A crosstalk sensitivity analysis on bundles of twisted wire pairs

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***Abstract*— Uncertainties in the geometry of complex cable bundles highly complicate crosstalk predictions. A change in for instance the position or the twist rate of individual cables in a bundle might have an impact on crosstalk levels. Application of sensitivity analyses can indicate which model parameters are most sensitive, and in which cabling configurations. In this paper, the efficient Stochastic Reduced Order Models (SROM) method is used to perform such a sensitivity analysis. It is applied to two cable bundles with two and seven twisted wire pairs, respectively. Monte Carlo simulations are performed to determine the accuracy of the SROM method. The sensitivity of parameters like inter-pair and intra-pair separation distance and the twist rate is determined in two different cases. Moreover, the effects of bundle twist and cable meandering to parameter sensitivities is investigated.**

Keywords*— *crosstalk; multi-conductor transmission line; sensitivity analysis; cable meandering; bundle twist

I. Introduction

The ongoing development towards More Electric Aircraft (MEA), in which electric systems replace for instance pneumatic, hydraulic and mechanical systems, requires an enormous amount of onboard cables – up to multiple hundreds of kilometres for larger aircraft types. Since the available space for cables is still decreasing, electromagnetic coupling or crosstalk remains an important EMC aspect.

An Electrical Wiring Interconnection System (EWIS) contains complex cable bundles with uncertainties in various model parameters, such as separation distances and twist rates. Such uncertainties can highly complicate a correct prediction of crosstalk levels. A sensitivity analysis can then be useful to detect the most sensitive parameters. Moreover, such analysis assists in the development of design rules that can be used in optimisation of cable bundles, or for early decisions about routing and segregation of low-risk signals. Sensitivity analysis can be performed in various ways. Paul experimentally determined sensitivities of crosstalk with respect to wire positions [1]. Analysing closed-form expressions for their level of dependency on different parameters is another alternative [2]. For more complex cable bundles statistical methods provide a structured way to determine the mean crosstalk and the corresponding standard deviation in various configurations. Therefore, such statistical methods are frequently used to perform sensitivity analysis.

Multiple run algorithms such as the conventional Monte Carlo (MC) method are a well-known way of determining statistical moments of a stochastic process, from which sensitivity can be computed. In [3] the authors use MC simulations to investigate the influence of non-uniform twisting and incomplete final twists to radiated susceptibility. For cable bundles with non-uniformities such as twisting and meandering of cables, MC computation times can become severe. Since MC requires a large amount of runs, other statistical methods are preferred. Many efficient alternatives have been presented in literature [4]-[6]. In this paper, we use the Stochastic Reduced Order Models (SROM) method, which was also used by Fei et al. [7] in an EMC context. This statistical method is non-intrusive and quite straight forward to implement. The authors of [7] applied the method to crosstalk in the simple configuration of two wires above a ground plane. In this paper, the SROM method is applied to two cable bundles that contain two and seven twisted wire pairs, respectively. In two crosstalk configurations concerning these bundles, sensitivity with respect to inter-pair and intra-pair separation distance is investigated. Moreover, twist rate sensitivity is discussed for twisted pairs with equal and unequal twist rates. Thereafter, in the second bundle both the bundle twist and the meandering of individual cables are included to investigate their effects on various parameter sensitivities. Realisations of meandering cables are obtained by the Random Displacement Spline Interpolation (RDSI) method [8].

In section II of this paper we introduce the cable that is used for sensitivity analysis, including the models that are used for electromagnetic simulations. Section III discusses the sensitivity analysis, while in section IV the results are given and section V contains the conclusions.

