in Fig. 11 versus theoretical prediction (solid/dashed curves) of the voltage induced by FC at the left termination of the victim circuit. To this end, the spurious effects introduced by the terminations of the receptor, and mainly due to the SMA connectors, were preliminary characterized by vector network analyzer measurement carried out at the ports of the victim circuit (in the absence of the generator circuit) and then included into the FC model [26], [27]. The plots in Fig. 11(a) and (b) were obtained for broadside incidence (i.e., $\psi = 90^\circ$) with the antenna in vertical ($\eta = 0^\circ$) and horizontal ($\eta = 90^\circ$) polarization, respectively, and elevation angle $\theta = 75^\circ$. The plots in Fig. 11(c)–(e) were obtained for the generic incidence conditions labeled as cases A, B, and C, respectively, in Table I. Finally, the plots in Fig. 11(f) refer to the special case of lateral line
excitation (here: $\psi = 0^\circ$, $\theta = 90^\circ$), with electric field in vertical polarization ($\eta = 0^\circ$).

For measurement, the left termination of the receptor circuit was monitored by the spectrum analyzer (input impedance 50 $\Omega$, i.e., $\beta_L \approx 1/6$), while the right termination was 1) loaded by a 50- $\Omega$ termination (i.e., $\beta_R \approx 1/6$; see squares and solid curves in Fig. 11), and 2) left open-ended (i.e., $\beta_R \approx \infty$; see circles and dashed curves in Fig. 11), to prove robustness of the proposed equivalence scheme for different degrees of mismatching of the victim circuit.

The feeding profiles were sampled by excluding the frequencies of the sharp peaks in the frequency responses in Fig. 8. This choice was motivated by the fact that, since the theoretical model here developed does not account for losses, the required voltage (and thus the associated forward power) predicted by (13) and (14) theoretically tends to infinite at those frequencies. Despite this approximation, the satisfactory agreement between measurement and prediction confirms the consistence of the proposed equivalence scheme also from the experimental viewpoint.

Actually, the observed discrepancies (on the order of few decibels) are mainly to be ascribed to the simplified representation of the test setup (rather than the equivalence scheme), where: 1) spurious effects due to terminal connectors are not currently included into the model of the generator circuit, and 2) high-frequency losses and radiation effects are neglected both for the generator and the victim circuits.

C. Discussion on Practical Feasibility and Limitations

In previous subsections, a canonical test setup involving RF instrumentation to mimic the equipment under test (EUT) was considered. However, for practical use of crosstalk for testing real-world EUTs, several feasibility issues and possible limitations have still to be investigated.

Concerning limitations, the proposed procedure accounts for FC with external harnesses, and unlike RS testing, it cannot reproduce effects of direct coupling with the EUT. However, this deserves to be considered only when the wavelength results to be comparable or shorter than the typical EUT dimension. Second, we considered only a single cable stretch running above ground without branches. On the other hand, also the aerospace standards [22]–[24] foresee a similar cable layout, where the antenna is placed very close to the metallic table and illuminates a limited portion of the test setup. More general standards, e.g., CISPR-25, foresee the use of anechoic environments allowing the illumination of large and complex test setups. In these tests, resonance phenomena related to the chamber itself and/or the metallic table hosting the EUT may occur. All these nonideal phenomena make the actual EM-field structure involved in RS testing more complex than the canonical plane-wave model here adopted. However, it is worth noting that aim of the proposed procedure is not full substitution of RS testing, but a fast and effective alternative procedure for precompliance verification ensuring high correlation of test outcomes with those obtained in field chambers.

Concerning feasibility, design of an ad hoc test fixture has to be faced, considering the following main features. First, the ground-plane size and the cable length have to be standardized so to ensure repeatable test results. Second, the distance between the generator and victim wiring should be modifiable, depending on the external dimensions of the victim cable so as to assure the weak-coupling assumption even in the case of complex cable bundles. Indeed, the victim circuit may involve multiconductor harnesses, whereas just a simple common-mode equivalent representation (i.e., a single wire above ground) is here adopted. Additionally, the characteristics of the generator circuit (i.e., wire diameter and rated power of matching resistors) have to be sized in consideration of the RF power needed to ensure equivalence with the desired field strength (e.g., 1–10 V/m in aerospace standards [24]). In order for these power levels to be reached, two power amplifiers have to be included in the test setup in Fig. 10.

V. Conclusion

In this study, equivalence between FC and XT has been investigated with the objective to develop an alternative test-bench procedure for RS assessment of units interconnected by wiring harnesses. It was proven that if the circuit used to generate XT is driven by both terminations by two synchronized RF generators, the voltages induced by XT and FC at the terminations of the wiring harness under test can be made equivalent for whatever conditions of incidence of the offending EM field. Additionally, if the terminations of the generator circuit are properly designed (i.e., matched with the characteristic impedance of the wiring structure), equivalence can be enforced in spite of the specific loads, whether linear or nonlinear, connected at the terminations of the victim circuit. Furthermore, since the two circuits should be weakly coupled (condition that could be easily expected to be satisfied in practice), the design of the generator circuit is not influenced by the specific geometrical characteristics of the wiring harness under test. Effectiveness of the proposed XT-based procedure has been experimentally verified by an ad hoc test setup in the frequency interval from 1 MHz up to 1 GHz and for different conditions of incidence of the external EM field.

Perspective activities include the extension of the proposed approach to victim circuits comprising complex wiring harnesses, with the objective to derive more general feeding profiles, possibly involving a precautionary instead of a rigorous interpretation of the concept of equivalence between FC and XT, as it was proposed here.

References

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