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A SIMPLIFIED PROCEDURE FOR DOSIMETRIC EVALUATIONS ON ELF SOURCES WITH COMPLEX WAVEFORMS

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The endorsement of the 2004/40 European Directive has renewed the interest in numerical electromagnetic dosimetry. In this field, a need is clearly perceived for dosimetric approaches able to reduce costs and the time necessary for this type of evaluations. In the low and intermediate frequency ranges, EM dosimetry makes use of quasi-static techniques in the frequency domain, which become onerous when dealing with sources emitting multiple frequencies. A procedure is then proposed, able to greatly simplify the numerical process needed to perform a dosimetric calculation involving a complex waveform. The procedure is based on the use of an 'equivalent' field intensity at an arbitrarily chosen 'reference' frequency and allows executing a single-frequency dosimetric evaluation able to take into account, with some approximations, the complete spectral contents of the source signal.

The endorsement of the 2004/40 European Directive on the occupational exposure to electromagnetic (EM) fields[1] has renewed the interest in the EM dosimetry. This discipline is aimed at studying the relationship existing between the unperturbed external EM fields to which a person is exposed and the physical quantities induced in his/her tissues and organs as a consequence of the exposure. According to the Directive, the dosimetric analysis can play a role in a risk assessment when one has to decide if the exposure could be allowed even if the external field levels are higher than the admitted maximum reference values (called *action values*, AV). In fact, in this case the exposure might be allowed only if compliance with basic restrictions on induced current density and SAR (called *exposure limit values*, ELV) is demonstrated.

An objection often raised by the employers (who have to meet the costs of risk assessments), consists in observing that checking compliance with ELV is meaningless, unless it is less expensive than applying solutions to reduce the exposure below AV. Moreover, it makes sense to afford a dosimetric evaluation only if there is some sound evidence that it could end with a favourable response; otherwise, the costs involved in the dosimetric analysis will eventually add to, not replace, those needed to reduce exposure.

As a consequence, it is worth to investigate how to reduce the costs of a dosimetric evaluation. Among specific costs (i.e. the ones that cannot be shared among several applications), there are those raised by the execution of a multi-frequency analysis, when necessary. The work presented in this paper is aimed at suggesting a possible approach to partially control this particular aspect.

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QUASI-STATIC NUMERICAL DOSIMETRY

EM dosimetry is today mainly based on numerical methods. Those most suited to treat problems in the low and intermediate frequency ranges (say, up to a few megahertz) make use of the well-known *quasi-static approach*. The most popular among them are[2] the *impedance network method*, the *current vector potential* method and the *scalar potential finite-difference* method. This last one is often preferred, for its ability to require the solution of just a scalar equation even with 3D problems.

All these methods share a common property: they work *in the frequency domain*, i.e. they are able to solve problems where the time dependency is purely sinusoidal and the frequency is a constant parameter. If a source emitting multiple frequencies is involved (called a *wideband source* in the following), then a separate analysis should be performed for each frequency (or spectral component) and all the results properly summed up. The procedure is always time consuming (thus, expensive); it can even result unfeasible, if too many relevant spectral components exist in the source waveform. One could obviously resort to a *time-domain* method, like the *finite-difference time-domain* method widely used at higher frequencies, for whom special formulations for lower frequencies exist. However, besides the intrinsic limitations of these formulations, even the time-domain methods have to face a serious difficulty when applied to wideband problems: the need to assign the values of the dielectric properties to the tissues, which the Gabriel's parametric model[3], the most accurate model available today, allows computing in the frequency domain only.

As a consequence, a simplified procedure is proposed here, which allows to execute a single-frequency dosimetric evaluation able to take into account, with some approximations, the complete spectral contents of the source signal. This procedure is based on the use of an 'equivalent' field intensity at an arbitrarily chosen 'reference' frequency.

THE SIMPLIFIED PROCEDURE

The ICNIRP guidelines[4], as well as the European standards based on them, treat the exposure to a wideband source in the same way as the exposure to multiple independent sources, one for each frequency emitted by the actual source. Assuming all frequencies are <100 kHz, checking compliance with ICNIRP basic restrictions (i.e. Directive ELV) is just accomplished through calculating the ICNIRP index I_J for the induced current density and verifying that its value is lower than 1. This index is given by

$$I_J = \sum_i \frac{J(f_i)}{J_L(f_i)} \tag{1}$$

where $J(f_i)$ and $J_L(f_i)$ are the *root mean square* (RMS) amplitudes of the spectral components at frequency f_i of the induced current density and of the corresponding ICNIRP basic restrictions.

