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Computer Simulation Model of Sun Sensor and Magnetic Sensor for Attitude Determination of a Small Satellite

Zaure Rakisheva, Anna Sukhenko and Rustam Povetkin

Department on Mechanics, Faculty of Mechanics and Mathematics
al-Farabi Kazakh National University
71 al-Farabi av., Almaty, Kazakhstan

Abstract

In this article mathematical and computer models of sun sensor and magnetic sensor are considered that can be used for determination of small satellite attitude. In particular, the mathematical models of slit sun sensor and flux-gate magnetic sensor are given.

Keywords: small satellite, attitude determination, sun sensor, magnetic sensor, computer simulation

1 Introduction

For attitude control of satellite, first of all, it is necessary to determine its attitude in space. Satellite attitude is determined by means of the set of several sensors on-board: sun sensors, magnetic sensors, star trackers and etc. Small satellites, as a rule, do not require high accuracy positioning and for determination their attitude in this case it is enough to use magnetic and sun sensors. It can be considered as an example Japanese microsatellite PRISM, attitude determination of which is based on output parameters of magnetometer and sun sensor [4], attitude of German satellite ABRIXAS was determined by means of Kalman filter based on output parameters of sun sensor and magnetometer [2], Russian satellite Chibis-M uses magnetometer and sun sensor for attitude determination on illuminated side of an orbit [10], nanosatellite BEESAT-2 of Berlin technical university also uses magnetic and sun sensor as attitude determination sensors [3].

2 Simulation of Sun Sensor

Sun sensor is one of the main measuring devices of the satellite and used mainly to provide the Sun-tracking mode, to determine the satellite current attitude, to carry out various satellite maneuvers. Actually sun sensor gives as output parameters the direction vector to the Sun or angular coordinates of the Sun in the coordinate system connected with sun sensor that in fact represent in itself one or two angles between device surface and direction vector to the Sun [6].

At present there are many types of sun sensors differentiating by function and principle of operation. Mainly they represent the types of optical and slit sun sensors. Slit sun sensors have small mass and dimensions in comparison with optical sun sensors, more simple construction and possibility of miniaturization that makes their application on small satellites more preferable. Generally for unique determination of direction vector to the Sun it is enough to allocate from 4 to 6 slit sun sensors on the surface of small satellites.

Let's consider a model of digital slit sun sensor. Example of the sensor of this type is the sun sensor [1]. Sun sensor consists of two detectors located perpendicularly to each other. Mask with two fine slits is located over detectors at the fixed height. The beam falling at an angle θ passes through a fine slit and falls on the sensor detector (fig. 1) [9], which generates digital signal depending on bias x of incident beam. For the coding of the digital signal the Grey code is used [9], which can be uniquely transferred to binary form and further to the decimal.

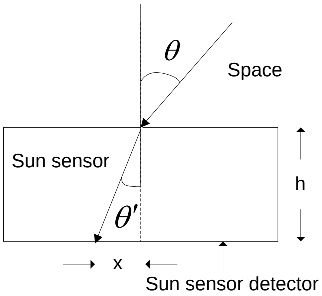

Fig 1. – Scheme of slit sun sensor

According to Shell refraction law we have [9]:

$$\sin\theta = n\sin\theta', \qquad (1)$$

where θ - angle between device surface and direction vector to the Sun, θ' - angle of Sun incidence to the sun sensor detector, n - refraction coefficient.

Bias of incident beam is determined by formula [9]:

$$x = K\,DS\,, \tag{2}$$

$$K = \frac{Length}{2^m}\,, \tag{3}$$

where *DS* – digital signal of *m*-bit sun sensor (in decimal form), $Length$ - sensor length.

Using fig.1, the angle between device surface and direction vector to the Sun or one of the angular coordinates of the Sun can be determined by formula [9]:

$$\theta = \arcsin\frac{\mathrm{nKDS}}{\sqrt{\mathrm{KDS}^2 + h^2}}\,, \tag{4}$$

where h - sensor height.

It is necessary to note that signal generation by sensor is conducted only in the case if beam incidence angle is in the range of sun sensor field of view:

$$DS = \mathrm{int}\left(\frac{\theta \cdot 2^m}{FOV}\right), \tag{5}$$

where FOV - sun sensor field of view.

Sun sensor field of view can be determined on the assumption of its physical dimensions:

$$\mathrm{FOV} = 2\arcsin\left(\frac{a}{\sqrt{a^2 + h^2}}\right), \tag{6}$$

$$a = \frac{Length}{2}\,, \tag{7}$$

where FOV - sun sensor field of view, h - sun sensor height.

