EMC aspects of compact wiring for future aircraft

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***Abstract*—The installation of wiring in future aircraft will become a big challenge. Available space for wiring will decrease, while the amount of wiring will increase, since more and more aircraft systems will be electronically driven instead of hydraulically. It is proposed to make wiring systems more compact. The aim of this paper is to investigate EMC aspects of this compact wiring by simulations and measurements in a representative part of a smart wing of a future aircraft.**

Keywords*—Electrical wiring, crosstalk, Aircraft, wing, electro-mechanical actuator

I. Introduction

Since many years the aviation industry is pushing the development of technologies for making aviation more sustainable in the future. Reduction of fuel consumption and reduction of CO2 and NOx emissions can be achieved by the integration of more efficient propulsion systems (such as Counter-Rotating Open Rotors (CRORs)), hybrid electric propulsion and the application of smart wings [1]. Such wings include the use of active flow and load control concepts in several parts of the wing with the aim to reduce the aerodynamic drag. In addition, hydraulic systems are being replaced by electrically powered systems, which results in More Electric Aircraft (MEA) platforms. On traditional commercial platforms, the Environmental Control System (ECS), Wing Ice Protection System (IPS) and pneumatic systems for actuation of flight control surfaces use hot air bled from the engine to 'power' the systems. On an MEA platform this bleed air is not required, because the systems are electrically driven. Such technology developments towards an MEA will increase the amount of electrical wiring, while the space for wiring in many parts of the aircraft reduces. As a consequence, there is a big challenge for the integration and the interconnection of electrical systems in aircraft. The solution proposed in this paper is to design the wiring explicitly for the electrical system architecture of the MEA platform and to make the wiring more compact.

The compact wiring concept is based upon reducing the separation distance between separate bundles and reducing the separation distance between bundles and adjacent structures. Wiring systems consist of bundles that are separated to avoid signal interference between adjacent bundles, to enable heat convection via airflow in between the bundles and for safety purposes like avoidance of arcing between wiring and fuel tank boundaries. When the separation distances are reduced to make wiring more compact, it has to be secured that no interference, overheating or arcing will occur. Therefore, research is required in the field of Electro-Magnetic Compatibility (EMC) and thermal analysis. The aim of the present paper is to discuss possible interference between wire pairs in bundles. To this end, crosstalk between wire pairs in bundles has been analyzed for two typical aircraft cable bundles in a setup that represents a metallic wing box of an aircraft. Possible effects of replacing the metallic skin of this wing box by a Carbon Fibre Reinforced Plastic (CFRP) skin on crosstalk between wire pairs have been presented in [2]. It was observed that for lower frequencies the CFRP skin behaves like an EM transparent skin, while for high frequencies the CFRP skin behaves like a metallic skin.

The outline of this paper is as follows. In section II, we present the design of compact wiring for a future smart wing of an Airbus A320 like aircraft. In section III we present the test setup. Results of crosstalk measurements and simulations are discussed in sections IV and V. Conclusions are given in section VI.

II. Design of compact wiring

Compared to conventional wiring, compact wiring can be obtained by:

- Reducing separation distances between bundles.
- Combination of separate bundles into one larger bundle.
- Moving part of the wiring from leading edge to trailing edge.

The latter cannot be applied to redundant power routing, but can be applied to for instance wiring to wing tip lighting. It is estimated that combination of all three options can yield volume reductions of up to 55%, when a reduction of separation distance of 20% is applied. Estimations of weight reductions are less evident, and probably also less substantial than this decrease in volume.

The design of the compact wiring in this paper concerns the electrical system architecture of a typical Short Range Aircraft (SRA) such as an Airbus A320, with the following modifications:

- The engine (an efficient CROR) is installed at the rear instead of the wing.
- The wing is smart: it is extended with a so-called Krueger Flap (to preserve upper surface laminar flow and to ensure effectiveness of National Laminar Flow) and an Active Flow Control System (AFCS) on the flaps to decrease the aerodynamic resistance.

