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Crosstalk between wire pairs above a composite ground plane

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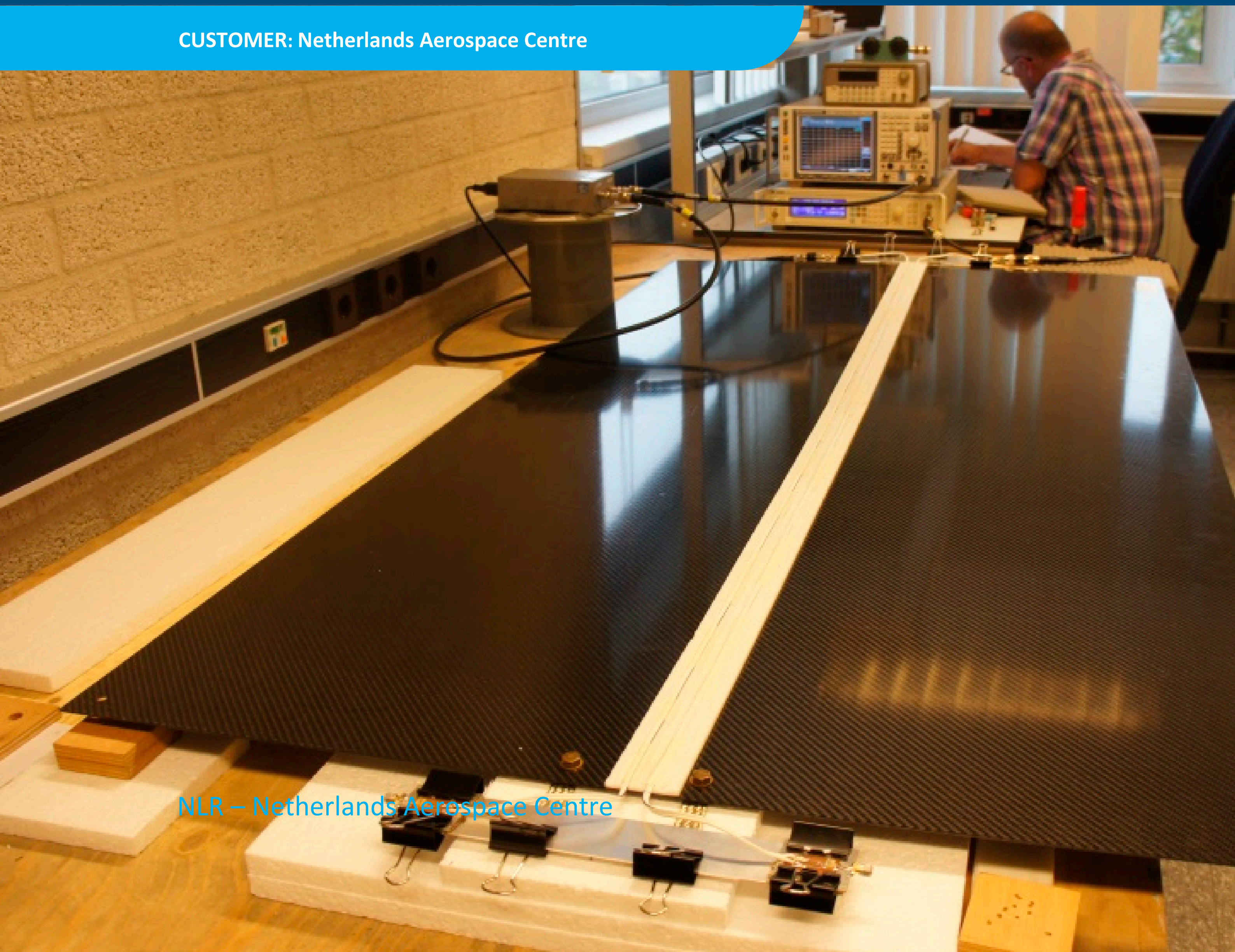

