People and Planes: Development of Broadband EMC Models of Biological Materials in Aircraft

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Abstract

At microwave frequencies, an aircraft can be modelled as a multi-mode, reverberant EM environment. The presence of people on board will damp its resonances, thus lowering their Q-factors and increasing the propagation loss between two points. The relevant parameter is the mean absorption cross section of the body, which is of the order of one sixth of body surface area. For EM simulations of aircraft it is necessary to develop broadband numerical phantoms to represent the people on the aircraft. These should be at an appropriate level of detail somewhere between millimetre-resolution dosimetry phantoms and homogenous dielectric spheres.

1. Introduction

The increasing complexity of electronic systems on aircraft is driving up the cost of design, testing and certification for electromagnetic compatibility (EMC). To make this testing more efficient, there is a push to replace many of the EMC measurements with computer simulations. However this requires the numerical models to include the effects of the physical ‘contents’ of, for example, aeroplane cabins, as well as the electronic communications and control systems themselves.

One part of these aircraft ‘contents’ that requires attention is the bodies of the passengers and crew. At frequencies of tens of MHz upwards, the compartments of an aeroplane or helicopter will form an electrically large cavity, which behaves as a reverberant EM environment. The electric and magnetic fields within this environment will have a statistical distribution, with a mean value that depends on the average Q-factor of the resonant modes. At RF and microwave frequencies the tissues of the body (muscle, fat, bone etc.) are lossy dielectrics, so their presence within the ‘cavity’ will dampen the resonances and generally lower the field levels.

It is therefore necessary to develop models that simulate the effects of human bodies in aircraft. Many phantom models are available for EM dosimetry but their intent is to provide accurate and detailed estimates of specific absorption rate (SAR) in the tissues themselves. For an aircraft simulation such detail would impose unfeasible demands on computing time and memory, especially as there are many bodies to consider. As we are interested more in the effects of the bodies on the fields than the other way around, we need to develop models which are simple enough to be run efficiently while still accounting for the damping of the aircraft resonances.

2. Aircraft considered as a reverberant environment

The absorption cross section (ACS) of anything contained within an aircraft will affect the Q-factor of any internal resonances and thus the overall level of EM fields as well as the transmission of interfering signals from one part of the aircraft to another. The absorption cross section σ_a of a passenger will depend on many factors, including the frequency of the EM waves, the height, mass and body shape of the person, and the dielectric properties of his or her body tissues. However it is possible to roughly estimate the value of σ_a at microwave frequencies from data available in the literature.

Robinson et al [1] investigated the effects of windows and of human bodies on the internal fields in aircraft by considering it as a reverberant EM environment, modelled as a screened room. By comparing the autocorrelation of the frequency response of the actual room with that of a multi-mode representation of the room, they were able to quantify the contributions to the overall average Q-factor of the room from apertures, and from numbers of ‘passengers’ increasing from one to nine (two female, seven male). Following the approach of Hill et al. [2], the various contributions to the Q of the room can be combined in the same way as resistors in parallel:

$$Q^{-1} = Q_1^{-1} + Q_2^{-1} + Q_3^{-1} + Q_4^{-1} \quad (1)$$

where Q_1 represents losses in the metal walls, Q_2 absorption by lossy dielectrics, Q_3 the effects of apertures (windows) and Q_4 the losses in any measuring antennas.

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If we assume that Q_2 can be broken down further (ie that that all the people have the same individual Q-factor Q_p, and that these can be added in parallel), then the value of Q_p can be found from the gradient of the gradient of Q_p^{-1} plotted against the number of people in the room. Doing this for the data in [1] we find that Q_p=2500 in a room of length 4.7m, width 3.0m and height 2.37m and at a frequency of 910MHz. Now taking Hill's formula [2] for Q_2 and rearranging to give the average absorption cross section $<\sigma_a>$

$$Q_2 = Q_p = \frac{2\pi V}{\lambda < \sigma_a >}, \quad < \sigma_a > = \frac{2\pi V}{\lambda Q_p} \tag{2}$$

where V is room volume and λ wavelength, we find that at 910MHz, $<\sigma_a> = 0.25\text{m}^2$. This is the value of σ_a averaged over all polarisations and directions of propagation.

