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BIOTELEMETRY ANTENNAS IN BIOMECHANICS: THE PROBLEM OF SMALL BODY-MOUNTED ANTENNAS

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1. INTRODUCTION

Telemetry transmitters are applied on athletes and patients in order to record various data with minimum encumbrance for the test subject (TS). Continuous, omnidirectional data transmission is required with small, efficient and body-mounted antennas. In 1975 a research program was started involving the interactions between electromagnetic fields (EMF) and biological systems. The goal is to find the relation between frequency (f), antenna-trunk distance (d_{at}), body diameter (D_C) and the transmission loss (E_V), and to develop the optimal, omnidirectional and small antennas. This report is a summary of extended measurements and computations and is intended to be a help for telemetry users.

2. SAFETY CONSIDERATIONS

In the vicinity of a transmitting antenna, various types of EMF with the wavelength λ exist. The radiansphere (Wheeler 1959) is a spherical volume around the antenna with a radius r of $\lambda/2\pi$. Within the radiansphere is the near field, which contributes little to radiation and stores energy. Outside is the radiating far field which propagates mostly radially to the antenna axis; the power decreases with $1/r^2$. Telemetry antennas are so close to the body of the TS that the body is within the radiansphere. The power density may be small, but the E- and H-field may be considerable. Tell and O'Brien (1976) and Neukomm (1976a) have shown that the power density of walkie-talkies may easily exceed the USA safety level. The USA Safety Standard (ANSI 1974) recommends a power density of max. 10 mW/cm^2 or an energy density of max. 1 mWh/cm^2, averaged over any 0.1 hour period. The safety levels of the eastern countries are much more stringent, e.g. USSR 10 μW/cm^2, max. 6h/day. Hundreds of articles about biological effects due to radio-frequency radiation have been collected by Glaser and Brown (1976). Till now,it has not been proven that power densities below the USA safety level will cause severe effects on man. Liu,Rosenbaum and Pickard (1975) have shown that power densities down to 50 μW/cm^2cause teratogenic effects (malformations) on insects if the pupae is irradiated during 2 hours. Guy et al. (1975) could produce acoustic effects on man and on cats with pulsed microwaves.A single pulse of only 0.01μWh/cm^2 energy density produced an audiable click, and a series of pulses with an averaged power density of 120 μW/cm^2 appeared as a buzzing sensation. Other authors describe changes in behaviour and EEG.

Due to these reasons, the power of telemetry transmitters should not exceed 200 mW if body-mounted, non-directional antennas are used. The occasional use of telemetry on healthy test subjects can be justified with this limitation.

3. THE INFLUENCE OF THE HUMAN BODY ON THE RADIATION PATTERN

A vertical antenna, mounted on the trunk of a TS, has a disturbed azimuthal radiation pattern. The complex field distribution in the vicinity of the TS does not allow a direct computation of the far field at the receiving antenna. However, the reciprocity theorem can be applied if the body medium is assumed to be passive, linear and isotropic. The direction of transmission can be reversed. The new, simplier problem is now to compute the field amplitude in the vicinity of the body, which is irradiated by a plane wave. The mathematical model

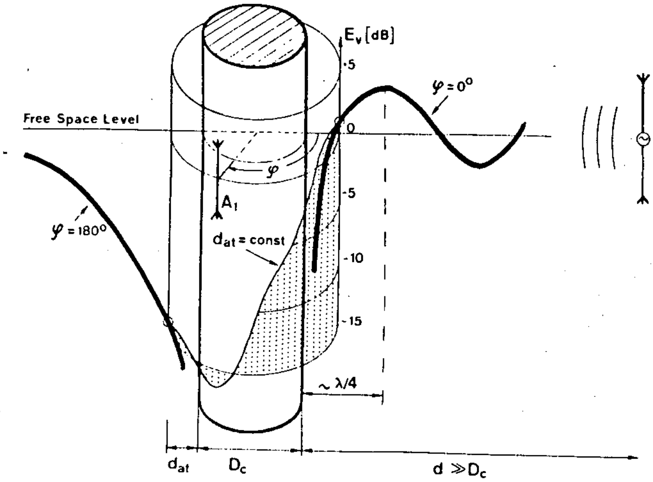

Figure 1 TRANSMISSION LOSS OF BODY-MOUNTED ANTENNAS

A conductive, infinite cylinder of D_c = 0.25 m represents the human test subject TS. The probe antenna A_1 is mounted at a distance d_{at} from the cylinder surface and records the field strength E_v, produced by a wave from the distant antenna A_2. When no TS is present, E_v is 0 dB. E_v is spacially depicted as a function of d_{at} (φ const.) and φ (d_{at} const.).

