Microwave Tomography in Biomedicine Using (A)Symmetry

Introduction

Applying symmetry to appropriate structures enables **significant decrease of simulation time, number of unknowns and required memory** in simulation of various electromagnetic (EM) problems.

In **WIPL-D software**, the most often used symmetry options are Symmetry and Anti-Symmetry. However, these types of symmetries can only be applied to multi-port structures if **All Generators (AG)** operation mode is used. This operation mode is mostly used for simulation of antenna arrays where all elements are active and they contribute to overall performance of the assembly (either to radiation pattern or near field).

However, for simulation in AG mode when it is required that generators at two different sides of symmetry plane have different (arbitrary) voltage, a different feature is required. The feature is called (A)Symmetry and it is particularly important for **One generator at Time (OGAT)** operation mode. It reduces number of unknowns and simulation time in both modes, especially for larger number of unknowns (electrically larger problems). It also **rather often extends the limits for simulation of electrically large** models.

One common scenario when the feature can be used is calculation of mutual coupling between elements of multi-port structures (via OGAT). In that sense, **WIPL-D Pro 3D EM** solver in this operation mode performs a series of calculations upon solving the impedance matrix. Number of calculations is equal to total number of ports. In the first calculation, the code excites the first port and short circuits all other ports. Such simulation yields return loss of the first port and coupling from the first to all other ports. Such simulation is repeated for all ports to obtain appropriate return loss for every port and mutual coupling between all ports. In most multiport simulations, this mode exactly is used to obtain S matrix of the system.

Applying symmetry to such a simulation requires (A)Symmetry if any of the ports is located outside of the symmetry plane. When we wish to calculate mutual couplings between ports, instead to simulate the entire model, we will use a **combination of PEC and PMC planes, which is the mechanism used in (A)Symmetry**.

Theoretical Considerations

We assume that arbitrary symmetric structure is analyzed. The structure is rotational with regards to z axis (Fig. 1). There are 24 ports in total, equally distributed around z axis. The order of WIPL-D generators follows ordinal number of ports. Example of four ports that are will be used in calculations is marked in red.

It can be shown by using the imaging theorem that currents for the entire structure in OGAT mode can be obtained after simulation and post-processing of 4 quarter models.

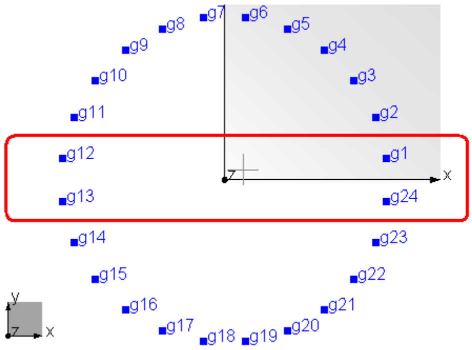


Figure 1. Example of symmetric structure with generators

In each model we use OGAT mode. We again excite generators one by one, with remaining 5 are short-circuited. In that sense, the active generator (and its current distribution) will be copied in accordance with Fig. 2. Four quarter models are created with four combinations of using PEC and PMC planes (x and y planes).

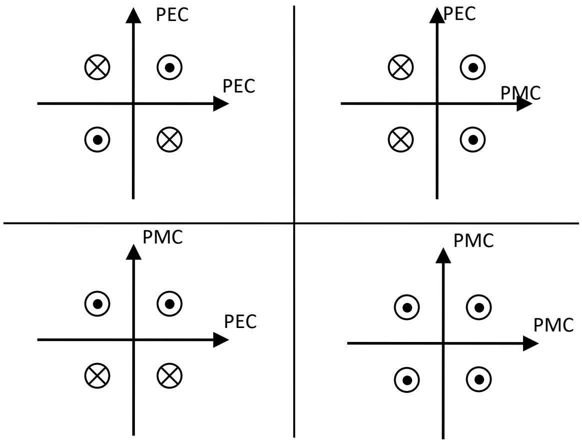


Figure 2. Imaging theory of currents

The obvious conclusion is that the following can be applied:

$$i_1 = (i_{EE} + i_{MM} + i_{EM} + i_{ME}) \cdot 0.25,$$

$$i_2 = (-i_{EE} + i_{MM} - i_{EM} + i_{ME}) \cdot 0.25,$$

$$i_3 = (i_{EE} + i_{MM} - i_{EM} - i_{ME}) \cdot 0.25,$$

$$i_4 = (-i_{EE} + i_{MM} + i_{EM} - i_{ME}) \cdot 0.25,$$

Where i_k is current in the k-th quadrant and i_{EM} is current calculated in project with PEC and PMC planes (E denotes PEC and M the PMC plane). For generators marked in Fig. 1:

$$i_1 = (i_{EE} + i_{MM} + i_{EM} + i_{ME}) \cdot 0.25,$$

$$i_{12} = (-i_{EE} + i_{MM} - i_{EM} + i_{ME}) \cdot 0.25,$$

$$i_{13} = (i_{EE} + i_{MM} - i_{EM} - i_{ME}) \cdot 0.25,$$

$$i_{24} = (-i_{EE} + i_{MM} + i_{EM} - i_{ME}) \cdot 0.25.$$

This feature, which is introduced as an extension and improvement to the existing symmetry feature, enables efficient EM modeling of symmetric structures with at least one and maximum three symmetry planes when arbitrary asymmetric excitation is applied. That efficiency refers to significant reduction of the number of unknowns and time needed to perform the analysis. In cases where the number of unknowns is very high and where the matrix inversion time is dominant (compared to the matrix fill-in time), it is possible to **accelerate the analysis** 4, 8 or 64 times. This depends on the number of symmetry planes used.

Based on the number of symmetries and the generator voltages, the feature automatically determines required number of runs and whether PEC or PMC will be used (or their combinations). The entire process (from the user point of view), consists of:

- Creating 1/2,1/4 or 1/8 of the structure,
- Setting (A)symmetry in all planes,
- Defining the appropriate generators voltage and the required operation mode.

Validating Accuracy

The theory presented in the previous section is verified using a simple example with 24 cylindrically placed dipoles (Fig. 3). Four models representing quarter of the structure (Fig. 4) were analyzed with PEC and PMC planes. Results calculated using full model (no symmetry planes applied) and results obtained using (A)Symmetry quarter models are presented in Table 1.

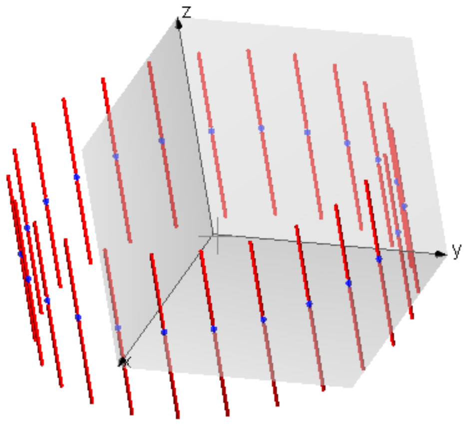


Figure 3. 24 dipoles array

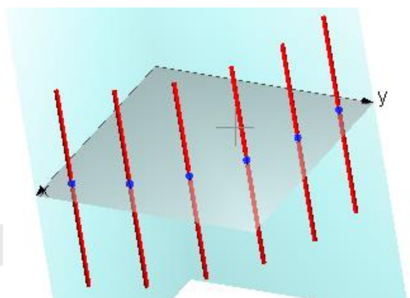


Figure 4. Quarter of 24 dipoles array with two PEC planes

Table 1. S parameters for the full and the asymmetry model.

Parameter	Full model		(A)Symmetry model	
	Magnitude	Phase	Magnitude	Phase
S11	0.399557	-147.263	0.399557	-147.263
S12	0.469655	37.7523	0.469655	37.7523
S13	0.293742	-11.2033	0.293741	-11.2032

Comparison of the number of unknowns for quarter models and the full model is shown in Table 2.

Table 2. Number of unknowns for the simulated models.

Scenario	Number of unknowns
PMC-PMC	18
PEC-PMC	18
PMC-PEC	18
PEC-PEC	18
No symmetry planes - full model	72

Proper using of WIPL-D symmetry features enables a significant decrease of number of unknowns (here 4 times). For electrically larger models, the simulation time is dramatically decreased.

After inspecting Table 1, one can conclude that agreement between results obtained by analyzing full model and (a)symmetry is excellent.

