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Abstract—**The workbench Faraday Cage method (WBFC) is a time efficient module pre-compliance test regarding radiated emission. This work investigates the method's usability and credibility and concludes that for this particular case the WBFC perform a tolerable compliance test for frequencies below 360 MHz while it is essentially useless for higher frequencies.**

I. Introduction

Electrical engineers have for years been interested in performing pre-compliance tests regarding radiated emission on IC or PCB level. The international standard IEC 61967 "*Integrated circuits – Measurement of electromagnetic emissions, 150 kHz to 1 GHz*" describes five different methods for measuring conducted and radiated electromagnetic emissions from integrated circuits. Part 5 "*Measurement of conducted emissions – Workbench Faraday Cage method*" [1] (WBFC method) describes a method to measure the conducted electromagnetic emission of integrated circuits either applied on the standardized test-board or on a final printed circuit board (PCB).

The WBFC method is a time efficient method which allows the engineer to do trial and error work at his workbench, i.e. he can do some changes in e.g. the filtering and immediately get a figure of the effect regarding radiated emission by measuring in the WBFC. Therefore the method is widely used in private companies where the objective is to pass the radiated emission requirements as fast and cheapest as possible. Although the method was developed in the beginning of the nineties [2] and first edition of the standard is from 2003, there has been no scientific investigation of the method's usability and credibility.

In this paper, we investigate the mode of operation of the WBFC method. Based on some impedance considerations supported by measurements and simulations of a rather simple test setup, we show in which frequency span the method is useful and fairly credible and where, conversely it makes no sense to do measurement with the WBFC.

In section II the WBFC method is introduced and some impedance considerations are given. In Section III the test setup and simulations are described. The results are presented and discussed in Section IV. Finally Section V draws the conclusions.

II. The WBFC method

A. Sources of Radiation

In contemporary audio/video products switched circuits like switched-mode power supplies (SMPS) and digital circuits are the primary sources of unintentional radiated electromagnetic emissions from electronic products in the frequency span from 30 MHz to 1 GHz.

However, SMPS and digital circuits are most likely too small to radiate significantly on their own. In order to radiate fields strong enough to cause regulatory problems, power must be coupled from the small noise source to larger structures that act as antennas such as circuit board planes, heatsinks, cables or chassis.

The conducted emission depends on the filtering and in practice you need a full operational PCB in order to have a full operational IC with associated unintentional electromagnetic emission. Therefore it is the PCB's conducted emission the WBFC method measures rather than the IC's emission.

PCB's can radiate by itself (at high frequencies, from large planes or long traces) or by coupling to cables and surrounding structures. There are three modes of coupling:

- Conducted coupling,
- Electric field coupling,
- Magnetic field coupling.

Assuming that the WBFC measures the conducted coupling correctly, the usability of the WBFC method depends on whether the conducted coupling in a certain frequency span is dominating.

Another source of radiated emission is EMI leaky connectors and cables but these are not possible to measure with the WBFC. We also assume that the desired signal – single ended or differential – does not radiate. In this paper, we concentrate on the common mode noise.

B. The Workbench Faraday Cage Method

The WBFC method assumes that supply and signal cable(s) are attached to an electrically small PCB, with dimensions $<\lambda/2$, i.e. 0.15 m at 1 GHz. The hypothesis is that connected cables become the dominant antennas, so RF emission takes

place via these antennas. It is suggested that the maximum conducted emission carried by a wire emerging from DUT can be estimated by loading the common-mode port with 150 Ω resistance and measuring the absorbed power. 150 Ω is widely used in RF emission and immunity standards as average common mode impedance and the justification for this value as a representation for the radiation resistance of long cables arises from empirical data [3].
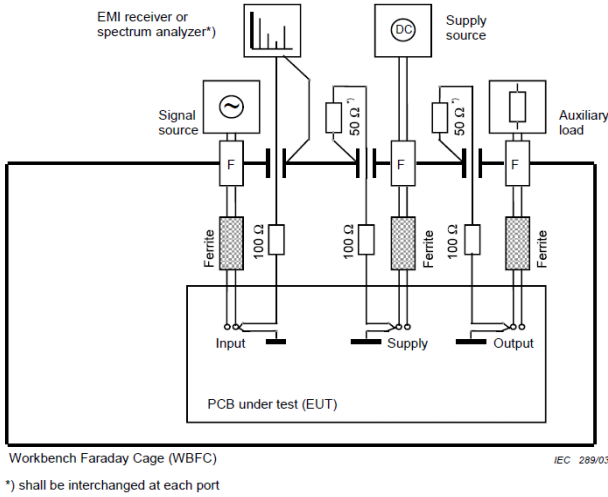

