A Fast, Accurate, and Sensitive Method for Calculating Surface Transfer Impedance

F. Calluso(*), M. Casti(“), G. Ferrero(~), L. Zanero($)

(*)Politecnico di Torino C.so Duca degli Abruzzi 24, 10129 Torino (Italy) Email fcalluso@freemail.it
(“)Università di Torino – Istituto di Fisica, v. Giuria 1, 10125 Torino (Italy) Email maurizio.casti@isiline.it
(~)ALENIA DIFESA, St. Pr. Aeroporto, 10077 S.Maurizio C. (To) Email g.ferrero@dsae.finmeccanica.it
($), v.Brandizzo 428, 10088 Volpiano (To) Tel.9884777 Fax 9885123

Abstract **The interest in the possible influence of electromagnetic fields on motor vehicles is a topic that is actual. The interest of the motor car industries is increasing because the electronic devices installed on board, actually achieve sophistication levels every time higher and higher. The engineering of the subsystems concerning the motor car market, now involves all the components of them. In particular, the cable harnesses employed for the information transmission between the above subsystems is one of the most critical component from the electromagnetic interference (EMI) point of view. Electromagnetic shielding of the cable harness is the key technique in protection against the leakage of information from electronic equipment.**

The method of analysis is presented, the measurement procedures based on the triaxial and the current injection method are given with practical hints. The procedural approach has been carried out by means of the development of a dedicated Computer Interference Simulation Program (CISP), designed in order to determine the Surface Transfer Impedance (STI) of a cable under test (CUT), which gets results quickly and with particular accuracy. A proper algorithm of the program allows to obtain an optimisation of the cable braid design by making a minimum number of code iterations. CISP numerical results are in good agreement with measures performed on a typical EC cable.

I. Introduction

A growing interest is developing in the design of cable shields being it among one of the most critical sources of introduction of electromagnetic interference in modern electronic equipment in motor vehicles. The strong electromagnetic pollution involving the motor vehicle cable harness, produces EMI voltages on the electronic equipment that are comparable to the used signals.

Electromagnetic shielding of the cable is the key technique in protection against the leakage of information from electronic equipment. If a current produced by an interference field flows over a cable braid, this generates a voltage drop on the inner surface of the braid, which acts an EMI voltage on the central conductors. This voltage can be evaluated by the STI parameter : little transfer impedance means a good Shielding Effectiveness (SE).

For analysing the EMI field coupling to cable harness it is necessary to know if this parameter satisfies the applicable specification limit.

A correct model of the cable which takes into account all the structural parameters, allows the braid design definition, with significant accuracy. Much of the present interest is in the STI data covering 100 KHz to 1 GHz.

II. “Triaxial” and “current injection” methods

In the triaxial method the CUT is connected at one end with its characteristic impedance (see fig. 1). This impedance and CUT are coaxially arranged in a metal pipe. This is connected to the cable screen by a short-circuit, soldered to the cable screen at the generator side.

Regarding to the current injection method, the difference with the above method lies in the fact that the interference current is produced by an “injection wire” laying parallel to the cable under test. The external current circuit is completed by two coaxial cables, which are connected to the ends of the parallel wire and the relevant cable screen (see fig. 2). The CUT is connected at one end to the EMI receiver; the other end is connected to its characteristic impedance.

III. Optimisation of screening braids

The design of cable braids is still based on experience, empirical techniques and experimental measures : a correct modelling of the STI shows good results only if all the construction parameters of the braid are taken into account.

If the SE of a cable is evaluated, a distinction is made between electric (E) and magnetic (H) field actions. Screening against E coupling is expressed in terms of transfer admittance. In a similar way screening against H coupling, which is caused by induced interference currents on the outer conductor, is expressed by the transfer impedance. In the paper only this last impedance is taken into account.

The characteristics of a cable braid can be defined in terms of the mean radius (r) and diameter (D) of the shield; the number of carriers (C) in the braid, the number (N) of wires in each carriers; the weave step (h) and the wire diameter (d). An enlarged illustration of one rhombus-shaped section of the braid is shown in fig. 3 while a braid pattern, developed on a plane, is shown in fig. 4.