Sensor sensitivity (error) depends on beam incidence angle and at the values close to the extreme ($\theta = \frac{\mathrm{FOV}}{2}$), the accuracy of sun sensor decreases. Maximum error can be calculated by formula:

$$\varepsilon = \arcsin\left(\frac{K(2^{m-1}-1)}{(2^{m-1}-1)^2 K^2 + h^2}\right) - \arcsin\left(\frac{K2^{m-1}}{\left(2^{m-1}\right)^2 K^2 + h^2}\right), \tag{8}$$

where ε - error of sun sensor.

The beam incidence angle φ in other surface is measured by means of the second detector and direction vector to the Sun in the coordinate system of sun sensor can be determined by formula:

$$\begin{cases} x_s = \sin\theta\cos\varphi, \\ y_s = \sin\theta\sin\varphi, \\ z_s = \cos\theta. \end{cases} \tag{9}$$

For verification of mathematical model of sun sensor the numerical experiments were carried out. For generation of incidence angle of the Sun θ the motion simulation of the small satellite and Sun is realized. The results of numerical simulation of one-axis slit sun sensor are given in fig. 2. The blue line in graphic shows the change of angular position of the Sun relative to sighting axis of sun sensor. By received results it can be seen that error of sun sensor increases when the incidence angle nears the maximum values.

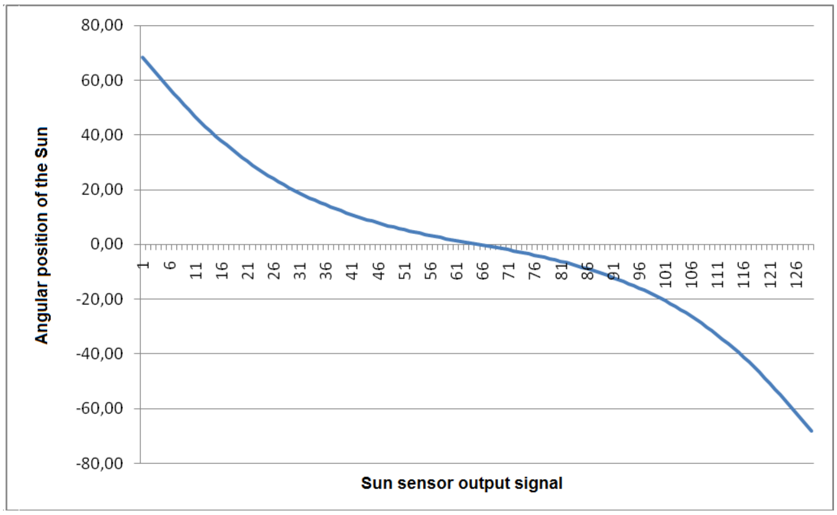

Fig. 2 Graphic of Sun angular position deviation from sun sensor axis

3 Simulation of Magnetic Sensor

Magnetic sensors measures different parameters of magnetic field. They are used in attitude determination and control system of small satellites as the sensors determining the angular position and velocity of small satellites in conjunction with other sensors.

The various physical phenomena occurring in semiconductors and metals in the process of interaction with a magnetic field are used for development of magnetic sensors. There are known the magnetic sensors using effects of Hall and Gauss, magneto resistance, Suhl effect, also magnetodiode and magneto-galvano-recombination effects and etc. Existing magnetic sensors are realized in the form of elements of Hall, magnetoresistors, magnetodiodes and magnetic transistors [5]. At present the most popular magnetic sensors are the magnetic sensors where the flux-gate is used as the sensing element. Flux-gate is the electric coil with core from soft magnetic material supplying by alternating current. The principle of sensor operation is based on the coil sensitivity to the value and direction of external magnetic field [8].

Let’s consider the model of three-axis flux-gate magnetic sensor. The example of such type of sensors is analog 3-axis fluxgate magnetometer of SSTL Ltd. Output parameter of the sensor is the voltage of electric coil which depends on the change of magnetic field:

$$\mathrm{V_i} = a\vec{H} + V_0, \quad i = 1..3, \tag{10}$$

where V_i - voltage of i-th coil (sensor is three-axis, correspondingly there will be three coils); a - sensor scaling factor; $\vec{\mathrm{H}} = [\mathrm{H_x}, \mathrm{H_y}, \mathrm{H_z}]$ - Earth magnetic field intensity vector.

