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MOMENTUM BIASED SATELLITE ATTITUDE STABLIZATION USING PD CONTROLLER WITH FUZZY GAIN ADJUSTMENT

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المحافظة على اتجاه الأقمار الصناعية باستخدام انحراف كميه الحركة

مع الضبط الغيمى لثوابت المتحكم التناسبى -التفاضلى

خلاصة

الأقمار الصناعية التي تستخدم الانحراف في كميه الحركة لضبط الاتجاه هى أقمار ثنائية الدوران حيث أنها تحتوى على عجله دواره يتم عن طريقها تزويد القمر بكميه حركه دورانيه ثابته. و حيث أن الانحراف فى كميه الحركة غير كاف للمحافظه على الاتجاه المطلوب , مما يحتم الاستعانة بالتحكم الإيجابي حيث تم دراسة التحكم فى زاويـــة العطـسوف و زاوية الزيغان (التعرج) باستخدام التحكم الإيجابي و ذلك بقياس زاوية التعرج أو عدم قياسها. و حيث أن مهندســـى التحكم يفضلون عدم استخدام حاسة قياس المعدل إلا لفترات قصيرة فانه يتم الحصول على معدل التغير عن طريــــق التفاضل و يستلزم هذا تزويد النظام مرشح للتخلص من الشوشرة. كما تم استخدام التحكم الغيمى لضبـــط ثـــابت المتحكم من أجل تقليل الخطأ.

ABSTRACT

Momentum biased satellites are dual spin satellites in which constant angular momentum is provided by a momentum wheel. The momentum bias is not sufficient to stabilize completely the momentum axis in space. Active control is used to assure accurate attitude stabilization. Control of the roll and yaw angles with and without yaw measurement will be analyzed. Control engineers prefer not to use angular rate sensors except for very special tasks and for short periods. The rate of Euler angles will be obtained by differentiation, with the adequate noise filters. Fuzzy gain adjustment is

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used for the case of momentum biased satellites without yaw measurement in order to minimize error. The gain, output scaling factor, of the controller is adjusted on line according to the current states of the controlled process.

KEY WORDS: Momentum Biased Satellites, Stabilization, Fuzzy Control, Self-Tuning.

1. INTRODUCTION

Momentum biased satellite are three axis stabilized as follow. The bias provides inertial stability to the wheel axis that is perpendicular to the orbit plane. Torque capabilities of the wheel about the wheel axis are used to stabilize the attitude of the satellite in the orbit plane. Most communication satellites especially those operating in Geo-stationary attitudes are momentum biased [1]. The momentum bias is not sufficient to adequately attitude stabilize the X_B Z_B lateral plane of the satellite. For any three axis stabilized satellite orbiting a planet. the horizon sensor (earth sensor for earth orbiting s/c) enables measurement of the roll angle φ and the pitch angle θ but not the yaw angle ψ. The pitch measurement allows control of the pitch attitude. For roll-yaw attitude control, it is theoretically necessary to measure both roll and yaw angles, which cannot be done by a horizon sensor. One alternative is to measure the yaw angle with the aid of a sun sensor, but it is of no use during eclipse. Another approach would use magnetometer. but fluctuation in the earth magnetic field make it impossible to estimate the yaw angle with an accuracy better than 0.5°, which generally not good enough for geo-stationary communication satellites. A third possibility is to use star sensors. These sensors allow very accurate attitude determination but they are quite complicated. sometimes unreliable. For low inclination orbiting satellites use of star sensors is too easier because the Polaris star is a good bright reference almost inertial with respect to the earth's north axis direction. Hence simpler star catalogs of moderate complexity can be used. A star sensor with a field of view 8-12° allows measuring the yaw angle of the satellite during all stages of its life including GTO-GEO transfer. Even so star sensors neither simple nor straightforward to use. These considerations underlie our desire to control the s/c attitude without measuring the yaw angle. In momentum biased attitude controlled satellite the roll and yaw angles are related via the constant momentum, and this property is used to design a complete momentum biased ACS without measuring the yaw angle. Both possibilities namely control of the roll and yaw angles with and without yaw measurement will be analyzed. Another problem is the need to use angular rate sensors. Such instruments are not very reliable when operated continuously for 8 to 10 years, the expected lifetime of the modern Geo-stationary satellites. Control engineers prefer not to use angular rate sensors except for very special tasks and for short periods. The rate of Euler angles will be obtained by differentiation, with the adequate noise filters.

