Experimental Benchmarking of Unstructured Transmission Line Modelling (UTLM) Method in Modelling Twisted Wires

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Abstract **─** In this paper the Unstructured Transmission Line Modelling (UTLM) method based on a tetrahedral mesh has been applied to modelling of the coupling between a single wire and a twisted wire pair. The effects of wire twisting on the crosstalk and coupling between wires are modelled by explicitly meshing wire geometries; simulation results are compared with experimental ones. Excellent agreement between simulated and measured results validates the viability and accuracy of the UTLM method and indicates the potential of the UTLM method for modelling complex wire structures.

Index Terms **─** Crosstalk, experimental benchmarking, Transmission Line Modelling (TLM) method, twisted wires, twisting effects, Unstructured Transmission Line Modelling (UTLM) method.

I. INTRODUCTION

Wires and cables play an important role in modern electronic systems, especially in the aerospace and automotive industries. They transmit signals between pieces of equipment and at the same time couple with the ambient electromagnetic fields. The electromagnetic interference (EMI) between wires and cables may affect the normal operation of equipment. It is therefore important to develop efficient and versatile methodologies that can predict the coupling strength between wires and cables.

The Unstructured Transmission Line Modelling (UTLM) method, fully presented and validated in [1-2], is a Transmission Line Modelling (TLM) method based on tetrahedral meshes [3]. Whilst the use of a TLM method based on structured cuboidal meshes has been widely reported, especially for Electromagnetic Compatibility (EMC) studies and microwave modelling, the advantages and characteristics of the UTLM method have not as yet been fully explored for such a variety of applications. For instance, when modelling curved structures, a very fine mesh is needed for the cuboidal mesh based TLM method to approximate the curved boundaries. This not only leads to large computational resources, even when using Octree sub-division technique [4], but also leads to stair-stepping problems [5]. Furthermore, its accuracy in representing the curved boundaries is piece-wise constant. In contrast, the UTLM method can better describe arbitrary shaped geometries, especially those involving curved structures, with no stair-stepping approximations and with a piece-wise-linear accuracy. One key feature of UTLM is the wide dynamic range of cell sizes that can be used. Importantly, a clustering technique whereby clusters of very small cells are grouped into larger cell entities for which the scattering is done implicitly, has been integrated into the UTLM method to allow a practical small time step to be used in a simulation [6]. These characteristics make the UTLM method a very good candidate to model in detail the coupling between wires and cables, a feature which is especially important within an aerospace context.

Some initial experimental benchmarking of a UTLM model explicitly meshing wires has been presented in [7], where the UTLM method was applied to the simulation of a canonical two parallel wire coupling problem. The paper discussed that small wire diameters lead to large computational costs in a discretized numerical simulation. Although an embedded thin wire model [8] has been widely adopted to reduce computational costs, it has difficulties in dealing with twisted wires, especially when other structures are in close proximity to the wire geometries. The purpose of this paper is to demonstrate how the wide dynamic range of cell sizes within ULTM enables the modelling of the coupling between a single wire and a twisted wire pair by explicitly meshing them, and to validate the approach by comparison with experiments. In the scenario considered the single wire is used for excitation and the twisted wire pair is used as victim on which crosstalk is observed. The crosstalk between wires is analyzed for different wire terminations, and both with and without twisting of the wire pair. The simulated results are compared with measurements. The paper is organized as follows: in the next section the experimental set up is described, followed by a description of the simulated model. Section IV outlines the comparison of the crosstalk between simulated and measured results and

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Section V summarizes the main conclusions of the paper.

II. PROBLEM DESCRIPTION

In this section, the experimental setup used to study the twisting effects on coupling between wires is described.

