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Preprint

This is the submitted version of a paper presented at *19th International Conference on Electromagnetics in Advanced Applications, ICEAA 2017, Verona, Italy, 11 September 2017 through 15 September 2017*.

Citation for the original published paper:

Malmström, J., Jonsson, L. (2017)

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In: *Proceedings of the 2017 19th International Conference on Electromagnetics in Advanced Applications, ICEAA 2017*, 8065579 (pp. 1547-1550). Institute of Electrical and Electronics Engineers (IEEE)

<https://doi.org/10.1109/ICEAA.2017.8065579>

N.B. When citing this work, cite the original published paper.

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An Effective Method for Antenna Placement on Platforms Based on the Reaction Theorem

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Abstract —

Simulations for antenna placement on large platforms are computational costly. We here suggest a very efficient method for antenna placement optimization of low-scattering antennas. The method utilizes the reaction theorem to calculate the mutual impedance between the antennas based on pre-computed electromagnetic fields. The method needs only one full-platform simulation together with post-processing of field data to estimate the coupling for all antenna positions in a given region. In the tested case, we see a speed-up with a factor of 2000, compared to full-wave simulations of every antenna position to be evaluated.

1 INTRODUCTION

When designing platforms with RF functionality, antenna placement is an important consideration to ensure electromagnetic compatibility (EMC). In antenna placement studies, the mutual coupling between antennas is a key quantity [1]. To ensure EMC, the mutual coupling should be low.

The mutual coupling can be determined from a full-wave simulation with the antennas installed on the platform. The mutual coupling usually depends strongly on the platform geometry and the antenna positions on the platform. In general, a simulation has to be performed for each antenna position to be evaluated. For large platforms, each full-wave simulation usually takes a considerable amount of time, which limits the number of antenna positions that are practically possible to evaluate.

Other methods to calculate the mutual coupling between antennas on large platforms has been proposed and investigated, see e.g. [2, 3, 4].

The reaction theorem can be used to determine mutual impedance between antennas [5, 6, 7]. It has been used in several applications recently, see e.g. [8, 9, 10], also for antennas installed on platforms.

The mutual impedance and the mutual coupling between antennas are closely related [11], in particular for weak coupling cases. Therefore, we can use the mutual impedance as a parameter for optimization instead of mutual coupling.

Figure 1: (a) The fields $\mathbf{E}_1, \mathbf{H}_1$ generated by Antenna 1, and (b) the fields $\mathbf{E}'_2, \mathbf{H}'_2$ generated by Antenna 2 in an alternative environment.

2 THEORY

The generalized reaction theorem can be formulated in terms of the mutual impedance Z_{21} between two antennas [6],

$$Z_{21} = \frac{-1}{I_{11}I'_{22}} \oint_{S_2} (\mathbf{E}'_2 \times \mathbf{H}_1 - \mathbf{E}_1 \times \mathbf{H}'_2) \cdot \hat{\mathbf{n}}_2 dS, \quad (1)$$

where the integration surface S_2 , with outward pointing normal $\hat{\mathbf{n}}_2$, encloses Antenna 2 but not Antenna 1, see Fig. 1. Antenna 1 generates the fields $\mathbf{E}_1, \mathbf{H}_1$ when excited with a current I_{11} , as in Fig. 1(a). Antenna 2 generates the fields $\mathbf{E}'_2, \mathbf{H}'_2$ when excited with a current I'_{22} , as in Fig. 1(b). The excitation currents I_{11}, I'_{22} are measured on each of the two antenna terminals. For (1) to hold, the terminal in antenna 2 must be open circuit when Antenna 1 transmits.

The generalized reaction theorem (1) allows the structure outside the integration surface to be changed when transmission with the antenna enclosed by the integration surface [6], as depicted in Fig. 1. Here, we utilize this to choose the exterior to S_2 to be empty.

We decompose $\mathbf{E}_1, \mathbf{H}_1$ as a sum of multiple scattering components as illustrated in Fig. 2. The decomposition together with the Silver-Müller radiation condition allows (1) to be reduced to [12],

$$Z_{21} = \frac{-1}{I_{11}I'_{22}} \oint_{S_2} (\mathbf{E}'_2 \times \mathbf{H}_1^+ - \mathbf{E}_1^+ \times \mathbf{H}'_2) \cdot \hat{\mathbf{n}}_2 dS. \quad (2)$$

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Figure 2: Separation of the fields E_1, H_1 generated by an antenna (left) and scattered on an arbitrary object (right) into either direct E_1^d, H_1^d and scattered fields E_1^s, H_1^s , or into outgoing E_1^+, H_1^+ and incoming fields E_1^-, H_1^- .

