Stabilization of an analog model of a satellite with flexible appendages driven by a discrete-time attitude control, 1

Marcelo Ricardo Alves da Costa Tredinnick

PUC-RJ, Pontifícia Universidade Católica do Rio de Janeiro, Department of Electronic Engineering.

Rua Marquês de São Vicente, 225 Rio de Janeiro, RJ, 22453-900, Brazil

tredinnick@ele.puc-rio.br

Marcelo Lopes de Oliveira e Souza / Luiz Carlos Gadelha de Souza

INPE/DMC, National Institute for Space Research, Space Mech. and Control Division, Electronics and Simulation Laboratory

Av. dos Astronautas, 1758, São José dos Campos, SP, 12201-970, Brazil.

marcelo@dem.inpe.br / gadelha@dem.inpe.br

Abstract

This paper presents the 1st. part of a simulation and theoretical study on the stabilization of an analog model of a satellite with flexible appendages when it is driven by a discrete-time attitude control. This control is the Tustin s-z mapping equivalent of a continuous-time asymptotically stable proportional plus derivative (PD) control. Its design is done considering aspects such as the aliasing and the hidden oscillations. It is tested with an analog reduced model (five vibration modes) of the CBERS1 (China-Brazil Earth Resources Satellite) launched with success on October 14, 1999. It is shown that the Tustin s-z mapping may instabilize some modes. To circumvent this, five techniques are tried: 1) reducing the sampling-period T_S; 2) using an anti-aliasing filter; 3) reducing the control gains; 4)increasing the structural damping-ratio; 5) changing the mapping to one of the Schneider' s-z mappings; getting partial success only. We go further and then 6) propose and use a new (ST1) mapping that behaves better than techniques 1-5 under the same conditions.

1. Introduction.

Digital controls of analog plants, including satellites, are becoming very common today due to their low price, extensive programming, logic and arithmetic capabilities, etc. Despite these advantages, their time sampling, amplitude quantization, and input, processing, and output delays are important disadvantages to be considered. They may become critical when the plant has oscillation modes that are above the Nyquist frequency (half of the sampling frequency), as happens in satellites with flexible appendages. Then, a careful study of their consequences on that control and even on its stability must be done.

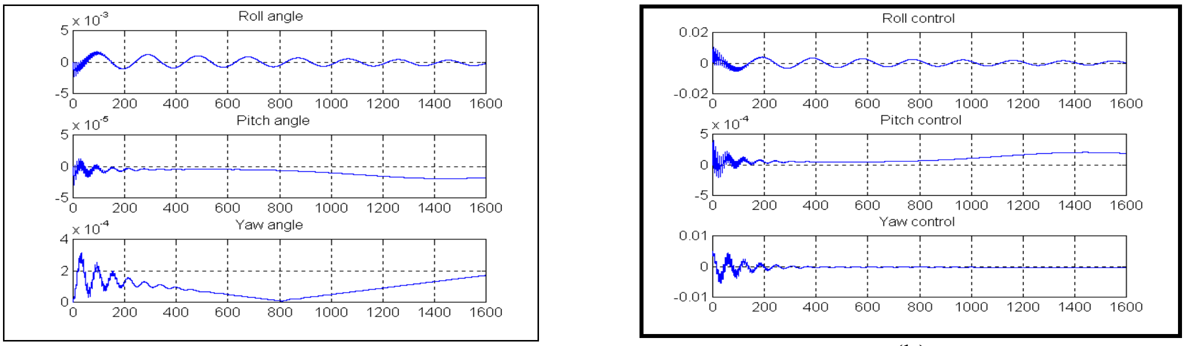
This paper presents the 1^{st}. part of a simulation and theoretical study of these consequences and their possible corrections (Tredinnick,1999c). Simulations that use discrete controls of analog plants are better than others that discretize the model too; and they are closer to the real case, that use digital controls of analog plants. In this work we mapped the same PD analog control law in three ways: by Tustin rule (Franklin & Powell, 1980), by Schneider rule (Schneider, 1994), and by a new (ST1) rule (Tredinnick, 1999a). This last one is new and a promising one that must be tested with other controls and models. Some model characterization of the CBERS1 satellite may be found in Tredinnick(1999c), where we just may see structural and control details around this three axis (roll, pitch and yaw) simulation. Structurally, the satellite simulated has a rigid body weighting 1.4 ton, with only one flexible appendage weighting 49 kg. This flexible appendage has 6.135 m x 2.4 m. In these simulations the atmospheric drag generating a center of pressure was near to the center of mass of the flexible appendage; and the perturbations due the pressure of solar radiation were small. Two cases were simulated: The first one with low gains and high sampling frequency ω_S, that is, low sampling period T_S. The second with high control gains and low sampling frequency, that is, high sampling period. This last case is a bad situation to the control system due to the aliasing and hidden oscillations phenomena (Tredinnick, 1999c), and brings the objective of this work: to test these discrete-time controller mappings for the same control law in presence of the aliasing and hidden oscillations phenomena to attain the stability. We'll see that the classical mappings and/or modifications around the controller (structural damping ζ changing, anti-aliasing filter, etc.) don't solve the instability problem and we'll see that the best alternative is to change the analog-digital control mapping using a new-rule proposed in Tredinnick(1999a). A controller that may work satisfactorily in this worst case would be cheaper than others, allowing to increase other satellite technical resources with the economy proportioned by the controller.

