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ATTITUDE DETERMINATION AND CONTROL FOR A SMALL REMOTE SENSING SATELLITE†

MICHELE GRASSI

Dipartimento di Scienza e Ingegneria dello Spazio "L.G. Napolitano", Faculty of Engineering, University of Naples "Federico II", P.le Tecchio 80, 80125, Naples, Italy

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Abstract—In this paper, a fully autonomous magnetic attitude control system is proposed for a small satellite for remote sensing applications. The attitude determination hardware consists of a horizon sensor and a pair of two-axis magnetometers. Three-axis attitude control is performed by means of three magnetic torquers. Control laws are derived separately for the attitude acquisition and the station keeping phases. The proposed control strategy is then tested by using a numerical code which simulates the satellite orbit and attitude dynamics and control, and the sensor measurement errors. Final results show that the proposed magnetic control system limits the attitude angles and rates within values adequate to low/medium resolution remote sensing applications. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

In the last decade, various space missions have been performed using small satellites. The interest in this class of satellites arises mainly from their low cost and short development timescales. The use of small satellites involves obvious limitations in size, weight and on-board available power. Moreover, technologies developed for traditional larger satellites are not always and immediately suitable for small satellites. This mainly affects the design of the attitude control, communication and power subsystems, especially in the case of remote sensing applications, which have stringent requirements [1]. Therefore, new solutions have to be investigated, and, in some cases, appropriate technologies have to be developed.

In this paper, a low-cost, low-weight magnetic system is proposed for the attitude determination and control of a small satellite for remote sensing applications. The attitude determination and control of a small satellite have been analyzed by several authors. Various control techniques have been proposed: the use of different configurations of momentum and/or reaction wheels has been particularly recommended owing to their reliability and capacity to provide high accuracy attitude control [2]. In these configurations, the use of magnetic torquers as momentum dumping devices has been proposed in alternative to the more traditional gas jets [3], in order to reduce the mass budget for the satellite. Magnetic control is particularly attractive for small satellites, owing to its low weight and power requirements. Magnetic torquers have been adopted extensively to despin satellites, and for attitude acquisition, nutation and precession control and momentum bias regulation on dual-spin satellites [4].

In this paper, a three-axis, fully autonomous magnetic control system (ADACS) is analyzed for a small satellite carrying a remote sensing payload on a sun-synchronous orbit at an altitude of 433 km with an inclination of 97.2°. The attitude control system, which consists of three magnetic torquers, performs attitude initial acquisition and three-axis attitude control during station keeping. The attitude measurement is provided by a horizon sensor and a pair of two-axis magnetometers. Control laws are analytically derived and, then, numerically tested using a numerical code which simulates the satellite orbital and attitude dynamics and control.

2. SATELLITE CONFIGURATION AND ATTITUDE REQUIREMENTS

Figure 1 gives a schematic representation of the small satellite. It consists of a main bus, weighting about 73 kg, and of a 2 m long rigid boom, which is deployed once the attitude acquisition phase has been completed. A 5 kg tip mass is attached at the end of the boom in order to perform gravity gradient and aerodynamic drag stabilization

The attitude dynamics study is performed considering the yaw (γ), pitch (β) and roll (α) angles of the satellite inertia principal axes (123) with respect to a right-handed orbiting reference frame (whose origin is at the satellite center of mass, the z-axis is aligned with the satellite position vector along the orbit and directed toward the Earth, the y-axis is perpendicular to the orbital plane, and the x-axis is directed along the velocity vector). Table 1 shows the small satellite main parameters [5].

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The small satellite under study is aimed at remote sensing applications. The payload is a nadir-viewing multispectral spectrometer which observes the solar radiation scattered from the Earth's atmosphere or from its surface to measure the atmosphere's content of ozone. The instrument detector is a 1024-pixel silicon array. The instrument has an instantaneous field of view of 86.7 km (cross-track) × 1.7 km (along-track). The attitude control system must limit the satellite attitude rotations about the three inertia principal axes according to the attitude requirements. For the proposed application, the attitude requirements must guarantee the global coverage and limit along-track swath variations. Considering the sensor swath width and the ground track minimum equatorial separation, the most critical aspect regards the roll angle, which must be kept within $\pm 2.4°$. The sensor geometrical resolution does not impose particularly stringent requirements for the attitude rates. Nevertheless, since the author is interested mainly in designing a multi-purpose bus, 10^{-3} deg·s^{-1} has been taken as allowable limit for the attitude rates, in order to include also high resolution remote sensing applications.