An approximation of the outgoing fields E_1^+, H_1^+ , can be formed by neglecting multiple scattering and only taking the direct components into account,

$$E_1^+ \approx E_1^d, \quad (3)$$

$$H_1^+ \approx H_1^d. \quad (4)$$

This approximations introduce the errors $\delta E_1, \delta H_1$

$$\delta E_1 = E_1^+ - E_1^d = \sum_{n=2,4,6,\dots}^{\infty} E_1^{s_n}, \quad (5)$$

$$\delta H_1 = H_1^+ - H_1^d = \sum_{n=2,4,6,\dots}^{\infty} H_1^{s_n}. \quad (6)$$

Note that the sums start at $n = 2$ since the first order scattering E_1^{s1}, H_1^{s1} on Antenna 2 do not affect the error. This is understood by the fact that E_1^-, H_1^- is not included in (2). The lowest order scattering component that contribute to the error is E_1^{s2}, H_1^{s2} . For low-scattering antennas, the errors $\delta E_1, \delta H_1$ will be small.

Mutual impedance and mutual coupling are closely related [11]. In a two-antenna system, the mutual coupling S_{21} is approximately proportional to the mutual impedance Z_{21} , if $|Z_{21}Z_{12}| \ll |Z_{11}Z_{22}|$. Therefore, we will consider an optimization on mutual impedance Z_{21} in this paper.

The reaction theorem, when used for analysing each antenna in separation, as in Fig. 1, has similarities with domain decomposition methods, described in e.g. [13].

3 METHOD

Assume that we have a platform with one antenna installed and want to find the best position for an additional antenna. Further, assume that “best” can be quantified in terms of the smallest mutual impedance between the two antennas.¹ An-

¹An additional criteria should describe the radiation requirements for the new antenna, e.g. requirements on the

Figure 3: (a) The complete environment including the platform and the installed Antenna 1 and (b) the alternative environment including only Antenna 2 and the structure within the surface S_2 .

Antenna 1 is mounted at a fixed position and the possible positions for Antenna 2 are restricted to a region V_1 on the platform. The platform is electrically large, whereas the size of the antennas is comparable to a wavelength.

The mutual impedance Z_{21} between the antennas will change for different positions r_2 of Antenna 2. With the above assumptions, the best location r_{opt} for Antenna 2 can be formulated as an optimization problem.

$$r_{\text{opt}} = \arg \min_{r_2} |Z_{21}(r_2)|. \quad (7)$$

The reaction theorem (2) can be used to reformulate (7) into

$$\arg \min_{r_2} \left| \frac{\oint_{S_2} (E_2' \times H_1^+ - E_1^+ \times H_2') \cdot \hat{n}_2 dS}{I_{11}I_{22}'} \right|. \quad (8)$$

The fields H_1^+, E_1^+ depend on the position r_2 of Antenna 2 (and the enclosing surface S_2). Hence, we can calculate the optimal antenna position with only the pre-computed electromagnetic fields on a closed surface S_2 separating the antennas in two disjoint regions. The currents, I_{11} and I_{22}' , are known from when the fields were generated. The excitation current I_{22}' is independent of the position r_2 of Antenna 2. The current I_{11} is also independent of r_2 if neglecting scattering on Antenna 2, see (3)–(4). The optimization problem simplifies to

$$\arg \min_{r_2} \left| \oint_{S_2} (E_2' \times H_1^d - E_1^d \times H_2') \cdot \hat{n}_2 dS \right|. \quad (9)$$

The fields E_1^d, H_1^d are determined in V_1 without the presence of Antenna 2, see Fig. 3(a), and can hence

far-fields pattern or reflection parameter thresholds. We assume that the radiation criteria are handled separate from the mutual impedance criteria.

Figure 4: The model used; a PEC platform with a 90° corner, Antenna 1 (fixed), and Antenna 2 (to be installed at some position).

be computed once. The integral in (9) selects a subset of $\mathbf{E}_1^d, \mathbf{H}_1^d$ in V_1 based on the position $\mathbf{r}_2$ of S_2 .

The suggested method is summarized as follows:

1. Determine the fields $\mathbf{E}_1^d, \mathbf{H}_1^d$ in the volume V_1 by solving the full-platform EM problem without Antenna 2, see Fig. 3(a).
2. Determine the fields $\mathbf{E}_2', \mathbf{H}_2'$ on the surface S_2 in the second environment with only Antenna 2 present, see Fig. 3(b).
3. Use the fields $\mathbf{E}_1^d, \mathbf{H}_1^d$ and $\mathbf{E}_2', \mathbf{H}_2'$ from steps 1–2 to evaluate the expression in (9). Repeat for all positions $\mathbf{r}_2$ of Antenna 2 (and the enclosing surface S_2) where $\mathbf{E}_1^d, \mathbf{H}_1^d$ are known.
4. Find the smallest value calculated in Step 3. The corresponding position $\mathbf{r}_2$ is the optimal placement for Antenna 2.