Fuzzy logic controllers (FLC's) have been reported to be successfully used for a number of complex and nonlinear processes. Sometimes FLC's are proved to be more robust and their performances are less sensitive to parametric variations than conventional controllers. Different types of adaptive FLC's such as self-tuning and self-organizing controllers have been developed and implemented for various practical processes. Even equivalence between FLC's and conventional controllers has been established. Recently many researchers are trying achieving enhanced performance and increased robustness of FLC's using neural networks and genetic algorithms in designing such controllers. Among the various types proportional integral (PI), proportional derivative (PD), and proportional integral derivative (PID) of FLC's.

An FLC has a fixed set of control rules, usually derived from expert's knowledge. The membership functions (MF's) of the associated input and output linguistic variables are generally predefined on a common universe of discourse. For the successful design of FLC's proper selection of input and output scaling factors (SF's) and or tuning of other controller parameters are crucial jobs, which in many cases are done through trial and error or based on some training data. Of the various tunable parameters, SF's have the highest priority due to their global effect on the control performance. However. relative importance of the input and output SF's to the performance of a fuzzy logic control system is yet to be fully established.

Unlike conventional control, which is based on mathematical model of a plant, a FLC usually embeds the intuition and experience of a human operator and sometimes those of designers and researchers. While controlling a plant, a skilled human operator manipulates the process input, (i.e. controller output) to minimize the error within the shortest possible time. Fuzzy logic control is a knowledge-based system. By analogy with the human operator, the output-scaling factor should be considered a very important parameter of the FLC since its function is similar to that of the controller gain. Moreover, it is related to the stability of the control system. So the output-scaling factor should be determined very carefully for the successful implementation of a FLC [2]. In this paper fuzzy gain adjustment of the conventional PD controller for the case of momentum biased satellite without yaw measurement is applied.

The paper proceeds as follow. In section 2 stabilization with and without active control is considered. Stabilization with active control is discussed both with and without yaw measurement. Discussion of noise effects is found in section 3. The proposed fuzzy logic gain adjustment is presented in section 4. System simulations are found in section 5. The main results and conclusions are found in section 6.

2. STABILIZATION WITH AND WITHOUT ACTIVE CONTROL

2. 1 STABILIZATION WITHOUT ACTIVE CONTROL

The axis of the momentum wheel (MW) is nominally in the direction of the normal to the orbit plane. The dynamic equations of the system include a single momentum wheel. aligned on the Y_B axis. This means that the control variables $\dot{h}_{wy}$ and h_{wy} will remain in the equations as follows [1]

$$T_{dx} + T_{cx} = I_x \ddot{\phi} + (a - \omega_0 h_{wy})\phi - (-b - \dot{h}_{wy})\psi \qquad (1)$$

$$T_{dy} + T_{cy} = I_y \ddot{\theta} + d\dot{\theta} + h_{wy} \tag{2}$$

$$T_{dz} + T_{cz} = I_z \ddot{\psi} + (-b + h_{wy})\dot{\phi} + (c - \omega_o h_{wy})\psi \tag{3}$$

Where $a = 4\omega_o^2(I_y - I_z)$, $b = -\omega_o(I_x + I_z - I_y)$, and $c = \omega_o^2(I_y - I_x)$. It can be noted that the second Eq.(2), which is the pitch dynamics, is separated from Eqs.(1,3). The pitch attitude is controlled with torque capabilities of the momentum wheel namely h_{wy}. Stabilization in the XZ plane (orbital plane) is more difficult. Neglecting the terms a, b, and c with respect to h_{wy} which in practical systems is large enough. The characteristic equation of the motion in the XZ plane can be determined as

$$s^4 + (\omega_o h_{wy}(\frac{1}{I_x} + \frac{1}{I_z}) + \frac{h_{wy}^2}{I_x I_z})s^2 + \frac{\omega_o^2 h_{wy}^2}{I_x I_z} = 0 \tag{4}$$

Eq.(4) can be approximated and rewritten as

$$(s^2 + \omega_o^2)(s^2 + \frac{h_{wy}^2}{I_x I_z}) = 0 \tag{5}$$

The above approximation is based upon the fact that $\frac{h_{wy}^2}{I_x I_z} \succ\succ\succ \omega_o^2$, so the addition of ω_o^2 to the coefficient of s^2 of Eq.(4), is possible. Also $h_{wy} \succ\succ \omega_o(I_x + I_z)$, so taking h_{wy} as a common factor from the coefficient of s^2, the coefficient of s^2 will be $(\omega_o^2 + \frac{h_{wy}^2}{I_x I_z})$. It is easily shown that Eq.(5) have second order poles. the first located at the orbital frequency and the second at the nutation frequency of the satellite. It can be shown that

$$\varphi(t) = T_{dx}[A\cos(\omega_o t) + B\cos(\omega_{nut} t) + C] \tag{6}$$

Where $A = \left[\frac{1}{\omega_{nut}^2 - \omega_o^2}\right]\left[\frac{1}{I_x} + \frac{h_{wy}}{I_x I_z w_o}\right]$, $B = -\left[\frac{1}{\omega_{nut}^2 - \omega_o^2}\right]\left[\frac{1}{I_x} + \frac{\omega_o}{h_{wy}}\right]$,

