

A WHITE PAPER FROM ANSYS, INC.

Electromagnetic Safety in Wireless Communications and Bio-Medical Technologies

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INTRODUCTION

In wireless-communication and in bio-medical technologies, no device can be brought to market without proof that it satisfies safety standards related to Specific Absorption Ratio (SAR). SAR is a measure for the electromagnetic power density absorbed by the human body and resulting locally in an increase in temperature. In the case of hand-held communication devices such as cellular phones, the concern is often about power density absorbed by the brain, the most critical and temperature-sensitive organ in the body. In other applications, such as radio transmitters, Magnetic Resonance Imaging (MRI), or medical implants transmitting data wirelessly, electromagnetic power can be absorbed by any organ. Ensuring that safety standards are met is essential for any equipment manufacturer. In this white paper, we will show how this can be done with ANSYS HFSS for four applications:

- Personal communication devices
- · Transmitting vehicle-mounted antennas, e.g. for police radio
- Magnetic Resonance Imaging (MRI) equipment
- Medical implants

In all cases, SAR in the human body is the quantity of interest.

THE FINITE ELEMENT METHOD

HFSS employs the Finite Element Method. This method offers several advantages over other methods that are sometimes used in the aforementioned applications, specifically methods based on the Finite-Difference Time-Domain (FDTD) method.

The most important advantage is the use of a mesh consisting of tetrahedral elements. This mesh will always be able to conform to oblique and irregular surfaces, which dominate in applications with complicated, real-life devices and human-body models. This contrasts with the brick-shaped mesh employed by FDTD. The Finite Element mesh will employ small elements where needed, in regions with geometrical details or large field gradients, and large elements elsewhere. Adaptive mesh refinement ensures that regions with strong field gradients will always obtain a sufficiently dense mesh. Thus, the mesh is always close to optimal for a given simulation.

Within mesh elements, the electromagnetic fields are described by so-called basis functions. These basis functions can have low, intermediate and high orders, indicating increasing accuracy. HFSS can employ Mixed Element Orders, determining autonomously as part of the adaptive mesh refinement process which orders are most appropriate for which mesh elements. The combination of adaptive mesh refinement and adaptive basis-order adjustment ensures that a desired accuracy is reached a minimal computational cost.

The solution process can use an iterative solver. This solver takes advantage of the fact that the basis functions are hierarchical. It produces a pre-conditioner based on lower-order basis functions and subsequently determines the accurate solution iteratively, using much less memory and time than the regular matrix solver would have needed. Also, when a network of computers is available, the solution process can use High Performance

Computing (HPC) to split the computational domain into many smaller domains and spread them out over the network.

HFSS solves in the frequency domain. This is an advantage for the applications of interest, since they are all singlefrequency applications. Even cellular phones capable of operating in multiple bands need to meet specifications at only a handful of widely-spaced individual frequencies and are best analyzed one frequency at a time.

ANSYS offers a couple of human-body models: a detailed adult male with over 300 muscles, organs and bones, as well as an adult female (Fig. 1). The objects in the models have a geometrical accuracy of 1-2 mm. The models can be tailored by the user for any specific application, e.g. by temporarily removing parts that are not needed.

PERSONAL WIRELESS COMMUNICATION DEVICES

Power transmitted by personal communication devices, such as cellular phones, and partly absorbed by the body, is of great concern for two reasons. It is the brain, the most critical organ in the body, that absorbs a large fraction of the power, and personal wireless communication devices such as cellular phones are used for hours per day by a very large number of people. A technical committee of the Institute of Electrical and Electronics Engineers (IEEE), ICES TC34, is in the process of defining Recommended Practices for the proper determination of SAR through measurements and simulations. ANSYS participates in the sub-committee on numerical methods.



Fig. 1 ANSYS human-body models

The local SAR is defined as

$$SAR = 0.5 \times \sigma E^2 / \rho$$

where σ denotes the electrical conductivity in S/m, E the magnitude of the peak electric field in V/m and ρ the mass density in kg/m3. The unit of SAR is Watts per kilogram, W/kg.

