The use of BCI techniques regarding immunity testing of modules, as an alternative method up to 1 GHz

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***Abstract*—The mandatory upper frequency limit for radiated immunity testing on modules is increasing to 2.7GHz and for some dedicated product standards even up to 3GHz. This paper proposes a realistic limit level for using the Bulk Current Injection method as an alternative to radiated immunity tests up to 1GHz and above.**

I. Introduction

The conducted immunity test method Bulk Current Injection (BCI) has widely gained acceptance as an alternative or supplementary immunity test method to radiated immunity testing and has been used for over 40 years already. It has been standardized by several organizations for a variety of applications from integrated circuits and subassemblies for automotive applications and aerospace systems. In comparison to radiated immunity measurements it is relatively cheap, well repeatable and easy to set up. That's why BCI is often used as a precompliance measurement method. Especially in the automotive industry, the current injection method is very popular.

Quite a large number of papers have addressed the equivalence between radiated and injected immunity testing. It should be clearly stated that this is not the aim of this research. In addition, most of the work that was published concerning the relation between radiated and conducted susceptibility tests was by comparison of plane wave excitation of the devices under test (DUTs) to current injection. In this paper, all measurements and simulations were done by placing the DUT in the near field of the emitting antenna because that is much more representative to real life conditions. As a realistic example, a mobile phone may be placed on the dashboard of a car which brings it very close to the electronics underneath. The distance between the equipment and the disturbance source may even become as small as a few centimeters.

Limit levels for Bulk Current Injection method currently only exist in military and automotive standards, and they are used as a reference in this paper. The upper frequency limit up to which the limit levels are defined in these test requirements is only up to 200 or 400MHz. Only in IEC 62132-3 [1] (BCI for integrated circuits), informative severity limits are given up to 1GHz. But these are taken from the automotive standard for electronic subassemblies [2] and have a constant test level across the entire frequency range which leads to overstressing as will be indicated in this paper. The validity of extending the calibration limit for BCI up to 1 GHz is investigated in this paper and validated by simulation and measurement.

II. State-of-the-Art

This paper focuses on the limit levels of BCI tests according to automotive and military standards for comparison purposes. As mentioned in the introduction, BCI limit levels aren't defined above 400MHz. In the military standard MIL-STD-461F [3], the maximum frequency is 200MHz as shown in Fig. 1. Different severity levels can be seen as well.

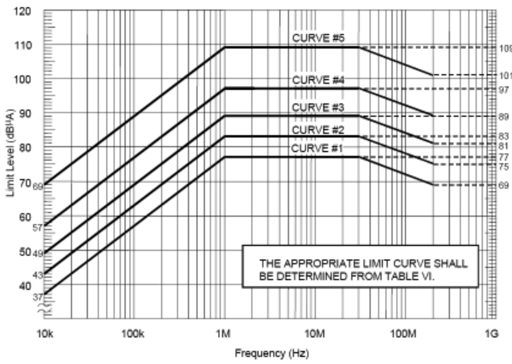

Fig. 1. MIL-STD-461F CS114 calibration limits

The applicable frequency range of most BCI standards and manufacturer requirements for automotive ESAs is up to 400 MHz. In Fig. 2, limits are given for the BCI test as defined by Ford, as the EMC test procedures of Ford Motor Company are freely available on the web [4]. The General Motors specification for BCI testing is equal to the Ford requirements but is not available for free.

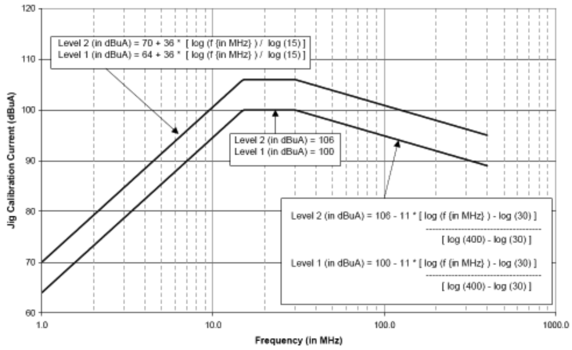

Fig. 2. Ford RI112 BCI requirements

It is not the intention to explain the limits already defined, but in Table I the correlation between the radiated and conducted limit curves from [3] is shortly illustrated for different application classes. It can be seen that for the peak limit (which is between 1 MHz and 30 MHz in the military standard) a constant current of 1.4 mA/V/m exists which is equal for all limit curves. From Fig. 1, a slope of -10 dB/decade is defined from 30MHz up to the upper frequency limit. At 200 MHz, a severity level of 0.56 mA/V/m is defined in contrast to the Ford requirements where a level of 0.8mA/V/m is defined.