(Fig.1) consists of a vertical, infinite, conductive cylinder with a diameter D_c, a probe-receiving antenna A_1 at a distance d_{at} from the cylinder surface, and a distant antenna A_2 which radiates a vertical polarized plane wave. The received field strength E_v corresponds with the transmission loss and is calibrated to 0 dB if no TS is present. The transmission loss is the same in both directions and can be computed with the formulas of King and Wu (1959) by means of Bessel and Hankel functions. This model is valid for $200 < f < 1000$ MHz and $0.05 < d_{at} < 4$ m. The results correspond with the actual measurements of a TS with an accuracy of 4 dB. Transmission loss measurements have been made in both directions, at 11 frequencies between 75 and 1000 MHz, and with 3 different bodies: metallic cylinder (0.25 ø x 1.8 m), phantom cylinder (identical in size, but filled with a kind of Ringer solution) and a TS (0.9 m waist circumference, 1.7 m tall). The main results from computer calculations and measurements are:

a.) The transmission loss in both directions differs within 2 dB for $100 < f < 1000$ MHz and $0.05 < d_{at} < 4$ m. This holds true for all three bodies at a power level of 1 mW.

b.) The highest loss occurs at an angle $140^\circ < \varphi < 180^\circ$. The angle decreases with f and increases with d_{at}.

c.) A gain of max. 2.5 dB (TS) can be observed at $\varphi = 0^\circ$ at a distance of $0.7\ \lambda/4 < d_{at} < 1.1\ \lambda/4$.

d.) The max. loss increases from 20 to 30 dB with increasing frequency from 200 to 1000 MHz at a d_{at} = 35 mm. With d_{at} = 77 mm, the losses increase from 17 to 24 dB in the same frequency range.

e.) At 75 MHz the actual transmission loss is much less than the calculated loss, and for very small d_{at} even a gain can be measured. This seems to be a $\lambda/2$ resonance effect depending on the length of the TS. A weak λ resonance effect can be noticed at 125 to 150 MHz.

f. The model is limited to frequencies above 200 MHz, since the phantom and the TS are more or less transparent for lower frequencies. Below 50 MHz, the TS has no measureable effect on the radiation pattern.

g. The ideal telemetry frequencies lie within the range of 75 to 150 MHz, since the losses are below 18 dB for d_{at} = 35 mm and below 14 dB for d_{at} = 77 mm.

4. GENERAL RULES FOR TELEMETRY ANTENNAS ABOVE GROUND

If the antennas are less than $\lambda/2$ above ground, additional transmission loss is caused by ground reflections. This is very important for telemetry on swimmers and rowers, and with horizontal polarized antennas. A good technical solution is a helmet antenna on the TS and a high groundplane or Yagi receiving antenna, if transmission distances greater than 100 m are required.

5. ELECTRICALLY SMALL, BODY-MOUNTED ANTENNAS

Antennas, having no dimension greater than the radiansphere, are called electrically small. They are a compromise among volume, efficiency, bandwidth and in our case also detunability due to the vicinity of the TS. King (1975) developed a small shoulder antenna, which consists of a multi-turn loop above a limited counterpoise. This mounted antenna has a loss of about 10-20 dB at 160 MHz and $0^o < \varphi < 360^o$. If an omnidirectional antenna must be mounted onto the trunk, the helical normal mode antenna seems to be a good solution and should be discussed here. This antenna (see Tong 1974 and Neukomm 1976b) is elliptically polarized and allows the TS to rotate on more than one axis. The antenna consists of a helical wound wire, with an axial length h of ca. $\lambda/10$ and a diameter D of ca. $\lambda/50$. The number of turns N, resp. N = n.h, can be calculated quite accurately with Tong's formula (λ,h.D in cm):

$$\log n = 0.4\left(\log\left(\frac{\lambda}{h} - 4\right) + \log\left(\frac{\lambda}{h} + 4\right) + 0.5\log\lambda - 3\log D\right) - 1$$