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EXECUTIVE SUMMARY

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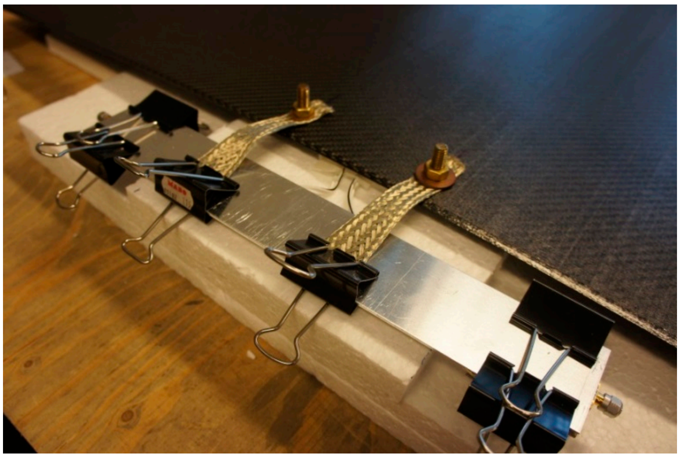

Problem area

Unintentional electromagnetic coupling between cables, which is called crosstalk, will remain one of the challenging EMC aspects on board an aircraft. Extensive research has been performed regarding crosstalk between cables that are close to metallic return conductors. However, the modern airframes comprise more and more composite materials, such as Carbon-Fibre-Reinforced-Plastic (CFRP). These light-weight materials have different electrical properties, which might have its effect on EMC aspects like crosstalk. Therefore, there is a need to investigate crosstalk between cables in the vicinity of CFRP ground planes.

Description of work

This paper discusses the crosstalk between wire pairs that are close to ground planes made of CFRP material. Three cases are considered, that comprise two wire pairs 1) in free space, 2) above a perfectly conducting ground plane and 3) above a CFRP ground plane. In these three cases crosstalk between the wire pairs is both measured and simulated, and the results are compared. Modelling of this case is

REPORT NUMBER
NLR-TP-2018-014

AUTHOR(S)
J.H.G.J. Lansink Rotgerink
J.J.P. van Es
F. Happ

REPORT CLASSIFICATION
UNCLASSIFIED

DATE
March 2018

KNOWLEDGE AREA(S)
Electronics Technology

DESCRIPTOR(S)
Crosstalk
Wire pairs
Modelling
CFRP composite
Method of Moments

performed by the Method of Moments, as implemented in the Concept-II software. The composites can be modelled by an isotropic layer with a certain thickness and conductivity.

Results and conclusions

Both measurements and simulations reveal the clear impact that the composite material has on crosstalk behaviour. For low frequencies the crosstalk behaviour is similar to that of wire pairs in free space, while for high frequencies the crosstalk behaviour resembles that of wire pairs close to an aluminium ground plane. Thus, for low frequencies the composite is electromagnetically transparent, while for higher frequencies it acts as a conducting ground plane.
Explanation for the interesting frequency behaviour of composites can be found in the skin effect. For frequencies such that the ground plane is thin compared to the skin depth, the panel will be transparent. The transition to conducting behaviour takes place at the frequency for which the skin depth and thickness of the panel are of the same order of magnitude.

Applicability

The results of measurements and simulations can be used to understand the effect of CFRP composites on crosstalk behaviour. Simulation results show that skin effect is the underlying cause of this interesting, frequency dependent, behaviour. This result can be used in reverse engineering, to obtain an equivalent conductivity of the composite material. From available measurements between crosstalk above such a composite ground plane, the observed transition frequency can be used to calculate this conductivity by making use of formulas for the skin effect.

GENERAL NOTE
This report is based on a presentation held at the 2016 International symposium on Electromagnetic Compatibility (EMC Europe), Wroclaw, September 5-9. Proceedings are found on: https://doi.org/10.1109/EMCEurope.2016.7739201.

NLR
Anthony Fokkerweg 2
1059 CM Amsterdam
p) +31 88 511 3113 f) +31 88 511 3210
e) info@nlr.nl i) www.nlr.nl

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AUTHOR(S):

J.H.G.J. Lansink Rotgerink NLR
J.J.P. van Es NLR
F. Happ Technische Universität Hamburg-Harburg

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DISTRIBUTION	**Unlimited**
CLASSIFICATION OF TITLE	**UNCLASSIFIED**

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J.H.G.J. Lansink Rotgerink	J. Verpoorte	M. Keuning
DATE 080318	DATE 080318	DATE 200318

Contents

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Crosstalk between wire pairs above a composite ground plane