3. ADACS HARDWARE

Table 2 summarizes the size, mass and power requirements for the attitude determination and control system hardware [6]. The satellite attitude measurement during station keeping is provided by a horizon sensor and a pair of two-axis magnetometers, mounted with their sensitive axes aligned along the satellite's principal axes. The magnetometers measure

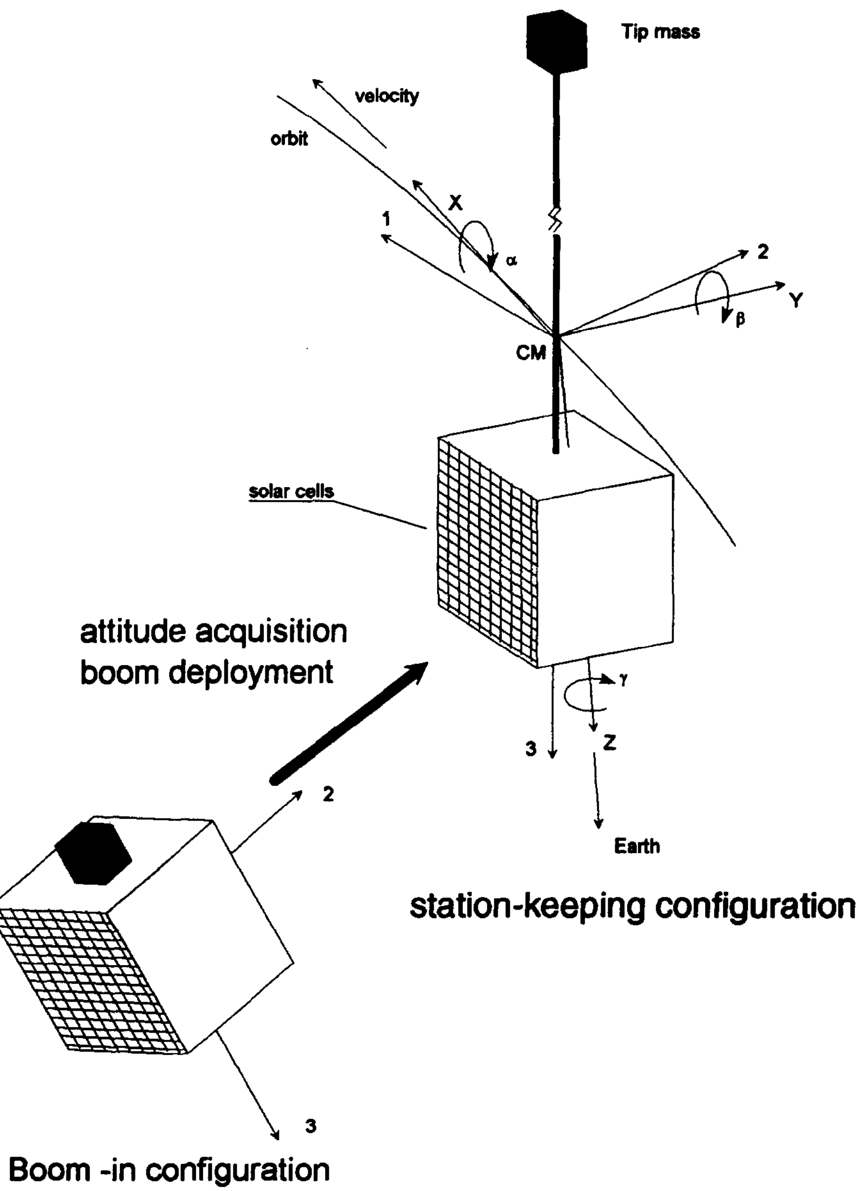

Fig. 1. Small satellite schematic representation.