The quantity of interest is the local SAR averaged over a small volume, usually 1 g or 10 g of mass. The proper way to perform the averaging is described in Appendix E of IEEE Standard C95.3 [1]. Every location in the body obtains its own small averaging volume and its own value of value of average SAR. Of the entire distribution of average SAR values, only the peak value in the body matters for compliance with safety regulations. It is this peak average SAR that has to be below a certain value, e.g. 1.6 W/kg for cellular phones in the U.S.A.

The head model used in the simulations is not a heterogeneous model with brain, skull, eyes, etc., but is the so-called Specific Anthropomorphic Mannequin (SAM). Figure 2 shows an image of the SAM with a cellular-phone model. The reason for uses the SAM is that it corresponds to the measurement setup, in which a head-shaped shell is filled with a fluid with appropriate relative permittivity and electrical conductivity. The IEEE technical committee has verified, in a comparison with inhomogeneous head models,





Fig. 2 The Specific Anthropomorphic Mannequin (SAM) model MKT0000528 , 2

under-estimated. The Recommended Practices for simulations describe how to position the SAM model relative to the phone model, how much detail to include in the phone model, how to generate the appropriate mesh for the simulation, how to ensure that the simulation tool produces correct results, how to assess computational uncertainty, etc.

A computational comparison between various commercial software tools, carried out by ten different participating organizations, showed that the SAR results computed with HFSS are close to the average computed with various other tools by eight other participating organizations [2, 3]. Figure 3 summarizes the results. The simulation was done with a complicated, realistic phone model. The horizontal axis refers to eight cases: case 1 through 4 are in the 900 MHz band and case 5 through 8 in the 1800-MHz band. Further variations pertain to the way the phone was held, along the cheek (odd-numbered cases) or tilted away from the cheek (even-numbered cases). The remaining variation is the SAR averaging: based on 1 gram of tissue (cases 1, 2, 5, 6) or 10 grams of tissue (cases 3, 4, 7, 8). The vertical axis represents the peak average SAR, normalized in each case to the average result of the nine participating organizations. In every simulation by every participant, care was taken to correct for the return loss, i.e. correct for S¹¹, so the accepted power would be the same. The ANSYS result always falls in the band defined by normalized average \pm standard deviation. In the first four cases, in the 900 MHz band, the standard deviation was large. This was largely due to the presence of one set of outlying results (not produced with HFSS), that were much too low, pulling down the average and increasing the standard deviation.



Fig. 3 Results of computational comparison: ANSYS results compared to the band defined by average ± standard deviation

Other studies [4, 5] have also shown that HFSS produces accurate results for this application.



Fig. 4 Attenuation of the electric field in the head. left: 900 MHz, right: 1800 MHz.

The electric field, shown in Figure 4 at 900 and at 1800 MHz on a linear scale, is attenuated rapidly as it penetrates the head. The region where the average SAR values are high is therefore relatively small, as shown below in Figure 5.



Fig. 5 The region where SAR is significant is relatively small. left: 900 MHz, right: 1800 MHz.

In addition, a sensitivity study was done. One may not always know all material parameters with high accuracy, or not be certain how much detail to include in the phone model. Table 1 lists the sensitivities to changes in the phone model for the peak 1g avg. SAR value. The sensitivities of the 10g avg. SAR were very close to these and are therefore not listed separately.

Change in phone model	Change in peak 1g avg. SAR 900-MHz band	Change in peak 1g avg. SAR 1800 MHz band
Double conductivity plastics	-20%	-19%
Double permittivity plastics	-8%	-8%
Simplify model	-3%	+2%
Move 2 mm along head	0%	-1.5%
Move 2 mm from head	-11%	-22%

Table 1 Sensitivity of the peak 1g avg. SAR to changes in the phone model

In all cases, an essential step in the analysis is to correct for the return loss, i.e. for S₁₁, so the accepted power is the same in all simulations. Otherwise, results are very sensitive to small shifts in the resonance frequency.

