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Three different attitude measurements of spinning projectile based on magnetic sensors

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ABSTRACT

Micro-inertial sensors currently could not provide long-time stability attitude information for the high spinning projectile because of drift errors. Meanwhile, the method of the navigation and attitude measurement with respect to the earth's magnetic field is still auxiliary, and the attitude angle information cannot be got only by measuring the three-axis components of the geomagnetic field. In view of the flying characteristics of high spinning projectile, three different attitude measurements only using magnetic sensors are researched. Through comparative analyses, the calculating principle, system composition, applicable condition and error range of these methods are explained. Meanwhile, the semi-physical experiments are made to prove the effectiveness of the three attitude measurements. The experiment results indicate that only scalar arithmetic operations are required for these angular measurements and they have the day/night and all weather capability. The three different measurements have same angle error range within ±1° but different attitude updating rate.

1. Introduction

At present, the attitude measurement of a moving body is involved in many fields, for example, in aerial and marine vehicles [1–3], robots and human pose tracking [4]. Especially for the military application, it is important to test the projectile flight attitude accurately. Accurate measurement of angular motions of spinning projectiles with on-board sensors has been recognized as a daunting task. The fundamental requirements for such measurement are lightweight, small-size, and low power consumption. The currently available micro-inertial sensors have relatively low accuracy and the drift could cause remarkable attitude errors [5]. Successful attitude measurement with inertial sensors requires the expensive gyroscopes and accelerometers with exceptionally increased accuracy and complex filtering algorithm [6–8].

Geomagnetic field is a vector field as the earth's natural resources. It provides the natural coordinate system for navigation with its rich element such as strength, inclination, declination and gradient. Recent progresses in magnetic sensor technologies have resulted in devices small enough, rugged enough, and sensitive enough to be useful in systems capable of making high-speed, high-resolution measurements of attitude relative to magnetic fields [9]. Because of its high reliability and anti-interference ability, attitude measurements with geomagnetic have become a hot spot in research of flying parameter measurement. Due to the fact that the three-component magnetic sensor cannot provide three independent equations, other methods are combined to calculate one of the three angles of yaw, pitch and roll to obtain another two. The problems make the magnetic sensor is still auxiliary in attitude measuring systems [10–13].

Thomas Harkins and David Hepner designed an attitude measuring system for spinning bodies, called

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"MAGSONDE" only with magnetic sensors. The "Zero Crossings Method" for the "MAGSONDE" has been provided in their report [14]. On this basis, an attitude angle measurement based on the ratio of extremum of two orthogonal magnetic sensors is introduced in this paper and this "Extremum Ratio Method" is extended to "Three Orthogonal Ratio Method". Through the theory research and Semi-physical experiments, the three different attitude measuring methods that only using magnetic sensors were compared in detail. In all the three cases, we do not need to know the magnetic field strength, only scalar calculation is required. These methods satisfy the requirement of high-spinning projectile's attitude determination. The results have an important signification for projectile design. Potential application for these methods includes determination of angular motion histories of experimental and development of fuze design.

2. Magnetic sensor configuration

Assuming that the gravity center of the spinning projectile is at the origin of the *o-xyz* coordinate system which fixed in body frame, its axis of rotation is on the x axis and its nose pointed in the $+x$ direction. As showed in Fig. 1, the magnetic sensors M_{sx}, M_{sy} and M_{sz} locate respectively along the x axis, y axis and z axis. The sensor M_{s1} locates in the *o-xy* plane and orients at a non-zero angle λ from the spin axis x.

According to coordinate system rotation matrix rules, the field strength along the sensitive axes of the four sensors are given by [15]

$$\begin{cases} M_{sx} = |\vec{\mathbf{M}}| \cos\psi \cos\sigma_m \\ M_{sy} = -|\vec{\mathbf{M}}| \cos\gamma \sin\psi \cos\sigma_m + |\vec{\mathbf{M}}| \sin\gamma \sin\sigma_m \\ M_{sz} = |\vec{\mathbf{M}}| \sin\gamma \sin\psi \cos\sigma_m + |\vec{\mathbf{M}}| \cos\gamma \sin\sigma_m \\ M_{s1} = |\vec{\mathbf{M}}| \cos\psi \cos\sigma_m \cos\lambda - |\vec{\mathbf{M}}| \cos\gamma \sin\psi \cos\sigma_m \sin\lambda \\ \quad +|\vec{\mathbf{M}}| \sin\gamma \sin\sigma_m \sin\lambda \end{cases} \tag{1}$$

