Sensor for in situ validation of cable transfer functions

SENSOR FOR IN SITU VALIDATION OF CABLE TRANSFER FUNCTIONS

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Abstract: The transfer impedance of cables is an important design parameter to evaluate EM immunity of systems, and many laboratory test set-ups have been described to determine and verify the transfer impedance of cables and connectors.
In complex systems with high performance demands in situ validation is preferred. For this purpose we developed a measurement procedure, which determines the transfer function of a cable (including connectors and attached electronics) with respect to the common mode current over the cable and the currents over the inner wires of a multi-conductor cable. A common mode current is injected via an EM injection clamp and measured with a standard current probe. For measuring the differential mode currents a special sensor was designed in a way that it can be inserted in the cable under test at existing interconnections. Its impact on both the common and differential mode circuits is kept to a minimum. In addition, it does not significantly increase the transfer function of the complete system.
The sensor and measurement procedure have been successfully applied in the validation process of a magnetic resonance system.

I. INTRODUCTION

A large body of knowledge exists for the design and engineering of cabling with respect to electromagnetic interference and electromagnetic emission [1,2]. The transfer impedance of cables is an important design parameter and many laboratory test set-ups have been described to determine and verify the transfer impedance of cables and connectors [3,4].

For high performance complex systems in situ validation is preferred as well. Advanced systems used for research, industrial and medical applications are often connected by cables containing up to tens of inner wires for control, monitoring and power delivery. These cables can have considerable lengths and are often placed in a strongly “EM-polluted” environment: large machines with heavy switching power electronics, bad layout possibilities for cabling, application of high-power high-frequency signal sources, etc. Induced CM currents can result through the transfer impedance in unacceptable DM signals over the critical inner wires. To study these effects we developed a measurement procedure, which determines the transfer function of a cable (including connectors and attached electronics) with respect to the common mode current over the cable and with respect to the currents over the inner wires of a multi-conductor cable.

The sensor described here aims for detection of frequencies as from tens of MHz up to over hundred MHz. It detects the high frequency components by means of H-field antennas positioned to selectively measure currents on critical inner wires of the cable. A photograph is shown in Figure 1. Additional requirements include:

- If the sensor is tailored for a specific design, its installation should not require any system modification
- The presence of the sensor may only have limited effect on the CM current distribution itself and the transfer function of the cabling system

Fig.1 – Sensor for cable transfer function.

- It should be able to operate in a wide range of industrial situations, including very high magnetic fields, thus in principle excluding the use of ferromagnetic material

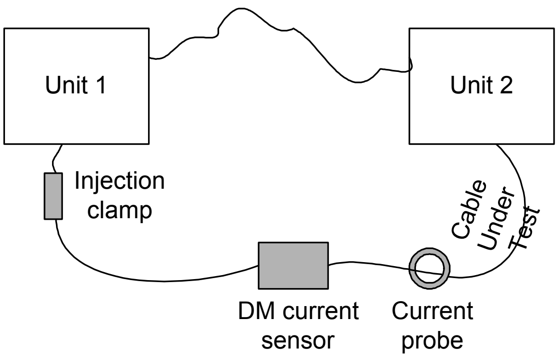


Fig.2 - Generic measurement set-up.

II. GENERIC MEASUREMENT SET-UP

Good engineering practices require that during normal operation common mode currents (CM) are small, while the validation measurements should prove that the system under test remains operational, even when large currents flow. Our measurement set-up therefore makes use of a common mode current injection with a wideband injection clamp (FCC EM injection clamp) as depicted in Figure 2. The induced current is measured with a wideband current probe (Fisher F75).

Differential mode (DM) voltage will be induced on the inner wires of the cable via the transfer impedance of the cable. This DM voltage in its turn will lead to a DM current over the inner wires. This DM current is measured with a dedicated sensor. In situation, where internal impedances are known the terminal voltages can be calculated from the DM current.

III. DIFFERENTIAL MODE CURRENT SENSOR DESIGN

The differential mode current sensor is designed for measuring the DM current induced in the most critical wires of the cable under test, while maintaining the signal integrity aspects and not significantly adding to the CM-DM transfer function itself. It can be inserted at existing interconnections in the system. In the sensor shown in Figure 3, two critical wires, defining e.g. a control circuit, are isolated and are connected via two parallel tracks on a PCB separated by 2 cm over a length of about 10 cm. In the centre of the PCB a single-loop H-field sensor is made by a track on the same PCB, as illustrated in Figure 4. The flux contained is the sum-flux from both wires. The sensitivity is given by $V_{ind}/I_{DM}=wM$. A value for the mutual inductance M can be calculated using:

$$M = \frac{\mu_0}{2\pi}\ell \ln(1+b/d) \qquad (1)$$

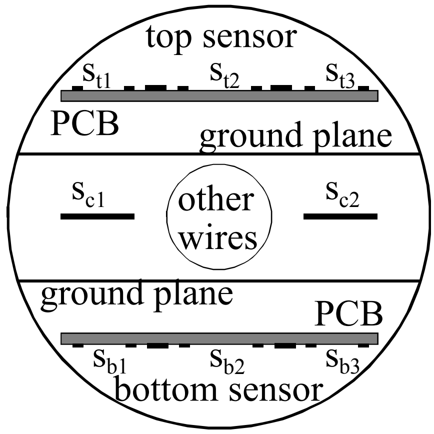
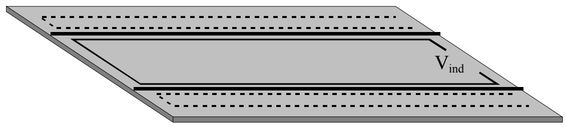


Fig.3 – Sensor cross-section.



H-field sensors on PCB

Fig.4 – H field sensor for DM current measurement.

Two additional loops are placed at both sides of the tracks. In the sensor design two identical PCB's with H-field sensors are installed, allowing two pairs of connections to be simultaneously monitored. As is shown in the figure, they are placed at the top and bottom of the cylindrical sensor. In the centre all other inner wires are mounted. At the left and the right side, there is space to install additional single turn loops, which measures the total flux from the other wires.

Shields are installed between PCB's and the wires in the centre to make the sensors selectively sensitive to the monitored wires only. Ideally, because of the symmetry, a net current over the bunch should not result in induced voltage in the sensors S_{t2} and S_{b2} (see Figure 3). Induced currents in the shielding ground planes will reduce cross talk even further [5].

Using boundary element simulation (Oersted version 6.0, Integrated Engineering Software), the effect of the ground plane on the sensitivity of the H-field sensor is numerically investigated. Also the distance between H-field sensor and neighbouring tracks was varied. The track width was taken 2 mm. The results are shown in Figure 5.

For a small distance of about 1 mm, e.g. if the copper PCB backside is used as ground plane, the sensitivity is reduced. The magnetic field lines are forced to be very close to the track and do not couple into the detection loop. At larger distances the sensitivity becomes better.

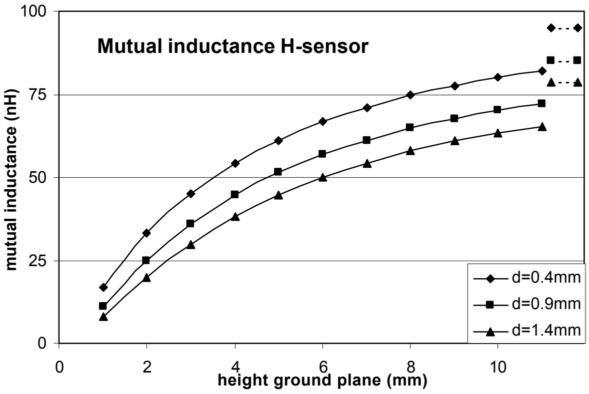


Fig.5 – Mutual inductance of H-field sensor with respect to loop formed by two tracks. Horizontal scale: the height of the ground plane with respect to the PCB for three "track-to-sensor" distances.

The dashed line elements at the right (Figure 5) correspond to the mutual inductances in absence of the ground plane. From these curves it is concluded that sufficient (close to 90% of maximum) sensitivity is obtained as from about 10 mm distance.

The self-inductance of the loop is about 140 nH (calculated without ground plane). For a frequency of about 60 MHz this corresponds to about 50 Ω. Therefore, if a 50 Ω measuring impedance loads the sensor the response will start to deviate from the time derivative of the track current at this frequency (the coil becomes "self-integrating"). Enlarging the sensor will also not result in higher signal amplitudes.

IV. SENSOR VALIDATION

Using a RF-generator (Marconi, type 2024) a 64 MHz sinusoidal signal was injected in one of the circuits formed by the PCB tracks. The signals on the various detection loops in the sensor were measured. The sensor numbering of the loops is indicated in Figure 3. In order to terminate the generator characteristically a 50 Ω resistor was used as a load on the tracks. The current in the injection circuit was detected by means of a current probe (Tektronix, type TM502A). From the ratio between the loop sensor voltage and the injected current the sensitivity was determined experimentally. The oscilloscope (HP54542A) input impedances of 50 Ω terminated the sensor loops of the RF-sensor. The sensitivity of the various loops in the sensor, expressed as the ratio between measured induction voltage and injected current, is summarised in Table I.

