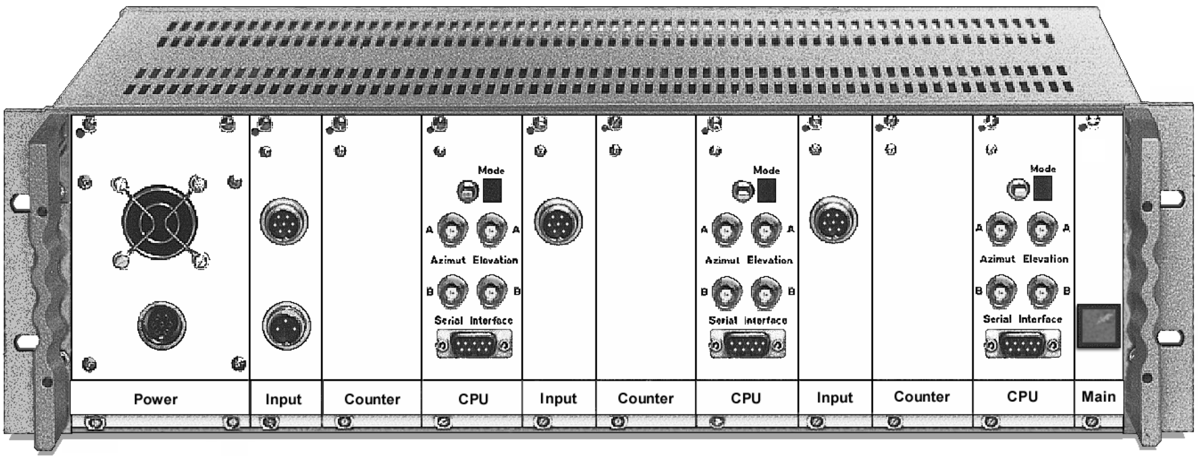
Angle-Meter

Measuring principle



Scleral search coil system for linear detection of three-dimensional angular movements

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Introduction

The magnetic field search coil technique introduced by Robinson [1] has become the most commonly used method for quantitative studies of eye and head movements in man and in experimental animals. The technique is based on phase-locked amplitude detection of the voltage induced in a search coil in the external ac magnetic field. The angular orientation or displacement of the search coil in three-dimensional (3D) space is detected by using two or three external magnetic fields, which are arranged in space quadrature. Demodulation of the induced signals with respect to the magnetic field directions is obtained on the basis of phase or frequency coding by driving the external magnetic fields in phase quadrature or at different frequencies [2].

Since the amplitude of the induced voltage is a trigonometric function of the angular orientation of the search coil in the external field, angular detection is basically a nonlinear operation. In systems operating with two different external fields, calibration of the output signals depends on the search coil characteristics (area bounded by the coil, number of turns) as well as on the magnetic field strengths. In order to obtain reproducible results, the search coil measurements have to be restricted to the uniform part of the external magnetic fields. Since the spatial characteristics of the magnetic fields depend on electro-magnetic couplings with the environment, both calibration and recordings must be performed in a defined and static situation. These methodological limitations are particularly difficult to handle when studying eye/head coordination in freely moving animals. Similar problems arise when recording vestibularly induced eye movements, which requires the animal to be moved together with the field coils relative to the laboratory environment.

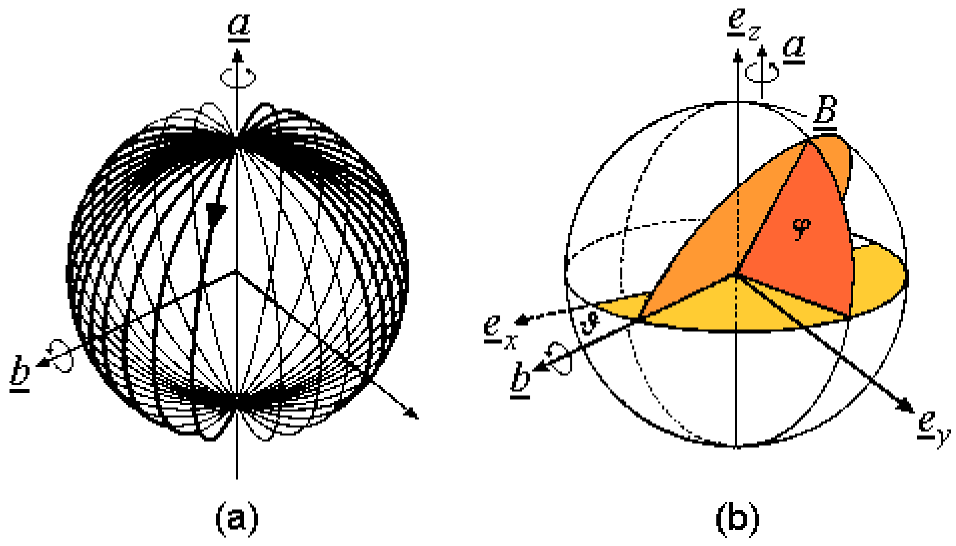
A modification of the original measuring principle proposed by Hartmann and Klinke [3] overcomes most of these difficulties. It is based on the detection of the phase of the search coil signal in a magnetic field with a uniformly rotating flux density vector. The measuring plane, i.e., the plane in which angular position and displacements of the search coil are faithfully detected, is determined by the plane of rotation of the magnetic field vector [4].