2. The CBERS1 model used

In this work we simulated a 3 axis, 18 modes (1rigid + 5flexible modes per axis) CBERS1 model in MATLAB 4.2.1.c with the block diagram of Figure 1, with the parameters of Table 1, and with the integration step of 0.01 s.

3. Analog PD control.

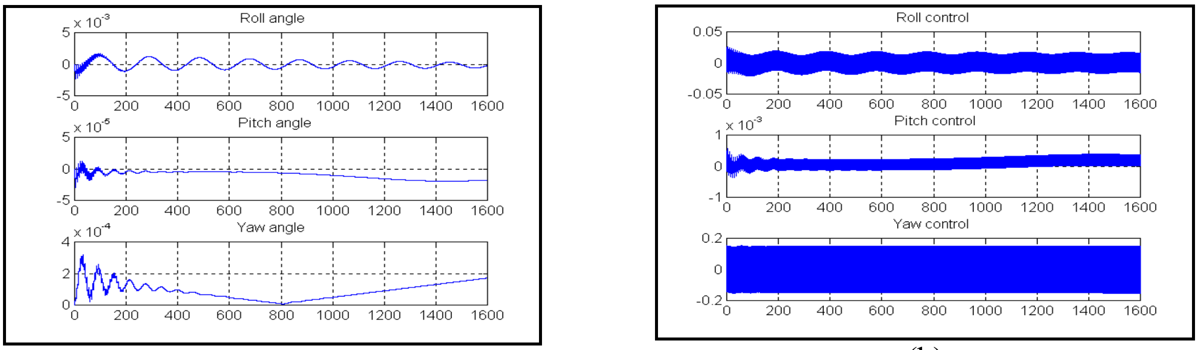
We use high control gains in this analog case and we may note from Figure 2 that the control easily stabilize the attitude angles of this satellite model. In Figure 2a we have the roll, pitch yaw attitude angles (in radians), respectively; and in Figure 2b we have their respective control signals (in N.m). Both use $\zeta = 0.02$ according to experimental results.



(a) (b)

Fig. 2. Analog attitude control of a CBERS1 model: (a) attitude angles; (b) control signals.

4. Discrete pd control designed by Tustin rule.



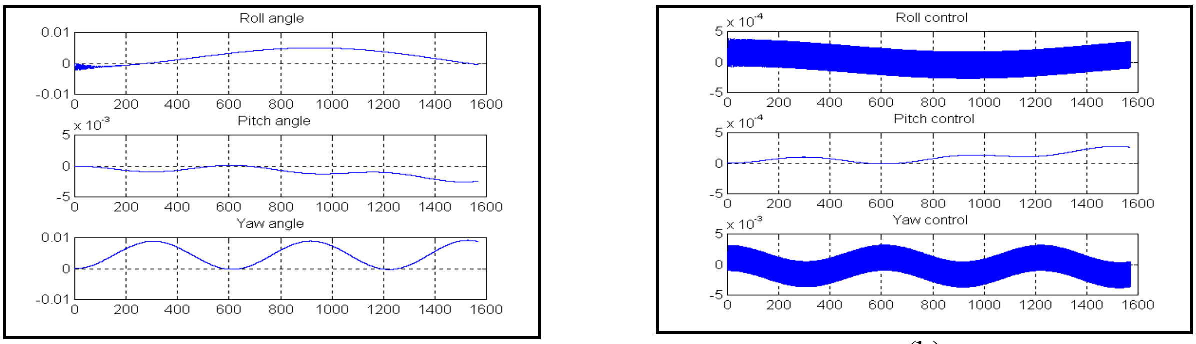
(a) (b)