$C = -\frac{1}{\omega_o h_{wy}}$, $\omega_{nut}^2 = \frac{h_{wy}^2}{I_x I_z}$

It is clear that $\varphi(t)$ consists of two harmonic cosines with frequencies ω_o and ω_{nut} of different amplitudes A and B, and a constant, which is the average value of time response. The amplitude A of the harmonic motion with orbital frequency ω_o is much larger than the amplitude B of the harmonic motion with nutation frequency ω_{nut}. The average error in both $\varphi(t)$ and $\psi(t)$ is given by

$$\varphi_{av} = \frac{-T_{dx}}{\omega_o h_{wy}} \tag{7}$$

$$\psi_{av} = \frac{-T_{dz}}{\omega_o h_{wy}} \tag{8}$$

Example 1: Choose a geo-stationary satellite with $\omega_o = 7.236e-5$, $I_x = 800 kg.m^2$, $I_z = 1000 kg.m^2$, and $h_{wy} = -10 N.m.sec$. Thus $\omega_{nut} = 0.0112$ rad/sec, A = -1358, B = -10, C = 1381, and

$$\varphi(t) = T_{dx}[-1358\cos(0.0000829t) - 10\cos(0.0112t) + 1381]$$

The nutation harmonic amplitude is smaller by a factor of 135 than of the orbital harmonic amplitude. In order to show the difference between the amplitudes of the orbital and nutation harmonic motions, this time response is telescoped for the first 10,000 seconds only. Even if the disturbance amplitude is as small as 10^{-5} N-m. The maximum error in roll will be $1.5°$. For geostationary satellite an acceptable roll error is only $0.05°$. This situation could be remedied by drastically increasing the value of the momentum biased. but such an approach would require large increases in the dimensions. weight and power consumption of the momentum wheel assembly, which for practical reasons are usually not feasible. Moreover because the open loop poles of the transfer function are not damped, harmonic disturbances having frequencies of ω_o or ω_{nut} will destabilize the system and hence the amplitude of the harmonic motion will increase linearly with time. We should keep in mind that various external disturbances acting on the satellite such as solar pressure disturbing torques might have harmonic components matching the basic orbital frequency ω_o. All these factors lead to the conclusion that attitude stabilization is mandatory.

2.2 STABILIZATION WITH ACTIVE CONTROL

2.2.1 Active Control Using Yaw Measurement

Eq.(5) shows that the two second order poles of the momentum–biased dynamics are undamped. Active control must damp these poles and also decrease the steady state errors. The simplest forms of control torque, which can achieve these tasks, are

$$T_{cx} = -(k_x\varphi + k_{xd}\dot{\varphi}) \quad (9)$$

$$T_{cz} = -(k_z\psi + k_{zd}\dot{\psi}) \quad (10)$$

Substitution from Eqs.(9-10). in Eqs.(1-3), and neglecting a, b, and c, the characteristic equation of motion will be

$$s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4 = 0 \quad (11)$$

where $a_1 = (k_{xd} I_z + k_{zd} I_x)/(I_x I_z)$,

$a_2 = [k_{xd} k_{zd} + h_{wy}^2 + I_z(k_x \omega_o h_{wy}) + I_x(k_z + \omega_o h_{wy})]/(I_x I_z)$,

$a_3 = [k_{zd}(k_x - \omega_o h_{wy}) + k_{xd}(k_z - \omega_o h_{wy})]/(I_x I_z)$,

$a_4 = [k_x k_z + (\omega_o h_{wy})^2 - \omega_o h_{wy}(k_x + k_z)]/(I_x I_z)$

A necessary but not sufficient condition for Eq.(11) to have stable roots, is that the coefficients of the polynomial must be positive. This condition can be achieved by choosing $h_{wy} = -h$, with h>0. To stabilize the system addition conditions on the control parameters k_x, k_{xd}, k_z, and k_{zd} are necessary. The parameter k_x and k_z are primarily responsible for the steady state errors in φ and ψ caused by disturbances T_{dx} and T_{dz}. Their values can be calculated from the steady state error requirements. Using the finial value theorem, it is easy to show that

$$\frac{\varphi_{ss}}{T_{dx}} = \frac{k_z + \omega_o h}{k_x k_z + (\omega_o h)^2 + \omega_o h(k_x + k_z)} = \varphi_{ssx} \tag{12}$$