A power-balance analysis shows that, when the conductivity of the plastics is doubled, the fraction of the accepted power absorbed by the plastics in the phone grows from 32% to 45% (low band, similar for high band), leaving less for radiation and for absorption by the head. When the permittivity is doubled, the power balance changes in a similar way, although to a lesser extent. This is partly due to the fact that higher permittivity with the same loss tangent corresponds to higher conductivity. Another effect is a shift in the resonance frequency. Although the accepted power is kept constant, the power distribution changes. This happens to mitigate the effect of the higher conductivity in this case, but it could be the other way round with a different phone.

In the simplified model, the following parts were kept: PCB, antenna, battery, major shield cans, one speaker near the antenna, plastic housing, display, and the vast majority of interior plastic objects, especially in the vicinity of the antenna. Removed were the other speaker, several screws, brackets and springs, and a small fraction of interior plastic objects that were not in the vicinity of the antenna. The resonance frequency was hardly affected. In the simplification process, it is essential to maintain electrical contact between major metal objects. In one variation on this model, the battery had lost electrical contact with the PCB. In that particular case, the power distribution changed significantly, and the peak avg. SAR came out 10% lower in the high band.

The sensitivity to the position of the phone along the head is small, as can be expected intuitively. When the phone is moved a few mm away from the head, the peak avg. SAR falls rapidly. Given this sensitivity, one may ask how reliable results produced by any individual software user will be. The draft IEEE Recommended Practice for this kind of simulation describes in detail how to position a phone geometry and the SAM head together in one model. In that procedure, the phone and the SAM are supposed to touch. Even if an individual user leaves a small gap, that gap won't exceed a few tenths of a millimeter. The uncertainty in peak avg. SAR due to positioning is therefore a couple of percent.

The sensitivity study teaches us the following. Since material properties of plastics are usually known within 10%, the uncertainty in peak avg. SAR due to materials is limited to a couple of percent. Also, the uncertainty due to positioning is a couple of percent. The most important question is to what extent a phone model can be simplified. This study shows that the aforementioned simplification changes the peak avg. SAR by 3% in the low band and 2% in the high band, provided electrical contact between the major metal objects is maintained.

Of course, although not part of the standard developed by the IEEE committee, a hand model can be added if desired (Fig. 6), e.g. to investigate its influence on the antenna resonance. The presence of the hand can shift the resonance down in frequency and influence the antenna pattern, so inclusion of a hand model is beneficial to the antenna designer and the system designer. Another effect of the hand is that it will absorb part of the power, leading to the possibility that inclusion of the hand will under-estimate the peak avg. SAR in the head. Therefore, usually a SAR evaluation is done without a hand model.

In conclusion, HFSS addresses the problem of electromagnetic safety of personal communication devices with great reliability.



VEHICLE-MOUNTED ANTENNAS

The aforementioned IEEE committee also develops a Recommended Practice for electromagnetic safety from vehicle-mounted antennas. A typical application is police radio, where the transmitters are much stronger than those of cell phones (tens of Watt), and the power absorbed by passengers and bystanders may be a concern. Figure 7 gives an impression of the model: the car with a monopole antenna on the trunk and a bystander standing one meter behind the car. The car and the person are standing on a slab of asphalt. The simulation at 450 MHz shows high SAR on the ankles, the knees and the throat.



Of particular interest is SAR at lower frequencies, since the electromagnetic fields penetrate deeper into the body at lower frequencies. Figure 8 shows the 1g avg. SAR inside the body at 150 MHz. The highest values, up to 0.18W/kg for a transmitter power of 10 W, occur in the throat, but some interior organs such as heart and intestines also have higher avg. SAR values than their surroundings.

Another metric of interest for a situation in which essentially the entire body is hit by radiation, is the whole-body SAR. For whole-body SAR, the safety limit for the general public is 80 mW/kg. At a transmitter power of 10 W, we find the following values for whole-body SAR:

At 150 MHz: 3.3 mW/kg At 450 MHz: 1.0 mW/kg

Clearly, both the 1g avg. SAR and the whole-body SAR are well below the safety limits at a transmitter power of 10 W. If the transmitter power were increased to 90 W, the 1g avg. SAR at 150 MHz would exceed the safety limit of 1.6 W/kg. The whole-body SAR, in that case, would still be well below its limit of 80 mW/kg. The whole-body SAR could be a concern at lower frequencies, at which fields penetrate deeper into the body.