Fig. 3. Discrete attitude control of a CBERS1 model using high control gains and T_S = 0.1 s: (a) attitude angles; (b) control signals.

In Figure 3b note the strong control signals needed to guarantee the attitude stabilization of Figure 3a. This phenomenon occurs due the sampler keying with frequency equal to the sampling frequency ω_S, probably due the presence of complex conjugated poles with negative real part inside the unit circle in z-plane. The analytic explanation of this effect is very well documented in Isermann (1989) and Franklin (1981).

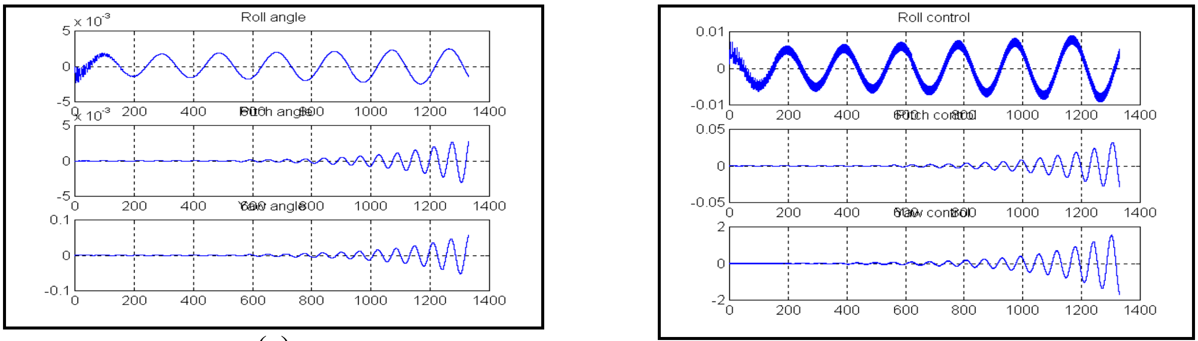
Figure 4 seems to be stable due to low gains, despite the Ts = 1.6 s.

In Figure 5 our problems begin. How could we stabilize the system when we have high control gains and high sampling period T_S? Classically, we may attempt to: 1) sampling period reduction; 2) an anti-aliasing filter; 3) control gain reduction; 4) and structural damping increase. We may try to stabilize the control system using these classical alternatives, as we will see in the next topics.



(a) (b)

Fig. 4. Discrete attitude control of a CBERS1 model using low control gains and T_S = 1.6 s: (a) attitude angles; (b) control signals.



(a) (b)

Fig. 5. Discrete attitude control of a CBERS1 model using high control gains and T_S = 1.6 s: (a) attitude angles; (b) control signals.

4.1. Stabilization by using sampling period reduction

It is the simplest and easiest solution. However, the availability and cost of processors, (A/D and D/A) converters, etc. with space quality may rule out this method.

4.2. Stabilization by using anti-aliasing filter

Here we insert anti-aliasing filters between the sensor outputs and the discrete controller inputs. The anti-aliasing filter is, basically, a low-pass filter that strongly attenuates the feedback of vibration modes higher than the Nyquist frequency, trying to eliminate/reduce the bad effects of their aliasing. In Figures 6 and 7 we used a fourth order Butterworth filter as an anti-aliasing pre-filter. Comparing Figure 6b with Figure 4b we note that the anti-aliasing pre-filter reduces the control energy (or fuel) used. However, Figure 7 shows that the anti-aliasing pre-filter included did not correct the instability problem shown in Figure 5.