J.H.G.J. Lansink Rotgerink[1], F. Happ[2], J.J.P. van Es[3]
[1] Aerospace Systems Division, Netherlands Aerospace Centre, Marknesse, the Netherlands, Jesper.Lansink.Rotgerink@nlr.nl
[2] Institute of Electromagnetic Theory, Technische Universität Hamburg-Harburg, Hamburg, Germany, Fabian.Happ@tuhh.de
[3] Aerospace Systems Division, Netherlands Aerospace Centre, Marknesse, the Netherlands, Jan-Joris.van.Es@nlr.nl

***Abstract*—Crosstalk between two wire pairs in three different configurations is compared to investigate the influence of replacing aluminium by carbon-fibre-reinforced plastic composite material in ground returns. Measurements and simulations show the same interesting effect involving a transition frequency at which the influence of the composite ground plane changes. For low frequencies it acts as a transparent layer on crosstalk behaviour, whereas for higher frequencies it can significantly decrease crosstalk levels. This phenomenon can be explained physically by investigating the skin effect of the composite ground plane. Reverse engineering can even lead to an estimation of the conductivity of the composite material when a crosstalk measurement is at hand.**

Keywords—Crosstalk; ground plane; carbon-fibre-reinforced-plastic; composites; skin effect; electromagnetic compatibility

I. INTRODUCTION

Nowadays modern airframes like Boeing's Dreamliner comprise a lot of Carbon-Fibre-Reinforced Plastic (CFRP) and other composites. Introduction of these composite airframes causes significant weight reduction compared to more conventional aluminium designs. The light-weight composite airframes can be produced with sufficient strength, but its different electrical properties introduce the necessity to reinvestigate the electromagnetic compatibility (EMC) of future aircraft. In the European project "Smart Fixed Wing Aircraft Integrated Technology Demonstrator" (SFWA-ITD), funded by R&T program Clean Sky, new technologies for active flow and load control are investigated. The installation of these new technologies requires also novel architectures for Electrical Wiring and Interconnection Systems. With the aim to reduce the amount of wiring for the new flow and load control technologies there is an interest to use data-on-power communication. The installation of data-on-power lines close to CFRP panels requires knowledge about the effects of these panels on unintentional electromagnetic coupling between data-on-power lines and other wiring nearby. The electromagnetic coupling between wiring systems is usually referred to as crosstalk. The research in the present paper has been performed as part of the SFWA Integrative Active Component Demonstrator (IACD).

Crosstalk is frequently investigated for wiring systems in the vicinity of perfectly conducting or aluminium ground planes [1], [2]. The good conductivity of such return conductors causes good protection against external fields. Moreover placing wire pairs close to aluminium parts can also significantly decrease crosstalk [3]. Composites like CFRP have lower conductivity, which might influence protection from external fields as well as crosstalk behaviour. The objective of the present paper is to investigate the effects of a CFRP ground plane on the crosstalk between wire pairs close to such a ground plane by means of measurements and simulations. Crosstalk measurements were performed between wire pairs in free space, close to an aluminium ground plane and close to a CFRP ground plane. The lower conductivity of the CFRP material appears to have a clear impact on the crosstalk behaviour. Computer simulations are performed to justify and explain the observed effects. For accurate modelling of the composite ground plane the full-wave simulation tool Concept-II enables the use of an isotropic layer on the surface of a body. For crosstalk between wire pairs in free space and above an aluminium ground plane, Multi-conductor Transmission Line (MTL) simulations based on the ideas of Paul [4] are also given as reference.

The outline of this paper is as follows. Section II describes the full-wave computational modelling of crosstalk between wire pairs in free space and above aluminium and CFRP ground planes. The test setup for measurement of crosstalk between wire pairs in these three different configurations is described in section III. Results of all crosstalk simulations and measurements are presented in section IV. Due to the lower conductivity of the CFRP material, the skin depth of the CFRP ground plane appears to be a relevant parameter, which is discussed in section V. The conclusions of the present research are presented in section VI.

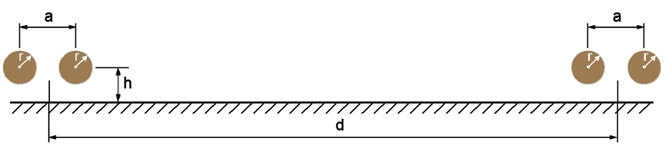

Fig. 1. Cross section of the test case with two parallel wire pairs above a ground plane

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Clean Sky Joint Technology Initiative under grant agreement number CSJU-GAM-SFWA-2008-001.