In the Ford requirements, radiated and conducted tests are used as complementary methods instead as alternative methods. BCI test levels are defined up to 400 MHz and radiated immunity test levels are only defined from 400 MHz on. At the 'transition' frequency of the conducted and radiated specification (400 MHz), a ratio of 0.56 mA/V/m is defined.

TABLE I
RADIATED VERSUS CONDUCTED IMMUNITY LEVELS IN MIL-STD-461F FROM 1MHZ TO 30MHZ

Class	RI [V/m]	CI [dBµA]	CI [mA]	Ratio [mA/(V/m)]
1	5	77	7.08	1.42
2	10	83	14.13	1.41
3	20	89	28.18	1.41
4	50	97	70.79	1.42
5	200	109	281.84	1.41

Another investigation on comparitive simulations and measurements between radiated and conducted immunity testing was done at CETIM [6]. The conclusion drawn there states that under standard conditions as defined in [2], i.e. a wire length of 1 m and a height of 5 cm above metallic ground plane, the relation between the radiated field strength and the current to be injected by BCI is n*E (V/m) ≤ I (mA) ≤ 4*n*E (V/m) with n = 1 under standard conditions. This means that the current is between 1 mA and 4 mA if the radiated electric field strength is 1 V/m. Although the height of the test harness is similar in all standards and specifications (i.e. 5cm above ground plane), the wire lengths vary as given in Table I.

TABLE I
BCI TEST HARNESS SPECIFICATIONS

Standard	Heigth [mm]	Length [mm]
ISO 11452-4	50 (+10)	1000 ± 100
MIL-STD-461F	50	2000
ES-XW7T-1A278-AC	50	1700 + 300
GMW3097	50	1700 + 300

III. EXPANDING BULK CURRENT INJECTION UP TO 1GHZ

A. *Measurements*

The idea behind the BCI test in the MIL-STD is to simulate external, unwanted electromagnetic fields impinging upon cabling that is routed close to a ground plane, e.g. a chassis. This disturbance generally originates from a nearby source and is consequently not a plane wave.

Hence, in the standard radiated susceptibility requirements, the transmitting antenna is placed at 1 m from the setup boundary. A single wire is placed at 5 cm above the ground plane to simulate real-life conditions as encountered in many applications. These parameters have also been applied in the measurement setup used for this investigation as in Fig. 3.

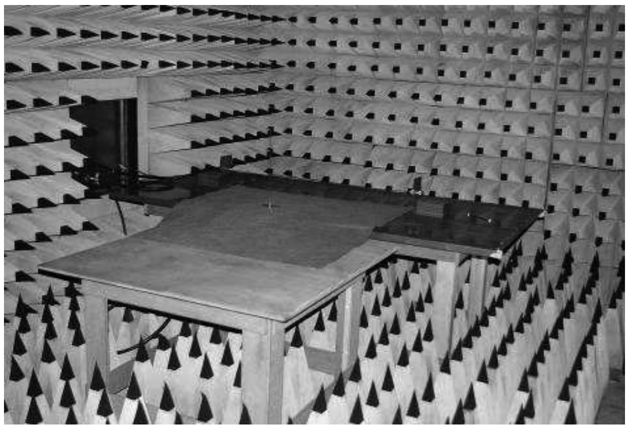

Fig. 3. Measurement setup

To ease the simulation setup, excitation at every frequency was done with a different monopole tuned at the frequency of interest as listed in Table II.

The wire was radiated by a constant field of 1V/m at a distance of 1m and monitored by an electric field meter in the middle of the wire. One side of the wire was terminated in 50 ohm and the other side connected to a measurement receiver with a 50 ohm impedance to monitor the induced voltage at the terminal.

Due to mechanical constraints at the time, measurements were only carried out for a wire length of 1m. Ideally, this should also be done for a wire length of 1.7m and 2m as specified in Table I. The current induced in a wire of 1m length at a height of 5cm and 10cm above the ground plane is shown in the diagrams of Fig. 4.