$$\frac{\psi_{ss}}{T_{dz}} = \frac{k_x + \omega_o h}{k_x k_z + (\omega_o h)^2 + \omega_o h(k_x + k_z)} = \psi_{ssz} \tag{13}$$

$$\frac{\varphi_{ss}}{T_{dz}} = 0 \tag{14}$$

$$\frac{\psi_{ss}}{T_{dx}} = 0 \tag{15}$$

Assuming h has already been determined, then k_x and k_z can be determined from the required values of φ_{ssx} and ψ_{ssz} as follows

$$k_x = (1 - \omega_o h \varphi_{ssx}) / \varphi_{ssx} \tag{16}$$

$$k_z = (1 - \omega_o h \psi_{ssz}) / \psi_{ssz} \tag{17}$$

In order to calculate k_{xd} and k_{zd}, it can be assumed without loss of generality, that Eq.(11) consists of two-second order damped poles as follows

$$(s^2 + 2\xi_1 \omega_{n1} s + \omega_{n1}^2)(s^2 + 2\xi_2 \omega_{n2} s + \omega_{n2}^2) = 0 \tag{18}$$

Comparing coefficients of Eq.(11) and Eq.(18), k_{xd} and k_{zd} can be determined.

Example 2: In this example choose a geostationary satellite with $I_x = 800 kg.m^2$, $I_z = 1000 kg.m^2$, $h_{wy} = -20 N.m.sec.$, $\omega_o = 7.236e-5$, $T_{dx} = T_{dz} = 5 * 10^{-5} N.m.$ From simulations it is noted that maximum permitted steady state errors in roll and yaw $\varphi_{ss} = 0.05^{\circ}$, and $\psi_{ss} = 0.2^{\circ}$. The controller parameters are $k_x = 0.00248$,

$k_{xd} = 22.9$, $k_z - 0.26 * 10^{-4}$, $k_{zd} = 12.8$, $\omega_{n1} = 0.0295 rad/sec.$, and $\omega_{n2} = 0.109 * 10^{-3} rad/sec.$

2.2.2 Active Control without Yaw Measurement

The control configuration based on measuring the roll and pitch angles only is the most popular today. The earth sensor, which is based on sensing the horizon contour of the earth with respect to satellite body frame, is the only sensor used to measure directly the roll error of nadir pointing satellites. Accuracies of order 0.02° are common with this technology. Statistical noise of about 0.03° RMS must be considered. The control torque command equations are as follows

$$T_{cx} = -(k_x \varphi + k_{xd} \dot{\varphi}) \tag{19}$$

$$T_{cz} = A T_{cx} \tag{20}$$

Eq.(20) is based on the fact that for a momentum-biased satellite the roll and yaw errors interchange every quarter of the orbit. This means that accumulated yaw error will change to roll error after a quarter of the orbit period. Since the roll is measured the accumulated yaw error will be controlled. Using Eqs.(1.3) together with Eqs.(19,20) results in

$$T_{dx} = I_x \ddot{\phi} - \omega_o h_{wy} \phi + h_{wy} \dot{\psi} + k_x \varphi + k_{xd} \dot{\varphi} \tag{21}$$

$$T_{dz} = I_z \ddot{\psi} + h_{wy} \dot{\phi} - \omega_o h_{wy} \psi + A k_x \varphi + A k_{xd} \dot{\varphi} \tag{22}$$

The characteristic equation for the motion described by Eqs.(21,22) is given by

$$s^4 + b_1 s^3 + b_2 s^2 + b_3 s + b_4 = 0 \tag{23}$$

where $b_1 = k_{xd} / I_x$.

$b_2 = [-\omega_o h_{wy}(I_x + I_z) + I_z k_x + h_{wy}^2 + A h_{wy} k_{xd}]/(I_x I_z)$,

$b_3 = [A k_x h_{wy} - \omega_o h_{wy} k_{xd}]/(I_x I_z)$,

$b_4 = [(\omega_o h_{wy})^2 - \omega_o h_{wy} k_x]/(I_x I_z)$

For stability reasons it is necessary, but not sufficient, that $h_{wy} = -h$ with h > 0. For the same reasons choose A<0, let $A = -A_\psi$. It is clear that k_{xd} must be positive in order to satisfy stability conditions. In order to find k_x, k_{xd}, and A_ψ, use

$$\frac{\varphi_{ss}}{T_{dx}} = \frac{1}{\omega_o h + k_x} = \varphi_{ssx} \tag{24}$$

$$\psi_{ss} = \frac{T_{dz}}{\omega_o h} + \frac{A T_{dx} k_x}{(\omega_o h + k_x)\omega_o h} \approx \frac{T_{dz} + A T_{dx}}{\omega_o h} \tag{25}$$