Table 1. Satellite mass and orbit parameters

Satellite mass (kg)		78	
Satellite inertia moments (kg m^2) (boom in)	9.1	9.41	8.1
Satellite inertia moments (kg m^2) (boom out)	27.818	28.128	8.1
Orbit		circular sun-synchronous, 10 pm–10 am	
Orbit altitude (km)		433.78	
Orbit period (min)		33.25	
Orbit inclination (deg)		97.17	
Separation between two successive in-time tracks (km)		2595.09	
Equatorial separation between adjacent ground tracks (km)		50	
Repeat cycle (day)		52	

the Earth's magnetic field components in the body reference frame. The horizon sensor provides the additional information needed for onboard autonomous attitude determination and control. The attitude control torques are provided by three TORQRODs mounted with their sensitive axes aligned with the satellite inertia principal axes.

4. ATTITUDE ACQUISITION PHASE

In a magnetic control system the attitude control torques ($\mathbf{T}_c$) are provided by the interaction of the TORQROD's dipole moment vector (**M**) with the Earth's magnetic field vector (**B**) as follows:

$$\mathbf{T}_c = \mathbf{M} \times \mathbf{B} \quad (1)$$

In the initial phase of the attitude acquisition only the magnetometers are used for the attitude measurement. Several Kalman filtering schemes have been proposed to estimate the satellite attitude angles and rates from the magnetometer measurements [7]. It has been shown that these techniques can provide the attitude angles with an error of 3° (3σ). Despite filtering techniques, the satellite attitude acquisition can be also performed without satellite attitude knowledge, simply selecting the TORQROD's magnetic dipole moments according to the following control law:

$$\mathbf{M} = K_p(\mathbf{B}_o - \mathbf{B}_r) + K_d(\dot{\mathbf{B}}_o - \dot{\mathbf{B}}_r) \quad (2)$$

where $\mathbf{B}_o$ is the measured (observed) magnetic field vector, $\mathbf{B}_r$ is the reference magnetic field vector, and K_p and K_d are 3×3 diagonal matrices containing the control law position and rate gains.

The control law, is based on the fact that a satellite attitude rotation causes a variation in the magnetometer outputs, which, at zero attitude and measurement errors, must coincide with the body components of the reference field. Therefore, if a variation is detected in the measured field with respect to the reference one, the three TORQRODs are switched on to damp the satellite attitude motion.

Considering the magnetometer resolution and measurement error, and the modelling error in the magnetic reference field (Table 3), a threshold can be defined for the application of the control law of eqn (2). Therefore, the TORQRODs are switched on when the following conditions are verified:

$$|B_1 - B_x| \geqslant 0.0074 \text{ Gauss}$$

$$|B_2 - B_y| \geqslant 0.022 \text{ Gauss}$$

$$|B_3 - B_z| \geqslant 0.015 \text{ G} \quad (3)$$

where B_1, B_2 and B_3 are the components of the measured magnetic field, and B_x, B_y and B_z are the components of the magnetic field model in the orbiting reference frame.

The analytical derivation of the control law position and rate gains, which is omitted for the sake of brevity, has been performed applying the state feedback technique [8] to the second-order differential equations which describe the satellite attitude dynamics under the assumption of small angles [5].

The proposed control law has been numerically tested using a numerical code which includes the main environmental perturbations (the gravitational force, including the second zonal harmonic of the gravity field, and the aerodynamic drag) [g] and adopts a dipole model to simulate the Earth's magnetic field [10].

In order to simulate the attitude acquisition phase a random generation of the satellite initial attitude has been considered. Since during the acquisition phase the attitude angles are not measured, a qualitative description of the satellite attitude dynamics can be obtained by plotting the angles that the measured and the reference fields form with the 3-axis of the body reference frame (Ψ) and the z-axis of the orbiting one (φ), respectively (Fig. 2). It is possible to see that, after a transitory phase lasting about one orbit, the satellite nominal orientation, with the 3-axis of the body reference frame pointing to the Earth and the 2-axis along the orbit plane