978-1-5090-1416-3/16/$31.00 ©2016 IEEE

II. Modelling crosstalk above composite ground planes

The computational modelling of crosstalk between wire pairs aims to simulate accurately the measurement setup given in section III. Fig. 1 gives an illustration of the cross section of the wire pairs above a ground plane. Two wire pairs are placed parallel at an equal height *h* of 4 mm above a ground plane. The separation distance *d* between the pairs equals 20 mm, whereas the intra-pair separation *a* equals 2.125 mm. The length ℓ of the transmission lines (TLs) is 1.8 m and the radius of the wires *r* is 0.56 mm. In simulation the dimensions of both the aluminium and CFRP ground plane equal 2 m by 0.5 m, which is large enough to avoid edge effects. The width of the measured ground planes is equal to 1 m. The aluminium and CFRP have a thickness of 1.3 mm. In simulations, both wire pairs are terminated with a differential impedance R_d equal to 112.5 Ω.

A. Method of Moments and isotropic layers

For the numerical calculations of all three situations an implementation of the Method of Moments (MoM) [5] is used. The MoM [6] is a full-wave electromagnetic field solver, which can calculate solutions to Maxwell's equations in the presence of field sources and boundary conditions that are enforced on surfaces. An advantage of MoM is that only the surfaces have to be discretized and not the whole volume of the computational domain.

Simulation of thin layers in the MoM with a standard approach could lead to numerical instabilities because two surfaces for the both sides of the layer would have to be defined, which are very close to each other. In addition this would increase the number of unknowns. To avoid this, a special kind of treatment for thin layers has been developed in [7], in which an analytical solution for the wave propagation inside the layer is combined with the MoM. Utilisation of this solution within the full-wave solver is achieved by creating a dielectric body, of which the entire enclosing surface, or part of it, can be assigned as such a thin isotropic layer (see for instance Fig. 2). When the surroundings of CFRP are free space the body can be given the properties of air. The layer technique is valid if the wave number inside the layer is considerably higher than in the surrounding space. Moreover the layer should be thin compared to the overall dimensions of the introduced dielectric body. The results of this method have been shown to be very accurate, even in the low-frequency region [8].

In principle every single layer of CFRP is an anisotropically conducting layer, where the direction of the main conductivity depends on the direction of the fibres in that layer. The CFRP consists of several of those layers. Investigations for the shielding effectiveness of such a structure have shown that an equivalent isotropic conductivity for the overall material can be used [9]. This approximation is used in this paper as well.

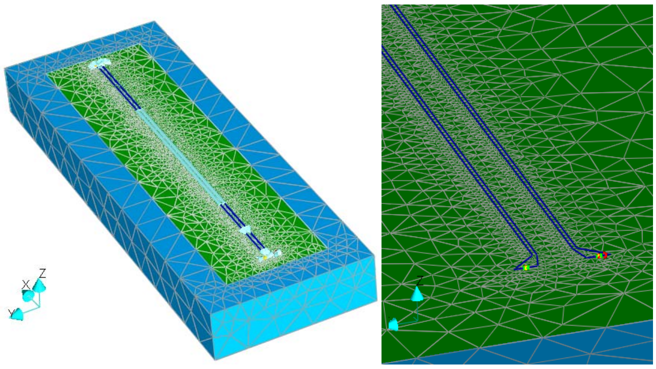

Fig. 2. Simulation setup for the case with a CFRP ground plane, in which the green surface represents the composite and the blue dielectric body is needed to construct the layer (left). Close up view of the terminations with voltage source (red) and the termination impedances (light green) above the ground plane (right).

B. Crosstalk simulations

Models of the two test cases involving wire pairs in free space and above an aluminium ground plane are obtained by creating four wires of 1.8 m length at the positions corresponding to the cross sections in Fig. 1. The surrounding of the wiring is given a relative permittivity ε_r equal to 2 to account for insulation around the wires and the foam that is included in the measurement setup. Termination networks as shown in Fig. 2 are created by using three small wire sections. The full-wave solver prescribes a limitation on how short wire segments can be when having wires of the specified radius *r*. This limitation is not violated when using the presented termination of the wire pairs. The central of the three termination wire sections carries a load equal to a differential mode impedance R_d. A voltage source is added to the centre wire of one of the four termination networks. Voltage probes are used to obtain the voltages at all terminations of both transmission lines across a certain frequency range. Finally because of its large dimensions, the aluminium ground plane can be modelled by an ideal and infinite ground plane.