For the sake of brevity, the analysis that follows will be relative to the magnetic field only, but all the conclusions apply to the electric field as well.

A time-varying magnetic field induces an electric current in a conducting object, such as a biological organism, on the basis of the well-known *Faraday's law of electromagnetic induction*. According to it, the induced current density J is directly proportional to the rate of change of the magnetic flux density B:

$$J = \bar{k}\frac{\mathrm{d}B}{\mathrm{d}t} \tag{2}$$

where $\bar{k}$ is a 'dosimetric' coefficient whose value depends on the problem geometry and on the dielectric properties (i.e. conductivity) of the involved material, which in general varies as a function of frequency. If the frequency span over which the source emits is not too wide, this dependency can be neglected and the value of $\bar{k}$ assumed independent from frequency.

Consider a source that emits a linearly polarised magnetic flux density with a complex waveform comprising a finite number N of spectral components having frequencies f_i (not necessarily multiple of a common fundamental frequency), RMS amplitudes B_i and phases φ_i. In this case:

$$B(t) = \sqrt{2}\sum_{i=1}^{N} B_i \cos(2\pi f_i t + \phi_i) \tag{3}$$

If eq. (3) is now substituted in eq. (2) and the ICNIRP index is calculated according to eq. (1), one obtains:

$$I_J = \sum_{i=1}^{N} \frac{k(f_i) f_i B_i}{J_L(f_i)}, \quad k(f_i) = -2\pi\bar{k} \tag{4}$$

where the dependency of the dosimetric coefficient on the frequency was explicitly declared.

Now, it will be shown that a 'reference frequency' f_0 can arbitrarily be chosen and a 'equivalent RMS amplitude' B_{eq} of the magnetic flux density at this frequency determined, so that the ICNIRP index for the current density, calculated with this *ad hoc* single-frequency component, is equal to the real one, calculated with eq. (4), keeping all the frequency components into account.

For the ICNIRP index due to the equivalent component at the reference frequency one has:

$$I_J = \frac{k(f_0) f_0 B_{eq}}{J_L(f_0)} \tag{5}$$

and if the condition is now imposed that eqs (4) and (5) give the same result, the expression for B_{eq} is immediately obtained:

$$B_{eq} = \frac{J_L(f_0)}{f_0}\sum_{i=1}^{N}\frac{f_i B_i}{J_L(f_i)} = \frac{J_L(f_0)}{f_0}\sum_{i=1}^{N}\alpha_i \tag{6}$$

where $\alpha_i = f_i\, B_i / J_L\,(f_i)$ (please observe that this parameter depends on the impressed field only, not on the exposed object). In order to obtain eq. (6), the previously declared condition was applied, that the dosimetric coefficient k could be regarded as independent from frequency. Only in this case, in fact, the expression for B_{eq} gets sufficiently simple to be of practical use. This hypothesis is equivalent to considering the tissue conductivity constant with varying frequency, a condition surely valid if the frequency range spanned by the source is small.

Eq. (6) is the expression sought for. It allows to calculate the RMS equivalent amplitude B_{eq} of a sinusoidal magnetic flux density field at frequency f_0 which gives the same ICNIRP index for the induced current density as the actual field described by eq. (3), with an accuracy sufficient for a preliminary, fast and (relatively) low-cost dosimetric evaluation.

An arbitrary value could be chosen for the reference frequency f_0. In the following paragraph, it will be shown that, in order to minimise the error due to having neglected the conductivity variation with frequency, it should be chosen for f_0 the frequency of the strongest component in the field spectrum of eq. (3) (properly weighted). If one is instead interested in guarantee that the error be directed in the precautionary direction, though not minimised, then it should be chosen for f_0 the frequency value, among those appearing in eq. (3), at which tissue conductivities reach their highest values.

EXAMPLE

The above-described simplified procedure is completely general. In order to illustrate and clarify its functioning, a simple problem will be addressed, where a homogeneous cylinder with undefined length and radius R is exposed to a uniform magnetic flux density B directed parallel to its axis. This problem, as anyone knows, has an analytical solution, according to which the current density J induced at frequency f at the boundary surface of the cylinder has an amplitude:

$$J = \pi f R \sigma B \tag{7}$$

where σ is the conductivity of the material constituting the cylinder. A particular case will be considered, in which the frequency spectrum of the magnetic field comprises just two components at frequencies f_1 and f_2; let σ_1 and σ_2 be the corresponding values of the conductivity and suppose $\sigma_1 < \sigma_2$.