Fig. 1. Test setup for measuring emission with the WBFC [1].

The test setup is shown in Fig. 1. The PCB under test is placed on an insulating support 30 mm above the bottom plate. All functional connections, e.g. the power supply and auxiliary equipment, to the PCB under test are fed through dedicated filters mounted on the wall of the cage. All wires from these filters need to be wrapped on ferrite ring cores to create impedances much higher than 150 Ω at the frequencies of interest.

The assumption is that the worst case arises when the measured absorbed power in the load impedance (150 Ω) of the WBFC, in the final apparatus is radiated from a matched dipole. This assumption gives the following conversion between the limit for radiated emission in 3 m distance according to CISPR 13 and the voltage limit across 50 Ω in WBFC [2]:

$$V_{\text{WBFC, limit}} \, [\text{dB}\mu\text{V}] = E_{\text{3m, limit}} \, [\text{dB}\mu\text{V/m}] + 4.8 \text{ dB} \quad (1)$$

C. Some Considerations About the Impedance

The purpose of using the Faraday cage is (with reference to the inventors [2]) only to shield the measurements from the irrelevant noise from outside. Under the assumption that the cage does not influence the measurements of the conducted emission it is reasonable to make a schematic of the equivalent circuit representing the EUT and the common-mode impedance as shown in Fig. 2. It is assumed that the source of the conducted emission inside the module has a

form of non-ideal physical source with internal impedance in series (represented by the voltage source and Z_s in Fig. 2).
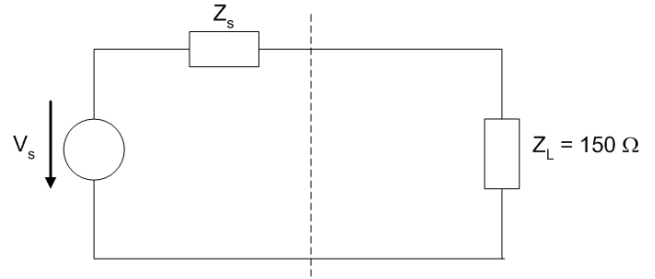

Fig. 2. Equivalent circuit representing the module and the common-mode impedance. The left side represents the EUT with a common mode noise source and the right side represents the 150 Ω load that we measure on.

The 150 Ω common-mode impedance forms the load impedance, Z_L, of this source for the particular connection that we want to measure. In addition to the 150 Ω load impedance, Z_L includes also the impedance of the return path, i.e. all the others 150 Ω connection terminations in parallel with the impedance between the EUT and the WBFC (see Fig. 1), so in practice Z_L in Fig. 2 can be higher than 150 Ω.

It is well-known that maximum transfer of power occurs when the source and the load impedances are matched

$$Z_S = Z_L^* \qquad (2)$$

while all other combinations result in non-optimal transfer.

The objective of a module test such as the WBFC method is to perform a modular pre-compliance test, i.e. the WBFC must predict the worst case in order to be sure to pass the final test, when the module is placed in the apparatus. To fulfil the worst case assumption we must actually assume that a) the common-mode load impedance in the apparatus is always 150 Ω, or b) the internal impedance of the source (Z_S in Fig. 2) is equal to 150 Ω and unchanged when you move the PCB from the Faraday cage to the apparatus. In the first case, if we use the 150 Ω load as suggested by the standard, then we measure the same power as in real situation (because it is assumed always to be 150 Ω) and the measurement is therefore representative and valid. In the second case, we allow the common-mode impedance in the apparatus to vary from 150 Ω, but we assume that the internal impedance, Z_s, is fixed to 150 Ω, and so measuring with $Z_L = 150$ Ω results in the best matching cf. (2) and, consequently, the upper bound of power transfer.

