Method-of-Moments Modeling of Conducting Objects within the Fast Irregular Antenna Field Transformation Algorithm

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October 30, 2023

Abstract

Reducing near-field measurement times is an important challenge for future antenna measurement systems. We propose to incorporate knowledge about material parameters of the antenna measurement environment within the simulation model. To do so, a method-of-moments code with surface discretization is implemented as a side constraint to the near-field far-field transformation problem performed with the fast irregular antenna field transformation algorithm. Transformation and source reconstruction results of synthetic measurement data demonstrate the effectiveness of the proposed method.
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Abstract—Reducing near-field measurement times is an important challenge for future antenna measurement systems. We propose to incorporate knowledge about material parameters of the antenna measurement environment within the simulation model. To do so, a method-of-moments code with surface discretization is implemented as a side constraint to the near-field far-field transformation problem performed with the fast irregular antenna field transformation algorithm. Transformation and source reconstruction results of synthetic measurement data demonstrate the effectiveness of the proposed method.

I. INTRODUCTION

A typical method for antenna characterization is to perform near-field (NF) measurements and a subsequent NF to far-field (FF) transformation (NFFFT) [1]–[3]. Existing algorithms are computationally efficient [4]–[6] and flexible regarding the measurement environment [7]–[9], in particular for echo suppression. They are able to provide diagnostic information about the antenna under test (AUT) as well if based on a surface-source reconstruction technique [10], [11].

The methods for echo suppression can be categorized in those which rely on spatial filtering, source localization or exploiting spectral properties [12]–[19], and those which incorporate additional knowledge about the echo sources, e.g., time-gating or modeling of echo sources [20]–[25]. For the latter, a recent trend is to link the solver of the NFFFT inverse problem to a forward problem for scattering objects, both for dielectric objects [26], [27] and for perfect electrically conducting (PEC) objects [28]–[31].

The topic of echo suppression is related to an important challenge of NF antenna measurements: Measurements shall be sped-up significantly, which is a particularly severe topic for electrically large antennas and for measurements with scatterers, since the mode spectrum increases significantly due to a larger minimum sphere. Hence, efforts have been made to directly integrate electromagnetic models of objects close to the AUT into the transformation problem [26]–[31].

From electromagnetic theory, the most efficient sampling methods and traditional sampling limits due to the spatial bandwidth of the radiated fields are well-known, with the most practical method being spiral sampling in various fashions [3], [32], [33]. More aggressive approaches to reduce the number of samples and, thus, the measurement time, seem to be rather unstable and unreliable if the made assumptions are not met; for instance in the case of compressed sampling, no speed-up is gained with random measurement locations [34]. To be reliable, the approaches to reduce measurement samples and time need to incorporate additional information such as geometrical data of the AUT.

We pursue an approach to incorporate knowledge about the exact geometry and material parameters of certain objects close to the AUT into the NFFFT and, subsequently, reduce the required field samples due to a significantly shrunk minimum sphere of the AUT [31]. However, some measurement efforts are transferred into the spatial domain: To save NF measurement time, the geometrical shape of some objects, which are part of or surrounding the AUT, can be captured using a high-accuracy 3-D laser scanner. This geometry information, combined with the knowledge of the material parameters, is utilized to treat the objects not as unknown radiation sources within the NFFFT inverse problem but as a standard scattering problem. This is implemented as a side constraint to the standard inverse problem.

The presented method is based on a method-of-moments (MoM) side constraint within the NFFFT of the fast irregular antenna field transformation algorithm (FIAFTA) and it is able to model any known scattering objects or any known part of the AUT as PEC. Field transformation results of simulated NF data demonstrate the effectiveness of this method.

II. THE INVERSE EQUIVALENT SURFACE-SOURCE PROBLEM AND THE FIAFTA

A typical procedure for equivalent source NFFFTs is to introduce a Huygens surface around the AUT. On it, surface sources can be employed to model the radiation of the antenna according to the equivalence principle. In this work, equivalent electric and magnetic surface current densities $f_S = \sum_n \beta_n [1]_n$
and \( m_s = \sum_n \beta_n \psi_n \) are chosen and discretized by Rao-Wilton-Glisson (RWG) basis functions \( \beta \) [35]. The respective coefficients are represented by the vectors \( i \) and \( \mathbf{v} \), summarized in the vector \( \mathbf{x} \) for convenience.

Of course, we are not restricted to modeling the AUT sources but can also include echo objects in the equivalent source representation. In principle, it is sufficient to place sources at all locations where radiation or scattering occurs; however, to restrict the degrees of freedom of the reconstruction (and reduce the number of required NF measurement samples), it can be beneficial to incorporate knowledge about the material properties and exact shapes of scattering objects. For now, we include all additional source coefficients also in \( \mathbf{x} \), assuming further RWG unknowns around echo objects.

The boundary condition of the integral equation inside the FIAFTA is determined by measurements around the AUT with testing functions modeling the probe receiving behavior (i.e., probe correction). Having the measurements in the vector \( \mathbf{b} \) and a NF evaluation of the equivalent sources \( \mathbf{x} \) by the forward operator \( \mathbf{A} \), the equation

\[
\mathbf{A} \mathbf{x} = \mathbf{b}
\]

states the NFFT inverse problem. Due to the various effects (ambiguous sources, oversampled measurements, limited AUT degrees of freedom, and others), regularization is necessary for a numerically stable solution. Without any other constraint, the most promising solution is to use the normal-error system of normal equations [36], [37]. With a regularizing side constraint, the more common normal-residual system of equations is well-suited and very intuitive to use.