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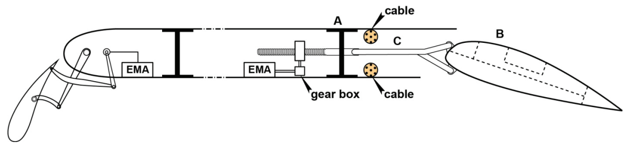

Fig. 1. Cross section of smart wing concept with electrically driven leading edge Krueger flap and trailing edge flap

TABLE I. OVERVIEW OF SYSTEMS TO BE INSTALLED IN A FUTURE SMART WING

Wing's systems	**Concept**
Flight-control systems	Electrically Actuated (EMA)
Active Flow Control System (AFCS)	Pulsed Jet Actuators
Landing-gear system	Electrically Actuated (EMA)
Fuel system	Conventional electrical sensors and electrical fuel pump
Anti-icing system	Skin integrated electrical anti-icing
Lighting	LED Navigation Light and Anti Collision Light

An impression of a smart wing with electrically driven Krueger Flap and flap is shown in Fig. 1. In case the Krueger Flap is retracted into the wing, there will be almost no space left for cabling.

The dimensions and wing shape are governed by an A320 wing. The wing will have flaps on both leading and trailing edge, which are both driven by Electro-Mechanical Actuators (EMAs). An inventory about primary systems to be installed in such a future wing is presented in Table I. The routing architecture for the wiring follows from the conceptual distribution of systems as shown in the wing layout of Fig. 2.

A compact Electrical Wiring & Interconnection System (EWIS) has been developed for the part of the wing as indicated by 'IACD sample' in Fig. 2. For the testing of the compact wiring, a typical rectangular wing box has been manufactured. The dimensions of this wing box are 180x180x21 cm (width x length x height). These dimensions are representative for the inner wing of an A320 aircraft. This rectangular wing box is further referred to as Iron Bird of the Integrated Active Component Demonstrator (IACD) and was developed in the JTI CleanSky1 project SFWA. The wing box contains aluminum frames (U-profiles) and planar aluminum skins on the lower and upper part. The trailing edge flap is a copy of the flap that was used for the evaluation of an Active Flow Control System (AFCS) with Pulsed Jet Actuators. The Iron Bird is equipped with an EMA and compact wiring. The EMA is used to move the flaps. The IACD was developed for EMC analysis of the compact EWIS and for testing of a movable component for the installation of AFCS in the trailing edge flap [3].

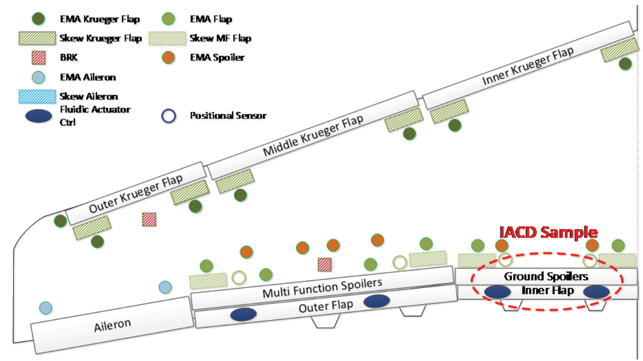

Fig. 2. Concept for installation of electrical systems in a future smart wing. The compact wiring in this paper is designed for the indicated location.

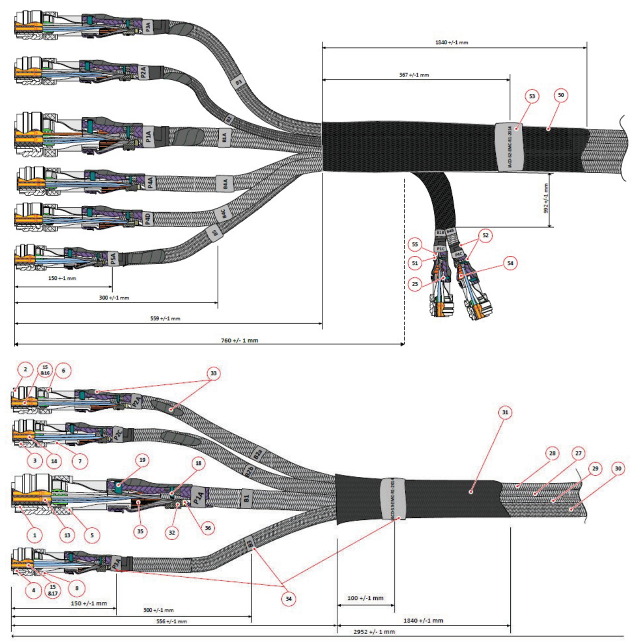

Fig. 3. Illustrations of cable bundles R1 (top) and R3 (bottom), as tested in IACD Iron Bird.