The weave angle (α) is, for r>>d :

$$\alpha = arctg(\pi D/h)$$

Fig. 5 shows the braid configuration with the weave step highlighted. The fill of the braid can be expressed by :

$$F = \frac{NCd}{4r\pi \cos(\alpha)}$$

The optical coverage of the shield is :

$$K = 2F - F^2$$

Each hole is a rhombus whose longitudinal axis is :

$$(W - Nd)/sen(\alpha)$$

and whose transverse axis is :

$$(W - Nd)/cos(\alpha)$$

If the weave angle $\alpha < 45^0$, the major axis of the rhombus-shaped holes is perpendicular to the H field, and the rhombus is oriented for minimum H coupling through the hole. If the weave angle $\alpha > 45^0$, the major axis is parallel to the H field, and the hole is oriented for maximum H coupling.

The transfer impedance will consist of two components :

- penetration component representing the energy diffusion through the metal of the screen
- coupling component representing the H field diffusion through the rhombus-shaped holes

The penetration term may be approximated by assuming that each wire of diameter d is isolated from all other, so that the resistance per unit length of the screen is :

$$R_{cc} = 1/\pi^2 rd F\sigma \cos^2(\alpha)$$

where σ = conductivity of the wires. Thus the approximated penetration term for the shield will be [with $\gamma = (1+j)/\delta$ and $\delta = (\mu\sigma\pi f)^{-1/2}$ = skin depth in the wire]:

$$Z_p \approx R_{cc}\left(d\gamma / \sinh(d\gamma)\right)$$

The coupling component is represented by a mutual inductance term for ν holes/m :

$$M_{12} = \nu \frac{m\mu_0}{4\pi^2 r^2}$$

where m = H polarizability of the rhombus shaped hole

ν = hole density per meter = $rdF\pi^2$.

The polarizability of the rhombus-shaped hole can be represented by those of an equivalent hole, such as ellipses-shaped hole.

The H polarizability of the elliptical hole has been derived in closed form for the H field parallel to either axis of the ellipse. For an ellipse of eccentricity $e = [1-(w/l)^2]^{1/2}$, where l is the major axis and w is the minor axis, the H polarizability is :

$$m_l = \frac{l^3\pi}{24}\left[\frac{e^2}{K(e) - E(e)}\right]$$

for the H field parallel to the major axis, and

$$m_w = \frac{l^3\pi}{24}\left[\frac{e^2(1-e^2)}{E(e) - (1-e^2)K(e)}\right]$$

for the H field parallel to the minor axis. K(e) and E(e) are the complete elliptic integrals of the first and second kind, respectively, defined by :

$$K(e) = \int_0^{\pi/2} \frac{d\varphi}{[1 - e^2 sen^2(\varphi)]^{1/2}}$$

$$E(e) = \int_0^{\pi/2} [1 - e^2 sen^2(\varphi)]^{1/2} d\varphi$$

On the basis of the previous equation the rhombic holes in a braided shield pattern can be simulated by ellipses having similar major and minor axis, we obtain, for mutual coupling associated with the holes, for $\alpha < 45^0$

$$M_{12} \approx \frac{\pi\mu_0}{6C}(1-K)^{3/2} \frac{e^2}{E(e) - (1-e^2)K(e)}$$

with $e = [1-tg^2(\alpha)]^{1/2}$ for $\alpha < 45^0$ and $e = [1-cotg^2(\alpha)]^{1/2}$ for $\alpha > 45^0$.

The complete transfer impedance for the braided-wire shield can then be written

$$Z_T \approx R_{cc}\frac{d\gamma}{senh(d\gamma)} + j\omega M_{12}$$

that is the expression used for the simulation program.

At very low frequency, the STI is equal to the direct current resistance of the braid. The low-frequency shielding properties are determined by number of wires NC, weave angle α and shield material conductivity σ. The high-frequency behaviour of the STI function are thus determined by the coverage K, weave angle α and the number of carriers in the weave. With increasing frequency, two effects will occur :

- due to the skin effect the STI will drop
- due to the H field coupling through the braid structure there will be a rise of the STI proportional to the frequency

IV. Computer interference simulation program

The CISP code has been developed to determine all the parameters needed to optimise the SE of the cable braid. The code is based on analytical method to predict the EMI coupling on cable braids, taking into account effects of weaving technique. It has written in the MATLAB technical computing environment, an interactive platform that incorporates numeric/symbolic computation and scientific visualisation. Regarding to the choice of the platform, one of the most significant aspects was that, trough MATLAB, final user is always able to implement new solutions in an user-friendly way. The code, joined to the development of the internal research of a work team, is composed of :

