

Electromagnetic Coupling for Wire Twisting Pitch Optimization for SRS Applications

Jean Razafiarivelo and Youssef Bouri
Delphi Automotive

ABSTRACT

In the sensitive automotive applications like the safety restraint systems (SRS), twisted lines can be used to link the components of the system because of their property of reduction of the electromagnetic interference (EMI) coupling. Compared to the parallel lines, the twisted lines present the drawback to consume more copper in their manufacturing due to the greater length of their conductors. A parametric study based on the numerical modeling and the measurement of twisted lines is conducted in order to analyze the effect of the twisting pitch and of the untwisted part of these lines on the level of EMI coupling. This study will enable to optimize these two parameters in order to reduce the level of EMI coupling as well as the length of the conductors of the lines.

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INTRODUCTION

In the sensitive automotive applications like the safety restraint systems (SRS), twisted lines can be used to link the components of the system because of their property of reduction of the electromagnetic interference (EMI) coupling.

Compared to the parallel lines, however, the twisted lines present the drawback to require a greater amount of copper for their manufacturing due to the greater length of their conductors related to the twisting of the lines. Regarding this aspect, the twisting pitch and the untwisted part of the lines are preponderant design parameters.

In this work, we analyse the effect of these two parameters on the level of EMI coupling and we identify optimal values for these parameters in order to reduce the level of EMI coupling and the length of the conductors of the bifilar lines.

In the 1st section, we remind the approach of theoretical modelling of twisted lines described in [1, 2]. We use it to compute the EMI coupling between a single line and a twisted bifilar line and to highlight the effect of reduction of the EMI coupling when twisted bifilar lines are used instead of parallel bifilar lines. In the 2nd section, we perform a parametric study based on the numerical modelling and the measurement of twisted bifilar lines to optimize the twisting pitch and the

untwisted part of the lines according to the level of EMI coupling.

THEORETICAL BACKGROUND

In this section, we remind the approach of theoretical modeling of twisted bifilar lines described in [1,2]. We use it to compute the EMI coupling on twisted bifilar lines and we highlight the effect of reduction of coupling obtained by using twisted bifilar lines instead of parallel bifilar lines.

Physical Phenomena

Generally speaking, lines twisting is used to reduce the electromagnetic coupling on these lines. Twisted lines can be schematically represented as a bifilar helix. The theoretical model of this helix can be represented as a cascade of alternating loops (Figure 1). The essential way in which the lines twisting reduces the electromagnetic field coupling is as follows (Figure 1). The magnetic flux issued from the generator line goes through each loop of the twisted bifilar line and induces emfs (electromotive forces) in the loop. Because the loops alternate in polarity, the induced emfs tend to cancel from one loop to another. Thus, the net emf induced in the receptor circuit of the twisted lines is reduced to the one of a half-twist (a loop being referred as a half-twist).

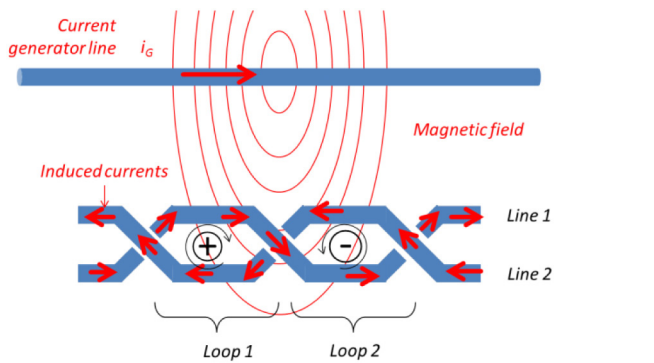


Figure 1. Coupling of the magnetic field on a twisted bifilar line: cancellation mechanism of the coupling from one loop to another

Theoretical Modeling of Twisted Lines for Coupling Evaluation

To evaluate the electromagnetic coupling on twisted lines, the deterministic model of cascaded transmission lines described in [1, 2] can be used. In this model, the twisted lines are described as a succession of transmission line sections and abrupt transition sections (Figure 2). For each section, the chain parameter matrix is derived. The total chain parameter matrix is then obtained as a multiplication of all these partial matrices. To describe the proposed theory, let's consider the case where the single line represents the disturber line and the twisted bifilar line, the victim line (Figure 2).

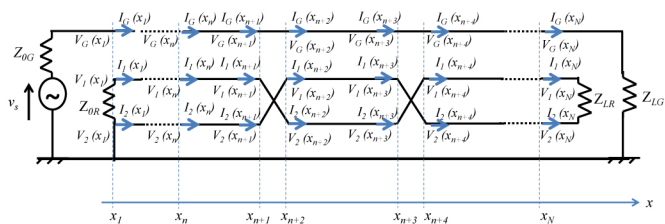


Figure 2. twisted lines modeling as a cascaded combination of uniform transmission line sections and abrupt transition sections.