Near-end crosstalk γ_{NE} is then defined as the voltage at the source side of the victim transmission line V_V, divided by that near the source in the culprit transmission line V_C. Usually crosstalk is given in dB:

$$\gamma_{NE} = 20\log_{10}\left(\frac{V_V}{V_C}\right). \tag{1}$$

For the simulation of crosstalk between two wire pairs above a CFRP ground plane, the MoM with an isotropic layer is applied. Therefore the model consisting of two surfaces which is shown in Fig. 2 is created. A first surface is for the ground plane itself (green), where the layer technique is used to model the thickness, dielectric constant and the conductivity. Together with the second surface (blue) the dielectric body is formed, which is given a relative permittivity of 2, with the usual dielectric boundary conditions. The properties given to the isotropic layer that models CFRP have values equal to σ=16.500 S/m and $\varepsilon_r = 2$.

The thickness of the plane equals 1.3 mm. The value for this effective conductivity was found by reverse engineering, which will be explained in the section V of this paper.

III. Measurement Setup

The three situations of wire pairs in free space and above a CFRP and aluminium ground plane described in the previous section have also been measured. Two photos of the setup for the CFRP ground plane are given in Fig. 3. The CFRP ground plane consists of 6 layers. In each layer the fibres comprise two perpendicular directions, respectively -45 degrees and 45 degrees in the second and fifth layer, and 0 degrees and 90 degrees in the other four layers.

Moulds made of rohacell foam are used to position the two wire pairs at the desired orientation and spacing over the complete length of the setup (1.8 m). Spacers made of polystyrene foam are used to set the distance between the wire pairs and the ground plane. These foams have no electric conductivity and a dielectric constant slightly greater than unity. A layer of polystyrene foam also separates the experiment from the table top.

To avoid edge effects, the ground planes have a width of 1 m, which is large compared to the spacing between the wire pairs and the height of the wire pairs above the plane. For the case of the CFRP ground plane, at each end the ground plane has a low impedance connection with the terminating circuits in the form of two tinned copper braids, as can be seen from Fig. 3.

At both ends of the 1.80 m parallel stretch along which the crosstalk occurs, the separation between the wires is quickly increased before they are terminated. The termination circuit for both sides of the transmission lines is illustrated in Fig. 4. The differential impedances R_d between the wire pairs given in Fig. 4 are equal to 112.5 Ω. The common mode impedances R_c are relatively high with a value of 450 Ω. Therefore nearly all currents are flowing through the two wires of a wire pair. This justifies the simplification in simulations, in which these ground connections with common mode impedances are neglected. In the MoM simulation the wire pairs are only terminated by the differential mode impedances R_d. Apart from these termination circuits in Fig. 4, RF transformers (Mini-Circuits ADT2-1T) are included to convert between the symmetric transmission lines of the wires pairs and the asymmetric transmission lines of the external coax cables and signal generator. The frequency-dependent transmission of the transformers is calibrated out of the measurement results.

The culprit wire is fed with a CW signal from an IFR 2023B signal generator. The signal has maximum available output power (+13 dBm) and the frequency is stepped through the range of interest. The crosstalk signal in the victim wire is amplified before it is measured using a Rohde&Schwarz FSW signal analyzer. A reference measurement is performed to calibrate out the amplification/attenuation of for instance the measurement amplifier, RF transformers and cables.

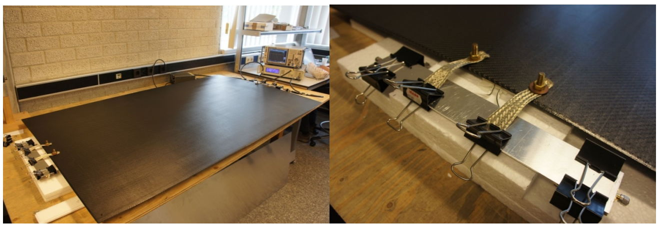

Fig. 3. Measurement setup for the case with CFRP ground plane (left). The connections of the baluns, which are attached to the aluminium strip, to the ground plane are ensured by metallic shields (right).