But what if the source and load impedances are both other than 150 Ω? Then, with 150 Ω load, we measure less power than may actually be emitted. This situation is quite likely to happen, because the internal source of emission may be similar to a voltage source (low internal impedance) and the cable running outside of DUT will often be close to the ground plane (low characteristic impedance, low load). These low impedances will likely be better matched and allowing for higher power coupling than with the 150 Ω load. The WBFC method will then show lower than maximum power.
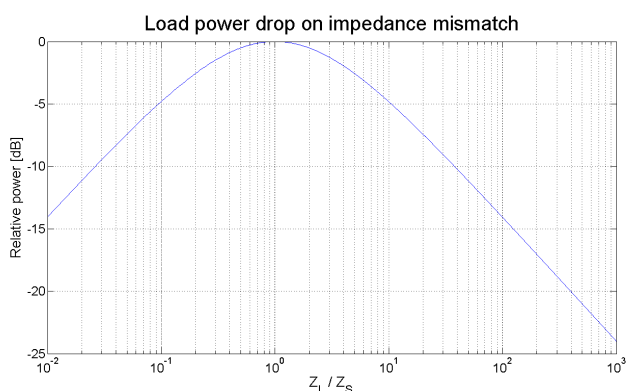
Fig. 3. Load power drop on impedance mismatch.

Let us assume, for simplicity, that both the source and the load impedances are real. If the load impedance happens to be the same as the internal impedance of the source ($Z_L = Z_S$), then the power measured on such load is indeed the maximum possible. However, when the load impedance is, e.g. ten times higher (or lower) than the internal impedance of the source, the measured power will be 5 dB lower (see Fig. 3). This means that if we do not measure the output power on the same impedance as the internal impedance of the source, the estimated power will always be lower than what the source could actually deliver.

D. Radiater directivity

The directivity of the radiating element (antenna), be it the cable itself or another structure it couples to (e.g. the chassis), is assumed as that of a matched dipole by the standard. This might be sufficient approximation for most of the situations, although higher directivity is theoretically possible. The most likely radiating elements are wires and slots in the chassis. Slots behave similarly to wires and dipoles, but they can occur in rows, increasing the overall directivity. A high directivity can cause the situation where a module passes the WBFC test but fail the radiated emission when placed in the final apparatus.

III. THE EXPERIMENTAL SETUP

A. The Objective of the Experiment

It emerges clearly from the impedance and directivity considerations that there is a lot of sources of error when you want to compare measurements in the WBFC and measurements in a 3 m semi anechoic (3 m SAC). Is the common mode impedance 150 Ω in the apparatus? Is the return path impedance low in the WBFC? Does the apparatus radiate with a high directivity? In addition, the WBFC is of no use if the dominating coupling is via electric and/or magnetic fields or if the PCB radiates by itself. Many questions arise and, as a result, some engineers and scientist question the usefulness and credibility of the method. A simple test setup

was made with the purpose of investigating the considerations mentioned in the first two sections.

B. The Test Setup

A comb generator with fundamental frequency of 20 MHz and a flat frequency response up to 1 GHz was used as a noise generator. It was mounted on the back of a 150 x 225 mm PCB with a 120 mm long, 50 Ω micro strip, terminated with 4 parallel 200 Ω resistors. The common mode noise on the PCB ground was measured in the WBFC. Next, the radiated emission from the PCB with an 80 cm angled cable soldered to the PCB ground was measured. With the purpose of distinguishing conducted coupling and field coupling it was also measured with no galvanic connection between the cable and the PCB ground.