II. Cable modeling

Consider the two cable bundles of which the cross sections are shown in Fig. 1. Both bundles are enclosed by a bundle shield and contain two and seven twisted wire pairs (TWPs), respectively. For both cases, the radii of the shield r_s and wires r_w are 6.8 mm and 0.4 mm, respectively. Moreover, the wire pairs are all separated 3.4 mm from the centre of the bundle, i.e. d_i = 3.4 mm (except for the centre pair in Fig. 1b). The intra-pair separation distance a between the individual wires of a single pair is 1.1 mm. The length of the cable bundles ℓ is 1 m and the terminations of all wire pairs are as in Fig. 5 of

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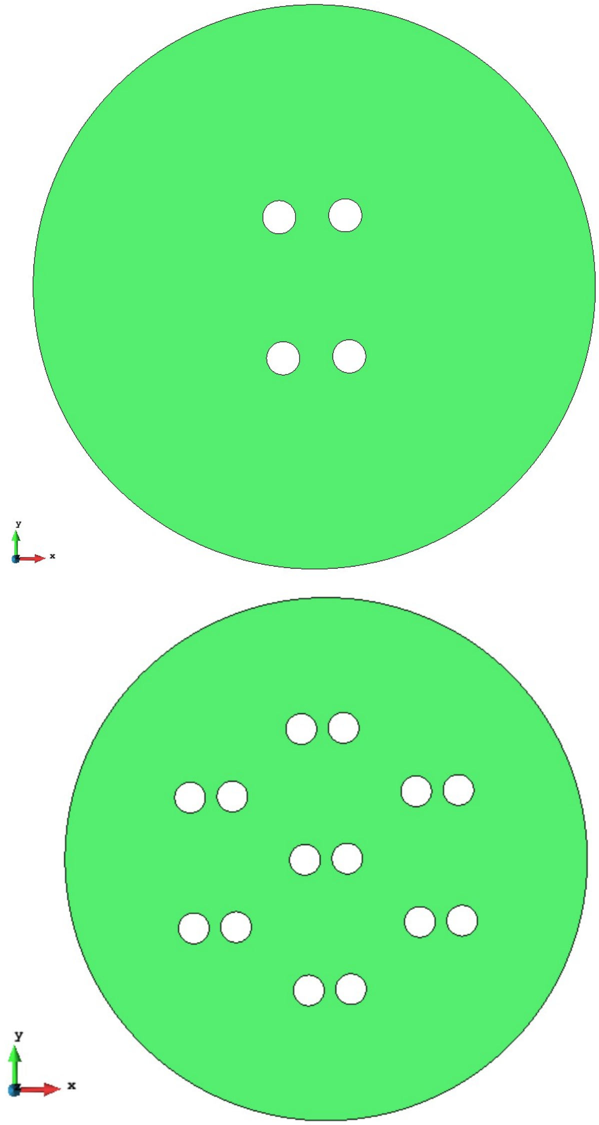

Fig. 1. Cross sections of the two bundles to which sensitvity analysis is performed: a) a bundle with 2 twisted pairs and b) a bundle with 7 twisted pairs.

[2]. Here the differential mode resistance is either 50 Ω or 1000 Ω to define a low and high-impedance case, respectively.

Cable bundles as shown in Fig. 1 can be regarded as multi-conductor transmission lines (MTLs). An MTL is characterised by its per-unit-length (PUL) parameter matrices: inductance **L**, capacitance **C**, conductance **G** and resistance **R**. For the simulations in this paper conductance and resistance are assumed to be zero. For the most accurate determination of the inductance and capacitance matrices numerical methods can be applied. However, for reasons of computation time, as well as the fact that all conductors in the bundles are separated by at least two layers of insulation, we use the analytical expressions for widely separated conductors in a cylindrical shield, which are given by Paul [9]:

$$\begin{aligned} l_{ii} &= \frac{\mu_0}{2\pi}\ln\left(\frac{r_S^2 - d_i^2}{r_S r_w}\right) \\ l_{ij} &= \frac{\mu_0}{4\pi}\ln\left(\frac{1}{r_S}\sqrt{\frac{\left(d_i d_j\right)^2 + r_S^4 - 2d_i d_j r_S^2\cos\theta_{ij}}{d_i^{\,2} + d_j^2 - 2d_i d_j\cos\theta_{ij}}}\right). \end{aligned} \tag{1}$$

Here d_i is the separation distance from conductor i to the centre of the bundle, θ_{ij} the angle between conductors i and j in the bundle, and μ_0 the free space permeability. It is assumed that the bundle contains a homogeneous medium, by which the capacitance matrix follows from:

$$\mathbf{C} = \mu\varepsilon\mathbf{L}^{-1}. \tag{2}$$

This implies that the insulation of wires can only be taken into account by an effective, homogeneous relative permittivity. Modelling the actual effects of nonhomogeneous media like insulation requires the computationally expensive numerical estimation of PUL parameters. However, the permittivity will only affect the average crosstalk and corresponding resonance frequencies, but not the sensitivity with respect to other model parameters. Therefore, in this paper we choose the medium inside the bundle to be free space.