- input interface
- calculation
- output presentation

The OS-independent user interface is equipped with flexible handle-graphics commands. The user will be asked to enter :

- the diameter under braid [D -mm]
- the number of carriers in the braid [C]
- the number of wires in each carrier [N]
- the diameter of wires [d - mm]
- the weave angle [α - rad]

The calculation section covers two fundamental aspects : STI determination in the frequency range 100 KHz – 1GHz and design optimisation routine based on the quadratic model algorithm.

Output of the program is the STI diagram and the optimisation design section results. A plot of numerical STI of the MTREK2700-ELETTRONICA CONDUTTORI cable is shown in fig. 7, with the braid parameters values : d=0,12mm; N=6; C=16; α=0,67rad; r=3,64mm. The optimisation section generates the combination of the computed values for the parameters of the cable braid to be designed. These combination of input parameters defines the minimum STI function, around the adopted fixed test frequency.

A software approach should mainly face important aspects. First of all the availability of a theoretical method to calculate the electromagnetic behaviour from the SE point of view. Another aspect is the definition of an indication about the problems that will be found during measurements. Finally, the most relevant aspect is the determination of the optimal geometrical parameters to be imposed during the manufacturing phase.

In order to optimize the STI design, we can operate with an iterative method, consisting in the evaluation of the function in a lot of combination of geometrical variable' values (at a fixed test frequency, f_0) and in the comparison between all obtained values with each others. Then we choose the combination that gives the desiderated behavior. The computer, in order to find the above combination, generates a grid of values, and perform a calculation loop on a single variable, with the other ones fixed, for all variables. The minimization of the computational time it's possible, keeping a close grid, expanding the STI function in its *Taylor Series*. If the variable range is relatively small, a quadratic model is applicable. It's possible to break the series at the second order, around the center values of the parameter range. Therefore we obtain a 2nd degree polynomial, quickly "handled" by a computer. If the range is large, the way is to expand the series up to a greater degree, or to subdivide the grid in linked sub-grids, in which the quadratic model is still applicable. The above polynomial consists in all possible combination of variables up to the 2nd degree, as shown in the following formula :

$$Z_T(f_0) = \sum_{i=0,14} T_i \times G_i$$

The Taylor expansion is made around a fixed point, called *center of develop*, in which we calculate the function value and the n-order mixed derivatives, in order to find the polynomial coefficients.

In the above formula the G_i terms are these coefficients, while the T_i terms represent the combination of variables, *shifted to their specific center value.*

V. Measurements carried out

The MTREK2700-ELETTRONICA CONDUTTORI cable experimental results, obtained with the triaxial method, are indicated in fig. 7. The test signal was generated by an HP 8648 synthesiser and picked up by a HP 8594E spectrum analyser. The specimen was connected to the signal source through a 50 Ω load in order to match the generator. The source was set at a power level of 0 dBm in order to have a current flow through the screen. A computer was used for data acquisition and RS-232 instrument control with Microsoft Excel add-in for direct analog I/O. Comparing fig. 7 and 8 one can see that no significant difference exists between the CISP and experimental results.

VI. Conclusions

The simulation program gives a precise formula to plot the STI diagram in mΩ/m vs. frequency and allows the optimisation of the structural parameters of the cable by means computer iterative techniques. An analytical method to predict the electromagnetic coupling due to interference fields on cable braids has been presented, it takes into account effects of weave system technique. On the basis of results coming from this kind of software validation, further improvements of SE prediction will be included in the future release of this tool to create a simple graphical interface to use advanced mathematical libraries to provide for an high coding velocity of new algorithms. By using comparison with measurement results performed with the triaxial test method in the frequency range 100 KHz - 1 GHz, predictions of the estimated STI of the cable under test have also demonstrated consistent results of evident accuracy. It can simulate all kind of coaxial cable structures in a short computation time. The comparison between measurements and simulations shows that all couplings involved in the measurement set up must be well understood to be able to explains the results of the comparison.