Applying eq. (1), the following exact expression for the ICNIRP index for the current density can be found:

$$\begin{aligned} I_J &= \frac{J(f_1)}{J_L(f_1)} + \frac{J(f_2)}{J_L(f_2)} \\ &= \frac{\pi f_1 R \sigma_1 B_1}{J_L(f_1)} + \frac{\pi f_2 R \sigma_2 B_2}{J_L(f_2)} \\ &= \pi R(\alpha_1 \sigma_1 + \alpha_2 \sigma_2) \end{aligned} \tag{8}$$

If the simplified procedure is applied instead, two cases are possible, depending on the choice of f_1 or f_2 as the reference frequency f_0. The values of the equivalent flux density (eq. (6)) and of the approximated ICNIRP index in the two cases are as follows:

$$\begin{aligned} B_{\text{eq}}^{(1)} &= \frac{J_L(f_1)}{f_1}(\alpha_1 + \alpha_2) \quad I_J^{(1)} = \pi R \sigma_1 (\alpha_1 + \alpha_2) \\ B_{\text{eq}}^{(2)} &= \frac{J_L(f_2)}{f_2}(\alpha_1 + \alpha_2) \quad I_J^{(2)} = \pi R \sigma_2 (\alpha_1 + \alpha_2) \end{aligned} \tag{9}$$

It appears immediately that, having assumed $\sigma_1 < \sigma_2$, then $I_J^{(1)} < I_J < I_J^{(2)}$. This result leads to an important conclusion: in order to guarantee that the error is directed in the 'precautionary' direction (i.e. it is a *round-up* error), then it should be chosen as the reference frequency the one, among those appearing as spectral components of the source, at which corresponds the higher value of the conductivity.

Furthermore, the following expression can easily be found for the relative error ER_i due to having used the approximate values of the ICNIRP index given by eq. (9) instead of the exact one of eq. (8):

$$\begin{aligned} ER_1 &= \left| \frac{I_J^{(1)} - I_J}{I_J} \right| = \left| \frac{(\sigma_1 - \sigma_2)}{\sigma_1 \alpha_1 + \sigma_2 \alpha_2} \alpha_2 \right| \\ ER_2 &= \left| \frac{I_J^{(2)} - I_J}{I_J} \right| = \left| \frac{(\sigma_2 - \sigma_1)}{\sigma_1 \alpha_1 + \sigma_2 \alpha_2} \alpha_1 \right| \end{aligned} \tag{10}$$

so that:

$$\frac{ER_1}{ER_2} = \left| \frac{\alpha_2}{\alpha_1} \right| \tag{11}$$

from which one can conclude that, in order to minimise the relative error (*regardless its direction*), it should be chosen as the reference frequency the one at which the α parameter reaches its maximum value. This parameter is clearly a measure of the intensity of the corresponding spectral component, weighted according to the frequency and to the inverse of the ICNIRP basic restriction for the current density at that frequency.

EXPERIMENT

The above-proposed simplified procedure was also tested in a real situation with a simple experiment. A measurement set-up was prepared, capable to acquire the time-domain waveform of the magnetic field produced by an AC appliance. This set-up comprised a coil-type probe, connected to the microphone input of a portable personal computer, running a popular sound processing software package (Cool Edit, today distributed by Adobe Systems Inc. with a different name). By means of this software, the signal collected by the probe could be sampled with an adjustable sampling rate, digitised at 16 bit per sample and stored as text file on the PC hard disk. A brushless electric drill was chosen as the source, because the waveform of its magnetic field presented two clear spectral lines at 50 and 150 Hz (plus a few smaller ones, which were neglected); a sampling rate of 6 kHz was far more than sufficient to accurately reproduce such a waveform. The samples were successively subjected to a spectral analysis by means of a discrete Fourier transform (DFT) routine and the spectral amplitudes so obtained were corrected in order to compensate for the frequency response of the probe.