In order to consider the twisting effects, a single core copper wire is excited as the source and a twisted wire pair is used as the victim. The single core wire has a radius of r_w = 0.04 cm. The separations between ports are $s1$ = 2 cm and $s2$ = 1 cm. The wires are placed near a L shape ground plane as shown in Fig. 1 (a) and mounted on to the two metal bulkheads using SMA bulkhead connectors as shown in Fig. 1 (b). The wires are situated above the bottom ground plane by a height, h = 8 cm. The distance between port 1 and the left ground plane is d = 12.5 cm as shown in Fig.1 (a). The length of the wires is L = 100 cm. The twisted wire pair has 20 twists along its length. The metal bulkheads each have dimensions of 30 cm × 30 cm.

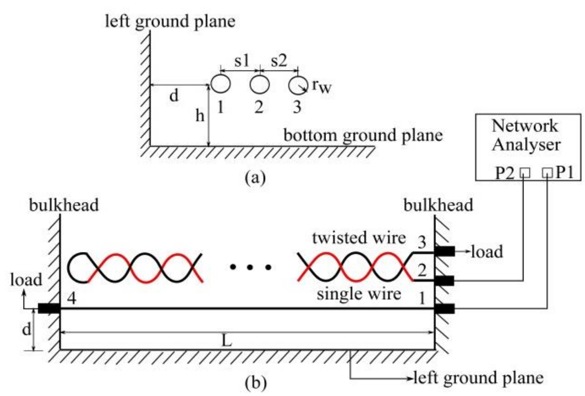


Fig. 1. (a) A single wire and a twisted wire pair are near the L shape ground plane; (b) the top view of the setup.

In the experiment, the twisted wire pair is made by folding a single core copper wire of length $2L$ and twisting the two halves to create the configuration shown in Fig. 1 (b). At the right end, one wire of the twisted wire pair is connected to port 2 and the other one is connected to port 3. Port 1 is connected to the right end of the single wire as an excitation. Measurements are made on port 2 using a Network Analyzer (Agilent E5062A). Port 3 and port 4 (the left end of the single wire) are connected to a load, which could be a 50 ohms load, a short circuit or an open circuit.

III. NUMERICAL MODEL

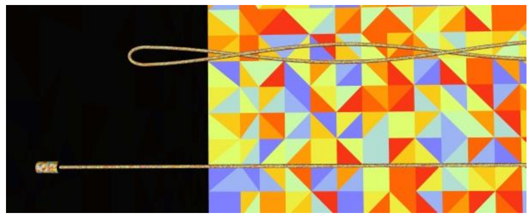
The problem defined in Section II is described for numerical modelling purposes using University of Nottingham (UoN) in-house geometry software that provides a triangulated surface representation of the structure. The single wire is built as a metal cylinder. Both ends of the single wire are connected to the cores of two coaxial probes, respectively. One of them is modelled as port 1 in Fig.1 (b) to excite the fundamental TEM mode and the other one is modelled as port 4 to terminate the wire.

The twisted wire pair is built by twisting two metal cylinders using a bifilar helix model. The circular cross-section of each wire is discretized by a N_1-sided polygon (where N_1 is an integer number). Each wire is then represented by N_2 piecewise linear segments (N_2 is also an integer number) that follow a helical path rotating around the axis of the twisted wires in such a manner that each wire's cross section remains perpendicular to its own axis. Figure 2 shows one example of a two wire twisted pair built with the UoN in-house geometry software.

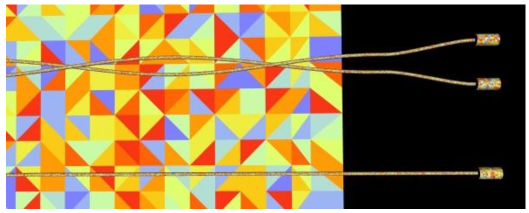
Fig. 2. The geometrical model for a two wire twisted pair.

At one end of the twisted wire pair, the wires are connected using a metal cylinder. The wires follow a curved route defined by a Bezier curve. At the other end, the two wires are connected to the cores of two coaxial probes, respectively. One of the coaxial probes is modelled as port 2 in Fig. 1 (b) to observe the coupling to the TEM mode of the twisted wire pair; the other one is modelled as port 3 in Fig. 1 (b) to terminate the wire.