The cable bundles in Fig. 1 are highly non-uniform along their length, which is caused by the combination of twisted wire pairs, bundle twisting and meandering cables. Therefore, the uniform cascaded sections method as extension to Paul's MTL theory is used to simulate the crosstalk behaviour in the bundles, as it has also been applied in [10]. The meandering of the cables along the length of the bundle is included via the Random Displacement Spline Interpolation (RDSI) algorithm [8]. This is applied to each twisted wire pair. To this extend, the start and end positions of all TWP centres are fixed in accordance with Fig. 1. Along its length, the cable is subdivided into 15 segments, to which a random displacement is added in the two orthogonal cross sectional directions. These displacements are normally distributed with mean zero and standard deviation taken equal to $d_i/2$. The segments are subdivided into smaller sub-segments on which spline interpolation is performed. This yields for TWP i an x and y-coordinate on each sub-segment, which are denoted by $x_{twpi,1}\left(z_k\right)$ and $y_{twpi,1}\left(z_k\right)$ and where the longitudinal position is z_k. The length of the sub-segments is determined by the minimum of either a tenth of a wavelength or the amount of cascaded sections that are needed to accurately model one twist. To the interpolated coordinates on these sub-segments the bundle twist is introduced by the following addition:

$$\begin{aligned} x_{twpi}\left(z_k\right) &= x_{twpi,1}\left(z_k\right) + x_{B,i}\left(z_k\right) \\ y_{twpi}\left(z_k\right) &= y_{twpi,1}\left(z_k\right) + y_{B,i}\left(z_k\right), \end{aligned} \tag{3}$$

in which:

$$\begin{aligned} x_{B,i}\left(z_k\right) &= d_{twpi}\sin\left(\theta_B\left(z_k\right)\right) \\ y_{B,i}\left(z_k\right) &= d_{twpi}\cos\left(\theta_B\left(z_k\right)\right) \end{aligned} \quad \text{with} \quad \theta_B\left(z_k\right) = \theta_0 + \frac{2\pi z_k N_{BTw}}{\ell}. \tag{4}$$

Here $x_{B,i}$ and $y_{B,i}$ describe the deviations that are caused by the bundle twist. N_{BTw} is the total amount of twists in the bundle. Usually, the length of a full bundle twist is equal to the length of the bundle divided by its diameter. Therefore, we take N_{BTw} equal to the first integer number larger than the bundle length divided by this twist length. In our case, this equals 8 bundle twists.

In this way, all the positions of the centres of the twisted wire pairs along the length of the line can be computed. The positions of individual conductors are obtained by the addition of the helix form:

$$\begin{aligned} x_{h,1}(z_k) &= +(a/2)\cos(\varphi_k) \quad y_{h,1}(z_k) = +(a/2)\cos(\varphi_k) \\ x_{h,2}(z_k) &= -(a/2)\cos(\varphi_k) \quad y_{h,2}(z_k) = -(a/2)\cos(\varphi_k), \\ \text{with} \quad \varphi_k &= \alpha_{twpi} + \frac{2\pi z_k N_{tw,i}}{\ell}. \end{aligned} \tag{5}$$

With α_{twpi} the starting angle of each twisted wire pair at $z = 0$ can be controlled. In this paper, the starting angles are as shown in Fig. 1, yielding $\alpha = 0$. The positions of each conductor along the length of the line can now be computed:

$$\begin{aligned} x_{twpi,j}(z_k) &= x_{twpi}(z_k) + x_{h,j}(z_k) \\ y_{twpi,j}(z_k) &= y_{twpi}(z_k) + y_{h,j}(z_k). \end{aligned} \tag{6}$$