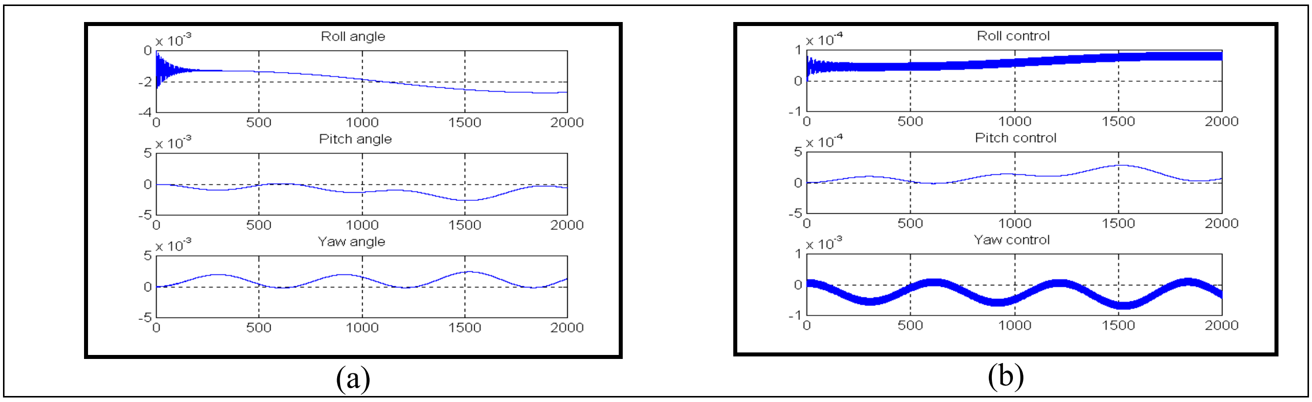


Fig. 6. Discrete attitude control of a CBERS1 model using low control gains, T_S = 1.6 s, and an anti-aliasing filter: (a) attitude angles; (b) control signals.

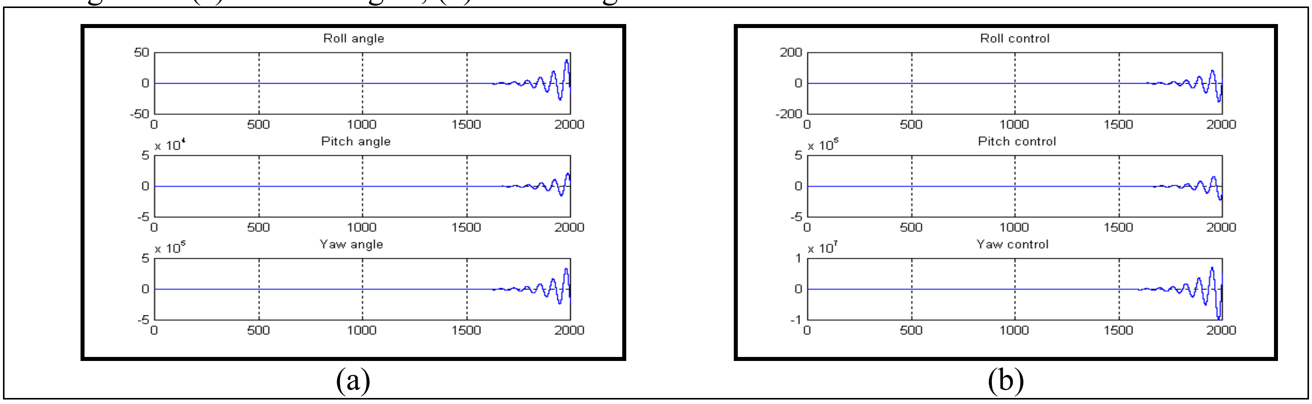


Fig. 7. Discrete attitude control of a CBERS1 model using high control gains, T_S = 1.6 s, and an anti-aliasing filter: (a) attitude angles; (b) control signals.

4.3. Stabilization by using gain reduction

The stabilization by control gains reduction must be tried but it has the inconvenient to change the closed-loop system specifications (settling time, rise time, overshoot, etc.).

4.4. Stabilization by using structural damping increase

We know that increasing the structural damping attracts the poles to the origin of the unit circle in z-plane, placing them inside this circle, that is the asymptotically stable region. This seems to be a powerful method to stabilize the system.Unhappily, this method seems not to be practical and efficient enough with high control gains and sampling period T_S , as shown in Figure 8 for the underdamped case, and in Figure 9 for the overdamped case.