The approximate value of ψ_{ss} results from the fact that $k_x >> \omega_o h$. Practically A must be less than one. The minimum momentum biased needed h can be determined from the last term of Eq. (25), with known and estimated external disturbances and with limits on the maximum permitted steady state error in yaw. From Eq. (24) k_x can also be found as

$$k_x = \frac{T_{dx}}{\varphi_{ss}} - \omega_o h \tag{26}$$

The same procedure of section 2.2.1 is used to find k_{xd}.

Example 3: The same data of example 2 is used. From simulations, it is noted that maximum permitted steady state errors in roll and yaw are $\varphi_{ss} = 0.05°$, and $\psi_{ss} = 0.4°$. The controller parameters are $k_x = 0.00427$, $k_{xd} = 42.8$, $A = 0.888$, $\omega_{n1} = 0.00008478 rad/sec.$, and $\omega_{n2} = 0.0381 rad/sec.$

3. NOISE EFFECTS

The Attitude Control System (ACS) is composed of a Momentum Wheel (MW) and an earth sensor (ES) only. The earth sensor can sense only the roll φ and the pitch θ Euler angles. Since no rate sensor is included, differentiation of the earth sensor outputs is necessary in order to implement the control law. The earth sensor is noisy, without appropriate filtering the Root Mean Square (RMS) noise amplification from the sensor to the command torque, will become infinite for white noise. Low pass filter is included in order to prevent amplification of noise.

3.1 Earth Sensor Noise Amplification

It is important to analyze the amplification of ES noise to the torque commands at the input of the controllers, which can be reaction wheels, magnetic torque-rods or solar panels and flaps. We will use a low pass filter having two simple poles with corner frequencies ω_c= 0.2 rad/sec, about 10 times higher than that of nutation frequency. The primary cause of the high amplification noise is the differentiation of ϕ together with the high gain of k_{xd} needed to provide high damping coefficient. The immediate consequence is that we will have to decrease this gain in order to decrease the ES RMS noise amplification. Naturally the damping coefficients of the closed loop poles, which is closer to open loop nutation pole, will be the most affected. The resulting new damping coefficients and amplification factors are shown in Table 1.
With the nominal case 1, the second damping factor ξ_2 is smaller than 0.7 owning to the low pass filter with the two corner frequencies ω_c = 0.2 rad/sec. It is clear that decreasing the derivative gain does not appreciably change the damping coefficient of the smaller closed loop pole, which is closer to the orbital frequency pole. However the second damping coefficient, pertaining to the much higher nutation frequency pole, is drastically decreased with smaller k_{xd}. For case 4 we even see instability of the nutation closed loop pole since ξ = -0.0004. It can be concluded that good earth sensor

is accompanied by a noise level of 0.03 (RMS). In the nominal case since the noise amplification amounts to 2.09, the X axis torque command will be accompanied by a noise level of T_{cxN}=(2.09*.03)/57.321= 0.001094 N.m. This level of amplification will affect the attitude control of a momentum-biased satellite.

Table 1: Noise amplification gain as a function of the derivative gain k_{xd}

Case	k_x	k_{xd}	ω_{n1}	ξ_1	ω_{n2}	ξ_2	T_{cx} / N_{ES}	T_{cz} / N_{ES}
1	$4.27*10^{-3}$	42.7	$7.49*10^{-5}$	0.7	0.07	0.52	2.09	1.76
2	$4.27*10^{-3}$	4.27	$1.32*10^{-4}$	0.65	0.03	0.07	0.19	0.17
3	$4.27*10^{-3}$	0.43	$1.42*10^{-4}$	0.65	0.02	0.00425	0.02	0.02
4	$4.27*10^{-3}$	0.21	$1.43*10^{-4}$	0.65	0.03	$-4*10^{-4}$	0.01	0.01

3.2 Roll Yaw Attitude Control With Momentum Exchange Devices

A straightforward way to stabilize the roll yaw attitude is to use additional momentum exchange device, a reaction wheel with its axis aligned parallel to the X_B axis. The problem of noise amplification doesn't exist here because the control torque levels of these devices are larger than 0.01 N.m. Another possible solution based on similar devices is to use two momentum wheels slightly inclined to each other in a V-geometry. In this configuration the two inclined momentum wheels allow control of the X_B axis attitude the roll angle ϕ and the pitch angle θ about the Y_B axis while providing the system with the desired momentum stabilization.