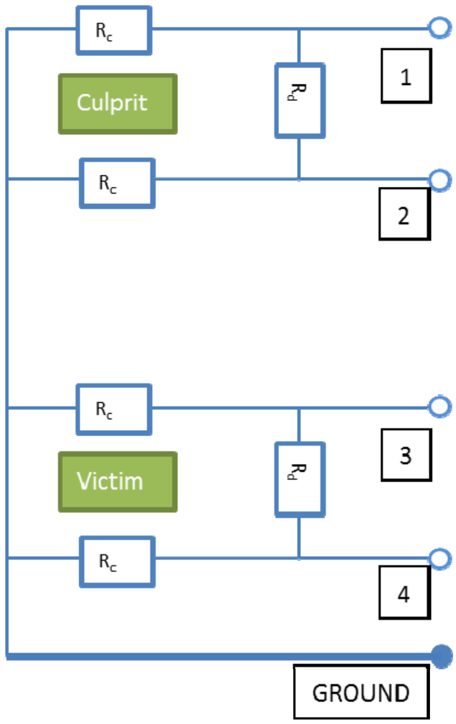

Fig. 4. Termination network for two wire pairs above a ground plane.

IV. Results

Results for full-wave simulations explained in section II are given in Fig. 5. Near-end differential mode crosstalk between the two wire pairs in free space and above an aluminium and CFRP ground plane is given respectively in blue, red and yellow. Corresponding measured crosstalk levels are also given, respectively with the purple, green and light blue results. Measurements and simulations match very well. As follows from analysis in [3] indeed crosstalk levels close to an aluminium ground plane are lower than in free space for the entire frequency region in both measurement and simulation. This difference will increase when the wire pairs are placed closer to ground or further apart. The configuration with the CFRP ground plane shows interesting behaviour in the frequency domain. For low frequencies the measured near-end crosstalk levels are similar to that between wire pairs in free space. The CFRP ground plane seems to have no effect on crosstalk in this frequency region. Around 1-6 MHz a transition takes place, and for higher frequencies the values are equal to those of crosstalk between wire pairs above an aluminium ground plane. Evidently, the CFRP ground plane behaves as a conducting ground return for frequencies higher than 1-6 MHz. The full-wave simulation results show the same effect. Only for low frequencies crosstalk levels in MoM simulations show some extra losses which appear to be absent in measurement. This might be a combined effect of numerical difficulty for a relatively high radius of the wires compared to the height above ground plane, as well as the approximation of CFRP as an isotropic layer. More research is desired to improve this result. Beside this small low-frequency difference the transition region of simulations matches very well to measurements.

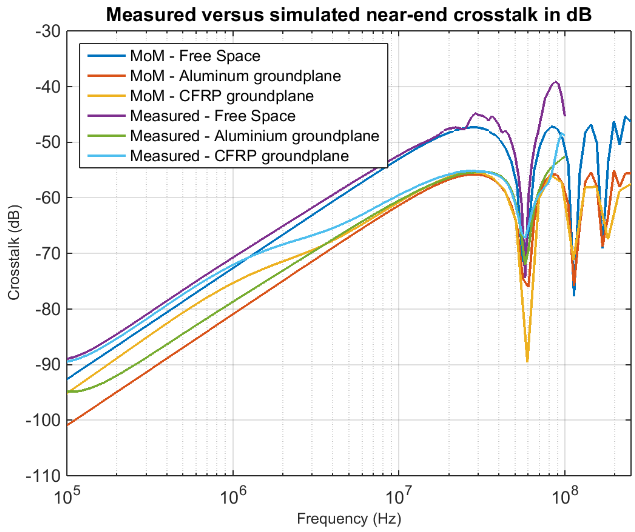

Fig. 5. Simulated near-end crosstalk levels between two wire pairs in free space (blue) and above a aluminium (red) and CFRP (yellow) ground plane, generated with MoM. Corresponding measurements are given in respectively purple, green and light blue.