The structure is meshed using our UoN in-house Delaunay Mesher software as a hybrid tetrahedral-cubic mesh. The meshed structure is shown in Fig. 3.



(a)



(b)

Fig. 3. The meshed geometry showing the triangulated interfaces between different materials: (a) left end of the structure and (b) the right end of the structure with a mesh size of 1 cm. Randomized colouring is used to show the triangle sizes and shapes.

Figures 3 (a) and (b) show the left and right ends of the structure as in Fig. 1 (b), respectively. The wires are meshed using a tetrahedral mesh, which is better able to describe curved structures, and the surrounding environment is meshed using a cuboidal mesh with a mesh size of 1 cm. Although the mesh is very small around the wires, the cell clustering enabled a time step of 0.08 ps to be used in the simulation [6]. The total number of time steps is 2,000,000. The success of meshing twisted wires with such small diameters indicates the great potential of the UTLM method in dealing with complex wire structures.

IV. CROSSTALK BETWEEN WIRES

In this section, the twisting effects on the coupling between wires are discussed for different termination conditions, using the UTLM simulation and experimental measurements.

The crosstalk between wires is described using the S_{21} parameter. In order to account for the influence of the twisting of the wires, the crosstalk between the single wire and a pair of parallel wires is also simulated and measured.

Figure 4 compares the UTLM simulation and experiment results for the crosstalk between the excitation single wire and the pair of twisted wires and the crosstalk between the single wire and the pair of parallel wires for different port 3 and 4 terminations, namely, (a) a short circuit, (b) a 50 ohms load and (c) an open circuit. The UTLM simulation results show very good agreement with those from experiment for all three terminations, so validating the accuracy of the UTLM simulations including the twisted wires.

The twisting effects on the coupling between wires can also be observed from Fig. 4. For short circuit and 50 ohms load terminations, the coupling between wires is reduced greatly in the relatively low frequencies. For example, at 1 MHz, a 20 dB crosstalk reduction for short circuit termination and a 17 dB crosstalk reduction for a 50 ohms load termination are observed in Figs. 4 (a) and (b). As the frequency increases, the crosstalk reduction becomes smaller. For open circuit termination, the twisting does not have any significant effect on the coupling between wires.

The twisting effects on the coupling between wires can be explained as follows. In the relatively low frequencies, the coupling between wires is the combination of inductive coupling and capacitive coupling as shown in [9]. Twisting the wires mainly reduces the inductive coupling, while it has no effect on the capacitive coupling. For low impedance terminations, the inductive coupling dominates the capacitive coupling, so the twisting reduces the total coupling; for high impedance terminations, the capacitive coupling dominates the inductive coupling, so the twisting has no significant effect on the total coupling.