4. THE PROPOSED FUZZY LOGIC GAIN ADJUSTMENT

Here PD controller is proposed. The gain. i.e. output scaling factor (SF). of this controller is adjusted on line according to the current states of the controlled process. For best performance, simultaneous adjustment of both input and output SF's is more justified. Our objective here is to adapt only the output scaling SF's to achieve better control performance. Observe that a self-tuning FLC is an adaptive controller. We call an FLC adaptive if any one of its tunable parameters changes when the controller is being used. Otherwise it is a conventional FLC. The tunable parameters are scaling factors, membership functions, and rules. An adaptive FLC that fine tunes an already working controller by modifying either its membership functions or scaling factors or both of them is called a self tuning FLC. On the other hand, when a FLC is tuned by automatically changing its rules, then it is called self organizing FLC. In this paper, our objective is to tune the output SF of an existing PD controller we describe it as a self-tuning PD controller. The detailed design considerations are discussed.

(a) Membership functions: All membership functions (MF's) for controller inputs, i.e. error (e) and change in error (Δe), are defined on the common interval [-1, 1], whereas the MF's for the gain updating factor (α) is defined on [0, 1]. We use symmetric triangles (except the two MF's at the extreme ends) with equal base and 50% overlap with the neighboring MF's. MF's for e, and Δe, are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB). While MF's for α are Zero (ZE), Very Small (VS), Small (s), Small Big (SB), Medium Big (MB), Big (B), and Very Big (VB).

(b) Scaling Factors : The relationship between the SF's and the input and output variables of the self-tuning FLC are as follows :

$$e_N = G_e \cdot e$$

$$\Delta e_N = G_{\Delta e} \cdot \Delta e$$

$$u = (\alpha \cdot G_u) \cdot u_N$$

G_e and $G_{\Delta e}$ are the input scaling factors, G_u is the output scaling factor. e_N, Δe_N, and u_N are the scaled inputs and outputs.

The Rule Bases: The gain-updating factor is calculated using the rule base in Table 2. Some of the important considerations must have been taken into account for determining the α rules. To make the controller produce a lower overshoot and reduce the settling time, the controller gain is set at a small value when the error is big, but e and Δe are of opposite signs. Depending on the process trend, there should be a wide variation of the gain around the set point. This type of gain variation around the set point will also prevent excessive oscillations and as a result the convergence rate of the process to the set point will be increased. A good controller should provide regulation against changes in load disturbances. This is accomplished by making the gain of the controller as high as possible.

Table 2 Fuzzy rules for computation of α .

$\Delta e/e$	NB	NM	NS	ZE	PS	PM	PB
NB	VB	VB	VB	B	SB	S	ZE
NM	VB	VB	B	B	MB	S	VS
NS	VB	MB	B	VB	VS	S	VS
ZE	S	SB	MB	ZE	MB	SB	S
PS	VS	S	VS	VB	B	MB	VB
PM	VS	S	MB	B	B	VB	VB
PB	ZE	S	SB	B	VB	VB	VB

5. SIMULATIONS AND RESULTS

Simulation results for the same data of example 2 is used. Simulations are done for both the two cases, namely with and without fuzzy gain adjustment. The output of first case (without fuzzy gain adjustment) is shown in Fig. 1. The output of the second case, using fuzzy gain adjustment, is shown in Fig. 2. It is clear that the maximum error in ϕ is improved using fuzzy Gain adjustment. The error in θ is approximately the same in both cases. The error in ψ is larger for the case of fuzzy gain adjustment. Better results can be obtained if more refinement was made for the choice of fuzzy rules of α .

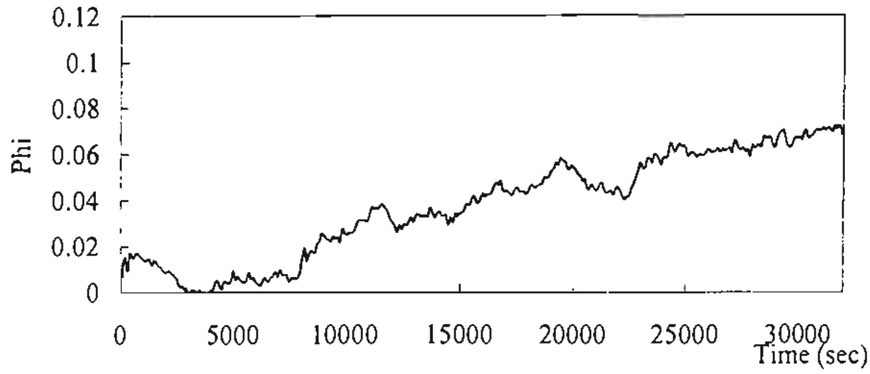

Fig. 1(a)