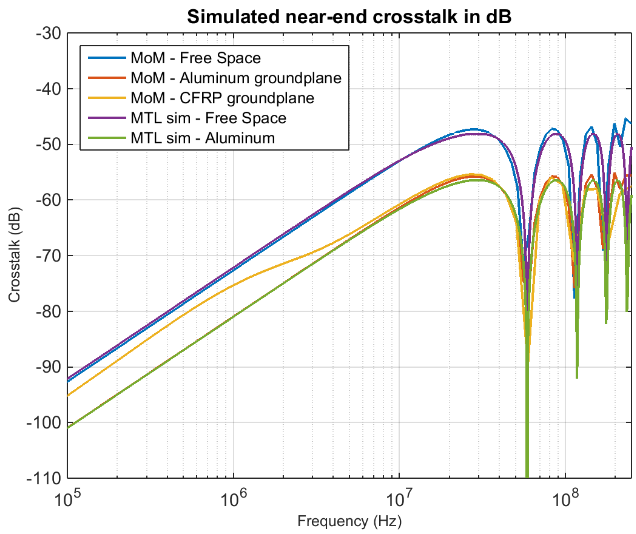

Fig. 6. Simulated near-end crosstalk levels given in Fig. 5 in blue, red and yellow, compared to MTL simulations in purple and green for wire pairs in free space respectively above an aluminium ground plane.

In Fig. 6 the MoM simulations are compared to MTL simulations for the cable configurations with wire pairs in free space and above aluminium. These MTL simulations use the solutions of the MTL equations given by Paul [4]. The perfect match that these results show illustrates that the simulated full-wave results correspond with theory. Indeed, as predicted in [3] crosstalk decreases when an aluminium ground plane is included close to the wires. When aluminium is replaced by CFRP one can benefit from this decrease only for high enough frequencies, in this case higher than 6 MHz.

V. Skin Effect

Physically, the effects that are observed in both measurements and simulations when replacing the aluminium by CFRP material, can be explained by the skin effect. This skin effect becomes important for frequencies where the skin depth becomes smaller than the thickness of the ground plane, in which the skin depth is given by:

$$\delta = \frac{1}{\sqrt{f \pi \sigma \mu}} \tag{2}$$

Equation (2) states that for a certain material with magnetic permeability μ and conductivity σ the skin depth decreases with frequency. This is also illustrated in Fig. 7, in which the skin depth is plotted against frequency f. This figure includes a dashed line indicating the thickness t of the CFRP panel, which is 1.3 mm. For frequencies where the skin depth reaches a magnitude similar to that of the thickness of the plate, currents start to flow only on the surface of the material, instead of through its entire volume. In this case this implies only currents on the top of the CFRP plane, which is also where currents flow in case of an aluminium ground plane. This explains that for frequencies where the skin depth is significant, crosstalk levels are equal to those for wire pairs above a conducting ground plane.

This physical explanation can also be utilised to find an approximation for the effective conductivity of composite material. Suppose this electrical property is not known, but crosstalk measurements are available. By using the transition frequency and the inverse of (2) an estimation for the conductivity can be found. In this case the effective conductivity for the CFRP ground plane of 16.500 S/m has been derived by the observation that when δ is about twice the thickness of the plate the crosstalk curve is at the steepest point of transition between behaviour of wire pairs in free space and above conducting material. Since in measurements this corresponds approximately to f equal to 2.5 MHz, application of the inverse of (2) indeed leads to the given conductivity.

Fig. 8 illustrates that the effective conductivity of the CFRP ground plane can indeed be estimated by only this transition frequency. By changing σ from 16.500 S/m to either 40.000 S/m or 5.000 S/m, for which skin depth is shown in Fig. 7 (purple and green lines), the high- and low-frequency levels of crosstalk are unchanged. Only the frequency at which the transition occurs is changed: it decreases when the conductivity is increased and vice versa.

The transition effect observed in crosstalk values above CFRP ground planes could also appear for aluminium ground planes. The high conductivity of aluminium causes the effect to take place for much lower frequencies. This is indeed illustrated by the yellow curve in Fig. 7, which shows that the skin effect for aluminium is significantly lower than for CFRP, by which a similar transition will never take place in the entire frequency region of interest of this paper.