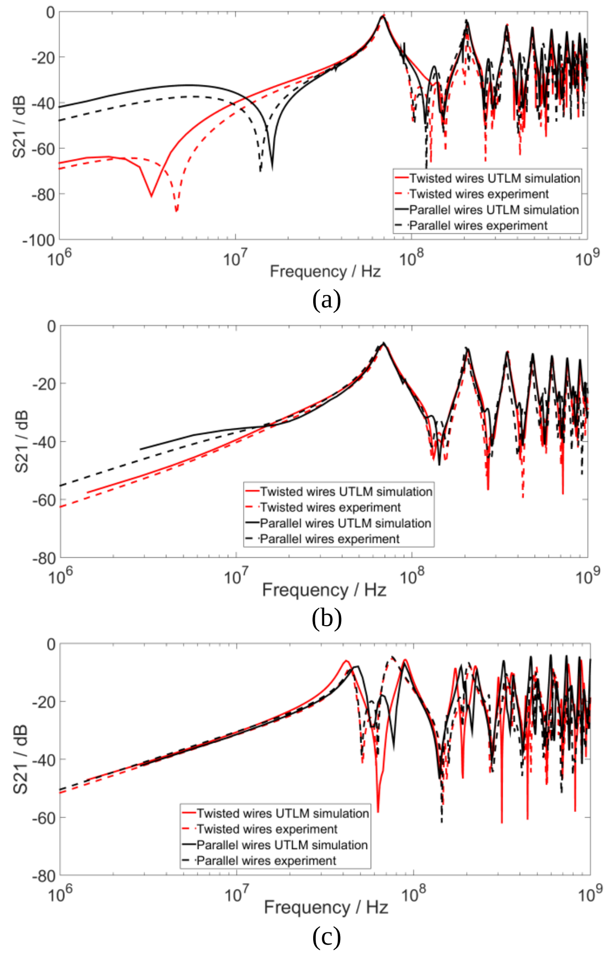


Fig. 4. Comparison of the UTLM simulation and experiment results for the crosstalk between the single wire and the pair of twisted wires and between the single wire and the pair of parallel wires, when ports 3 and 4 are terminated with: (a) a short circuit, (b) a 50 ohms load, and (c) an open circuit.

It is also noted that in Fig. 4 (a), for short circuit termination, there is a big discrepancy in the frequency at which the first dip in the crosstalk between the single wire and the twisted wire pair occurs. This can be explained since, for very low impedance (short circuit), the crosstalk at relatively low frequencies is very sensitive to the twist [9]. Even a very small non-uniformity in the twist could lead to a big change in the crosstalk. In the experiment, although every effort was made to make the twist uniform along the length, it was still unlikely to be a perfectly uniform twist. In the simulation it is quite easy to incorporate a perfect twist. To explore this further, two experiments have been undertaken, in which twisted wire pairs were made from two identical wires with a twist rate of 20 twists/m. The S_{21} parameters measured for each case are shown in Fig. 5. It is seen that the two results agree well with each other for the relatively high frequencies but not for the relatively low frequencies. The frequency at which the first dip in S_{21} occurs in each experiment is different. The same experiments were also conducted for the 50 ohms load and open circuit terminations; in both these cases, the two sets of experimental results agree very well with each other. In conclusion, it is impossible to precisely predict the coupling between the single wire and the twisted wire pair at very low termination impedance at relatively low frequencies because of the sensitivity to the exact twist. Nevertheless, the UTLM simulation is able to predict the coupling for very low termination impedance at relatively high frequencies and for low and high termination impedances over the whole frequency range, very well.

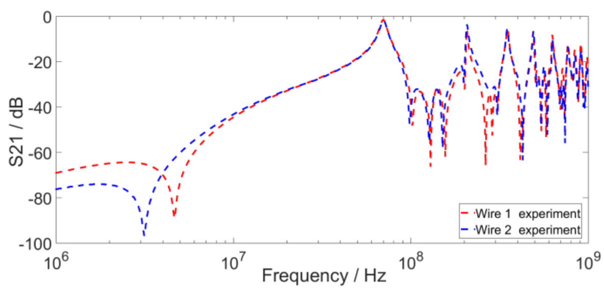


Fig. 5. The coupling between the single wire and the twisted wire pair with a short circuit termination; results from different experiments.

V. CONCLUSION

The Unstructured Transmission Line Modelling (UTLM) method has been successfully applied to model the coupling between a single wire and a pair of twisted wires by explicitly meshing the complete wire geometry. This is enabled by the wide dynamic range of mesh size that can be used within UTLM. The method shows powerful capability in meshing wires with small diameters within a large space. The accuracy of the UTLM method for this class of problems has been validated for the first time by comparing the simulated results for coupling between wires with experimental ones. The close agreement between the simulated and experimental results confirms that the UTLM method is a very useful and powerful tool that can be used for modelling complex wire structures.

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