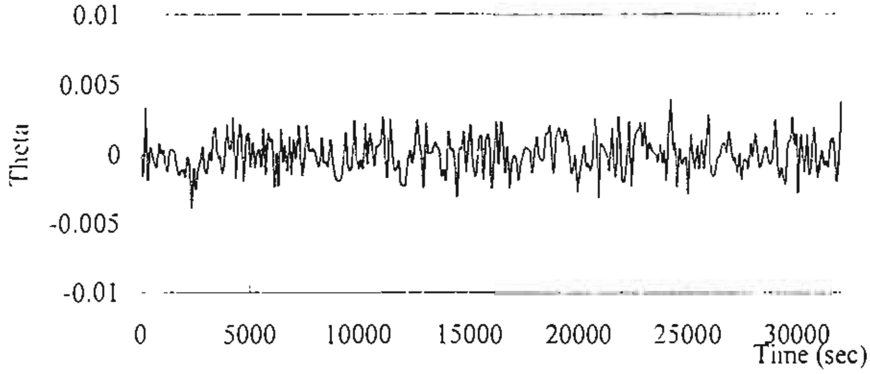

Fig. 1(b)

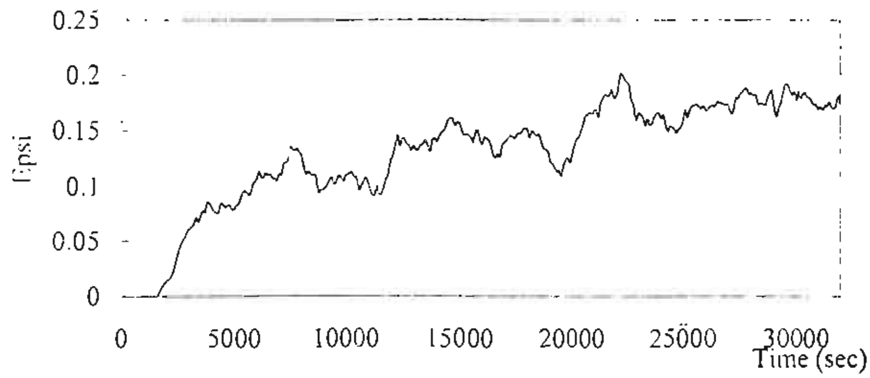

Fig. 1(c)

Fig. 1: Simulation Results Without Fuzzy Gain Adjustment

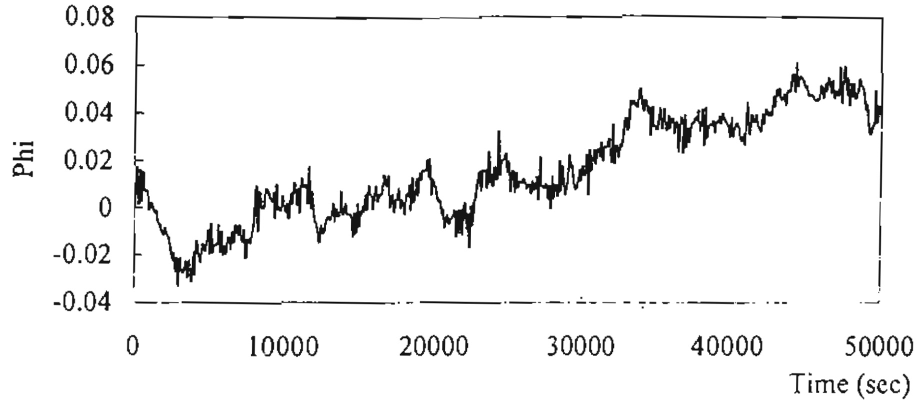

Fig. 2(a)

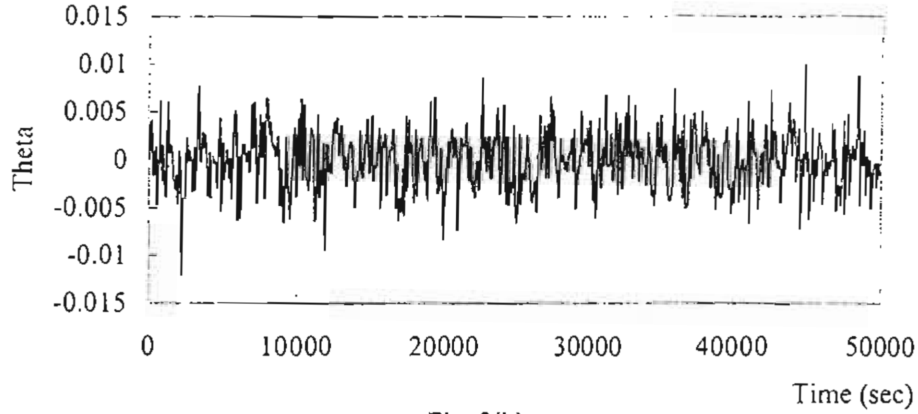

Fig. 2(b)