The operation of the Angle-Meter is based on this measuring principle and is mainly comprised of the following components:

- Three pairs of one-turn field coils, arranged as a cube, which are building the inductive part of three resonance circuits and generate a magnetic field with a rotating flux density vector $\underline{B}$
- The Matching Box with capacitor networks, which are building the capacitive part of the three resonance circuits.
- The preamplifier with AGC for the amplification of the search coil signals.
- The main unit with power supply, magnetic field generation-, demodulation- and control-electronics.

[1] D. A. Robinson, "A method of measuring eye movement ..." IEEE Trans. Biomed. Eng., vol. BME-l0, pp. 137-145, 1963
[2] R. S. Remmel, "An inexpensive eye movement monitor ..." IEEE Trans. Biomed. Eng., vol. BME-31, pp. 388-390, 1984
[3] R. Hartmann and R. Klinke, "A method for measuring the angle of ..." Pflugers Arch., Suppl. 362, R52, 1976
[4] H. J. Kasper, B. J. M. Hess, and N. Dieringer, "A precise and ..." J. Neurosci. Meth., vol. l9,pp. 115-124, 1987

Magnetic field generation



Schematic drawings illustrating the measuring principle: (a) Scheme showing part of the trajectory of the magnetic flux density vector $\underline{B}(t)$ on the surface of a sphere. Axes $\underline{a}$ and $\underline{b}$ are the rotation axes of the horizontal and vertical component of $\underline{B}$, respectively. Note that axis $\underline{b}$ changes continuously its orientation in a plane is perpendicular to $\underline{a}$, whereas axis $\underline{a}$ remains stationary in space; (b) scheme showing the orientation of the flux density vector $\underline{B}$ at a time instant t with respect to a Cartesian reference frame defined by the basis vectors e_x, e_y, and e_z. The orientation of $\underline{B}$ at any instant of time t is defined by the horizontal angular displacement $\theta(t) = 2\pi ft$ and the vertical angular displacement $\Phi(t) = 2\pi aft$, where f = 400 Hz and af = 51.2 kHz are the field frequencies around $\underline{a}$ and $\underline{b}$, respectively (a = 128). The orientation of a search coil in the magnetic field can be similarly described in terms of horizontal and vertical angular orientations α and β of the search coil area vector $\underline{n}$ (not shown).

Three ac magnetic fields of equal magnitude are generated in space and phase quadrature. The magnetic flux density vectors $\underline{B}_x$, $\underline{B}_y$, and $\underline{B}_z$ of the three fields define an orthogonal reference frame with unit vectors $\underline{e}_x$, $\underline{e}_y$ and $\underline{e}_z$:

$$\underline{B}_X = B\underline{e}_X \,,\ \underline{B}_y = B\underline{e}_y \,,\ \underline{B}_Z = B\underline{e}_Z \qquad (1)$$

The two horizontal fields $\underline{B}_x$ and $\underline{B}_y$ are driven in phase quadrature at a frequency of 400 Hz. This results in a horizontally rotating density vector $\underline{B}_{xy} = \underline{B}_x + \underline{B}_y$. Similarly, the horizontal and the vertical fields $\underline{B}_{xy}$ and $\underline{B}_z$ are also driven in phase quadrature but at a frequency of 51.2 kHz. The ratio of the two field frequencies is 1:128. The spatial trajectory of the magnetic flux density vector $B(t)$ can be described by (see also schematic drawings above):

$$\begin{aligned}\underline{B} &= \underline{B}_X + \underline{B}_y + \underline{B}_Z \\ &= B(\underline{e}_X \cos 2\pi aft \cos 2\pi ft + \underline{e}_y \cos 2\pi aft \sin 2\pi ft + \underline{e}_Z \sin 2\pi aft) \qquad (2)\end{aligned}$$

where f = 400 Hz and a = 128. The power of this revolving magnetic field is concentrated in a narrow frequency band around $af \pm f$. As a consequence, the magnetic field is relatively insensitive to selective damping by electromagnetic couplings with the environment.