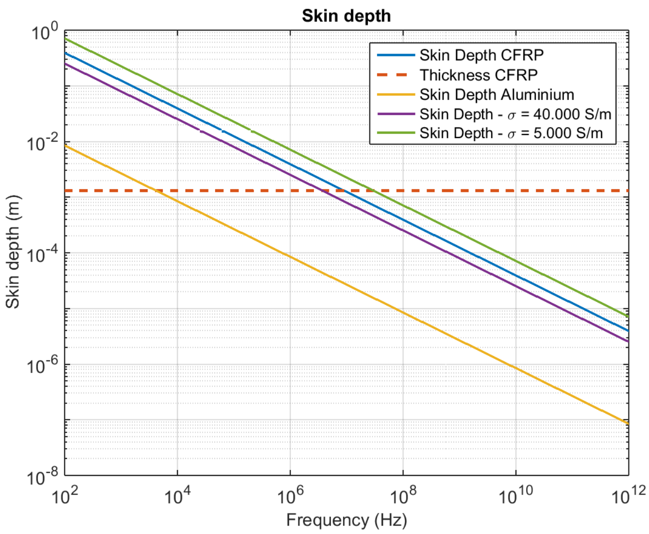

Fig. 7. Skin depth of CFRP (blue) and aluminium (yellow) versus frequency. The dashed red line indicates the thickness of the CFRP ground plane. Purple and green lines indicate the skin depths for two other conductivities, for which crosstalk is also given in Fig. 8.

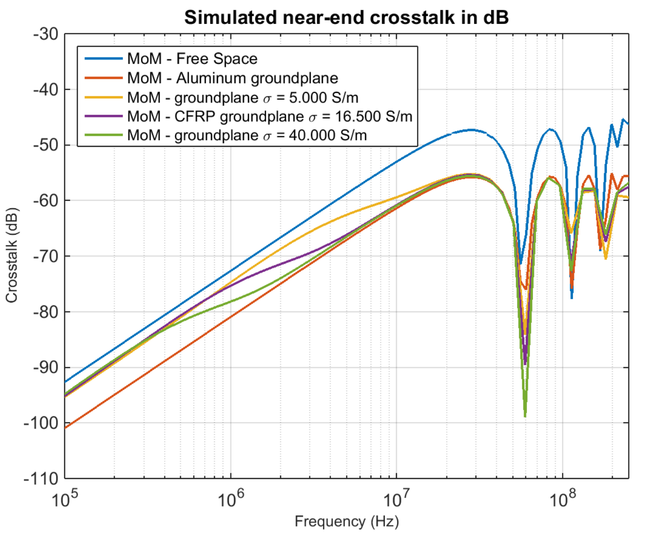

Fig. 8. Simulated crosstalk results between wire pairs in free space and above an aluminium ground plane given in respectively blue and red. Yellow, purple and green results indicate the effect to crosstalk levels when changing the CFRP conductivity from 16.500 S/m to lower and higher values.

VI. Conclusions

In this paper measurements and full-wave MoM simulations of crosstalk between two wire pairs in three different cases have been analysed. To investigate the electromagnetic effect of replacing aluminium by CFRP composite parts in airplanes, wire pairs have been placed close to ground planes of these two materials. Crosstalk levels were analysed and compared to a third situation in which the ground plane was removed. The comparison revealed that the lower conductivity of the CFRP material has a clear impact on the crosstalk behaviour. In both simulations and measurements a transition appeared that separates low- and high-frequency behaviour of crosstalk in the vicinity of CFRP material. In measurements crosstalk is not affected by the presence of the CFRP ground plane for low frequencies. The CFRP appears to be electromagnetically transparent and crosstalk behaviour is similar to that in free space. However, for higher frequencies the crosstalk above the CFRP ground plane is equal to that of an aluminium plane. Both the measured transition frequencies as well as high-frequency crosstalk levels match very well to simulations. For lower frequencies the CFRP in simulations introduces a small decrease of crosstalk levels.

Analysing simulation results reveals a physical explanation for the transition in crosstalk behaviour. The lower conductivity of the CFRP material causes the skin depth to play an important role. Starting at a transition frequency that can be calculated from electrical properties and the thickness of CFRP, the skin effect causes the behaviour of the CFRP ground plane to be similar to conducting material. This implies that by simple reverse engineering a crosstalk measurement could yield an estimation of the effective conductivity of the composite material, by making use of expressions for skin depth.

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NLR

Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113 f) +31 88 511 3210
e) info@nlr.nl i) www.nlr.nl