Simulations have also been performed with this model at 900 MHz. This makes for a very challenging simulation: both the car and the body have a very large detailed mesh, while the air, the body and the asphalt consist of many cubic wavelengths: about 9,000. This is a situation in which the Finite Element Method does very well for the reasons mentioned in the section on the method: small elements where necessary, large elements where possible, mixed element orders (typically lower near insignificant details and higher in the many wavelengths of air), adaptive mesh refinement and adaptive order adjustment. For this simulation, the final mesh had 1.35 million



Fig. 8 Avg. SAR in the body at 150 MHz

elements, and the total number of complex-valued unknowns in the Finite Element matrix equation was 20.2 million. This system can be solved by using either the iterative solver on one computer or High-Performance Computing (HPC) on a network. The table below shows the RAM and real time (not CPU time) time needed to solve a system this big, and how these depend, for this particular model, on the number of unknowns N.

	RAM (GB)	Dependence on N	Elapsed time (min)	Dependence on N
Iterative solver	168	N^1.2	653	N^1.2
HPC, 24 nodes	181	N^1.3	274	N^1.5

A very interesting dependence on N emerges for HPC when one can assign more and more nodes on a network. Partitioning is done at the mesh level by the software, so all the user has to do is specify the number of available processing nodes on the network. Suppose the number of nodes is given by M. Then, the total RAM needed for a simulation will be proportional to $M \times \left(\frac{N}{M}\right)^{1.3}$ and the total time will be proportional to $\left(\frac{N}{M}\right)^{1.5}$

If sufficient network resources are available to let the number of nodes M grow linearly with the problem size N, then the total RAM will be proportional to N, i.e. grow linearly with the problem size, while the total time will be constant, since all matrix factorizations are done in parallel!

In summary, this example combines geometric complexity and size in terms of cubic wavelengths. It is a situation where HFSS excels, thanks to its meshing technology, mixed element orders, and advanced solver technology.

MAGNETIC RESONANCE IMAGING EQUIPMENT

Not only manufacturers of wireless communications devices have to comply with electromagnetic safety regulations: during MRI scans patients are exposed to strong fields, and without proper safety standards power absorbed by the body can easily be strong enough to lead to discomfort. Like with communication devices, the safety standards concentrate on peak average SAR.



Figure 9 shows the ANSYS human body model in an open MRI machine. Open MRI machines, with the extra room they provide over traditional MRI machines, have several advantages: they can handle patients who have to remain connected to life-saving equipment, they can handle obese patients, and, whether obese or not, the patient will not feel claustrophobic, which may help him to lie still longer so the doctor can obtain higher-quality images. Open MRI equipment is much harder to design than traditional cylindrical-bore equipment, since it's harder to obtain a homogeneous magnetic field, and the fields interact with the entire examination room, so the entire room has to be simulated. In order to verify compliance with SAR regulations, it's not enough to simulate the MRI equipment with the human body present in one position. Rather, an entire MRI scan needs to be simulated, in which the body moves through the scanner. To this aim, in the HFSS model the body was moved over a parameterized distance. With Optimetrics[™], a tool integrated with HFSS for parametric sweeps and optimization, the distance was varied such that the body moved over span of two meters in steps of 2.5 cm. In each position, the peak local SAR was determined. The result is plotted in Figure 10.



Fig. 10 Peak local SAR as a function of position during an MRI scan

Notice from the plot how strongly the peak SAR varies with position, confirming that simulating just one position is not enough. The peaks in the first 75 cm in the plot are due to SAR in the legs. In that part of the scan, the legs are between the MRI coils.

Next, at 87.5 cm, the highest peak occurs. At this position, the hips and hands are between the coils. That position deserves extra investigation. The 1g avg. SAR was determined, and, ignoring the SAR in the finger, which is an extremity for which a different rule applies, it turns out that the peak 1g avg. SAR occurs in the lower arm, as shown in Fig. 11.



Fig. 11 Average SAR at position 87.5 cm

Note how the red dots in the lower arm appear to be under the green dots. The green dots are on the surface while the red dots are in the flexor and tensor muscles. Figure 12 shows this more clearly.