In the configuration of the Figure 2, the line G is a single line connected to the voltage source v_s at its left extremity through a load Z_{OG} and grounded at its right extremity through a load Z_{LG} . The line G acts as the disturber in this configuration. The lines 1 and 2 in the twisted bifilar line are terminated by the resistances Z_{OR} and Z_{LR} and act as the victim line. In addition, the lines 1 and 2 are connected to their left extremities to the ground (*unbalanced* configuration). The formulation that follows can be easily generalized to the case of multiple twisted bifilar lines. According to the geometry shown in Figure 2, the line sections from X_n to X_{n+1} , X_{n+2} to X_{n+3} , and so on are uniform transmission lines while the lines twisting is represented by the abrupt transitions at $X_{n+1} = X_{n+2}$, $X_{n+3} = X_{n+4}$, and so on. Note that, although the distance over which the abrupt transition takes place (for instance, from X_{n+1} to X_{n+2}) is infinitesimal, the two end points of the transitions are drawn separated from each other in Figure 2 to show the exchange of voltages and currents explicitly within the lines of the bifilar line. It is also assumed that the length of the twist loops is constant

everywhere along the line, i.e., $\Delta L = X_{n+1} - X_n = X_{n+3} - X_{n+2}$. The total length of the lines L is given by $L = x_N - x_1$. The chain parameter matrix ϕ_s which relates the voltages and the currents at point X_{n+1} to the voltages and the currents at point X_n according to (1)

$$\begin{bmatrix} V_G(x_{n+1}) \\ V_1(x_{n+1}) \\ V_2(x_{n+1}) \\ I_G(x_{n+1}) \\ I_1(x_{n+1}) \\ I_2(x_{n+1}) \end{bmatrix} = \phi_s \cdot \begin{bmatrix} V_G(x_n) \\ V_1(x_n) \\ V_2(x_n) \\ I_G(x_n) \\ I_1(x_n) \\ I_2(x_n) \end{bmatrix} \tag{1}$$

is given by (2):

$$\phi_s = \begin{bmatrix} \cos(\beta \cdot \Delta L) \cdot I_3 & -j \cdot \sin(\beta \cdot \Delta L) \cdot Z_c \\ -j \cdot \sin(\beta \cdot \Delta L) \cdot Y_c & \cos(\beta \cdot \Delta L) \cdot I_3 \end{bmatrix} \tag{2}$$

where I_3 is the 3×3 identity matrix and Z_c and Y_c are the 3×3 characteristic impedance and admittance matrices of the three lines. Z_c and Y_c are determined from the computation of the matrices L and C representing the per-unit-length inductance and capacitance matrices of the three lines system [3]. β represents the phase constant given by $\beta = \omega/v = 2\pi/\lambda$, where ω is the pulsation, λ is a wavelength at the frequency f and v is the velocity of propagation in the surrounding medium related to λ by $\lambda = v/f$.

The chain parameter matrix P for the transition section from point X_{n+1} to point X_{n+2} is a 6×6 permutation matrix given by (3):

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{3}$$

And thus, we can write (4):

$$\begin{bmatrix} V_G(x_{n+2}) \\ V_1(x_{n+2}) \\ V_2(x_{n+2}) \\ I_G(x_{n+2}) \\ I_1(x_{n+2}) \\ I_2(x_{n+2}) \end{bmatrix} = P \cdot \begin{bmatrix} V_G(x_{n+1}) \\ V_1(x_{n+1}) \\ V_2(x_{n+1}) \\ I_G(x_{n+1}) \\ I_1(x_{n+1}) \\ I_2(x_{n+1}) \end{bmatrix} \tag{4}$$

By successively multiplying the chain parameter matrices for the short transmission line sections and the transition sections, we can define the total chain parameter matrix ϕ_T which relates the voltages and current at point X_N to the voltages and currents at point X_1 according to (5) :

$$\begin{bmatrix} V(x_N) \\ I(x_N) \end{bmatrix} = \phi_T \cdot \begin{bmatrix} V(x_1) \\ I(x_1) \end{bmatrix} \quad (5)$$

where V and I are the vectors of voltages and currents at line terminations. The chain parameter matrix ϕ_T is given by (6):

$$\phi_T = \begin{bmatrix} \phi_{T11} & \phi_{T12} \\ \phi_{T21} & \phi_{T22} \end{bmatrix} = \begin{cases} \phi_s \cdot (P \cdot \phi_s)^{N-1}, & \text{if } N \text{ odd} \\ (P \cdot \phi_s)^N, & \text{if } N \text{ even} \end{cases} \quad (6)$$

where N is the number of loops.