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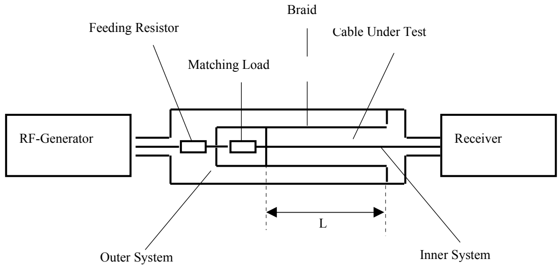


FIGURE 1 TRIAXIAL TEST SET UP

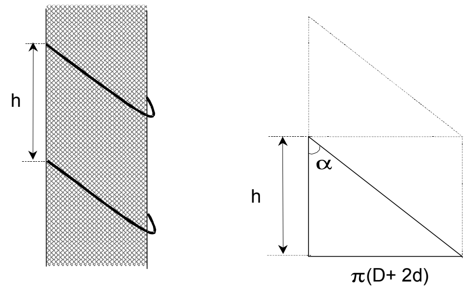


FIGURE 5 WEAVING STEP PARAMETER

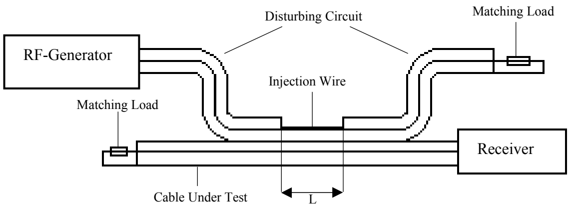


FIGURE 2 CURRENT INJECTION TEST SET UP

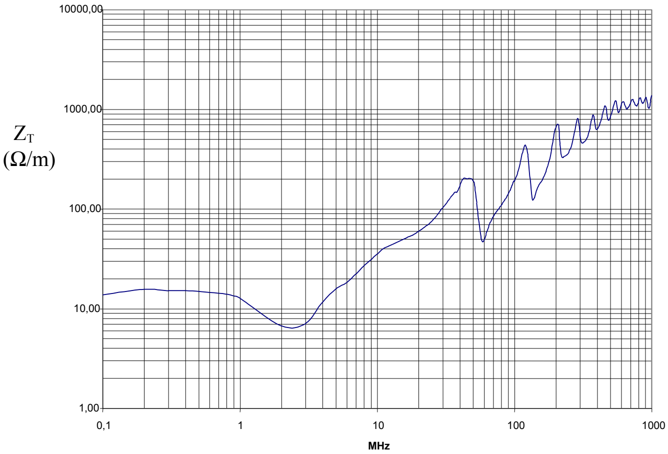


FIGURE 6 Z_T MEASUREMENT RESULTS (MTREK2700)

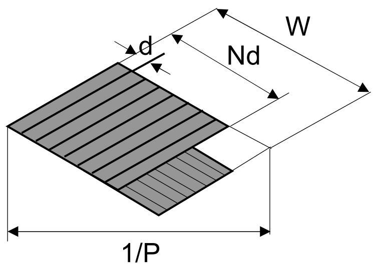
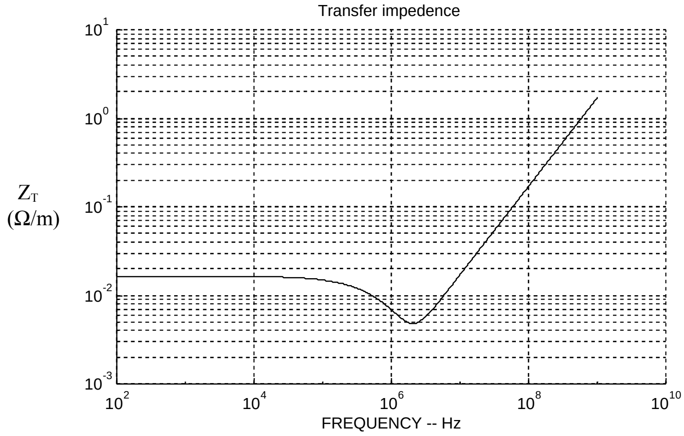


FIGURE 3 RHOMBUS SHAPED SECTION OF THE BRAID



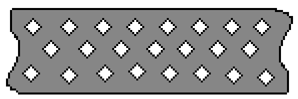


FIGURE 4 BRAID PATTERN DEVELOPED ON A PLANE

FIGURE 7 Z_T FUNCTION CALCULATED BY CISP