With the purpose of estimating the common mode source impedance the current through the cable connection to the PCB was measured, see Fig. 5.
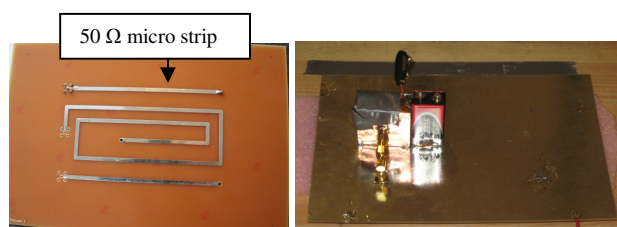

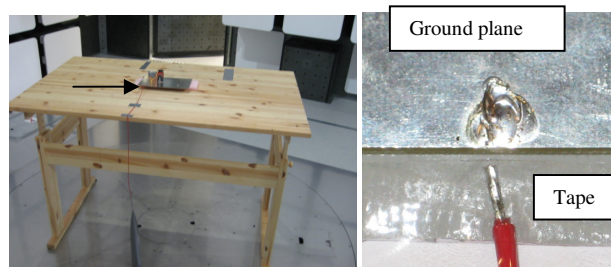Fig. 4. The PCB and the comb generator used in the experiment.

Fig. 5. The test setup in the 3 m semi anechoic chamber and a close-up photo of the setup with no galvanic contact between the cable and the PCB. In addition the current through the cable connection (marked by the arrow) was measured with a current probe.

C. The Simulations

With the purpose of understanding the measured results, 3D full wave FIT simulations of the experiment were set up [4]. The model has perfect lumped elements without parasitic capacitance and inductance.

Also the radiated emission from PCB and cable and the common mode impedance of the cable was simulated. (See Fig. 6.)
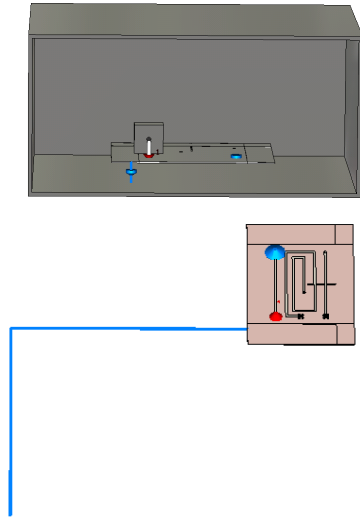
Fig. 6. Models for the 3D full wave simulations.

IV. RESULTS AND DISCUSSION

In Fig. 7 the measured voltage across the 50 Ω input resistance in the spectrum analyser is compared with the simulated results. The simulations and measurements are in agreement up to 450 MHz, above 450 MHz they have similar trends. The difference above 450 MHz can be caused by the fact that the component used in the measurement has parasitic capacitance and inductance. In addition, there can be loss in cables and connectors when the frequency increases. Last but not least, cavity resonances of the box arise after 450 MHz. Both simulations and measurements have a quite flat frequency response up to 400 MHz after which they rise to a peak at approx. 500 MHz. Above 550 MHz the common mode noise decreases and the response is no longer flat.
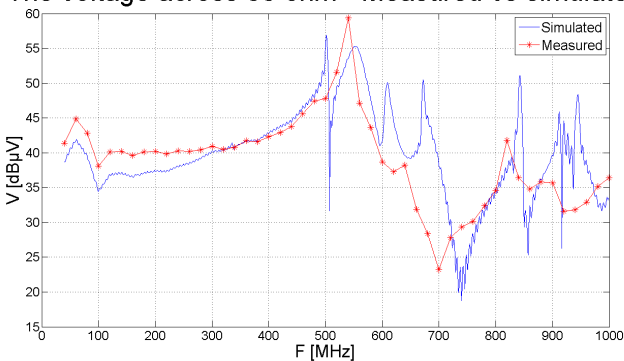

Fig. 7. Simulated and measured common mode noise obtained by the WBFC method. The red markers indicate the measured comb generator frequencies.