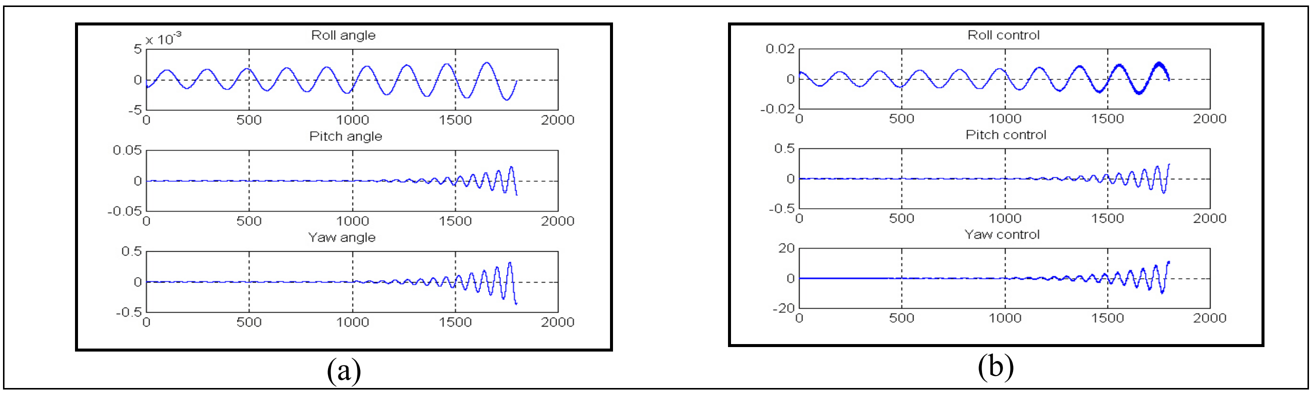
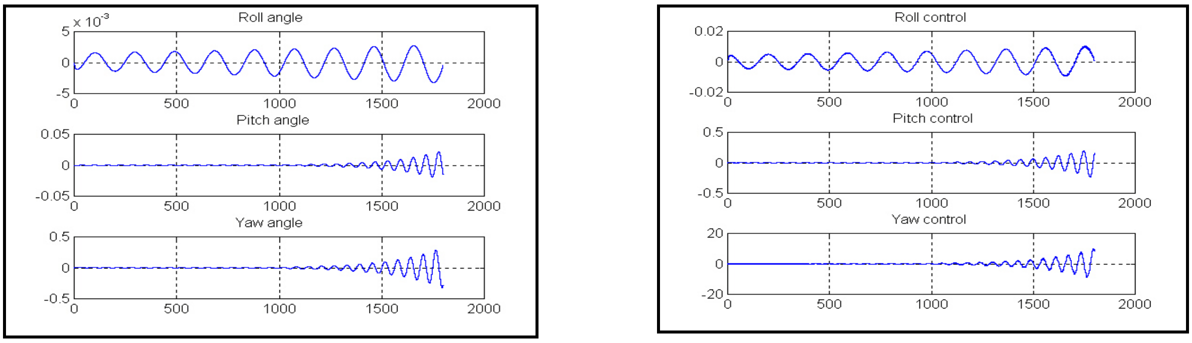


Fig. 8. Discrete attitude control of a CBERS1 model using high control gains, T_S = 1.6 s, and middle damping. Underdamped case with ζ = 0.6. (a) attitude angles; (b) control signals.



(a) (b)

Fig. 9. Discrete attitude control of a CBERS1 model using high control gains, T_S = 1.6 s, and high damping. Overdamped case with ζ = 2. (a) attitude angles; (b) control signals.

Now, we outline how a closed-loop discrete time control system working over an overdamped plant is presented the oscillations shown: this phenomenon occur in each axis due the superposition of the contributions of: a) two closed-loop complex conjugate poles generated from two open loop poles at s = 0 or z = 1 from the rigid mode; b) two closed-loop real or complex conjugate poles generated from two open loop real or complex conjugate poles in of each flexible mode; c) and one closed loop pole at z ≅ -1 generated by the z = -1 pole from the Tustin rule. This one is on the transient as a keying at the sampling frequency, describing a strong signal superposed to the mode frequency, as explained in Isermann (1989), Section 3.5.1, and Franklin (1981), Section 2.4.