The present EWIS design for IACD, which is representative for actual EMC design, consists of two shielded cable bundles with several branches that carry separate shields. The bundles are finished by several representative connectors, as shown in Fig. 3. Both bundles are mounted on the U-profile at the rear side of the wing box. However, bundle R1 has a branch that is directed to systems on the front side of the wing.

III. TEST SETUP

An artist impression of the installation of compact EWIS in the Iron Bird of IACD is shown in Fig. 4. The cables are installed on the U-profile at the rear side. These are illustrated by the yellow and blue tubes from left to right, with one yellow branch going to the front side. The connector plugs of the wiring branches have been mounted on U-profile structures with receptacle connectors (see Fig. 5). The U-profile structure also contains test setup components such as "*Balanced-to-*

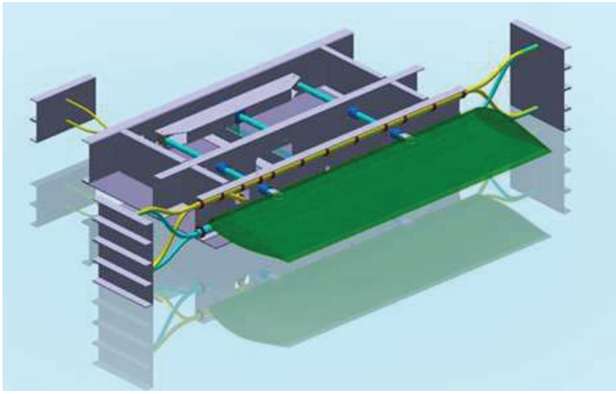

Fig. 4. Artist impression of EWIS harnesses installed in IACD connected to measure EMC crosstalk. Cables (yellow and blue tubes) at the rear end above and below the flap, with one branch (yellow) going to the front end.

Unbalanced" conversion circuits (Balun boards) to convert the balanced RF signals on the wire pairs to unbalanced RF signals suitable for high frequency measurements. All crosstalk measurements are performed between two wire pairs in near-end (NE) and far-end (FE) configuration. We define crosstalk in the following way:

$$\gamma_{NE/FE} = \frac{V_{v,NE/FE}}{V_c}. \qquad (1)$$

Here V_c is the voltage at the source side of the generator or culprit transmission line (TL). Near-end or far-end crosstalk is obtained in (1) by taking the voltage in the NE or FE termination of the victim TL, $V_{v,NE}$ or $V_{v,FE}$. Moreover, in this paper we primarily discuss differential-mode crosstalk.

The crosstalk measurements are performed by applying a continuous wave (CW) RF signal in the culprit TL with the RF generator and measuring the resulting voltage in the victim circuit. A pre-amplifier is required for measuring very low levels of crosstalk.

IV. Crosstalk measurements

Measurements of crosstalk between Twisted Unshielded Pairs (TUP) will be discussed in this section. Both inter-bundle and intra-bundle measurements will be considered. In the first case, the culprit TUP is located in bundle R3 and the victim TUP is located in R1 (or vice versa), while in the second case the culprit is located in the same bundle as the victim. Due to the frequency range of operation of the Baluns, which is up to 450 MHz, the given measurements are not fully reliable above this frequency.

Crosstalk behaviour is always influenced by termination impedances of the transmission lines. For low-impedance circuits inductive crosstalk will dominate and twisting will reduce the crosstalk but shielding will not. For high-impedance circuits we will have mainly capacitive crosstalk and shielding is needed to reduce crosstalk, not twisting. In the crosstalk measurements, the differential mode termination is equal to 100 Ω, for which one can usually expect both types of coupling to be significant.

Fig. 5. Test setup with cable bundles connected to U-profile with connector receptacles. The relevant pins of the connector receptacles are connected to the Balun boards.

A. Inter-bundle measurements

Inter-bundle crosstalk measurements were performed between a fixed subset of all available TUPs. To investigate the influence of bundle separation distances, these measurements were repeated after the bundles were dismantled from the IACD demonstrator setup as shown in Fig. 5. Crosstalk levels were measured with no separation between the bundles (giving 35 mm heart to heart separation), and with a bundle separation of 150 mm. Both near-end crosstalk (NEXT) and far-end crosstalk (FEXT) measurements have been performed. The level of NEXT is always equal to or higher than the level of FEXT, since NEXT equals the sum of inductive and capacitive crosstalk, as opposed FEXT, which equals the difference of those two. Some results of NEXT measurements are shown in Fig. 6 for the two different separation distances, as well as the bundles installed in the wing-box. It is observed that the crosstalk levels are all low enough to reach noise levels, and these levels don't change when the separation distance is minimal. This noise doesn't increase with the well-known 20 dB/octave for low frequencies. Moreover, the metal parts of the wing-box don't influence crosstalk levels when the bundle is installed.