From this, the corresponding angles θ_{ij} and separation distances d_i inside the bundle shield can be computed, from which the inductance and capacitance can be computed by (1). Then, the cascaded multi-conductor transmission line theory is used to solve the termination currents and voltages on each conductor. From this, the near-end crosstalk is computed:

$$\gamma_{NE} = \frac{V_{v,NE}}{V_{c,NE}}. \tag{7}$$

Here $V_{v,NE}$ and $V_{c,NE}$ are the near-end differential-mode voltage in the victim wire pair and the culprit wire pair, respectively.

III. SENSITIVITY ANALYSIS

The sensitivity of crosstalk with respect to any model parameter can be defined by the ratio of standard deviations of output and input. The standard deviation, σ, should be normalised by the corresponding mean value, μ, yielding a quantity that is called the coefficient of variation c_v:

$$c_v = \frac{\sigma}{\mu}. \tag{8}$$

Then the sensitivity of crosstalk with respect to an input parameter is given by the ratio of the estimated $c_{v,\gamma}$ for crosstalk and the assumed $c_{v,i}$ in the input parameter:

$$S = \frac{c_{v,\gamma}}{c_{v,i}}. \tag{9}$$

Therefore, to determine the sensitivity with respect to various model parameters a stochastic distribution with certain mean and standard deviation is assumed for each input parameter that is under evaluation. The SROM method is then used to estimate the corresponding mean and standard deviation of the near-end crosstalk. In comparison to the Monte Carlo method, the SROM method is a multiple run method that contains a limited set of sample values for the uncertain input parameter (compare: order of 10 (SROM) versus order of 10^5 (MC) for one uncertain parameter). These samples are chosen in such a way that the SROM accurately describes the probability distribution of the input variable. An optimal SROM can be obtained by using the pattern classification method (see [7]). Output of this algorithm is a set of m realisations of the model parameter that forms the SROM, $\hat{\mathbf{x}} = (\hat{x}_1, \ldots, \hat{x}_m)$, including corresponding probabilities for each sample $\mathbf{p} = (p_1, \ldots, p_m)$. Since for sensitivity analysis we consider one parameter at a time, $\hat{x}_i$ represents a scalar sample. In this paper, we choose a number of $m = 25$ samples. This number is higher than was concluded for a single variable uncertainty in [7]. Sensitivity in for instance twist rate can be very high and therefore we use more samples to increase the accuracy of the SROM results. Still, compared to the MC method, which needs in the order of 100 thousand runs for convergence, a huge decrease in computation time can be achieved. For each realisation k the corresponding near-end crosstalk $\gamma_{NE,k}$ is computed as described in section II. Statistical moments of crosstalk are then estimated by:

$$\begin{aligned} \hat{\mu}_\gamma &= \sum_{k=1}^{m} p_k \gamma_{NE,k} \\ \hat{\sigma}_\gamma &= \sum_{k=1}^{m} p_k \left(\gamma_{NE,k} - \hat{\mu}_\gamma\right)^2. \end{aligned} \tag{10}$$

With these, the sensitivity is computed by application of (9).

A useful way of displaying sensitivity results is shown in Fig. 2. The dashed lines indicate various zones of sensitivity. Below 0 dB, the sensitivity is such that the variability in the output is less than in the input. The further below 0 dB, the more we can neglect the uncertainty in this model parameter. In the orange area, the relation between variability in input and output ranges from linear (0 dB) to quadratic (6 dB). Above