From the ratio of about 22 detected with the middle PCB sensors (either s_{t2} or s_{b2}) upon an excitation current in the tracks nearby a mutual inductance of 55 nH is found. One problem observed is that the side PCB sensors give somewhat different output signals. This may be explained by additional capacitive coupling between the H-field sensors at the sides and tracks take place, which is unequal to both sides, because the injected current is not balanced. The signal cross talk between the sensor section, where the current is injected (top/bottom), and the other sections (bottom/top or centre) is less than about 2% compared to the measured DM signal in the injection section.

V. APPLICATION EXAMPLE

In order to determine the practical usefulness of the described procedure and sensor, they have been applied in a magnetic resonance imaging (MRI) system (see Appendix). Since the common mode current circuit can be influenced by the presence of the sensor, two configurations were investigated. Firstly, the sensor was mounted directly onto the device under test and direct galvanic contact existed. Secondly, the sensor was insulated from the device, resulting in only capacitive coupling. In addition to the set-up depicted in Figure 2, a coupling interface box (IB) was added to the cable under test (see Figure 6). Two existing coupling interface boxes were investigated, differing in internal grounding and signal filtering. They are referred to as "IB 1" and "IB 2".

A sine wave current (I_{CM}) was injected. Two pairs of wires from the cable, which normally operates a control function within the MRI system, were monitored during injection of a 64 MHz CM current. The results are summarised in Table II.

The loops detecting the differential mode current of the monitored wires show that the screened and filtered IB 2 has an order of magnitude lower transfer function with respect to IB 1. Comparing the responses of the loops on one PCB, the responses are complicated by the fact that probably not only inductive coupling takes places, but signals can also couple capacitively as discussed earlier.

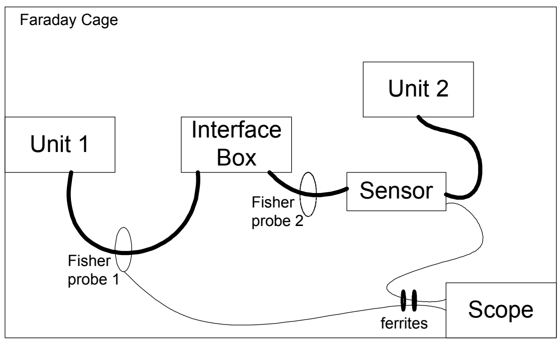


Fig.6 – Measurement set-up for testing the sensor performance.

Table I - Sensitivity of H-field sensors upon an injected 64 MHz sine wave, and cross talk between different sections within the sensor.

Sensor	injection in top PCB	injection in bottom PCB
	sensitivity (V/A)	sensitivity (V/A)
S_{t1}	7.5	0
S_{t2}	22.5	0.5
S_{t3}	11.3	0
S_{b1}	0	13.1
S_{b2}	0.3	21.9
S_{b3}	0.3	11.3
S_{c1}	0	0
S_{c2}	0.1	0

Table II - Signals obtained from the various H-field loops from the sensor during a test on a MRI system for two interface boxes. The sensor was either in direct galvanic contact with the system or insulated.

Sensor	Transfer function IB 1 (V/A)		Transfer function IB 2 (V/A)	
	galvanic contact	insulated	galvanic contact	insulated
S_{t1}	2.0	3.3	0.1	0.1
S_{t2}	5.0	7.7	0.1	0.0
S_{t3}	2.0	3.3	0.2	0.2
S_{b1}	0.6	0.9	0.3	0.3
S_{b2}	3.3	4.7	0.2	0.1
S_{b3}	2.0	4.7	0.1	0.1
S_{c1}	0.1	0.0	0.0	0.0
S_{c2}	0.3	0.5	0.0	0.0

VI. DISCUSION

The normal current path is disturbed over some distance by the presence of the inserted sensor. This may alter the current distribution over the different wires. However, it can be expected that, because of the relatively short distance of the sensor both with respect to the total cable length and to the wavelength at 64 MHz, this effect is negligible.

A few improvements of the sensor and the measuring method are still under consideration:

- Introducing grounded strips between tracks and loops can reduce the effect of possible additional capacitive coupling. Electric field lines will preferably end on these extra tracks. However, the sensitivity will be slightly reduced.
- The sensor signals are coupled by means of cables to the measuring device. These cables can pick-up a CM signal themselves, which via their transfer impedance result in a measured DM signal. A second shield over the measuring cables can be considered in order to reduce the transfer impedance. Further, ferrites (if allowed) can be placed over the measuring cables to give high impedance to this CM current. Alternatively, in case narrowband suppression is sufficient, a bazooka type balun can be applied [8].