Table 2. ADACS hardware

Component	Dimension (cm)	Mass (kg)	Average power (W)
Two-axis magnetometer	11.4 × 5.8 × 2.5	0.25	0.004
1 A m^2 TORQROD	1.3 dia. × 12.7	0.08	0.025
Horizon sensor	9.9 dia. × 11.8	1.1	<9.5

Table 3. Magnetometer and horizon sensor error budgets

	Magnetometer	Horizon sensor
Range	±600 μGauss	
Resolution	±5 μGauss	
Measurement error (1σ)	±3 μGauss	±0.1°
Model error (1σ)	±2 μGauss	
Total attitude error (1σ)	±0.8°	±0.1°

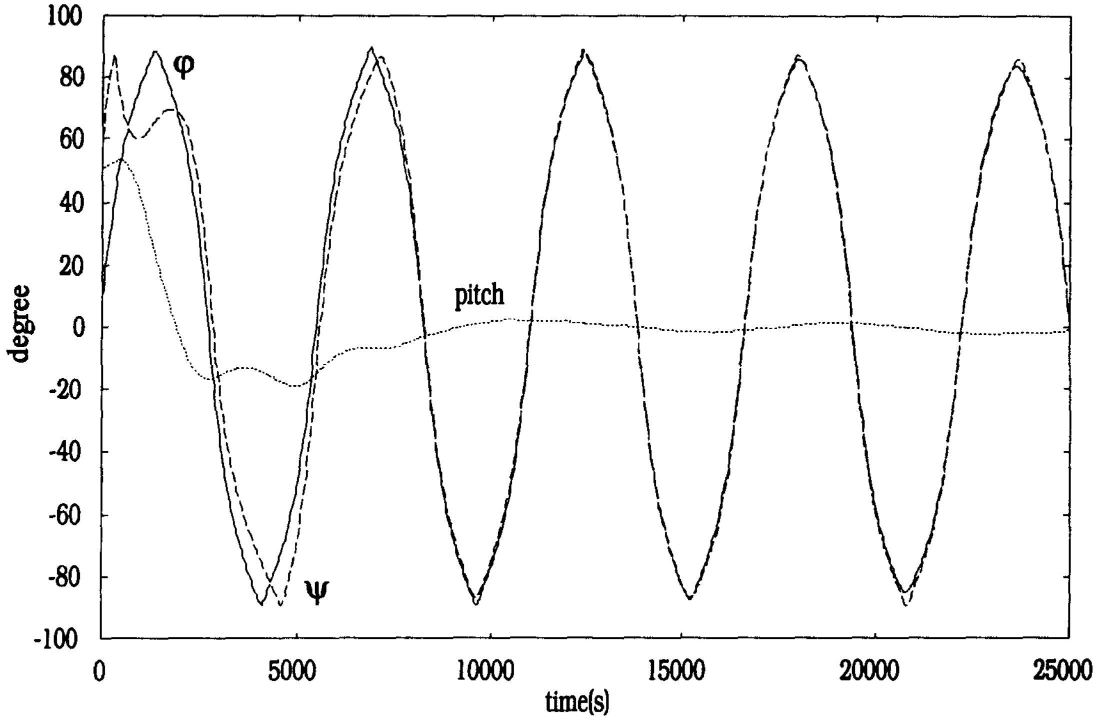

Fig. 2. Attitude acquisition phase.

perpendicular, is recovered with a residual attitude error of about 3–5°.

5. STATION KEEPING PHASE: ATTITUDE DETERMINATION

In the station keeping phase the satellite attitude is measured adding a horizon sensor to the magnetometers. The attitude angles are estimated with a deterministic method, in which the attitude matrix is computed from two triads of orthonormal directions constructed on the basis of the reference and observation vectors (sensor outputs), respectively [5]. The reference directions are given by a dipole model of the Earth magnetic field and by the satellite geocentric vector, obtained from the orbit propagation.