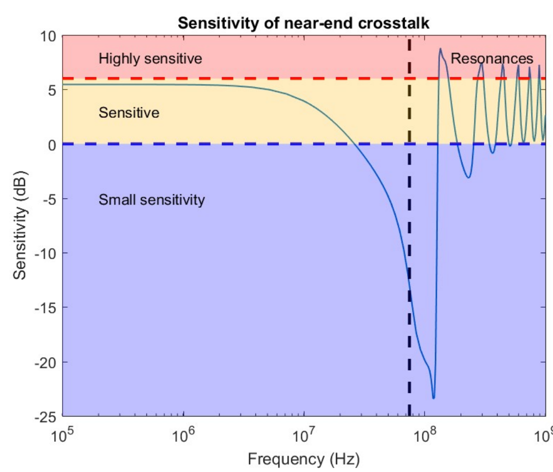

Fig. 2. Layout for sensitivity plots.

this, the sensitivity becomes really high. In the low-frequency area we can also distinguish between inductive and capacitive crosstalk by creating cases with low and high-impedance terminations. For frequencies in the resonance area the sensitivity can also obtain resonances. Moreover, when the sensitivity with respect to for instance permittivity is investigated, large peaks are expected. A slight change in permittivity will shift the resonance frequencies slightly. At such a frequency, the crosstalk value can change drastically with a small change of permittivity, while in general the effect to the entire crosstalk curve is quite small. Therefore, in this high-frequency area one has to be cautious while interpreting the sensitivity values.

IV. Simulation results

This section describes the results of sensitivity analysis. Two different situations are considered:

1. Case 1 - Crosstalk between the two twisted wire pairs in bundle 1.
2. Case 2 - Crosstalk between the centre and top twisted wire pairs in bundle 2.

In the following, firstly a comparison will be made between the sensitivity in these cases with respect to parameters like inter and intra-pair separation distance, as well as the twist rate. Here both bundle twist and cable meandering are not taken into account. The parameters under investigation are assumed to follow a normal distribution, of which mean and standard deviation will be given. Secondly, the bundle twist is included to observe its influence to parameter sensitivities. Finally, also the cable meandering is included.

In aircraft industry the application of twisted wire pairs with equal twist rate is not unthinkable. However, it is known that combinations of twisted pairs with a difference in twist rate are preferred from a crosstalk perspective. Therefore, sensitivities and average crosstalk for both cross sectional parameters and twist rates are discussed for situations concerning twisted pairs with equal and unequal twist rates.

A. No bundle twist and no meandering

Consider the cable bundles introduced in section II and assume that the only non-uniformity of the cable along its length is that of the twisting of wire pairs. Bundle twists and cable meandering are not taken into account in this section.

Fig. 3 shows the results of sensitivity analysis with respect to the inter-pair separation distance for case 1 and case 2. For case 1 only the low-impedance case is shown, for which inductive coupling is dominant. Distinction is made between the case where both pairs have the same twist rate of 51 twists per metre (tpm), and where the two pairs have different twist rates of 51 tpm and 71 tpm. For these results the computed Monte Carlo sensitivities are also shown. These are obtained by simulations of 10 thousand realisations of the separation distance. For case 1 the separation distance is assumed to be normally distributed with a mean of 6.8 mm and a standard deviation of 0.68 mm, while for case 2 the mean and standard deviation are 3.4 mm and 0.34 mm, respectively (see also Fig. 1 – case 2 considers crosstalk between centre and top TWP).

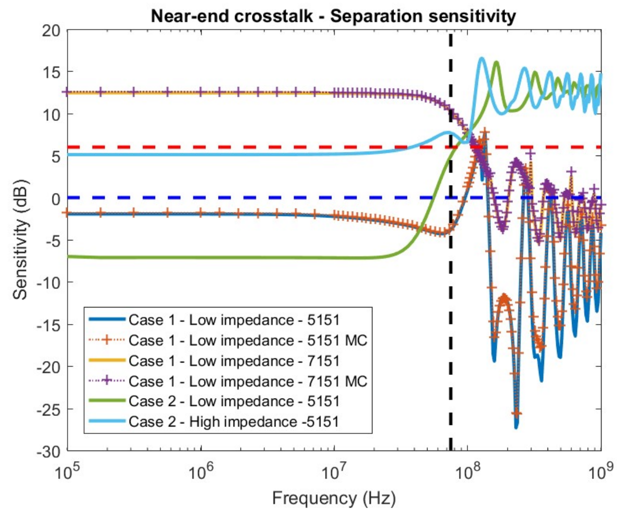

Fig. 3. Sensitivity with respect to the inter-pair separation distance. Comparison is made between sensitivities when both TWPs have a twist rate equal to 51 (blue), and when the twist rates are 71 and 51 (yellow). As validation, Monte Carlo results are also shown (red and purple with '+' markers). Finally, also the sensitivities for high and low-impedance terminations in case 2 are shown (green and light-blue).