### III. METHOD-OF-MOMENTS SIDE CONSTRAINT

Another possibility of regularization of the inverse problem is a Love current condition [10], [11]. In this work, we consider a side constraint (i.e., Tikhonov regularization). The interesting part is modeling of PEC echo objects: In principle, the same MoM implementation is employed. However, instead of the Love condition, the combined field integral equation (CFIE) enforces the PEC boundary condition for the impinging field radiated by the AUT.

Summarizing the Love condition of the AUT surface and the CFIE on PEC scattering objects in the matrix \( \mathbf{S} \)— both with RWG basis and testing functions —, we employ the normal-residual system of equation

\[
\mathbf{A}^H \mathbf{A} + \gamma \mathbf{S}^H \mathbf{S} \mathbf{x} = \mathbf{A}^H \mathbf{b}
\]

including a Tikhonov-style regularization with a suitably determined weighting \( \gamma \).

### IV. AUT-ONLY SOURCE RECONSTRUCTION

Consider the simulation setup in Fig. 1 including a horn antenna and a PEC scatterer, a square cube. In the simulation with Altair Feko [38], we extract the FF of the horn antenna part and compare it to the horn simulated in free space. The mutual coupling with the cube distorts the FF up to a level of \(-26\) dB, see Fig. 2, if the complex deviation between the maximum-normalized FFs is considered. In the following, the task is to retrieve the currents which are only influenced by mutual coupling; reconstructing the free-space solution requires, for instance, knowledge about the material composition and shape of the horn antenna itself.

In the following, we consider two different source-reconstruction techniques for the scenario in Fig. 1. For both of them, we extract the same electric NF samples around the AUT including the cube with a spiral sampling [33]. For the methodology of how to extract the AUT currents, consider [31].

#### A. GPU-Accelerated Dipole Code

An alternative method has been presented in [31]. The equivalent sources are Hertzian dipoles and the NFs are evaluated massively parallelized on a graphics processing unit [39]. For the PEC object modeling, the method of auxiliary sources (MAS) is employed. As demonstrated in the following results, it exhibits problems with edged objects. To be able to cope with the exemplary cube at all, it is necessary to place the equivalent sources on the outside of the zero-field boundary of the PEC cube (which is an unusual approach; usually, the sources are shifted inwards). The reconstructed fields are depicted in Fig. 3, where the PEC boundary condition was enforced for the cube in the source reconstruction. The singularities of Hertzian dipoles excite some evanscent modes in the region around the AUT and cube surfaces. The zero field inside the cube is realized on a level of approximately \(-20\) dB as compared to the surrounding fields.
This is the author’s version of a paper presented at the 2019 Antenna Measurement Techniques Association Symposium (AMTA). Changes were made to this version by the publisher prior to publication. The final version of record is available at https://doi.org/10.23919/AMTA.2019.8906355

Figure 3. Electric field magnitude in the \( z = 0 \) plane for MAS reconstruction.

Figure 4. Electric field magnitude in the \( z = 0 \) plane for MoM reconstruction.

B. FIAFTA with MoM Constraint

This methodology has been explained in Sections II and III. The surface integral equations code is basically implemented as in [40]–[43]. If we look into the reconstructed NFs in Fig. 4, the null field of the MoM solution is much more expressed than for the MAS solution, and evanescent modes around the Huygens surfaces are excited only to a minimal extent. Furthermore, the Love current condition on the AUT surface enforces a null field inside the AUT Huygens surface. The NF is visually identical to the simulation result of Feko. Minor differences to the Dipole/MAS solution can be identified.

C. Far-Field Evaluation

After the source reconstruction, only the AUT currents are considered and the respective FF is calculated. Hence, the echo object is effectively excluded from the retrieved solution. Nevertheless, mutual coupling effects of course persist. The AUT currents are effectively excluded from the retrieved solution.

In Fig. 5, the FF of the solution of the dipole code is shown, where the cube was modeled with the MAS during the iterative solution process. The complex deviation of the FFs goes up to \(-15\) dB in the direction where the cube is located. Certainly, this is caused by a wrong modeling of the cube scattering and thus erroneous separation of AUT and scatterer currents.

The FF of the FIAFTA/MoM solution is given in Fig. 6. Since the CFIE is able to model the scattering behavior of the PEC cube very well, also the AUT currents are retrieved in a very accurate manner. This translates to the FF, where the maximum complex deviation is down at \(-55\) dB, below typical measurement accuracies.

V. CONCLUSION

The FIAFTA was extended to handle known geometry and material information of PEC scattering objects. The MoM implementation was demonstrated to be superior to the MAS/dipole source reconstruction since the reconstruction accuracy is better and evanescent modes are excited to a lower extent.

ACKNOWLEDGMENT

This work was supported by the Deutsche Forschungsgemeinschaft (DFG) under Grant EI 352/20-1.

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