Reducing Number of Unknowns

A theoretically well-known example is the monostatic RCS of PEC cuboid (3x2x3 m at 3 GHz). Assume the calculation of monostatic scattering from cuboid in XoY plane (with theta polarization).

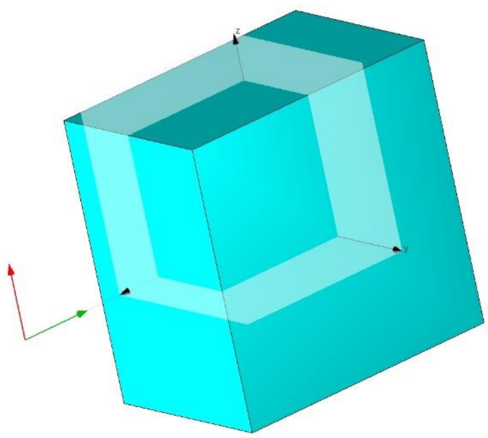


Figure 5. Monostatic RCS from PEC cuboid

This problem can be efficiently analyzed using the symmetry option. First of all, excitation is anti-symmetrical so define just a half of the structure using anti-symmetry plane XoY.

This geometry possesses two additional symmetry planes so only a quarter of the structure should be modelled. The additional symmetry planes should be defined as A(Symmetry) (A is abbreviation for asymmetric excitation and Symmetry indicates that the geometry itself is symmetrical).

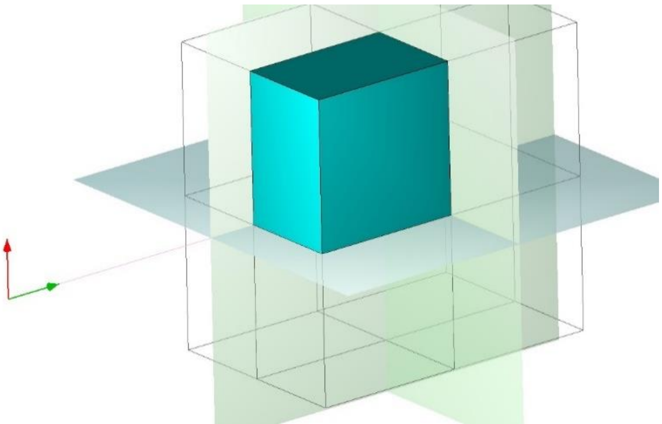


Figure 6. PEC cuboid with 3 symmetry planes

After running the project 4 simulations will be performed (all combinations for two symmetry planes, PEC/PEC, PEC/PMC, PMC/PEC and PMC/PMC).

Table 3. Simulation details for full and asymmetry model.

Model	Number of unknowns	Simulation time [sec]
Full	57,528	221
(A)Symmetry	14,280	137 (4x34)

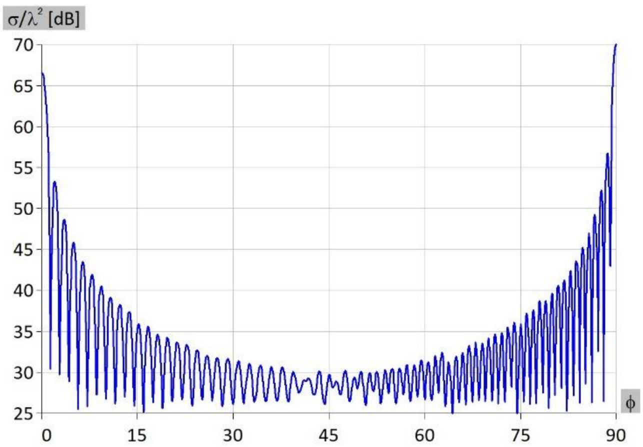


Figure 7. Monostatic RCS from the PEC cuboid

Simulation is performed on a regular desktop PC (quad core i7 CPU 7700) with 64 GB of RAM. The simulation time has been improved by adding a single inexpensive CUDA enabled GPU card (GTX 1080) and by using WIPL-D GPU solver. One of the side effects of using the (A)Symmetry, besides reducing the simulation requirements, Is that required WIPL-D license is dramatically reduced as well in terms of the required number of unknowns.

3D MW Tomography Imaging System

The inversion algorithms for reconstructing images of the permittivity and conductivity profiles of the object of interest (OI) typically require measuring the electric field intensity within the imaging domain with and without the OI present.