Demodulation of angular position parameters

The voltage V induced in a search coil placed in an extemal magnetic field with flux density vector $\underline{B} = B\underline{e}$ is given by Faraday's law:

$$V = -g\, d/dt \int_A \underline{B} \bullet \underline{n}\, dA$$
$$= -gB\, d/dt \int_A \underline{e} \bullet \underline{n}\, dA \qquad (B = \text{constant}) \qquad (3)$$

where A is the area bounded by the search coil windings, g is the coil coupling constant and $\underline{n}$ is the unit area vector of the coil (pointing parallel to the coil axis). The integration in (3) is to be taken over the coil bounded area A.

To describe the demodulation process, we consider the scalar product

$$r_{\alpha\beta} = \underline{e} \bullet \underline{n} \qquad (4)$$

over which the surface integration is to be taken in (3). This is no restriction since integration and time derivation are linear operations. Introducing spherical coordinates with angular parameters α and β, we obtain

$$r_{\alpha\beta} = \cos\beta \cos(2\pi ft - \alpha) \cos 2\pi aft + \sin\beta \sin 2\pi aft \qquad (5)$$

This signal can be electronically demodulated in terms of the angular position parameters $\alpha(t)$ and $\beta(t)$ as described in the following.

Demodulation of Angular Position $\alpha(t)$

The signal $r_{\alpha\beta}$ is split into a high- and low-frequency component by multiplying it with the high-frequency carrier $\cos 2\pi aft$:

$$c_{\alpha\beta} = r_{\alpha\beta} \cos 2\pi aft$$
$$= 1/2 \cos\beta \cos(2\pi ft - \alpha) + 1/2\, [\sin\beta \sin 4\pi aft$$
$$- \cos\beta \cos 4\pi aft \cos(2\pi aft - \alpha)] \qquad (6)$$

After low pass filtering, we have:

$$[c_{\alpha\beta}]_{LP} = 1/2 \cos\beta \cos(2\pi ft - \alpha) \qquad (7)$$

The angular parameter $\alpha(t)$ can now be obtained by phase comparison with respect to the rotating horizontal field component.

Demodulation of Angular Position $\beta(t)$

Knowing the value of the angular parameter $\alpha(t)$ at a given instant of time t, the signal $r_{\alpha\beta}$ is sampled at the instants $t_\alpha = \alpha / 2\pi f$ (modulo $1/f$):

$$r_{\alpha\beta}(t_\alpha) = \cos\beta \cos 2\pi aft_\alpha + \sin\beta \sin 2\pi aft_\alpha$$
$$= \cos(a\alpha - \beta) \qquad (8)$$

While the value $r_{\alpha\beta}(t_\alpha)$ is held for one sampling period of 19µs, the angular parameter $\beta(t_\alpha)$ is evaluated. For each revolution in the horizontal plane, one revolution in the vertical plane is used to sample the angle β. Note, however, that the factor $\cos(2\pi ft - \alpha)$ in (5) varies slowly with respect to the much faster revolutions of the vertical field since the frequency ratio of the two fields is rather large. As a consequence, (8) holds in very good approximation in a certain time interval $t_\alpha \pm n/af$, i.e.

$$r_{\alpha\beta}(t) \approx \cos(a\alpha - \beta) \qquad \text{for } |t - t_\alpha| \leq n/af \qquad (8')$$

We have, for example, $\cos(2\pi ft - \alpha) >= 0.97$ for $n = 5$. The parameter $\beta(t)$ can therefore be measured without any appreciable loss in precision within a time interval as large as ±5 fast field cycles around the time instant t_α. When using a digital demodulation procedure, one can take full advantage of the search coil signal characteristics by analyzing the parameter β within a larger time interval and eliminating the phase error by averaging over symmetrical signal portions.