The attitude measurement errors have been numerically evaluated from the sensor errors using the following expression for the attitude covariance matrix [11]:

$$P_{\alpha\beta\gamma} = \sigma_{\mathrm{h}}^2 I + \frac{1}{|\hat{R}_{\mathrm{o}} \times \hat{B}_{\mathrm{o}}|}\Big[\Big(\sigma_{\mathrm{h}}^2 - \sigma_{\mathrm{m}}^2\Big)\Big(\hat{R}_{\mathrm{o}}\hat{R}_{\mathrm{o}}^{\mathrm{T}}\Big) + \sigma_{\mathrm{h}}^2\Big(\hat{R}_{\mathrm{o}}\cdot\hat{B}_{\mathrm{o}}\Big)\Big(\hat{R}_{\mathrm{o}}\hat{B}_{\mathrm{o}}^{\mathrm{T}} + \hat{B}_{\mathrm{o}}\hat{R}_{\mathrm{o}}^{\mathrm{T}}\Big)\Big] \quad (4)$$

where σ_{h} and σ_{m} are the horizon sensor and magnetometer standard deviations, respectively, $\hat{R}_{\mathrm{o}}$ and $\hat{B}_{\mathrm{o}}$ are the measured directions of the satellite geocentric vector and of the magnetic field, respectively, and I is the identity matrix. Despite the introduction of the horizon sensor, which improves the accuracy in the measure of the roll and pitch angles to approximately 0.1°, since the satellite orbit is sun-synchronous, the overall measurement accuracy is reduced when the satellite passes over the Earth's poles, as shown in Fig. 3. Since in the attitude determination scheme the first vector has been taken coincident with the one with the smaller variance (i.e. the satellite geocentric vector), the yaw angle measurement accuracy is particularly affected.

6. STATION KEEPING PHASE: ATTITUDE CONTROL

At the end of the attitude acquisition phase, the rigid boom is deployed to provide gravity gradient and aerodynamic drag stabilization. Three-axis attitude control is, then, performed by selecting the dipole moments of the TORQRODs according to the following expression:

$$\mathbf{M} = \frac{\mathbf{m} \times \mathbf{B}}{B} \quad (5)$$

which accounts for the variation of the Earth's magnetic field direction along the orbit. In the previous expression $\mathbf{m}$ is the control vector given by

$$\mathbf{m} = K_{\mathrm{p}}\hat{\mathbf{e}} + K_{\mathrm{d}}\dot{\hat{\mathbf{e}}} \quad (6)$$

where $\hat{\mathbf{e}}$ is the estimated attitude error vector. The analytical derivation of the control law position and rate gains, which is omitted for the sake of brevity, has been performed applying the state feedback technique [8] to the second-order differential