VII. CONCLUSION

A properly functioning current sensor for measuring the differential mode currents in a cable has been designed and implemented. This sensor has been successfully applied in validating the EMC performance of an instrumentation cable in a magnetic resonance system.

A weak point in the measurement procedure is the positioning of the injection clamp. Before transfer function measurements start, additional experiments have to be performed to define the proper location of the injection clamp, such that the large common mode currents, which can occur in real life, are properly reproduced.

REFERENCES

[1] Vance, E.F., *Coupling to shielded cables*, New York: John Wiley & Sons, Inc., 1978.

[2] Degauque, P., J. Hamelin, *Electromagnetic Compatibility*, Oxford: Oxford University Press, 1993.

[3] IEC 62153-4-2: Metallic communication cable test methods - Part 4-2: Electromagnetic compatibility (EMC) -Screening and coupling attenuation - Injection clamp method.

[4] IEC 62153-4-3: Metallic communication cable test methods - Part 4-3: Electro Magnetic Compatibility (EMC) - Surface transfer impedance - Triaxial method.

[5] Wouters, P.A.A.F., M.J.A.M. van Helvoort, P.C.T. van der Laan, “Mitigation of B-fields, background and practical examples”, EMC Europe 2000, Brugge, tutorial pp. 122-126, September 2000.

[6] Vlaardingerbroek, M.T., J.A. den Boer, *Magnetic Resonance Imaging*, Berlin: Springer-Verlag, 1999.

[7] Hornak, J.P., *The Basics of MRI,* http://www.cis.rit.edu/htbooks/mri/

[8] Helvoort, M.J.A.M. van, E. Holle, C. Possanzini, M.L.A. Vrinten, P.C.H.A. Haans, “Modified bazooka balun for common mode suppression”, *EMC Europe 2004*, Eindhoven, September 2004.

APPENDIX.
THE ROLE OF RF AND EMC IN MRI

Magnetic Resonance Imaging (MRI) is based on the fact that certain nuclei posses a magnetic momentum. If a set of these nuclei is exposed to a strong (quasi) static field, each nucleus will either align parallel or anti-parallel with this field. The set of nuclei will have a small remaining net magnetization.
When the aligned nuclei are excited by an RF pulse with proper frequency they start to resonate and will de-align. The frequency at which this happens is linearly proportional to the strength of the applied (quasi) static field. At a typical field strength of 1.5 T the resonance frequency is 64 MHz.
When the exciting RF pulse is switched off the nuclei will re-align. In turn they transmit a small RF pulse, varying between 3.5 fT and 35 nT. See Figure 7 for clarification. The response depends on the density of resonant nuclei and on the tissue in which they are residing; therefore the response gives a characterization of the tissue.

Before 2D or 3D images can be acquired it is necessary to identify which volume (or voxel) generates which part of the response. Therefore a small gradient is imposed on the static magnetic field, such that every voxel has a slight difference in field strength, thus in resonance frequency. Via Fourier transformation on the digitised response the original image can be reconstructed.
Due to the combination of the strong excitation and the small response, it is obvious that EMC plays a direct role within MRI.

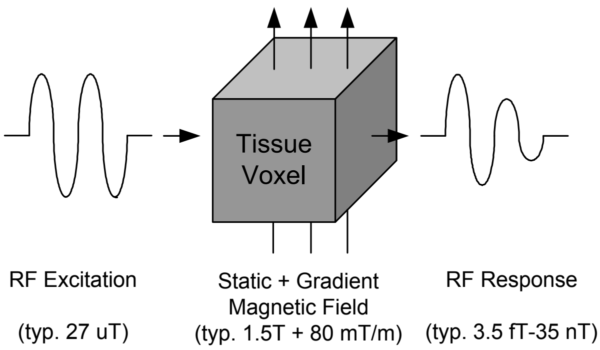


Fig.7 – After external excitation a tissue voxel transmits a response based on the tissue properties.

In the first experimental systems the main EMC problem was tackled by placing the patient in a Faraday cage, giving rise to strong claustrophobic feelings. The strong excitation pulse was kept very local with this approach. Successful clinical systems however demand a better patient friendliness, therefore the Faraday cage around the patient within the system has been replaced by a Faraday cage around the system (see Figure 8). This cage keeps the 27 μT burst in and keeps disturbances to the small response signal out, but it is clear that the electronics and their attached cables within the cage have to operate in a quite harsh environment. Since future systems will operate at higher field strengths (thus higher frequencies, improved signal-to-noise), or will be more open (improved patient acceptance) EMC will remain an intrinsic design issue.

For further reading on MRI and MRI equipment we refer to [6] or [7].

Fig.8 – Philips MR Achieva 3.0 T.