Equation (5) simplifies the complex multi-conductor transmission line formulation for the arrangement shown in Figure 2 into a simple two-port network configuration characterized by its chain parameter matrix ϕ_T . To obtain the terminal voltages and currents for such a network, we need additional equations derived from terminal constraints and line configuration. The equations for the termination networks of the unbalanced configuration in Figure 2 are obtained as:

$$V_G(x_1) = v_s - Z_{0G} \cdot I_G(x_1) \quad (7.a)$$

$$V_1(x_1) = -Z_{0R} \cdot I_1(x_1) \quad (7.b)$$

$$V_2(x_1) = 0 \quad (7.c)$$

$$I_G(x_N) = (1/Z_{LG}) \cdot V_G(x_N) \quad (7.d)$$

$$I_1(x_N) = (1/Z_{LR}) \cdot (V_1(x_N) - V_2(x_N)) \quad (7.e)$$

$$I_2(x_N) = (1/Z_{LR}) \cdot (V_2(x_N) - V_1(x_N)) \quad (7.f)$$

Writing (7) in matrix form gives:

$$V(x_1) = V_s - Z_0 \cdot I(x_1) \quad (8.a)$$

$$I(x_N) = Y_L \cdot V(x_N) \quad (8.b)$$

Where V_s is a 3×1 vector and Z_0 and Y_L are 3×3 matrices given by:

$$V_s = \begin{bmatrix} v_s \\ 0 \\ 0 \end{bmatrix} \quad (9)$$

$$Z_0 = \begin{bmatrix} Z_{0G} & 0 & 0 \\ 0 & Z_{0R} & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (10)$$

$$Y_L = \begin{bmatrix} (1/Z_{LG}) & 0 & 0 \\ 0 & (1/Z_{LR}) & (-1/Z_{LR}) \\ 0 & (-1/Z_{LR}) & (1/Z_{LR}) \end{bmatrix} \quad (11)$$

By substitution of (8) into (5), the equations for the terminal currents of the line are obtained as:

$$I(x_1) = [Y_L \phi_{T11} Z_0 - Y_L \phi_{T12} - \phi_{T21} Z_0 + \phi_{T22}]^{-1} \cdot [Y_L \phi_{T11} - \phi_{T21}] \cdot V_s \quad (12.a)$$

$$I(x_N) = \phi_{T21} V_s + [\phi_{T22} - \phi_{T21} Z_0] \cdot I(x_1) \quad (12.b)$$

Equations (12.a) and (12.b) enable to respectively solve the terminal currents at $x = x_1 (= 0)$ and $x = x_N (= L)$. For the terminal voltages at $x = x_1 (= 0)$, equation (8.a) is used. However, to solve the terminal voltage at $x = x_N (= L)$, the circuit equations: $V_G(x_N) = Z_{LG} \cdot I_G(x_N)$, $V_{LR} = Z_{LR} \cdot (I_1(x_N) - I_2(x_N))$ are directly used since Y_L in (8.b) is singular.

For the case of the parallel (untwisted) bifilar lines, we point that the terminal network equations are the same as those for the twisted lines case given in (8). Let's then define the global chain parameter matrix ϕ by the equation (13), where L is the total length of the lines:

$$\phi = \begin{bmatrix} \cos(\beta \cdot L) \cdot I_3 & -j \cdot \sin(\beta \cdot L) \cdot Z_c \\ -j \cdot \sin(\beta \cdot L) \cdot Y_c & \cos(\beta \cdot L) \cdot I_3 \end{bmatrix} \quad (13)$$

Since we have been careful to sequence the variables of voltage in the vectors, $V(L = x_N)$ and $V(0 = x_1)$ and the variables of current in the vectors, $I(L = x_N)$ and $I(0 = x_1)$, the global matrix ϕ may be directly used with the terminal network equations (8) to obtain the equivalent equations for the terminal currents to the equations (12) where the coefficients ϕ_{Tij} are replaced by the corresponding coefficient ϕ_{ij} of the matrix ϕ .

The electromagnetic coupling received at the left extremity and at the right extremity of the twisted lines in Figure 2 (respectively the *near end* coupling (NEXT) and the *far end* coupling (FEXT)) can then be evaluated by the ratio of the Page 3 of 8 induced voltage on the line 1, $V_1(x_1)$ on the voltage $V_G(x_1)$ of the line G of the generator (NEXT) and by the ratio of the voltage $V_1(x_N)$ on the voltage $V_G(x_1)$ (FEXT).