B. Intra-bundle measurements

For the intra-bundle measurements the following cases are considered: 1) inter-branch measurements, where the culprit and victim wire pairs are located in different cable branches but within the same cable bundle, and 2) intra-branch measurements with culprit and victim wire pairs located within the same cable branch.

Inter-branch crosstalk measurements have been performed in both cable bundles R1 and R3. Examples of NEXT measurements between several TUPs in cable bundle R3 are given in Fig. 7. Different cable types were taken as both victim and culprit. The crosstalk levels vary depending on the cable type and the position of the wire pairs in the bundle. In all measured cases the level of crosstalk is very low, since at least two shields of the branches are involved. Influences of these shields on crosstalk behaviour are observed in the plateaus of some traces in Fig. 7 (black, blue and yellow trace). These shields cause the lack of 20 dB/octave increase

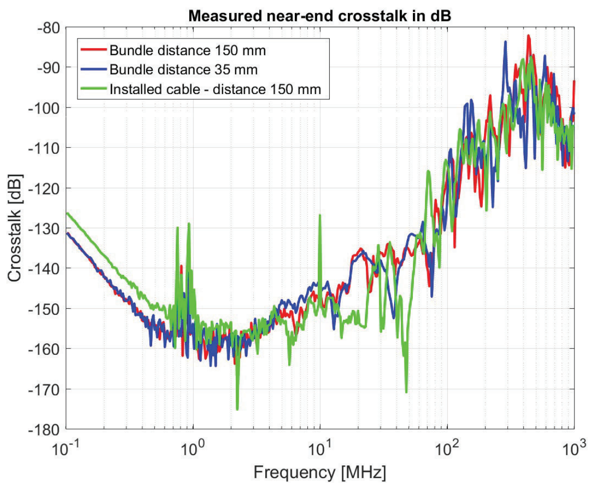

Fig. 6. Near-end crosstalk between a TUP in bundle R1 and a TUP in R3.

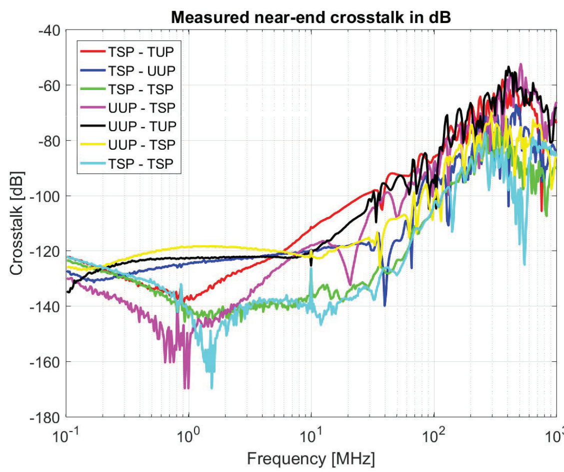

Fig. 7. Inter-branch Crosstalk (NEXT) in R3 for various cable and branch combinations.

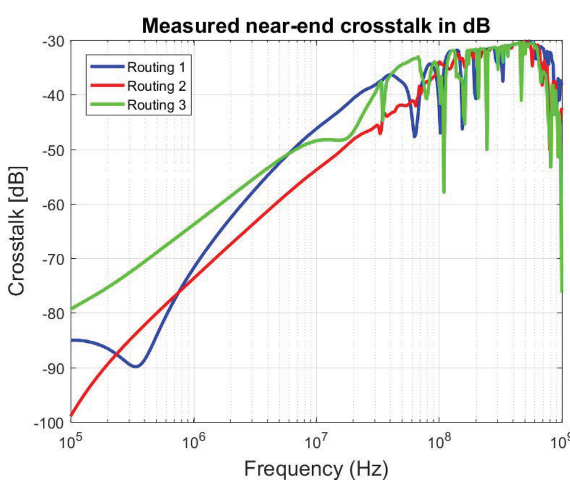

Fig. 8. NEXT crosstalk for different routing of the wire pairs: 1) two pairs in parallel to the front end, 2) one pair to front end, one pair along trailing edge, 3) two pairs in parallel along trailing edge.