TABLE II
MONOPOLE PARAMETERS

Frequency [MHz]	Monopole length [m]
106	0.71
131	0.57
200	0.38
299	0.25
430	0.17
628	0.12
833	0.09
1013	0.07

Only a minor difference exists between the measurements at two different heights in the lower frequency region from 100MHz to 400MHz. Logarithmic trend lines are given to get an indication of the tendency of the magnitude of the induced current. Measurements clearly indicate a decrease in the induced current going from -10dB/decade for a height of 5cm to -6dB/decade for 10cm. Expressed in milli-amps, the current decreases from about 1mA to about 0.4mA which is a decrease of over fifty percent and is quite close to the levels defined in Section II.

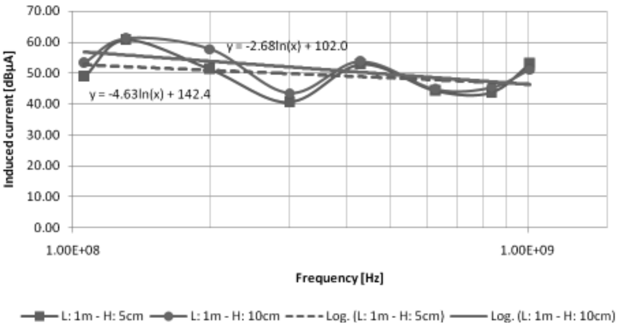

Fig. 4. Current induced in the test wire at 5cm and 10cm above ground

B. Simulations

It is relatively simple to implement the measurement setup as described in the previous section into a numerical simulation model. All simulations were performed using NEC-WIN Pro v1.1 which uses the Numerical Electromagnetic Code (NEC) based on a Method of Moments. The main difference between the 'real' setup is the infinite ground plane used in the simulation model. The antenna is modelled as a vertical wire with a voltage source of 50 ohm impedance. Figure 5 shows the vertical E field component, generated by the antenna.

The simulation model is represented in Fig. 6, where both the monopole antenna and the wire are shown. The wires are divided in a sufficient number of segments with respect to the frequency being simulated. Obviously, the length of the antenna is varied accordingly the frequency being tested, to obtain the resonant length according to a quarter wavelength.

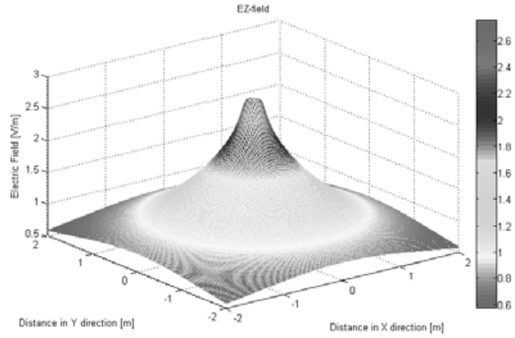

Fig. 5. Vertical component of E-field

A Matlab program was written to adapt the voltage source automatically to create a 1 V/m field strength at 1 m distance near the wire. The line is terminated in 50 ohm impedance at both sides thus reflecting the measurement setup. Wire length, wire height above the ground plane and the frequency to be simulated could be varied by software control, using the Matlab program.

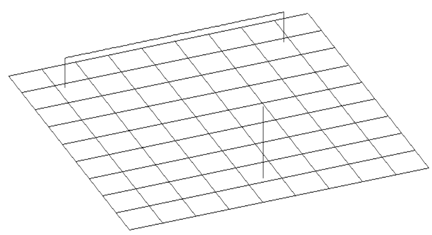

Fig. 6. Antenna-wire model for numerical simulation

Simulation results of the induced current for different wire lengths and at a height of 5 cm above ground plane, are given in Fig. 7. As in the measurement results, the decrease in amplitude of the induced current is noticeable. The slope of the trend lines goes from -7dB per decade for 1m length, -8.5dB/decade for 1.7m and -10dB/decade for a wire length of 2m. The resonances occurring in the higher frequency are due to non-matched conditions between the characteristic impedance of the wire and the terminations of 50 ohm.

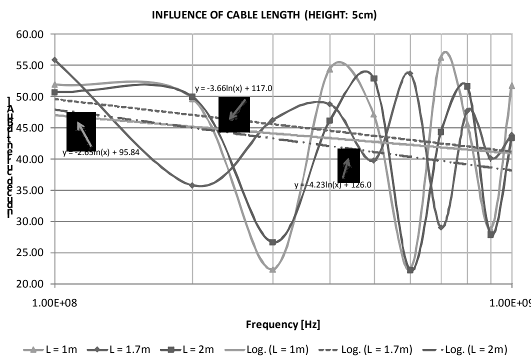

Fig. 7. Induced current on wires of different lengths by 1V/m radiation

IV. DISCUSSION

In the previous sections, the setup and results for both measurements and simulations were presented. Fig. 8 shows the comparison between the simulation and measurement of a wire of 1 m length and a height of 5cm above a ground plane. As the graph clearly indicates, the simulation and measurement are very alike. Of course, there are some large deviations but that is mainly due to an imperfect measurement setup and the infinite ground plane used in the simulations. Generating a constant electric field of 1V/m in the near field is not easy, even when monitoring with a field strength meter at the centre of the test wire.