For almost 30 years, there have been different experimental systems developed for data collection for Microwave Imaging (MWI) system. There has been no software of 3D modeling which includes the entire geometry of Microwave Tomography (MWT) system, transmitter and receiver antennas with ability to power the antennas ones at the time and calculate the reflection and transmission coefficients the same as measurement. Here, the MWT system with 24 receiver and transmitter double-layer Vivaldi antennas using WIPL-D software and compare the results of simulation with measurement data.

The University of Manitoba imaging group has developed and constructed a MT prototype (a plexiglass shell cylinder with 24 antennas in the circular array mounted with 15o space between them). The system is shown in Figure 8.

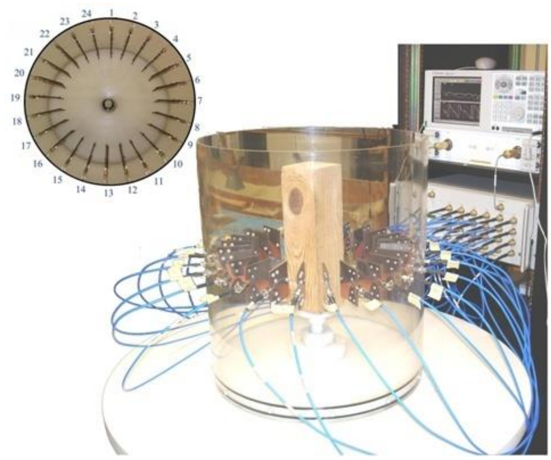


Figure 8. Measurement setup

The WIPL-D setup is shown in Figure 9.

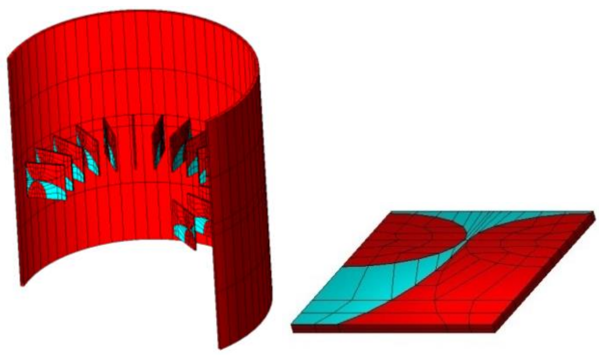


Figure 9. WIPL-D simulation and single Vivaldi antenna

The efficiency of the asymmetry is demonstrated in Table 4. Hardware used is modest GPU workstation: Intel® Xeon® Gold 5118 CPU @ 2.30 GHz (2 processors) with 192 GB RAM,4 NVIDIA GeForce GTX 1080 Ti GPU cards, 5 HDs INTEL SSDSC2KB019T7 in RAID-0. The GPU cards are used for matrix inversion.

Table 4. Simulation details for full and asymmetry model

Frequency [GHz]	Full model		(A)Symmetry model	
	Number of unknowns	Simulation time [s]	Number of unknowns	Simulation time [s]
3	71,216	324	17,804	4x55
9.2	270,888	5,755	67,722	4x266

Fig. 10 shows agreement for single Vivaldi antenna in free space.

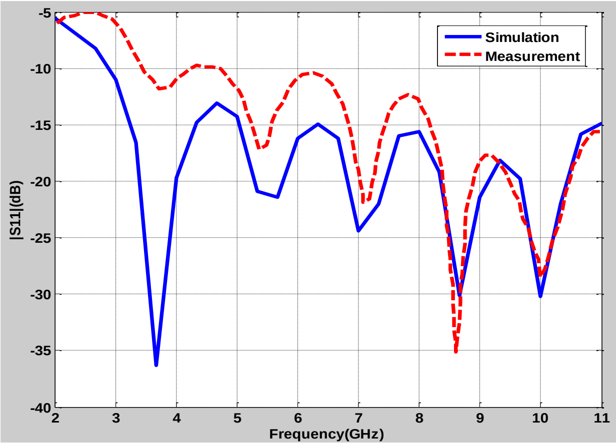
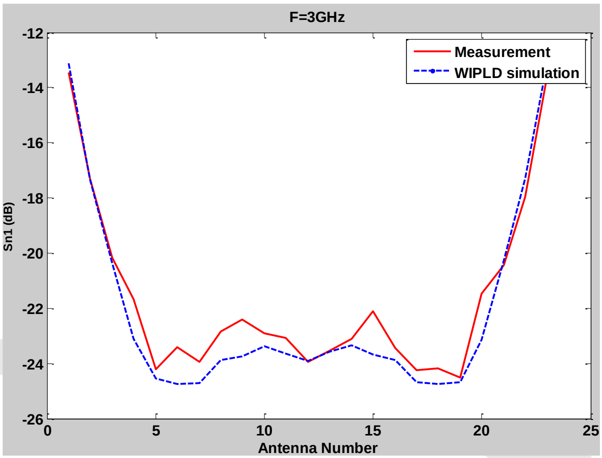