In Fig. 8 the WBFC measurement is compared with the measured radiated emission according to (1) in the setup where the cable has galvanic contact to the PCB. Except for 120, 280 and 300 MHz the comparison shows that up to 360

MHz the WBFC predict worse case, i.e. $E_{WBFC} \geq E_{3m\ SAC}$. At 120 and 280-300 MHz the measured radiated emission is 2 dB and 4 dB higher respectively than the predicted. Due to the large measurement uncertainty it is hard to draw firm conclusions. But the suggested WBFC limit from the standard [1] does not take into account the effect of the conducting reflecting floor in the semi anechoic chamber. A simulation of the far-field at 120 and 300 MHz including the conducting floor gives a directivity of 5.5 dBi and 8.8 dBi respectively, so it is not unlikely that this is an example of a setup where the standard's WBFC limit is not sufficient because of high directivity, in this example mainly caused by the conducting floor.

Above 560 MHz the WBFC measurement is considerably below the measured radiated emission.
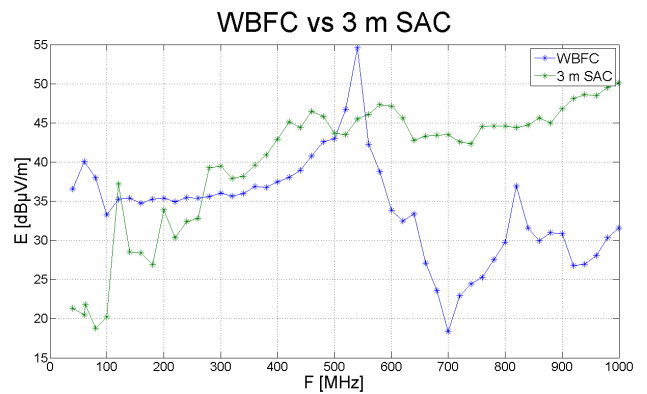

Fig. 8. Worst case predictions of the radiated emission based on WBFC measurement compared to the 3 m semi anechoic chamber measurements of the setup with galvanic contact between PCB and cable. The markers indicate the measured comb frequencies.

In Fig. 9 the simulated radiated emission is compared with the measured, both for the setup with galvanic contact between the cable and the PCB and for the setup without galvanic contact. The simulated radiated emission is the maximum electric far-field evaluated at all points in the upper half of the hemisphere in a 3 m radius. The simulated radiation pattern is quite inhomogeneous at high frequencies. The measurement is done according to CISPR 13 with a 1.5 m broad biconical antenna which in several ways differs from a precise far-field measurement, so the measurement and simulation are not completely comparable. For example according to CISPR 13 we only measure the field from theta = 45° to theta = 90° in traditional spherical coordinates.

Because the measurement uncertainty in a 3 m SAC is up to 6 dB it is hard to draw conclusions based on differences of the same magnitude between two measured values. But if both simulations and measurements show the same difference it is reasonable to trust that the difference is real.

Fig. 9 shows that at about 120 MHz and 300 MHz the radiation from the setup with galvanic contact between the cable and the PCB is considerably higher than from the setup with no galvanic contact. At 200 MHz it is only the measurement that shows a significant difference, which is why we attribute this difference to measurement inaccuracy.

At frequencies above 400 MHz both simulations and measurements show that it does not matter whether the cable has galvanic contact or not, i.e. the PCB radiates by itself or the dominating coupling above 400 MHz is via magnetic and electric fields and not via conducted coupling.

Here it must be mentioned that simulations and measurements of the radiation from the PCB and comb generator alone, i.e. without the cable, shows the same level of radiated emission compared to the setups with the cable, so above 400 MHz the radiation is mainly caused by radiation from the PCB itself.
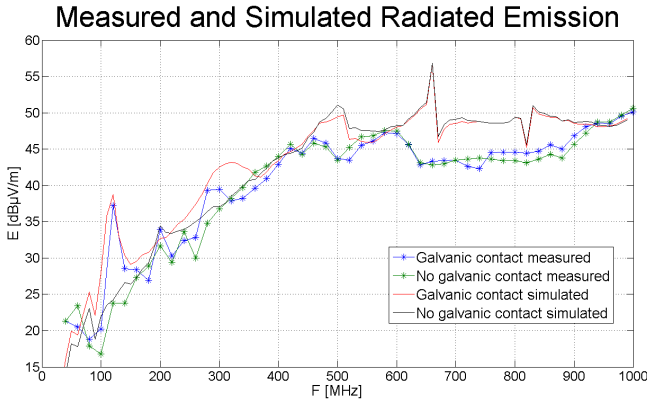