5.1. EFFICIENCY OF SMALL ANTENNAS

The equivalent circuit of an antenna is a serie resonant circuit with the elements L,C and R, whereby R is $R_{rad} + R_{loss}$ (radiation resistance and loss resistance). R_{rad} of a helical antenna can be calculated with $(25.3\ h/\lambda)^2$ and is relatively small. R_{loss} is determined by ground losses (in the case of asymmetrical antennas with a counterpoise of less than $\lambda/4$ in radius), by skin effected ohmic losses and by losses in impedance matching and/or balancing devices. Since the efficiency decreases with small antennas, it should always be determined using the Wheeler method:
The Smith Chart of the antenna in free space is recorded, and one reads the real impedance R at resonant frequency f_{res}. The antenna will be located in a conducting vessel with the dimension of the radiansphere (±50%). The Smith Chart is again recorded, and the highest ohmic resistance near f_{res} represents R_{loss}. The efficiency Eff can be calculated with $(R-R_{loss})/R$ with an absolute

accuracy of 25 % and a relative accuracy of 5 %.
Below 300 MHz it is hardly possible to design a sufficent counterpoise (e.g. telemetry case); therefore, efficent antennas should be symmetrically designed in the shape of a dipole.

5.2. BANDWIDTH, MATCHING TO 50Ω, BALANCING TO COAXIAL LINE.

Any small antenna has a reduced bandwidth (Wheeler). Additional L and C elements are required to obtain f_{res}. The bandwidth B, approximated by $R \cdot \sqrt{C/L}$, is narrow in the case of the helical antenna, since the helix represents a distributed L. A further bandwidth reduction results from the matching of the low R to the 50Ω feeding line. Therefore it is not appropriate to classify the performance of a helical antenna with the VSWR only. A matching can be obtained with: bifilar helix (folded helical dipole), top loading (Δ and T match) and varying pitch of the helix. The gain increases, but B and Eff decrease and the antenna may be severely detuned by the proximity of the TS. Dipoles may be balanced to the 50Ω asymmetrical coaxial line with a parallel λ/4 conductor bazooka, with the smallest possible spacing between the two conductors. Below 1 watt power and below 300 MHz a ferrit 1:1 balun can be used with only 10 % additional loss.

5.3. COMPARISON OF DIFFERENT TELEMETRY ANTENNAS AT 230 MHz

Five antennas have been selected for a discussion of the performance: The GROUNDPLANE ANTENNA GA is a vertical λ/4 whip on 4 ground rods, each λ/4 (32.6 cm) and at an angle of 135^{o} to the whip. The HELMET ANTENNA HGA is a vertical λ/4 whip on a plastic helmet, coated with a copper mesh. The ROUND HELICAL DIPOLE RHD consists of a helix with 2h = 22 cm , D = 2 cm , 2N = 18 turns and is fed over the four center windings (Δ match and bazooka). The FLAT HELICAL DIPOLE FHD is a flat helix with 2N = 10.5 turns, 2h = 20 cm , D_1 = 5.3 cmm, D_2 = 0.5 cm. 5 cm of the wire in the center are parallel to the axis 2h, with symmetrical center feeding. The FLAT

FOLDED HELICAL DIPOLE FFHD consists of a 240Ω parallel line with the electrical length of λ/2, wrapped in the shape of a helix with single conductors at the ends (see Li and Beam 1957). This center feed antenna has the same dimensions like the FFD, but 2N is 13.5.

TABLE 1 COMPARISON OF HELMET AND BODY-MOUNTED ANTENNAS

Antenna type (see text)	Antenna data in free space without test subject TS					Vertical antenna mounted dorsally on the TS with d_{at} = 57 mm, φ = azim. angle with 180° = TS between antennas				
	Resonant frequency [MHz]	Band-width [MHz]	Gain [dB]	Effi-ciency [%]	VSWR [1]	Resonant frequency [MHz]	Band-width [MHz]	Gain φ = 0° [dB]	Gain φ = 180° [dB]	Freq. shift [MHz]
GA	220	65	2.15	-	1:1.4	-	-	-	-	-
HGA	237	47	+0.5	-	1:1.3	-	-	-	-	-
RHD	236.3	18	+0.2	89	1:2.5	229.2	23	-7.7	-20	7.1
FHD	237.5	25	+0.8	79	1:4	231.8	24	-6.1	-21	5.7
FFHD	242.1	8.8	+1.0	78	1:1.3	236.8	9.6	-4.0	-20	5.3

Table 1 presents the performance of these antennas. The helical antennas were mounted on the phantom, the antenna center was spaced 57 mm from the phantom surface. These results hold true within 2 dB when mounted dorsally on a TS. The best antenna for telemetry in biomechanics seems to be the FHD, since varying body distance does not detune the antenna out of its bandwidth.

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