To calculate the surface area of a sphere of the same volume as an adult body, we assume a mass of 70kg for a male and for a female 58kg [3]. A density of 1000 kg/m^3 gives volumes of 0.07m^3 and 0.58m^3 for male and female respectively, and the surface areas are then 0.82m^2 and 0.72m^2. However the sphere has the smallest surface area of any shape of a given volume, so the surface area of the body will be bigger than this. A more realistic estimate [3] is 1.8m^2 for a male and for a female 1.6m^2.

The average absorption cross section of the body has also been investigated for *acoustic* waves by Conti et al [4]. Using an acoustic reverberant chamber they found that for adults, $<\sigma_a>$ is typically 0.1 to 0.2m^2. Although the absorption mechanism is different (sound waves are mostly absorbed by clothes, EM waves by high-water-content tissues) the ACS is of a similar order of magnitude.

A different approach to estimating ACS is to use data from dosimetry studies. Many measurements and simulations have been performed to estimate the specific absorption rate (SAR) due to exposure to EM waves. The absorption cross section is just the ratio of absorbed power to incident power density, and we can obtain the former from the product of SAR and mass m, and the latter from E^2/η_0 (in the far field) where E is electric field strength and η_0 the impedance of free space, approximately 377Ω:

$$\sigma_a = \text{SAR} \times \frac{\eta_0 m}{E^2} \tag{3}$$

Hand [5] describes how the whole-body SAR varies with frequency when exposed to a plane wave of E = 1V/m: there is a broad resonance between 10 and 100MHz (the peak varying slightly for male and female phantoms and also depending on whether they are grounded), followed by a slower variation and almost constant value from 300 to 1000MHz. Substituting this limiting value (which is 18µW/kg or 22 µW/kg for male/female phantoms) into the above equation gives σ_a at low microwave frequencies as 0.48m^2 for males and 0.46m^2 for females. The peak value at VHF frequencies (30 – 90MHz) is four to five times higher than this. In dosimetry studies the exposure conditions are simulated for worst-case SAR, giving the maximum ACS, whereas we need the value averaged over all directions and polarisations. We can therefore say that at low microwave frequencies, $<\sigma_a>$ is between zero and 0.47m^2, which is consistent with the estimate of 0.25m^2 from reverberant-environment studies.

It is interesting to compare the effect of human bodies on aircraft internal fields to that of apertures. In the analysis of Hill et al [2], the contribution to the average Q from the windows is $Q_3 = 4\pi V / \lambda < \sigma_l >$ where the transmission cross section $<\sigma_l>$ is half the total window area. An absorption cross section of $<\sigma_a>$ therefore has the same effect on the average Q as a window of area $4<\sigma_a>$. So a body with ACS of 0.25m^2 is equivalent to a window of 1m^2. As most windows on aircraft are smaller than this, and there are often more people than windows, this suggests that the influence of the passengers and crew on the internal EM environment is more important than that of apertures.

3. Development of broadband phantoms

Figure 1 (left) shows a schema by which absorption cross sections of bodies in aircraft could be estimated. The dielectric properties of body tissues – the permittivity and conductivity – are both strongly correlated with tissue water content, especially at microwave frequencies [6]. It is also possible to estimate the total body water (TBW) of a typical person from his or her age, height and weight using empirically-derived formulae.

It is also necessary to consider what level of geometric detail is needed for a body simulation. Many highly detailed models are now available, having been developed for dosimetric studies of exposure to communications devices such as mobile phones. These include the phantoms produced by the Visible Human Project, the 'Norman' and 'Naomi' models developed by the UK Health Protection Agency, and the Virtual Family of adult and child phantoms from IT'IS in Switzerland. Unfortunately their very high resolution (generally finer than 2mm) makes them computationally unsuitable for our application: a Boeing 747 (for example) has a fuselage volume of approximately $2500m^3$. At 2mm mesh size this would require an unfeasible 300GB of RAM to simulate.