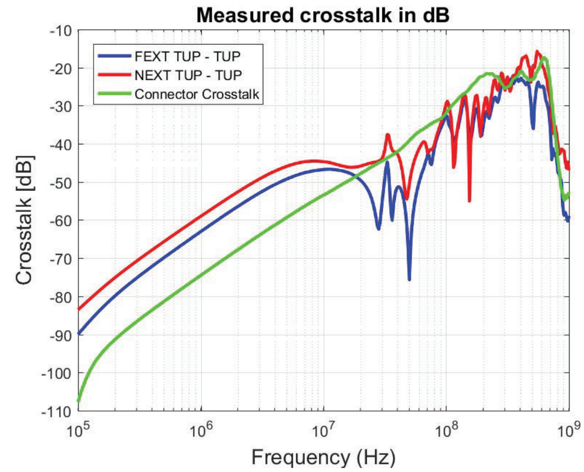

Fig. 9. Crosstalk between two TUPs (NE & FE) and between connector pins.

in the low-frequency area. Especially in this lower frequency range differences in crosstalk can be observed. In general, when yet another level of shielding is involved (Twisted Shielded Pair (TSP)), the measurements reach noise levels, except for the combination of an Unshielded, Untwisted Pair (UUP) with a TSP. Finally, variations in crosstalk between equal combinations of cable types are most likely due to differences in the position of the culprit and victim wire pairs with respect to each other.

Intra-branch crosstalk measurements were performed between wire pairs in cable bundles R1 and R3. In Fig. 8 the crosstalk is shown between Twisted Unshielded Pairs (TUPs) in the same branch in R1. The variations in crosstalk are due to the different routing for each combination, and thus the length over which the wire pairs run in parallel. This is largest for the pink curve and smallest for the green curve. In general, this intra-branch crosstalk is at least 20 dB higher than the inter-branch crosstalk.

When measuring crosstalk between wire pairs in a cable bundle terminated on the same connector, one should be careful that the crosstalk in the connector does not exceed the crosstalk in the cable. Although the wire pairs run in parallel only over a short length in the connector, they are usually unshielded, untwisted and closely spaced. In Fig. 9 an example is given of the crosstalk in the connector versus the crosstalk in the cable bundle (including the connector) between TUPs. In this case, the connector crosstalk is sufficiently low to perform accurate measurements on the cable bundle. However, other measurements indicated that whenever individual cables are shielded (TSPs) and terminated on the same connector, then connector crosstalk dominates. In Fig. 9 also the influence of the length of the wire pair on the resonances can be seen. The short length of the pins in the connector causes the resonances to start at a higher frequency than for the complete cable.

V. CROSSTALK SIMULATIONS

This section discusses crosstalk simulations between cables in a single branch of cable bundle R3. Typical cable bundles used in aircraft, such as those illustrated in section II, can be

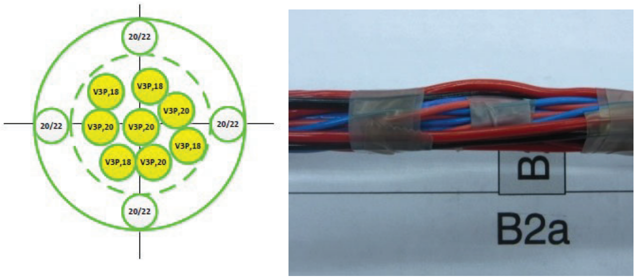

Fig. 10. Cross section (left, yellow circle = TUP, white circle = UUP) and photo (right) of part of the branch in cable bundle R3 that has been simulated.

modelled as non-uniform multi-conductor transmission lines. Creating accurate models of such bundles is highly complicated, since the bundles contain twisted wire pairs, both shielded and unshielded, and the entire bundles of cables are twisted as well. Moreover, practical cable bundles comprise a lot of uncertainties, for instance in the conductor positions along the line, the twist regularity, transfer impedances of shields, et cetera. As a consequence, predicting exact crosstalk levels is not possible. However, one can perform statistical analyses, which is done in for instance [4]-[6]. In this paper, simulations of deterministic realisations of cable bundles are performed, that do take into account uncertainties in for instance cable positions. Instead of performing statistics, we observe only trends in crosstalk behaviour, based on various combinations of wire pairs inside a cable bundle.