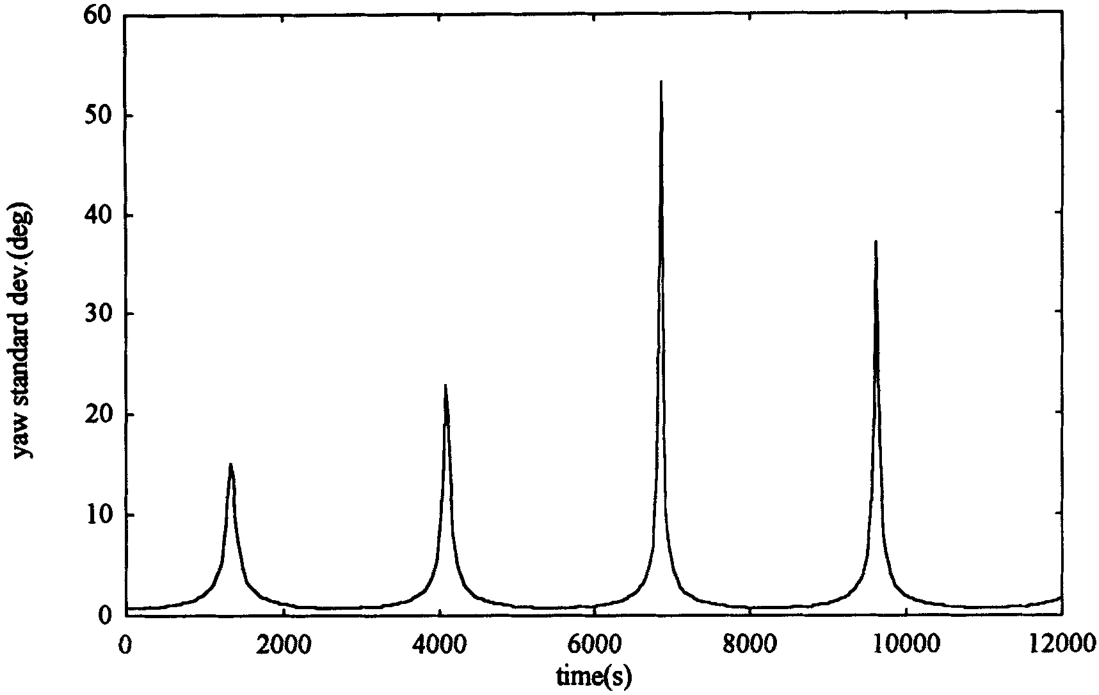

Fig. 3. Yaw angle standard deviation.

equations which describe the satellite attitude dynamics under the assumption of small angles [5].

In the numerical simulation of the station keeping phase the rigid boom deployment has been assumed to be instantaneous. Owing to the loss of measurement accuracy, the attitude control is not active in the polar regions of the orbits. Figure 4 shows the roll angle: it exhibits amplitudes within the limits required by the proposed application ($\pm 2°$). Nevertheless, owing to the variation of the attitude measurement accuracy along the orbit, the roll rate shows peak values of about 10^{-2} deg·s^{-1}, which are adequate only to low/medium resolution remote sensing applications. Similar results have been

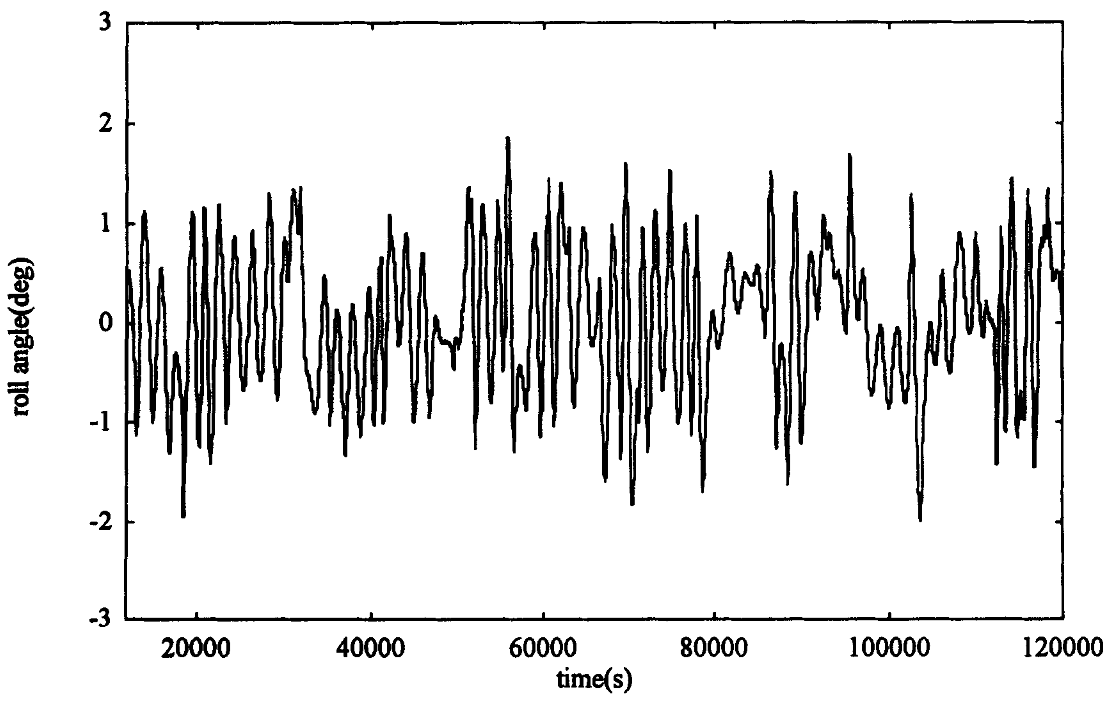

Fig. 4. Roll angle with magnetic control.