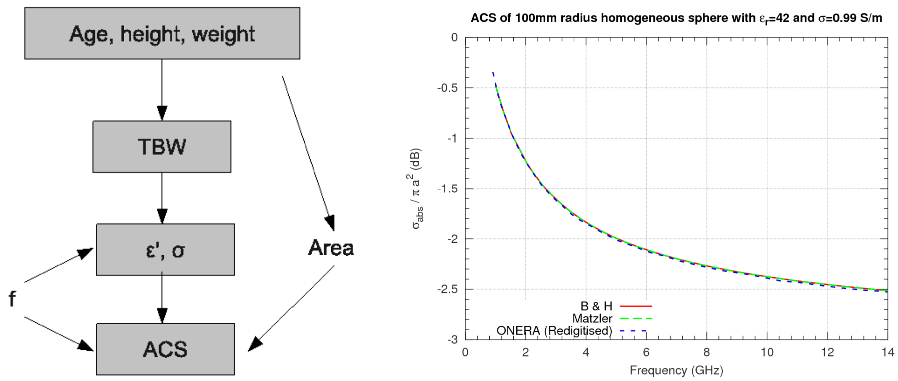

Figure 1: scheme for estimating body ACS (left) and calculated ACS of homogeneous sphere (right).

At the opposite extreme, the body could be simulated by a homogeneous sphere of a single dielectric material. The advantage of this highly simplified model is that its scattering coefficients can be obtained analytically from a Mie series which matches spherical wave functions at its surface. This also gives the ACS. Figure 1 (right) shows the ACS of a homogeneous sphere of radius 100mm, which has been calculated by two different Mie codes available online [7, 8] and is compared to results provided by one of the project partners (ONERA) [9]. Although this test case is intended primarily to validate the methods (which it does), it also has the same volume as a person of mass approximately 4kg, ie a small child. The ACS is shown relative to the 'shadow' or 'silhouette' area πa^2 rather than the total surface area which is of course four times larger, $4\pi a^2$, where a is radius. Interestingly, the ratio of surface area to absorption cross section $4\pi a^2/\sigma_a$ varies from 4.5 to 7 over the frequency range 1-14GHz for this material.

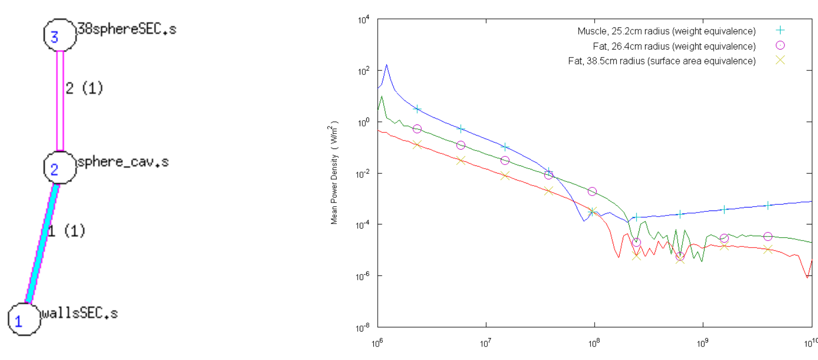

Figure 2: power balance model for phantom (left) and results for various homogeneous spheres (right).

A problem with using a homogeneous phantom is that there is actually a wide variation in the permittivity and conductivity of actual tissues, which is likely to affect the impedance mismatch at the body surface and hence the ACS. To investigate this we ran power-balance simulations of homogeneous spheres in cavities using the 'PWB' code of ONERA [10]. Figure 2 (left) shows the model where the lower tube represents a 1W power source and the upper tube the sphere. Two extreme case were selected with the dielectric properties chosen to match either fat (a low water content tissue) or muscle (high water content). As can be seen in Figure 2 (right) the absorbed power is significantly different. This figure highlights a further difficulty with the spherical model which is what geometrical parameter of the body should be modelled by the phantom – volume or surface area? We would expect the answer to depend on frequency: at lower frequency the waves will be transmitted through the body so a volumetric equivalence might be better, but at higher frequency the wave penetration will be much less so the interaction is mainly with the surface layers of tissue. As a sphere is a very different shape from the body, the two possibilities give different results as can be seen in Figure 2 (right).

A more useful phantom geometry would be a cylinder, as this has radius and height and can therefore be matched to both surface area and volume of the body. A multi-layer cylindrical phantom would enable the model to be usable over a broader frequency range. Figure 3 (left) shows the penetration depth in three tissues, as calculated using standard EM methods from the tissue dielectric properties, which were obtained from the parametric model of Gabriel et al [11]. The penetration depth is such that over the frequency range of interest, the interaction does indeed change from being volume-dependent to surface-dependent. A suitable phantom is suggested in Figure 3 (right) where the outer layer represents the low-water fat and skin, and the inner layer the high-water muscle and internal organs.