Fig. 9. Simulated and measured radiated emission from the PCB and the cable, with and without galvanic connection. The markers indicate the measured comb frequencies.

Fig. 10 shows the measured current at the cable connection in the setup with galvanic contact between the cable and the PCB (see Fig. 5). In same figure on a secondary axis the simulated common mode impedance of the attached cable at the same point is plotted (see Figs. 5 and 6).

By comparing the two plots it becomes clear, that there is a connection between currents peaks/dips and the common mode impedance. When the common mode impedance is low, there is a current peak, and conversely high common mode impedance causes a current dip. Therefore we can conclude that the common mode noise source is a voltage source with comparatively low internal impedance. This is also in agreement with the fact that low common mode load impedance causes effective conducted power transfer according to the 120 and 300 MHz peaks in Fig. 9.

Above 600 MHz the measured cable current at the connection decreases in accordance to the WBFC measurements in Fig. 7, i.e. the lower conducted emission level above 600 MHz. For some reason the 500 MHz current peak has lower amplitude in contrast to the WBFC measurement, which peaks at approx. 500 MHz. But the low current is in agreement with Fig. 9 that shows that in the radiated emission test setup, field coupling is dominating above 400 MHz. Hence the broad WBFC peak around 500 MHz is probably due to some resonance caused by the measurement method which does not occur in the radiated emission test setup.
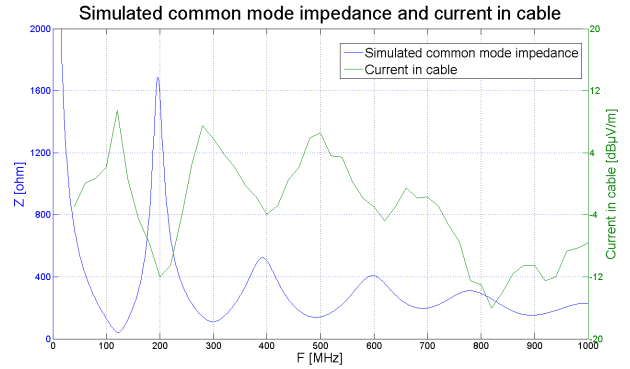
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Fig. 10. On left y-axis the simulated common mode impedance of the attached cable (see Fig. 5). On right y-axis the measured current at the cable connection (see Fig. 5) in the setup with galvanic contact between cable and PCB.

To sum up, below approximately 360 MHz the conducted coupling dominates the emission. Hence if the module passes the WBFC test it will likely also pass the final radiated emission test. But high directivity (e.g. caused by reflecting waves from the conducting floor in a semi anechoic chamber) or impedance mismatch can cause excesses.

Whether the PCB/cable setup radiates depends on the common mode impedance of the cable, i.e. whether there is impedance match between the common mode noise generator and the cable. The common mode noise generator acts like a voltage source with comparatively low source impedance.

Above 400 MHz field coupling or radiation from the PCB itself dominates although the WBFC measurement has its maximum values around a broad peak at about 500 MHz. This peak indicates a resonance that occurs in the WBFC set-up but not in the apparatus

V. Conclusions

The usability of the WBFC method and its mode of operation have been investigated. With a 4 dB safety margin the WBFC method is a fairly useful pre-compliance test up to 350 MHz regarding radiated emission where conducted coupling is dominating. Above 400 MHz field coupling or radiating from the PCB itself is dominating and the WBFC method is essentially useless.

Whether the above conclusions are representative for contemporary PCB's used in electronic apparatus is a subject of ongoing work.

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