The time for Step 1 depends on the size of the platform. On large platforms, it is by far the most time consuming step. The time for Step 3 depends on the number of samples on the integration surface S_2 .

4 NUMERICAL RESULTS

We illustrate the here proposed method for finding the optimal antenna position by investigating the platform depicted in Fig. 4. The platform is designed to give strong backscattering. Antenna 1 and 2 are 25 mm monopoles excited at 3 GHz. At this frequency, the platform size is $20\lambda \times 10\lambda \times 5\lambda$.

The volume V_1 is $1\text{ m} \times 1\text{ m} \times 50\text{ mm}$. The integration surface S_2 is a Cartesian box enclosing Antenna 2. The volume enclosed by S_2 is $100\text{ mm} \times 100\text{ mm} \times 50\text{ mm}$, with the smallest dimension perpendicular to the platform. The sample spacing in the volume V_1 and on the surface S_2 is 2.5 mm.

Figure 5: Mutual impedance magnitude $|Z_{21}(x, y)|$ in Ω for 30 430 different positions $\mathbf{r}_2 = (x, y)$ of Antenna 2 on the platform. The optimal position $\mathbf{r}_{\text{opt}}$, according to (9), is marked with arrows.

To evaluate the integral in (9), we sum over 6 402 discrete points on S_2 for each position $\mathbf{r}_2$.

The position $\mathbf{r}_2$ of Antenna 2 is swept in x, y within V_1 , as illustrated by the 2D mutual impedance map in Fig. 5. Each position on the color coded map reflects the mutual impedance between Antenna 1 and Antenna 2 for that specific position $\mathbf{r}_2$ of Antenna 2.

For the tested case, the time t_0 to calculate the mutual impedance in n antenna positions with a full-wave simulation (FIT in CST Microwave Studio (MWS) with 12 mesh cells per wavelength) is

$$t_0(n) = n \cdot 400 \text{ s.} \quad (10)$$

As a comparison, the time t_1 with the suggested method is

$$t_1(n) = \underbrace{410 \text{ s}}_1 + \underbrace{20 \text{ s}}_2 + \underbrace{n \cdot 0.2 \text{ s}}_3 + \underbrace{0.001 \text{ s}}_4, \quad (11)$$

where each term corresponds to the time for the four steps² described in Sec. 3.

The incremental time to evaluate one antenna position is 400 s with the full-wave method and 0.2 s with the suggested method. That is a speed-up with a factor of 2000. To calculate the 30 430 mutual impedances in Fig. 5 would take $t_0(30\,430) \approx 4.7$ months with full-wave simulations, compared to $t_1(30\,430) \approx 1.7$ hours with the suggested method.

The accuracy of the method is verified by comparing with full-wave simulations of Z_{21} using CST MWS for a subset of the evaluated Antenna 2 positions, see Fig. 6. Neglecting scattering from Antenna 2 introduces small discrepancies in $|Z_{21}|$. However, the position of the minimum of $|Z_{21}|$ agrees excellent, which indicate that the method correctly finds the optimal antenna position.

²The dependence of n in Step 4. is neglected.

Figure 6: Mutual impedance magnitude $|Z_{21}|$ for Antenna 2 positions $x = 1.5$ m, $y = [0, 0.425]$ m.

5 DISCUSSION AND CONCLUSIONS

In this paper, we suggest an efficient method to find the optimal antenna position on large platforms. The method uses the reaction theorem to formulate an optimization problem involving only electromagnetic fields generated by the two antennas. The fields can be obtained in two full-wave simulation; one with the platform present, and one with only the new antenna. The optimization is performed as a post-processing step based on EM fields, e.g. from a commercial EM simulation software. It does not require any internal data from the full-wave simulation. The suggested method correctly finds the optimal antenna position for low-scattering antennas.

The method significantly decreases the computational time for antenna placement studies involving electrically large platforms. In the studied case, we see a speed-up with a factor of 2000, compared to running a full-wave simulation for each antenna position.

Additional antenna types can be evaluated using fields from one additional simulation with the new antenna type in isolation. The same pre-computed fields with the platform present can be re-used.

Acknowledgments

The authors acknowledge Saab Surveillance for funding. LJ is grateful for funding from SSF/AM130011 and Vinnova/ChaseOn through iAA.

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