5. Stabilization by changing the s-z mapping

The previous results opened the path to suggestions of new methods of stabilization, including changing to a s-z mapping that produces asymptotically stable z poles, as follows.

5.1. Stabilization by using Schneider rule 1

Schneider (1991 e 1994) presented some s-z mappings based in high order Adams-Moulton integration methods. In Schneider (1991) the third-order Adams-Moulton integration method (Eq. 1) is presented. This may be rewritten as a finite difference equation, as shown in Eq. 2. After the application of the z-transform over Eq. 2 we finally obtain the first Schneider s-z mapping, as we may see in the Eq. 3.

$$u_k = u_{k-1} + \frac{T_S}{12}.(5.e_k + 8.e_{k-1} - e_{k-2}) \qquad \text{(Eq. 1)}$$

$$e_k = \frac{1}{5}.\left(\frac{12}{T_S}.\nabla u_k - 8.e_{k-1} + e_{k-2}\right) \qquad \text{(Eq. 2)}$$

$$\frac{E(s)}{U(s)} = s \sim \frac{E(z)}{U(z)} = \frac{12}{T_S}.\frac{z.(z-1)}{5z^2 + 8z - 1} \qquad \text{(Eq. 3)}$$

These new s-z mappings called attention because they promised to be better than other mappings methods (Schneider, 1994) with integral actions of control. Figure 10 shows the results of a simulation using Schneider rule 1(Eq. 3) to map the analog PD control using T_S = 1,6 seconds, damping ratio ζ = 6 and high control gains. It becomes unstable even with ζ = 6; and it grows faster than the Tustin simulation with ζ = 2 at Figure 9. The explanation for that may be seen in Tredinnick (1999a).

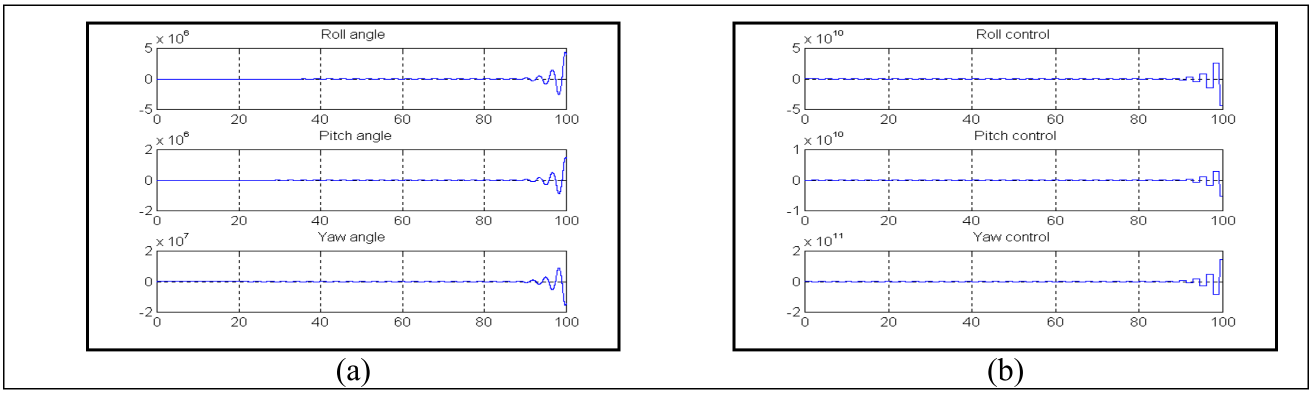


Fig.10. Discrete attitude control of a CBERS1 model using high control gains, T_S = 1.6 s, and Schneider rule 1. Overdamped case with ζ = 6. (a) Attitude angles; (b) control signals.

5.2. Stabilization by using new rule 1

A close look of the previous mappings and results motivated us to propose a new s-z mapping obtained by shifting the pole in z = -1 of the Tustin rule to z' = -ξ , 0 < ξ < 1. This avoids or retards the instabilization in closed-loop by moving that pole to the interior of the unit circle; and uses ξ as a design parameter. Therefore, we propose:

$$e_k = \frac{2}{T_s}.\nabla u_k - \xi.e_{k-1} \qquad \text{(Eq. 4)}$$

$$s \sim \frac{2}{T_s}.\frac{z-1}{z+\xi} \qquad ;0<\xi<1 \qquad \text{(Eq. 5)}$$

This new rule covers cases from the Tustin (ξ = 1) to the Backward (ξ = 0) mappings, which become particular cases of this new rule. Figure 11 shows the simulations with the new-rule using high gains, sampling period T_S = 1,6 s, damping ratio ζ = 6, and ξ = 0,2. It also shows that stability was reached in presence of aliasing and hidden oscillations.