This experimental set-up did not allow to measure the absolute field intensity, but rather just the ratios between its spectral components. A measurement taken with a standard ELF magnetic field probe (Emdex II by Enertech Consultants) revealed that more than 100 μT RMS could be detected close to the drill engine. Thus, this value was used to normalise the RMS amplitude of the main (50 Hz) spectral line calculated by the DFT, while the 150 Hz one was scaled accordingly. The time-domain waveform and its corresponding spectrum are reported in Figures 1 and 2, respectively.

As the next step, the test cylinder introduced in the previous section was virtually exposed to the magnetic field of the drill. The cylinder was assumed to have a radius $R = 60$ cm and to be composed by a material having the conductivity of the human muscle tissue.

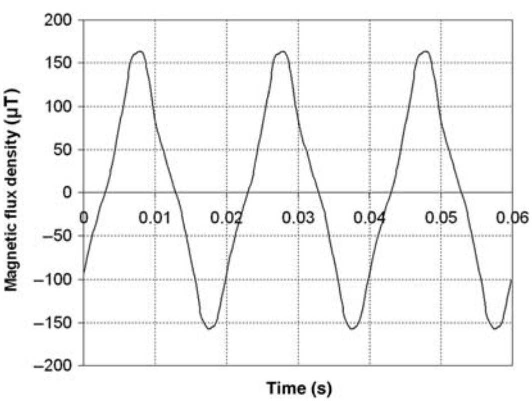

Figure 1. Time-domain waveform of the magnetic flux density generated by the source employed in the experiment.

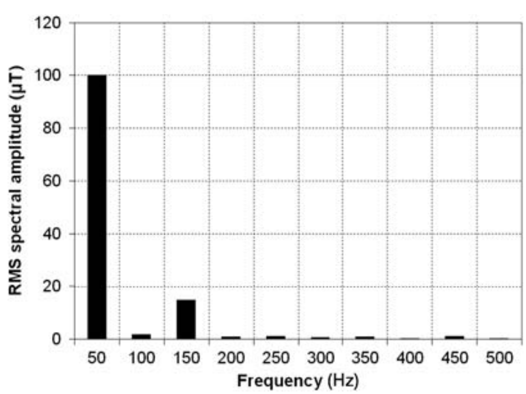

Figure 2. RMS amplitude of the spectral components of the magnetic flux density generated by the source employed in the experiment.

Table 1. Example of application of the simplified procedure.

	f_1	f_2
Frequency (Hz)	50	150
RMS spectral amplitude (μT)	100	14.9
Conductivity (muscle) (S m^{-1})	0.233	0.283
Exposure limit value (A m^{-2})	0.01	0.01
Parameter α (SI units)	0.500	0.224
Contribution to the exact value of the ICNIRP index	0.220	0.119
Exact ICNIRP index	0.339	
Estimated ICNIRP index with $f_0 \equiv f_1$	0.318	
Estimated ICNIRP index with $f_0 \equiv f_2$	0.386	

The exposure of a cylindrical object to the (homogeneous) magnetic field described in Figures 1 and 2 is considered. The cylinder has undefined length, radius $R = 60$ cm, main axis parallel to the field and is constituted by a material having the electrical conductivity of the human muscle tissue.

Table 1 summarises the main data of the experiment. As it is clearly shown, if the value $f_1 = 50$ Hz (at which the parameter α achieves its maximum value) is chosen as the reference frequency of the simplified procedure, than the procedure gives a round-down estimated value for the ICNIRP index affected by an error of approximately 6%. If, on the contrary, the value $f_2 = 150$ Hz (at which the conductivity σ achieves its maximum), the error increases up to 14%, but in this case it is a round-up error, i.e. it is directed in the precautionary direction, as it is preferred in many cases.

CONCLUSIONS

A simplified procedure was presented, which allows to reduce to a single evaluation at a predefined 'reference frequency' the dosimetric problem arising from the exposure to a multi-frequency EM field, assumed that the spectral components of the field are known and that all these components have the same polarisation and are fully comprised in the frequency range of validity of the quasi-static approximation.

The procedure is based on the physical characteristics of the coupling mechanism between low-frequency EM fields and biological systems. It is particularly accurate when the frequency range spanned by the source is so small that the material dielectric properties could be regarded as constant, and particularly well suited when the impressed field could be regarded as uniform in space.

The accuracy of the procedure was estimated and it was shown how to choose the reference frequency in order to minimise the error or to guarantee that it is directed in the precautionary direction.

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