Mode Matching for the Modeling and Safety Assessment of Multiple-Channel Waveguide Transmission

Jan Paška[1], David O Brunner[2], Juerg Froehlich[1], and Klaas P. Pruessmann[2]

[1]Laboratory for Electromagnetic Fields and Microwave Electronics, ETH Zurich, Zurich, Switzerland, [2]Institute for Biomedical Engineering, University and ETH Zurich, Zurich, Switzerland

Introduction

Travelling wave with multiple channels (TWM) is a new RF system. First experimental results in phantoms exist [1]. EM-modeling for design optimization or a safety assessment is necessary. EM-simulations of the TWM are difficult due to the large setup and the multimodal waveguide extension. In a previous work, the EM-domain was divided into subdomains and combined in a post-processing step [2], the FDTD method was used for EM-simulations, which has difficulties in modeling evanescent modes and the waveguide discontinuity, resulting in low precision and a conservative safety assessment. Therefore, the goal of this work was to address these limitations, by refining the domain splitting and using more suitable simulation methods. A separate domain for the most critical part, the waveguide discontinuity, was added. FEM was used for the simulation of all subdomains, which is more suitable for simulating evanescent modes. The improved method yields more precise EM-simulations and a less conservative power limit.

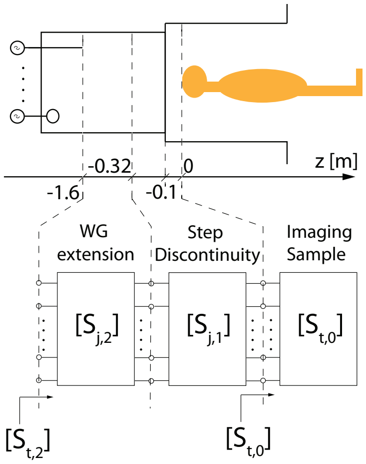

Fig. 1: Diagram of the RF-setup.

Methods

The RF setup is described in [1] in detail. It consists of a 2m long waveguide extension (WGE) with a diameter of 56cm filled with 52 PMMA tubes (Ø 4cm) filled with water. The WGE is covered with a conducting mesh. One end is shorted and the other end is left open. Eight excitation elements (seven stubs and a loop) are inserted at the shorted end to couple the coaxial cable modes to the modes of the WGE. The open end is inserted into the scanner's bore (7T Philips Achieva, Philips Healthcare, Cleveland, OH), whose RF screen has a diameter of 59.6cm, to excite spatially diverse field distributions inside the imaging object that is placed 10cm away from the end of the WGE.

The RF system can be divided into 3 parts, as shown in Fig.1, for each of which individual EM models are calculated and joined in a post-processing step with the mode matching technique [3]. In this method the EM field in multimodal waveguides at given reference planes is developed in modes that are treated as ports. Therefore coupling and reflections of modes can be described in terms of scattering matrices.

The first part is a 1.5m long uniform piece of the WGE, this can be modeled as a multimodal waveguide. The modal fields and propagation constants were computed with the 2D eigenmode solver in COMSOL, with those, the junction matrix $[S_{j,2}]$ can be computed describing this sub-domain. The second part is the step discontinuity from the WGE into the scanner's bore. This region was modeled in the 3D FEM solver in COMSOL. The significant modes are fitted on both sides of the junction yielding the junction S-matrix $[S_{j,1}]$ that describes this sub-domain. The scanner's bore is modeled as a circular waveguide, whose modes are computed analytically. The last part is the scanner's bore filled with the imaging object – a cylindrical phantom for validation, and the human body for the safety assessment. Both cases were computed using the FEM solver HFSS (ANSYS, Inc.), exciting the significant modes, found in the previous step, through a 10cm piece of empty bore. This domain can be represented as an EM-field in the imaging object and a corresponding termination S-matrix $[S_{t,0}]$. To assess the quality of the 3D EM-simulations, the relative field error of the mode matching residuum in RMS terms is computed. Only those modes were considered whose forward wave amplitude is greater than -30dB over the length of the waveguide.

The individual subdomains are now joined in MATLAB. The EM-fields in the imaging object are transformed through the corresponding junction matrices, to the reference plane at z=-1.6m. With the transformed termination matrix $[S_{t,2}]$ and the modal field distributions, the forward power can be computed for a given forward wave vector. For the validation, B_1^+ maps in a cylindrical phantom filled with a tissue simulating liquid were acquired for each port. The simulated fields were fitted with a magnitude least squares fit [4] to the measured fields, and normalized to the same forward power of 1kW.

The worst case SAR [5], with respect to the worst combination of forward wave modes in the WGE, normalized to the forward power of 1W was computed, and a power limit based on [6] was derived. Homogeneously RF-shimmed spoiled gradient echo images of the sagittal plane were acquired with the MultiX system with 8 independent transmit/receive channels (Philips Healthcare, Cleveland, OH). The sequence was played out according to the SAR limits. The TWM was used in transceive mode.

Fig. 3: In-vivo image, travelling wave multiple channel, transceive.

Results

19 significant modes in the WGE and 16 significant modes in the scanner's bore were identified. The most critical part in the simulation was the step-discontinuity, here the maximal error with respect to the modal fields was 8.5% for the E- and 12.2% for the H-field. The measured and simulated B_1^+ maps for the individual ports are shown in Fig. 2, the simulated fields are overestimating the experimentally acquired fields. The deviation of overestimation factors for the individual ports are attributed to different losses in the experimental setup due to standing waves. The limiting worst case local SAR of 0.32 W/kg was found in the neck region yielding an average power limit of 31W. The resulting in-vivo image is shown in Fig.3.

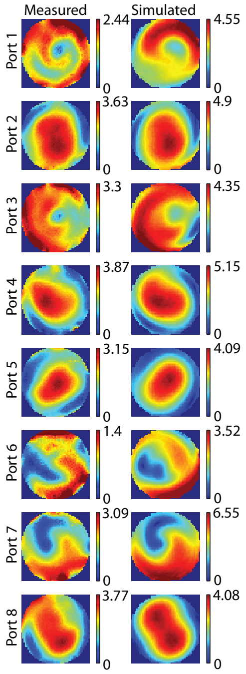

Fig. 2: Measured and simulated B_1^+ in $\mu T/\sqrt{kW}$.

Discussion & Conclusion

The safety assessment for the travelling wave setup with multiple channels was improved and successfully validated. It was found that FEM is more suitable for the EM-modeling of evanescent modes than the FDTD method. The higher fidelity in the EM-simulations leads to a less conservative safety assessment as compared to a previous work [2], therefore a higher power limit was derived for the imaging sequence. The excitation section is not included in the EM-modeling, therefore the power limit is independent of the positioning of the excitation stubs and loops.

References[1] Brunner, MRM 66:290–300, 2011; [2] Paska, ISMRM, p2674, 2012; [3] Wexler, IEEE 9:508-517, 1967; [4] Setsompop, MRM 59:908-915, 2008; [5] Brunner, ISMRM, p1320, 2008 [6] IEC 60601-2-33 ed3.0