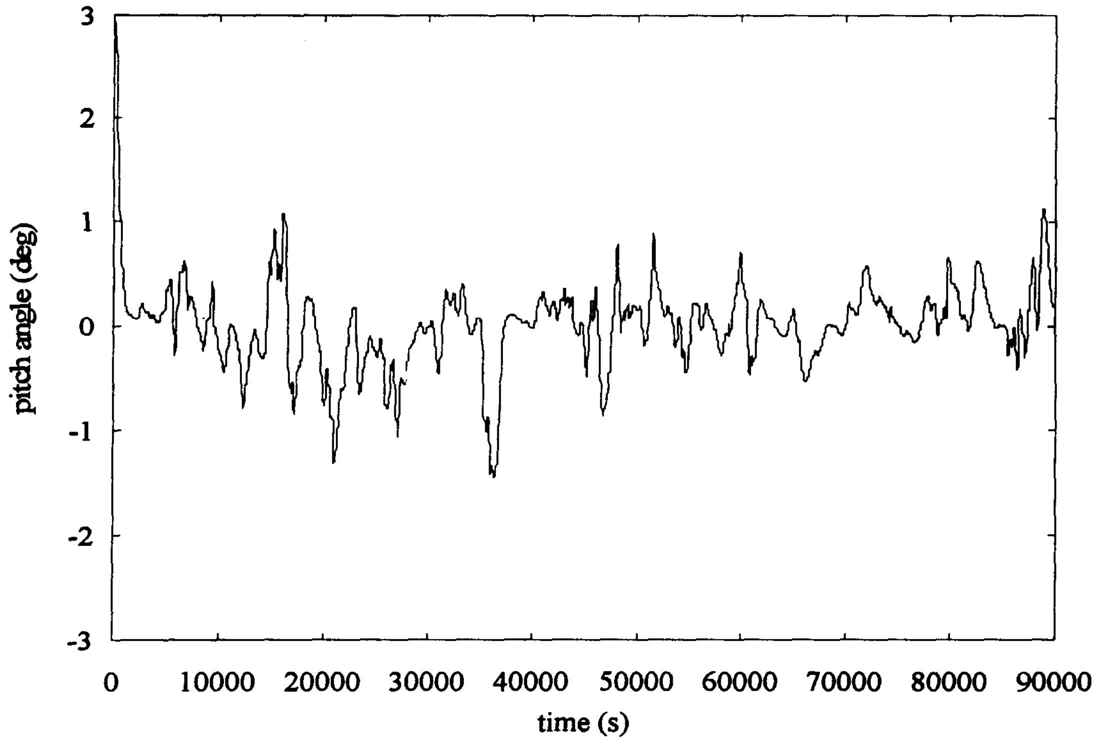

Fig. 5. Pitch angle with magnetic control.

obtained for the pitch angle, which is shown in Fig. 5. Finally, numerical results show that the order of magnitude of the control torques (maximum torque of 0.0001 N m) allows TORQRODs of limited size and weight to be used.

7. CONCLUSIONS

A system for on-board autonomous attitude determination and control has been proposed for a small satellite for remote sensing applications. The attitude determination hardware consists of a horizon sensor and a pair of two-axis magnetometers; the attitude control hardware consists of three magnetic torquers, mounted with their sensitive axes aligned with the satellite principal axes. Control laws have been derived separately for the attitude acquisition and the station keeping phases.

The proposed magnetic control system allows the along-track and cross-track swath variations to be kept within the limits required by the considered application. Moreover, the attitude control is performed by using low-mass and power sensors and actuators. Nevertheless, owing to the loss of attitude measurement accuracy in the polar regions of the satellite orbit, the attitude rates exhibit values which satisfy the considered application requirements, but are not adequate for high resolution remote sensing missions.

Critical aspects which need further investigation are: (a) analysis of a low-weight, low-power reaction wheel system, to provide a finer attitude control for high resolution remote sensing applications; (b) analysis of momentum dumping techniques, based on the use of the magnetic torquers; (c) analysis of the effects of the structural vibration of the rigid boom on the satellite attitude dynamics.

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