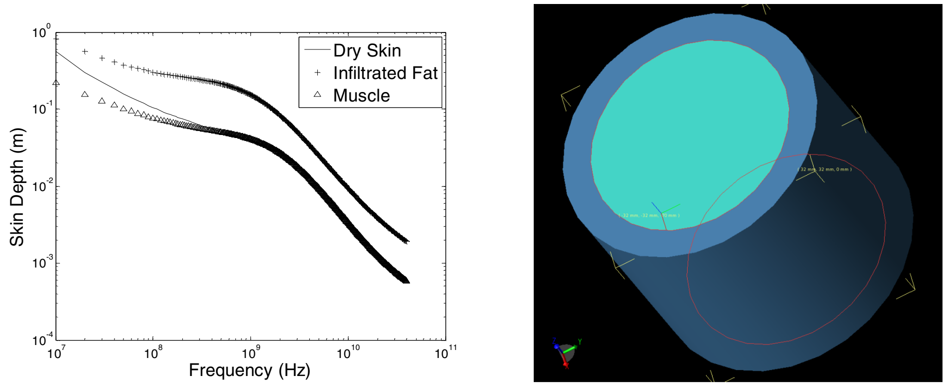

Figure 3: penetration depth in some tissues (left) and multilayer cylindrical model (right)

4. Discussion

Our research indicates that the ACS of a person in a reverberant environment is roughly one sixth their actual surface area, but depends on their tissue permittivity and conductivity, and on frequency. For a fully loaded passenger airliner the Q due to the passengers Q_p should be very approximately 100. The effect on propagation would then depend on the unloaded Q: if this were 1000 then the loaded Q would be 91 and the transmission between two points would be reduced on average by 10.4dB. However if the unloaded Q were as low as 100 then the reduction would be only 3dB. This shows the importance of quantifying the various loss mechanisms in aircraft, including modelling the ACS of the passengers and crew at an appropriate level of detail.

5. Acknowledgement

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6. References

1. M P Robinson, J Clegg and A C Marvin 2006. 'Radio frequency electromagnetic fields in large conducting enclosures: effects of apertures and human bodies on propagation and field-statistics' *IEEE Trans. EMC* vol. **48** pp304-310
2. D A Hill, M T Ma, A R Ondrejka, B F Riddle, M L Crawford and R T Johnk 1994 'Aperture excitation of electrically large, lossy cavities' *IEEE Trans. EMC* vol. **36**, pp 169-178
3. International Commission on Radiological Protection 1975, *Report on the Task Group on Reference Man*, ICRP Publication 23, Pergamon, Oxford
4. S G Conti, P Roux and D A Demer 2003, 'Measurements of the total scattering and absorption cross-sections of the human body', *J. Acoust. Soc. Am.* vol. **114**, pp. 2357-2357
5. J W Hand 2008, 'Modelling the interaction of electromagnetic fields (10 MHz–10 GHz) with the human body: methods and applications', *Phys. Med. Biol*. vol. **53**, pp R243-R286.
6. M P Robinson, J Clegg and D A Stone 2003. 'A novel method of studying total body water content using a resonant cavity: experiments and numerical simulation' *Phys. Med. Biol*. vol. **48**, pp 113-125.
7. C F Bohren and D R Huffman 1998, *Absorption and Scattering of Light by Small Particles*, Wiley Science Paperback Series, John Wiley.
8. C Matzler and J Ricka 2009, 'Radiative Transfer (Advanced Course)', Institute for Applied Physics, University of Bern, http://www.iapmw.unibe.ch/teaching/vorlesungen/radiative_transfer
9. U Carlberg, P-S Kildal, A Wolfgang, O Sotoudeh, and C Orlenius 2004, 'Calculated and measured absorption cross sections of lossy objects in reverberation chamber', *IEEE Trans. EMC,* vol. **46**, pp. 146-154
10. J Parmantier and I Junqua 1999, *EM Topology: Theory and Application*, Springer, Ch. 1, pp 3-12
11. S Gabriel, R W Lau and C Gabriel 1996, 'The dielectric properties of biological tissues. III. Parametric models for the dielectric spectrum of tissues', *Phys. Med. Biol*. vol. **41**, 2271-2293