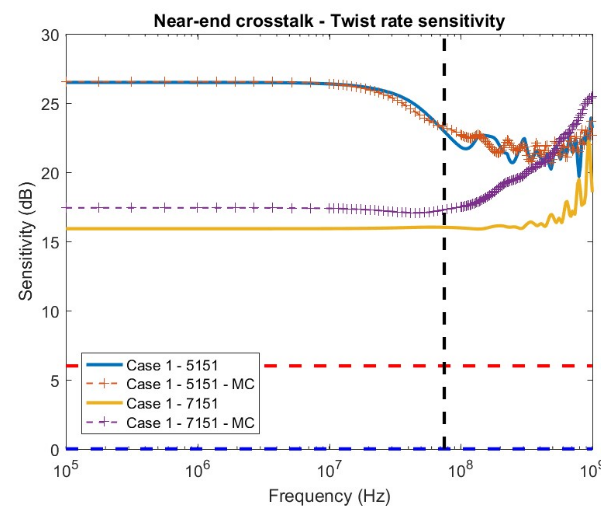

Fig. 4. Sensitivity with respect to twist rate. A comparison is made between sensitivities when both TWPs have a twist rate equal to 51 (blue), and when the twist rates are 71 and 51 (yellow). As validation, Monte Carlo results are also shown (red and purple with '+' markers).

The MC simulations validate the SROM results, since they show a perfect match for the separation distance sensitivity for both equal twist rates and different twist rates, as is shown in Fig. 3. Moreover, the results show that there can be large differences in sensitivities when the twist rate of one twisted pair is changed. The difference in sensitivity with respect to the separation distance for the case of equal twist rate is roughly 14 dB when compared to unequal twist rate. This change in twist rate also greatly decreases the average near-end crosstalk, as will be concluded from Fig. 5.

Fig. 3 also shows a sensitivity result for case 2. The average separation distance is here 3.4 mm, which is smaller than in case 1. The logarithmic terms in the inductance matrix then cause that this lower separation distance also implies a lower sensitivity on separation distance. As is shown by Fig. 3 sensitivities differ for inductive and capacitive crosstalk. In the high-impedance case the capacitive crosstalk dominates inductive crosstalk for the frequencies below the resonance area. This shows that capacitive crosstalk is roughly 12 dB more sensitive to separation distance than inductive crosstalk.

Apart from the cross sectional parameters, sensitivity analysis can also be performed with respect to twist rates of twisted wire pairs. Fig. 4 shows the results of such sensitivity analysis by the use of SROM and MC methods. In this case, 100 thousand MC simulations were used. Results of the low-impedance case are shown, since the twisting is mostly used to reduce inductive crosstalk. Both results for the case of equal and unequal twist rates are given. In Fig. 5 the corresponding mean values for near-end crosstalk are given. In the statistical simulations the victim pair is assumed to have a twist rate that is normally distributed around 51 tpm with a standard deviation of 5.1 tpm. Therefore, the twist rate can be a non-integer, yielding incomplete terminal twists. The culprit transmission line has a fixed twist rate of either 51 or 71 twists per metre. If both twisted pairs were to be modelled with complete terminal twists, a discrete distribution such as the binomial distribution with parameters $n = 104$ and $p = 51/104$ could form an alternative. Such results are not shown here.

SROM and MC sensitivity results coincide quite well in the entire frequency range when the twist rates are equal. In case the twist rates are unequal there is a difference in the results. Moreover, for various SROM simulations the sensitivity shows variability of 1 or 2 dB. Actually, even for the 1e5 MC simulations sensitivity results still show some variations. However, the average crosstalk has converged and MC and SROM results match perfectly for both cases (see Fig. 5). Apparently, these statistical estimations of the standard deviation for twist rate uncertainties are less accurate for the case with unequal twist rates in victim and culprit TWPs.