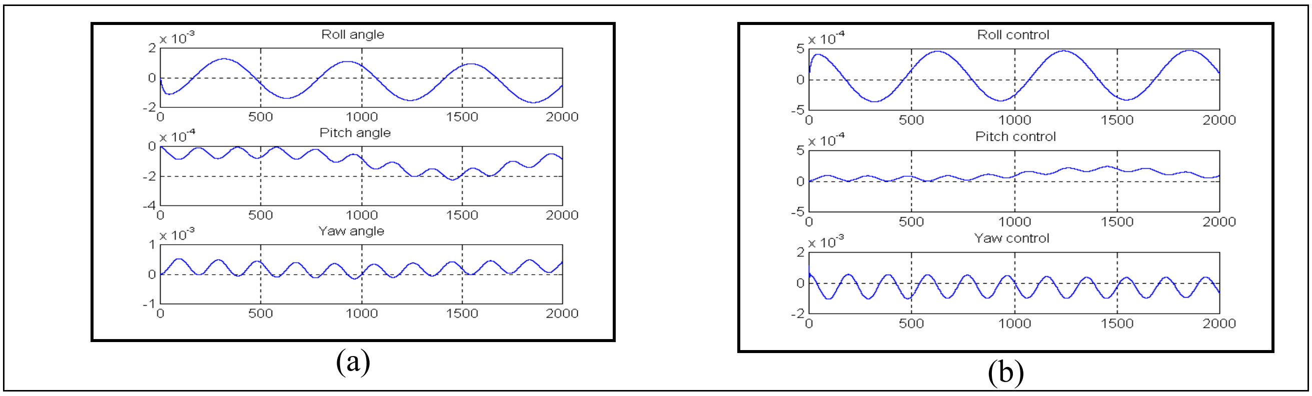


Fig. 11. Discrete attitude control of a CBERS1 model using high control gains and T_S = 1.6 s. Overdamped case with ξ = 0.2 and ζ = 6. (a) attitude angles; (b) control signals.

5. Conclusions.

Initially, is important to call the attention for the existence of the instability problem that may be introduced in discrete time control systems of flexible plants. That is, the choice of the sampling period T_S, anti-aliasing filters, control gains, structural damping, and the kind of s-z mapping chosen to design this discrete-time controller will be the decisive factors to keep the stability.

We may note that the new rule represents a promising alternative to the stabilization of discrete-time control systems when the plant is a flexible structure and it has high values in the sampling period T_S.

The simulations with the new-rule shown a performance very much better than the other tested under the same conditions.
It is also important to note that this model of CBERS1 satellite doesn't consider the increasing damping ratio with the number of the vibration modes and other non-linear phenomena. Thus, the conclusions obtained here are valid for the model used in this work but not necessarily for the real satellite.

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Appendix: a CBERS-1 model and its parameters

The structural analog model of CBERS-1 satellite using the assumed modes method was done by Silva (1997), in your Master Thesis at INPE, and it is capable of execute simulations for until five vibration modes, considering the coupled dynamic equations for this MIMO system.

The simulation using a CBERS-1 model (an asymmetric satellite) has used the following structural data:

- total mass: 1400 kg;
- flexible appendage mass: 49 kg;
- flexible appendage length: 6,135 m;
- rigid body inertia tensor:

$$I_0 = \begin{bmatrix} 1983 & -12{,}8 & 21{,}5 \\ -12{,}8 & 1002 & 9{,}8 \\ 21{,}5 & 9{,}8 & 1831 \end{bmatrix} \qquad \text{(Equ.6)}$$

- flexible appendage inertia tensor:

$$I_a = \begin{bmatrix} 720 & 0 & 0 \\ 0 & 22{,}744 & 0 \\ 0 & 0 & 698{,}06 \end{bmatrix} \qquad \text{(Equ.7)}$$

From the equation 7 we may note that although the calculations has been done for an Euler-Bernoulli thin beam, it was considered inertia around the y axis (pitch axis $\mathrm{I}_{a22} = 22{,}744$) trying to oblige the model to work as it was a plate, that is interesting to do a more simplify calculation without affect the results of a bad form. Figure 12 shows the relationship between the X,Y,Z with the attitude axis roll, pitch and yaw.