Figure 10. Vivaldi in free space return loss compared to the measured data

Next, we compare the transmission coefficient values for the 3D simulation with the raw measured data at different frequencies (3, 3.5, 4.5, 5, 6, 8, 9.2 GHz) when the antenna number 1 chosen as transmitter antenna and the rest of the antennas are selected as receiver (Sn1: n is the number of the antenna) (Fig. 11). These frequencies have been selected to show this comparison at the resonance frequencies as well as those frequencies that the mutual coupling between antennas is relatively high. It can be seen that the 3D simulation and measurement results does matches in some frequencies but not for all of them. It means that the calibration works differently at different frequencies which is expected. The simulation and measurements seem to follow consistently same pattern with a small shift. There is good agreement between the results.



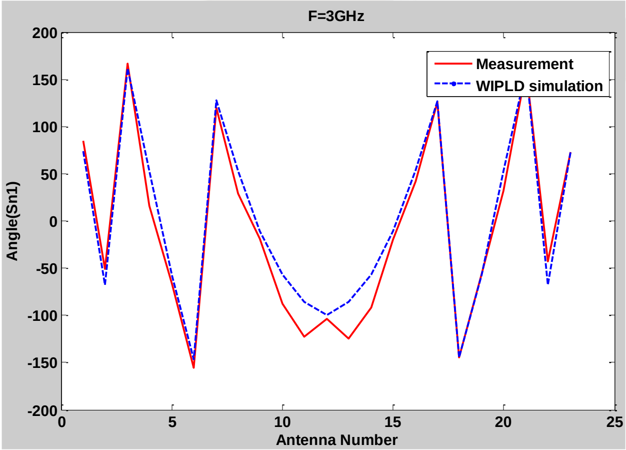


Figure 11. Selected results showing agreement between measurement and simulation

Conclusion

This application note provides detailed theoretical explanation on how the asymmetry feature is implemented in the WIPL-D suite. The user effectively models half, quarter or one eight part of the structure and sets asymmetry planes. The last step is to adjust the required voltages of generators (equal amplitudes are the default value). The code afterwards determines minimum number of simulations required (by combining simulations with PEC and PMC planes).

The usage of the feature reduces number of unknowns 2/4/8 times and simulation time up to 4/16/64 times. The simulation time reduction depends on the electrical size of the problem and is more pronounced for the electrically larger problems. The usage of the feature allows using tremendously less powerful WIPL-D license and extends the range of structures that can be simulated.

The simulations have been carried out on inexpensive hardware platforms owing to GPU technology and the GPU solver. The examples include a simple circularly placed array of dipoles (to verify accuracy), canonical PEC cuboid (to verify reduction of number of unknowns and simulation time) and realistic 3D microwave tomography system. Last example shows how asymmetry allows solving demanding example in engineering acceptable time in UWB application.

References

[1] Abas Sabouni ; Majid Ostadrahimi ; Sima Noghanian ; Milos Pavlovic: “Three-dimensional accurate modeling of the microwave tomography imaging system”, 2011 IEEE International Symposium on Antennas and Propagation (APSURSI), DOI: 10.1109/APS.2011.5997046, July 2011

[2] Gilmore, C.; Mojabi, P.; Zakaria, A.; Ostadrahimi, M.; Kaye, C.; Noghanian, S.; Shafai, L.; Pistorius, S.; LoVetri, J.; , "A Wideband Microwave Tomography System With a Novel Frequency Selection Procedure," Biomedical Engineering, IEEE Transactions on , vol.57, no.4, pp.894-904, April 2010.