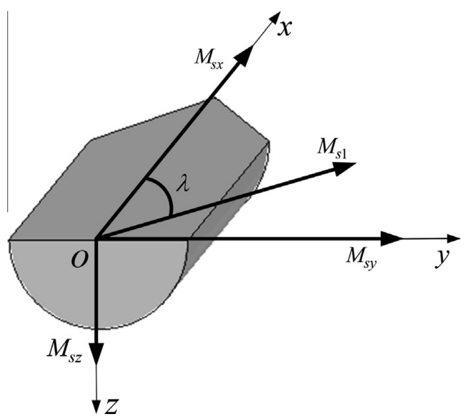

Fig. 1. Installation of magnetic sensors in coordinate *o-xyz*. M_{sx} locates respectively along the body's rotation axis and M_{sy} and M_{sz} are installed along the other two coordinate axis. M_{s1} is in the *o-xy* plane with a non-zero angle λ from the M_{sx}.

where $\vec{\mathbf{M}}$ is the strength and direction of geomagnetic field. The angle between $\vec{\mathbf{M}}$ and x axis is designated as $\sigma_m \cdot \psi$ is the sum of the declination and real yaw. The projectile roll angle is described by the γ. There are three unknown parameters in (1), but no three independent equations. Therefore, one or more attitude angles must be known from other ways in order to calculate the rest attitude angles [5].

3. Theory analyisis for three different methods

According to the flight characteristic of the high spinning projectile, some basic hypotheses are as follows:

(1) Velocity vector is in the firing plane all the time [16], that is, ψ is invariable.
(2) σ_m changes much slowly with time relative to the roll rate.

With the above hypothesis, the "Zero Crossings Method" was anew explained below. Based on it, the other two new methods were introduced in this section.

3.1. Zero crossings method

The normalized field strength along the sensitive axis for two non-orthogonal sensors M_{sy} and M_{s1} throughout several roll cycles is plotted in Fig. 2 with $\sigma_m = 45°$, $\psi = 30°$ and $\lambda = 60°$. Denoting the two pairs of roll angles at the zero crossings for the two sensors as (γ_{sya}, γ_{syb}) and (γ_{s1a}, γ_{s1b}). By (1), with fixed ψ and λ, the value of ratio $R = (\gamma_{s1b} - \gamma_{s1a})/(\gamma_{syb} - \gamma_{sya})$ only depends on σ_m [14,17]. The corresponding relation of ratio R and σ_m is showed in Fig. 3.

The combination of the $R - \sigma_m$ calibration curve and a parity check completely specifies the angle σ_m between the projectile axis and the magnetic field [17].

3.2. Extremum Ratio Method

Not only the ratios of zero crossing, but also the ratios of maximums and minimums of the two magnetic sensors have corresponding relationship with σ_m and they are proved as follows: σ_m and ψ change slowly with time compared with γ, so when M_{sy} and M_{s1} reach the maximum or the minimum, that is $dM_{sy}/dt = 0$ and $dM_{s1}/dt = 0$, we always have

$$\cos\sigma_m \sin\psi \sin\gamma + \sin\sigma_m \cos\gamma = 0 \tag{2}$$

It is seen from (2) that M_{sy} and M_{s1} reach the maximums and minimums at the same time, respectively. Denoting the ratios of the maximums and minimums of two magnetic sensors as $R_{\max} = (M_{s1\max}/M_{sy\max})$ and $R_{\min} = (M_{s1\min}/M_{sy\min})$. When M_{sy} or M_{s1} reaches the extreme values, the attitude angles must satisfy (2), so combining (1) and (2), the relationships between $R_{\max}$, $R_{\min}$ and σ_m are as follows:

$$R_{\max} = \sin\lambda + \frac{\cos\psi \cos\lambda \cos\sigma_m}{\sqrt{\sin^2\sigma_m + \sin^2\psi \cos^2\sigma_m}} \tag{3}$$