Simulations have been performed for crosstalk between the different cable types inside a single branch of cable bundle R3. This branch consists a group of 8 TUPs, surrounded by 4 single UUPs (see also Fig. 10). The branch as shown in the picture has a diameter of roughly 4.5 mm. All twisted wire pairs have a fixed amount of 51 twists per meter. In simulations, twist irregularity has not been taken into account. However, the meandering of wire pairs throughout the cable length, and the twisting of the group of twisted pairs has been taken into account. As part of the entire cable bundle R3, this branch was also enclosed by a braided shield. For the simulation of intra-branch crosstalk between the cables inside this branch, the uniform cascaded sections method as extension of the multi-conductor transmission line theory by Paul [7] is used, which is also used by many others, e.g. [8]-[9]. The random displacement spline interpolation (RDSI) algorithm is implemented to include the effect of meandering cables [10].

Results of crosstalk simulations between 6 combinations of the four UUPs are shown in Fig. 11. By symmetry of the cable cross section multiple traces are equal in the low-frequency range. Measurements between 6 combinations of UUPs in the same branch are shown in Fig. 13. Below 450 MHz, the cut-off frequency for the Baluns, crosstalk trends in simulations and measurements are comparable. For low-frequencies the spreading in measured values is slightly higher. Moreover, traces of different combinations of UUPs are not equal, as is the case in simulation. This is caused by UUPs being assumed to be entirely uniform in simulations, while in practice also the wires of a UUP change positions (see the photo in Fig. 10).

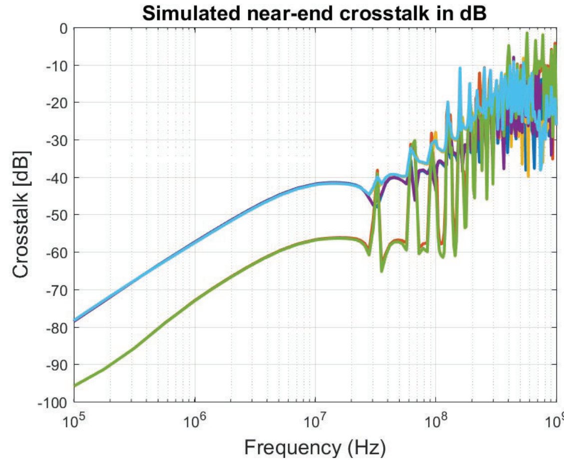

Fig. 11. Simulated near-end crosstalk between all combinations of UUPs in one branch of bundle R3.

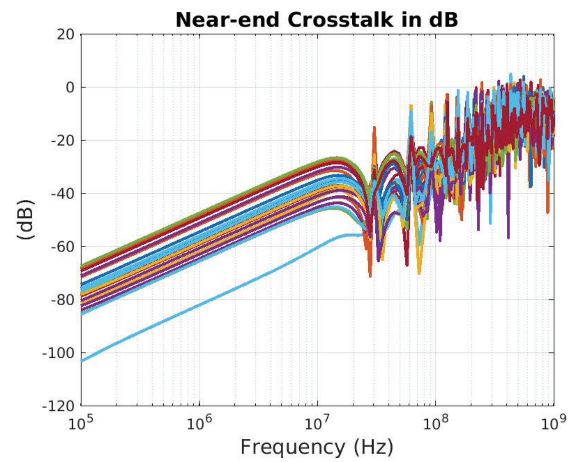

Fig. 12. Simulated near-end crosstalk between all combinations of TUPs in one branch of bundle R3.

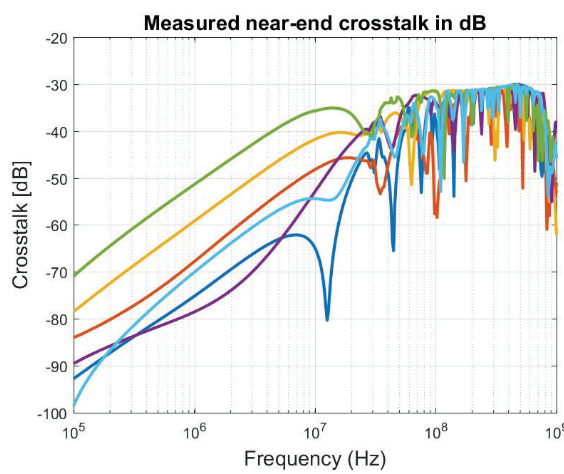

Fig. 13. Measured near-end crosstalk between all combinations of UUPs in one branch of bundle R3.