In Fig. 8, extended BCI limit levels starting from the 400 MHz values in the Ford standard, are also given. The upper two BCI limits correlate to radiated field strength of 50V/m and 100V/m. These limits were recalculated to the equivalent injected current when a field strength of only 1V/m is applied. Comparing this limit with the average trend lines shows an equal, but about 15dB higher level than the simulation.

However, it is clearly from the graph, that the "Ford limit" of 1V/m touches all the maxima of the simulations and those of the measurements above 400MHz. This suggest a type of worst case approach, by taking the maxima, and a realistic limit for the current to be induced is obtained. The worst case will even be more severe when open ends (or high input impedance modules) are used instead of 50 ohm terminations.

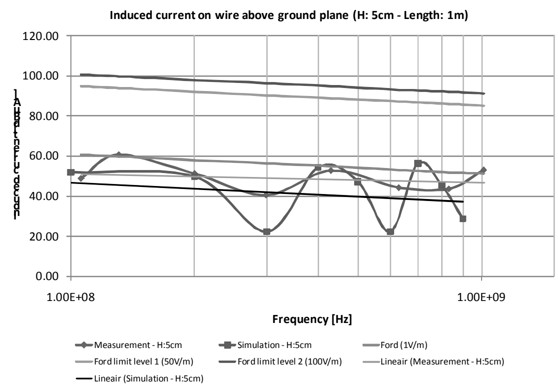

Fig. 8. Comparison of measurement, simulation and extended Ford limit

V. FUTURE WORK

For the frequencies above 1GHz, only simulated values are available But it is clear that the tendency that was found up to 1GHz is continuing. This is clearly shown in the next Fig. 9.

For wires and cable harnesses that are not closely routed near a ground plane, only simulated data are available. But they show a different behaviour of the frequency dependency of the injected current, suggesting a – 20 dB/decade slope at the higher frequencies. This is shown in Fig. 10.

Injecting currents up to 1GHz is done using the absorbing injection clamp [7]. From 1GHz up to 3GHz, the wave coupler developed by Körber is available [8]. For both clamps, injecting 100 mA and more is easily done.

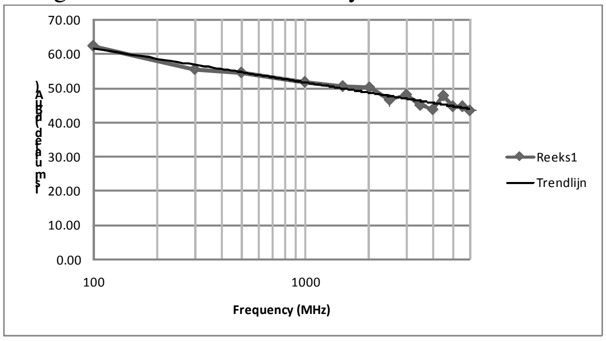

Fig. 9. Simulation results up to 3GHz

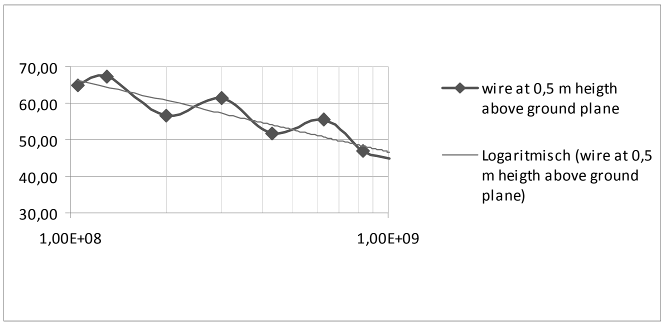

Fig. 10. Simulation results for 1 m height above ground plane

VI. CONCLUSION

In this paper, an extension of the BCI method as an alternative to radiated immunity is presented and showing a frequency dependency of the injected current. Obtained results will allow to correlate field strengths and injected currents into realistic conditions for immunity testing of modules.

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