According to data of output voltage the components of magnetic inductance vector or the intensity of Earth magnetic field can be calculated as:

$$\vec{H} = \frac{\mathrm{V_i} - V_0}{a}, \ i = 1..3 \tag{11}$$

The magnetic field intensity used in formula (11), is determined on the basis of Earth magnetic field model 2005 (WMM 2005) [7]:

$$\mathrm{U} = \mathrm{f}(\mathrm{r}, \varphi, \lambda, \mathrm{t}) = \mathrm{a}\sum_{\mathrm{n=1}}^{\mathrm{k}}\left[\left(\frac{r_e}{r}\right)^{n+1} \sum_{\mathrm{m=0}}^{\mathrm{n}}\left[g_n^m \cos(k\lambda) + h_n^m \sin(k\lambda)\right] P_n^m(\cos\lambda)\right], \tag{12}$$

where U - potential of Earth magnetic field, r, φ, λ - spherical coordinates of the satellite, r_e - Earth radius, g_n^m , h_n^m - coefficients of magnetic field model WMM 2005.

On the basis of formula (12) the components of Earth magnetic field intensity vector can be calculated as:

$$H_r = -\frac{\partial U}{\partial r} = \sum_{n=1}^{k}\left[\left(\frac{r_e}{r}\right)^{n+2}(n+1)\sum_{m=0}^{n}\left[g_n^m\cos(k\lambda)+h_n^m\sin(k\lambda)\right]P_n^m(\lambda)\right]. \tag{13}$$

$$H_\lambda = -\frac{\partial U}{r\partial\lambda} = -\sum_{n=1}^{k}\left[\left(\frac{r_e}{r}\right)^{n+2}\sum_{m=0}^{n}\left[g_n^m\cos(k\lambda)+h_n^m\sin(k\lambda)\right]\frac{\partial P_n^m(\lambda)}{\partial\lambda}\right]. \tag{14}$$

$$H_\varphi = -\frac{\partial U}{r\sin\lambda\partial\varphi} = -\frac{1}{\sin\lambda}\sum_{n=1}^{k}\left[\left(\frac{r_e}{r}\right)^{n+2}\sum_{m=0}^{n}m\left[-g_n^m\sin(k\lambda)+h_n^m\cos(k\lambda)\right]P_n^m(\lambda)\right] \tag{15}$$

The numerical experiments for verification of mathematical model of magnetic sensor were carried out. The numerical simulation of small satellite attitude with the magnetic actuators on-board was carried out for generation of Earth magnetic field change with time. The results of numerical experiments are given in fig. 3. The change of three components of Earth magnetic field with time depending on satellite attitude changing by the B-dot law is designated by three lines on graphic.

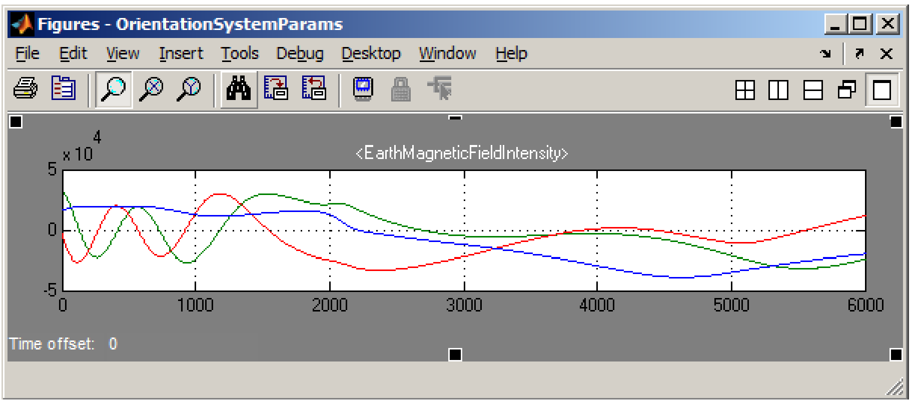

Fig. 3 Components of Earth magnetic field intensity vector

4 Conclusions

In this article the mathematical models of slit sun sensor and flux-gate magnetic sensor were introduced. As it is known slit sun sensors have less mass and dimensions in comparison with other types of sun sensors (for instance, optical sun sensors), have more simple construction and possibility of miniaturization that makes its application on small satellite more preferable. Flux-gate magnetic sensors are currently the most used sensors on-board the small satellites as they can be used in magnetic attitude control systems and in addition allow in conjunction with sun sensors determining the attitude of small satellite in accordance with known algorithms of attitude assessment, for instance TRIAD and Kalman filter. Thus, the choice of current sensors for consideration is quite explainable and actual.

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