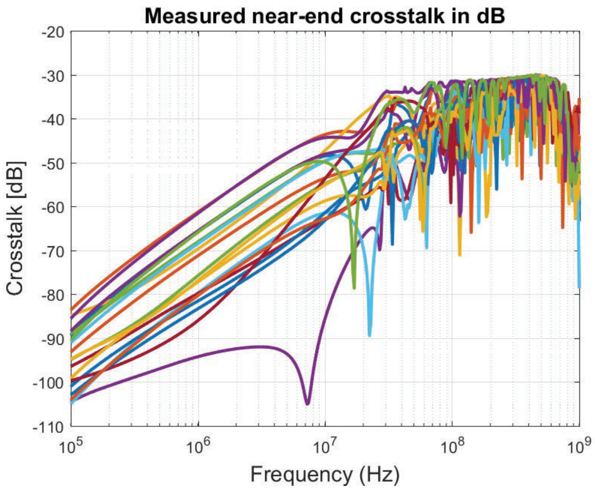

Fig. 14. Measured near-end crosstalk between all combinations of TUPs in one branch of bundle R3.

Simulated crosstalk values between all combinations of TUPs in the same branch are shown in Fig. 12. Compared to simulations shown in Fig. 11, on the one hand the twisting in TUPs should decrease crosstalk, while on the other hand separation distances between the TUPs are smaller than between the UUPs, which increases crosstalk. The combination on average leads to comparable crosstalk levels. Moreover, trends in crosstalk behaviour relate quite well to measurements shown in Fig. 14. In contrast to crosstalk between UUPs, these measurements show less spreading than corresponding simulations. In simulations twist irregularity is not taken into account, yielding more extreme best and worst cases regarding the cancellation of electromagnetic fields by twisting.

VI. Conclusions

This paper describes the design and manufacturing of compact wiring with appropriate harnesses for a wing section of a future Smart Fixed Wing Aircraft. For a selected set of wire-pairs far-end and near-end crosstalk measurements have been performed to determine inter-bundle and intra-bundle crosstalk. The inter-bundle crosstalk measurements show very low crosstalk levels (<-120 dB for frequencies up to 100 MHz). Such crosstalk levels are considered negligible in this configuration and can be attributed to the quality of the present harness (quality of shields for cables). The influence of the separation between the cable bundles and the contribution of the metal parts of the wing-box demonstrator to the reduction of crosstalk showed to be insignificant.

Intra-bundle crosstalk measurements have also been executed on a large number of different signal lines. Such coupling can be separated into inter-branch crosstalk (between two cables in different branches inside one cable bundle) and intra-branch crosstalk (between two cables inside the same branch). In general, intra-branch crosstalk is higher than inter-branch crosstalk because of two reasons: 1) the inter-branch set-up involves the extra harness around the branches, and 2) the influence of the connector is higher for the intra-branch set-up, since the TLs are attached to the same connector, while they are attached to different connectors for the inter-branch set-up (see Fig. 3). Therefore, the measured crosstalk is a combination of the crosstalk between the signal lines and between the connector pins. For shielded lines, the contribution of the connector crosstalk dominates the overall crosstalk behaviour. For unshielded signal lines, the crosstalk in the cable is dominant. The simulations in this paper show similar trends as observed in the measurements. For UUPs, the measured crosstalk values show slightly larger variations, since traces of UUPs are different in the measured and modeled cable bundle. For TUPs, the measurements show less spreading than the simulations, since twist irregularity in the measured bundles has not been considered in the modelling.

Finally, the inter-branch crosstalk measurements in the present generic wing-box show relatively low crosstalk levels (<-80 to -100 dB) for both far-end and near-end crosstalk due to shields around the branches.

For the design of bundles in the wing section additional exterior shields have been applied around the bundles with the aim to reduce EMI so that the bundles can be placed close to each other. As a consequence, the inter-bundle crosstalk is very low (<-120dB) which makes compact wiring feasible. Then, the separation distances can be reduced which results in a significant reduction of space occupied. This contributes to successful implementation of technologies like Natural Laminar Flow and Active Flow Control Systems in space constrained areas in smart wings.

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