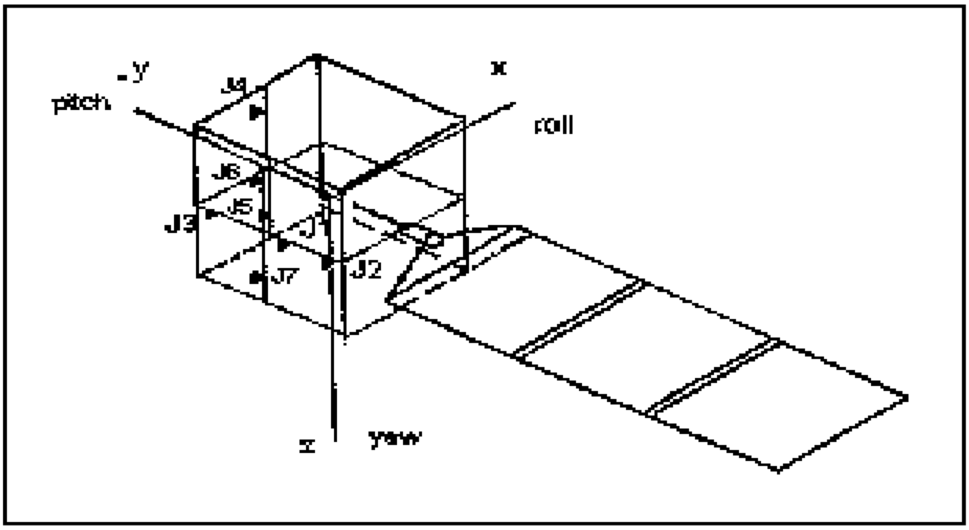

Fig. 12: Attitude axis for the simulation with a CBERS-1 satellite model.

As shown in Silva (1997), were considered in the dynamical equations some disturbs due atmosferic drag, solar pressure radiation and to magnetic residues.

These disturbs repel the attitude axis of its initial conditions considered null (0 rad). Trying to correct the effect provoked by these disturbs the attitude control starts its task. This control is done by torques and in these simulations we didn’t considered boundaries for these. Therefore would be interesting to consider these boundaries in a next work. In this present work the main objective is the stability analysis of the discrete-time control, where we don’t need to consider these boundaries.

We use a fix integration step of 0.01 seconds to the computer can simulate the more higher vibration mode (obeying the Nyquist criterion). By this form we may avoid the aliasing and hidden oscillations phenomena during the simulation process. As we may note in Table 1, the more higher vibration mode frequency is 25.7241 Hz, implying that we be free of the aliasing and hidden oscillations phenomena if, at least, a frequency of 51.4482 Hz be used as frequency of the integrator of this simulation, with Nyquist frequency of 25.7241 Hz. As we use 100 Hz as frequency of the integrator of this simulation, with Nyquist frequency of 50 Hz, we may be secure that all the five first modes, in each three axis, will be simulated in the computer without problems. The single problems are the high elapsed time of the simulation and the great data size. In Table 1 the x, y and z axis corresponds, respectively, to the roll, pitch and yaw axis.

TABLE 1 –VIBRATION MODES TO AN ASSYMETRIC MODEL OF CBERS-1 SATELLITE.

Mode	Axis	Frequency (Hz)	Damping ratio
Rigido	x	0	0
	y	0	0
	z	0	0
1	x	0.1312	0,02
	y	0.1331	0,02
	z	0.4526	0,02
2	x	0.6874	0,02
	y	0.6883	0,02
	z	1.8999	0,02
3	x	1.9005	0,02
	y	2.8361	0,02
	z	3.7141	0,02
4	x	3.7146	0,02
	y	6.1346	0,02
	z	6.1350	0,02
5	x	7.9411	0,02
	y	15.5614	0,02
	z	25.7241	0,02