Both the SROM and MC results indicate that the average crosstalk decreases by roughly 25 dB when the twist rate of the culprit pair is changed from 51 to 71 tpm. Actually, if incomplete terminal twists would be avoided this decrease can even be larger. Also the sensitivity of crosstalk with respect to the twist rate decreases when unequal twist rates are used. However, in general crosstalk values are very sensitive with respect to these twist rates.

B. Influence of bundle twist and meandering cables

In this section, the bundle twist is included in the model to investigate its influence to sensitivity results. Subsequently, cable meandering is also taken into account. The meandering of cables along the length of the bundle introduces new stochasticity, since the deviations from the connector positions are normally distributed. In principle, statistical simulations are therefore also applicable to cable meandering, yielding an average crosstalk for the combined uncertainty in cable meandering and another model parameter. However, this

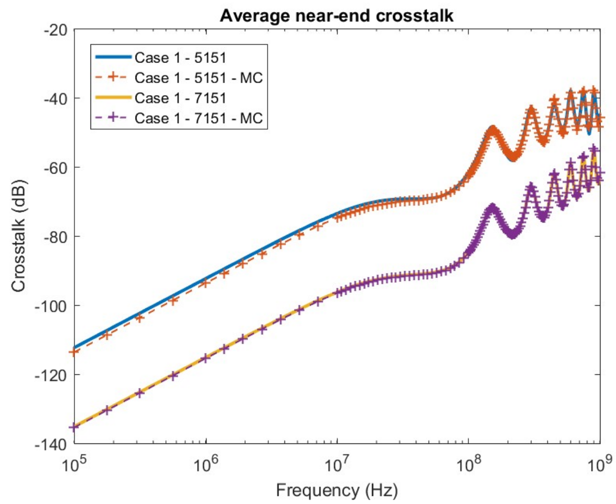

Fig. 5. Average crosstalk with uncertain victim twist rate. Results are shown when both TWPs have a twist rate equal to 51 (blue), and when the twist rates are 71 and 51 (yellow). As validation, Monte Carlo results are also shown (red and purple with '+' markers).

requires a large amount of simulation runs, and to determine whether there is any effect of cable meandering it suffices to repeat the SROM sensitivity analysis for a certain model parameter for a few realisations of meandering cables. Each realisation results in an average crosstalk and sensitivity for that specific model parameter. Sensitivities of various realisations are then compared to investigate the effect of meandering. Average values for model parameters are equal to those in the previous sections, and in this case we discuss low-impedance terminations. The intra-pair separation distance is assumed to be normally distributed with a mean of 1.1 mm and a standard deviation of 0.11 mm.

Fig. 6 shows results of sensitivity analysis for case 2 with respect to the inter and intra-pair separation distance. In both cases, the twisted pairs have equal twist rate (51 tpm). The results in this section are all given in a similar way, where the solid line represents sensitivity without bundle twist and cable meandering, the dotted line with '+' markers includes bundle twist and the dotted line with 'o' markers includes both bundle twist and cable meandering. The results in Fig. 6 show that bundle twist and cable meandering barely influence the sensitivity with respect to separation distance. For this case, only one realisation of cable meandering is shown, since other realisations yield the same result. In the high-frequency area, only the sensitivity with respect to intra-pair separation deviates slightly when the cable meandering is introduced. However, for all other sensitivities the bundle twist and cable meandering could be neglected.