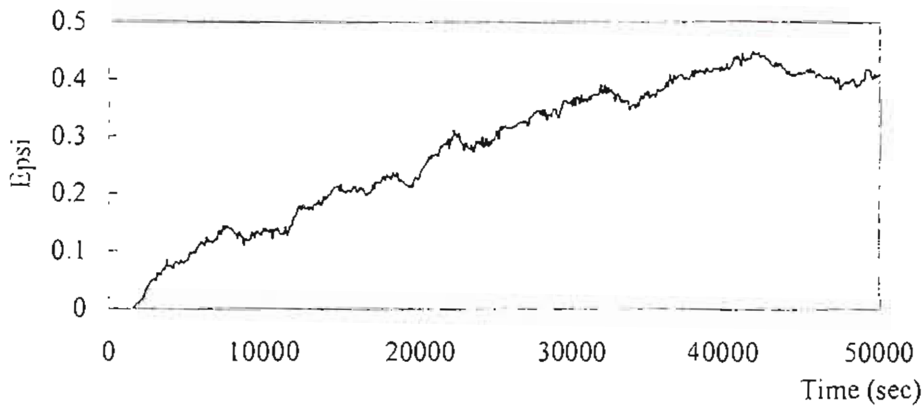

Fig. 2(c)

Fig. 2: Simulation Results With Fuzzy Gain Adjustment

6. CONCLUSIONS

This paper deals with momentum bias control systems. These systems have some nice features. Only one momentum exchange device is needed to attitude stabilize the satellite. The yaw attitude error need not be measured, thus simplifying greatly the onboard attitude determination hardware and algorithms. External disturbances tend to increase the error in roll and yaw angles. Active control of these errors can be achieved. A simple robust fuzzy logic gain adjustment mechanism is used to minimize error.

REFERENCES

1. Sidi, M.J., "Spacecraft Dynamics and Control". Cambridge University Press, 1997.
2. Rajani, K.M., and Nikhil, R.R., " A robust Self Tuning Scheme for PI and PD Type Fuzzy Controller, IEEE Transactions on Fuzzy Systems, Vol. 7, No. 1, February 1999.
3. Panagiotis. T., Haijun, S., and Chris, H., "Satellite Attitude Control and Power Tracking with Energy/Momentum wheels", J. of Guidance, Control. and Dynamics, Vol. 24, No. 1. pp. 23-34, 2001.
4. Kaplan, M.H., "Modern Spacecraft Dynamics & Control", John Wiley & Sons. 1976.
5. Wertz, J.R., and Larson, W.J., "Space Mission Analysis and Design", The Space Technology Library, 1999.
6. Wiesel, W.E. "Spaceflight Dynamics", McGraw-Hill, 1997.
7. Brown, R.G., and Hwang, P.Y.C., "Introduction to Random Signals and Applied Kalman Filtering", John Wiley & Sons. 1997.
8. Noton, M., "Spacecraft Navigation and Guidance", Springer Verlag London Limited, 1998.

9. Chobotov, V.A., "Spacecraft Attitude Dynamics and Control", Krieger Publishing Company, 1991.

10. Wertz, J.R., "Spacecraft Attitude Determination and Control", D. Reidel Publishing Company, 1985.

11. Bryson, A.E., "Control of Spacecraft and Aircraft", Princeton University Press, 1993.

12. Nise, N.S., "Control Systems Engineering", The Benjamin/Cummings Publishing Company, Inc., 1995.

NOMENCLATURE

X_B, Y_B, Z_B	: Satellite body axes.
φ, θ, ψ	: Euler angles.
T_{cx}, T_{cy}, T_{cz}	: Control torques.
T_{dx}, T_{dy}, T_{dz}	: Disturbance torques.
I_x, I_y, I_z	: Moments of Inertia.
h, h_{wy}	: Reaction wheel angular momentum.
ω_o	: Orbital angular velocity.
ω_{nut}	: Nutatin frequency.
k_x, k_y, k_z	: Controller proportional gains.
k_{xd}, k_{yd}, k_{zd}	: Controller derivative gains.
$e, \Delta e$	: Error and change in error.
ξ, ω_n	: Damping ratio and natural frequency.
α	: Gain updating factor.
N_{ES}	: Noise level of the earth sensor.