Fig. 12 Average SAR at position 87.5 cm; flexor and tensor muscles only

This shows that if one would determine the average SAR on the surface only, or work with a homogeneous body model, one may miss important information. At low frequencies (42.6 MHz in this case), fields penetrate deep into the body. Only a detailed analysis with the interior structure present can ensure that the correct peak avg. SAR is obtained.

The next peak occurs at 112.5 cm. Figure 13 gives an impression of the distribution of the 1g avg. SAR in that position. It is high in a relatively large region in the back, as well as under an armpit. In the back, it can be higher in muscles than on the surface as shown in Figure 14.



Fig. 13 Distribution of 1g avg. SAR at position 112.5 cm



Fig. 14 Avg. SAR at position 112.5 cm in a cross section, showing how the highest values occur in muscles

In summary, with Optimetrics one can simulate efficiently an entire MRI scan, involving an entire examination room with a lot of geometrical detail inside, and determine peak local SAR and peak avg. SAR. In contrast, the combination of small details and relatively low frequencies makes this type of simulation take a prohibitively long time with traditional time-domain methods, since the details dictate a small time step in the entire model while the low frequency dictates a relatively long simulation to reach steady state.

MEDICAL IMPLANTS

Medical implants that transmit data wirelessly to the outside world form a relatively new development. Examples of such implants are cardiac pacemakers, neuro-stimulators, pain-suppression devices, drug dispensers, many types of sensors and monitoring devices, and control devices for other implants. The American Federal Communications Commission (FCC) has designated a frequency band for wireless communication for such devices: the Medical Implant Communication Services (MICS) band, ranging from 402 to 405 MHz. These frequencies form a reasonable trade-off: they are high enough to allow high data rates while low enough to penetrate the human tissue. As for transmitted power, the FCC sets a limit for Effective Radiated Power (ERP) outside the body of 25 µW.

With HFSS, two generic implant antennas and their matching circuits were designed. The matching circuits were optimized to achieve low return loss *when embedded in a body*. Performing this optimization with simulation is a lot easier than through experiments. One antenna is an electrical dipole with arms of 10 mm while the other is a magnetic dipole with a square loop of 10 mm on a side. The implant antennas with their matching circuits and plastic housings are shown in Figure 15.



Fig. 15 Generic antennas for implanted devices, with optimized matching circuits, in plastic housings

Both antennas were implanted in the abdomen of the human body model, under a 2-mm layer of skin and a 2-cm thick layer of fat. Their input powers were adjusted such that they both had an ERP outside the body of just under 25 μ W, the limit for radiated power.

It turned out that the implant with the magnetic dipole antenna still satisfied the FDA limit for peak average SAR of 1.6 W/kg, while the implant with the electric dipole exceeded it by a factor 7.5, reaching 12 W/kg. See Figure 16 for a plot of average SAR of the two implants.





The fundamental reason for the large difference between the SAR values produced with the electric and magnetic dipole antennas is the fact that, in the near field, the electric field of the magnetic dipole is relatively weak compared to that of the electric dipole. This has two consequences. First, the attenuation by the surrounding tissue is smaller, so a given ERP can be reached with lower input power. Second, the SAR, being proportional to the square of the electric field, is smaller in the near field of the magnetic dipole, even if the input powers of the two antennas would be the same.

In summary, with simulation the antenna and its matching circuit can be optimized for low return loss in their specific environment in the body. Effective radiated power outside the body and peak average SAR inside the body can be determined, and compliance with regulations can be ensured.

CONCLUSION

The determination of the Specific Absorption Rate (SAR) is a crucial step in the development of wireless communication devices, MRI equipment and medical implants. Without compliance with SAR safety standards, a device cannot be brought to market and the investment in its development is lost. This paper shows examples of each of these applications. HFSS excels in each application, thanks to the flexible meshing method with adaptive refinement, mixed element orders, and powerful solver technology. Detailed human-body models are available that work well with HFSS. High-performance computing (HPC) technology has the ability to distribute simulations over a network, such that models of very large size and high geometric complexity can still be simulated easily.

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