Since for twist rate uncertainties SROM sensitivity values showed to be slightly unstable, Fig. 7 shows corresponding average crosstalk results when the bundle twist or cable meandering is included. Multiple realisations of cable meandering are shown, which lead to equal results for the case of equal twisting. For unequal twisting the bundle twist has no influence on the average crosstalk, while cable meandering increases the results with roughly 10 dB. However, various

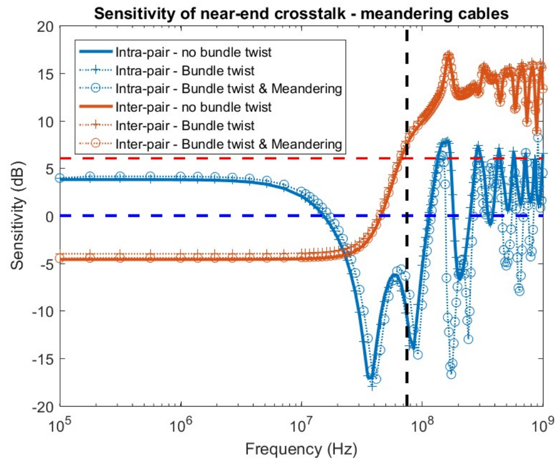

Fig. 6. Sensitivity of near-end crosstalk in case 2 with respect to the intra-pair (blue) and inter-pair (red) separation distances. The solid lines represent the case of a bundle with straight cables, i.e. no bundle twist and no meandering. For the dotted lines with '+'-signs the bundle twist is included, and for the 'o'-marked lines also cable meandering is included.

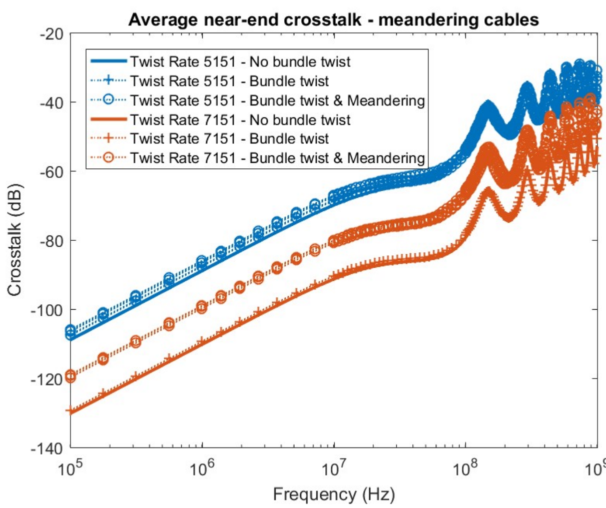

Fig. 7. Average near-end crosstalk in case 2 for twist rate uncertainty for 51 tpm versus 51 tpm (blue) and 71 tpm versus 51 tpm (red). The solid lines represent the case of a bundle with straight cables, the dotted '+'-marked lines include bundle twist and the 'o'-marked lines also include cable meandering.

realisations of meandering cables yield results that are nearly equal along the entire frequency range.

V. Conclusions

The Stochastic Reduced Order Model is applied to perform sensitivity analysis to two cable bundles containing two and seven twisted wire pairs. The SROM method can reduce computation times by a factor in the order of a thousand when compared to the Monte Carlo method. The sensitivity results have been compared to that of the Monte Carlo method. For cross sectional parameters the result is very accurate in the entire frequency range. For longitudinal parameters like the twist rate, results of the SROM method appear to be slightly unstable with variations of a few dB. However, average crosstalk is computed accurately and equal to that of MC simulations, but estimation of the standard deviation appears to be slightly less accurate for such cases.

Sensitivities with respect to the twist rate of a twisted wire pairs can be very high. Both these sensitivities and the average near-end crosstalk can be greatly reduced by using different twist rates for the culprit and victim transmission lines. Therefore, creating cable bundles with many different types of twisted pairs would be good from a crosstalk perspective.

The influence of bundle twisting and the meandering of individual cables in the bundle are discussed. For the case of twisted pairs with equal twist rates the bundle twist and cable meandering have no influence on the sensitivities with respect to inter-pair and intra-pair separation distance. Only in the high-frequency area minor changes in the intra-pair separation sensitivity are observed when cable meandering is included. For the estimation of average crosstalk in case of twist rate uncertainty, the bundle twist and cable meandering don't affect the results when twist rates are equal. If victim and culprit TWP have unequal twist rate, bundle twist does not change average crosstalk, but cable meandering should be included in the model, since it increases the estimated average near-end crosstalk.

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