A STUDY ABOUT DEPLOYMENT OF A SOLAR ARRAY ON A SATELLITE USING DC MOTORS

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Abstract. *This investigation addresses the problem of deployment of a solar array on a satellite. For this purpose, the solar panel is considered as a rigid multibody system and DC motors are used for the final desired configuration. Each one of the rotating axes necessary for the task is provided with a light actuator. The mathematical model is developed through the Lagrangian formalism and the resulting governing equations of motion are integrated through a fourth order Runge-Kutta. All nonlinear terms are kept on the analysis and the numerical simulations show the effects of these nonlinearities on the evolution of the system dynamics before, during and after the deployment of the solar array. The nonlinearities make the time of deployment very fast, the use of the DC motor makes this time longer showing a softer deployment.*

Keywords *deployment, satellite, nonlinearities, motor.*

1. Introduction

The knowledge of the attitude angles is very important to determine the behavior of the satellite (Roberson, 1979) and to define the control actions. If the launch vehicle is previously stabilized, as the Long March 4B used to launch the China Brazil Earth Resources Satellite CBERS-1, the attitude is easily determined. However after the deployment phase it is disturbed, so that the knowledge of the attitude becomes important (Thomson and Reiter, 1960). The determination of these variables through mathematical modeling and computer simulations (Wie, 1986; Porro, 2002), allows the verification of the impact of some critical actions under satellite attitude, such as the draft of solar panels to the sun or as in this work the solar array deployment (Meirovitch and Calico, 1972; Wie, 1998).

Here the orbit described by the satellite will be considered circular and every part will be considered as rigid bodies. Three different phases were considered: the instant in which the appendages are closed, the instant in which the appendages are opening, and the instant in which the appendages are completely opened (Porro, 2002; Fenili, 2003).

Two different torque profiles were used to control the opening of the appendages. The first was prescribed (Porro, 2002) and a DC motor generated the second one.

All the nonlinear terms associated with the centripetal and Coriolis effects are considered (Smith, Balchandran and Nayfeh, 1992) and the control actions are not included.

The Lagrangian formulation is utilized for the derivation of the governing equations of motion. A fourth order Runge-Kutta algorithm is utilized to integrate these equations.

Fig. 1 shows the array deployment. After the complete deployment, the attitude angles behave as shown in Fig. 3.

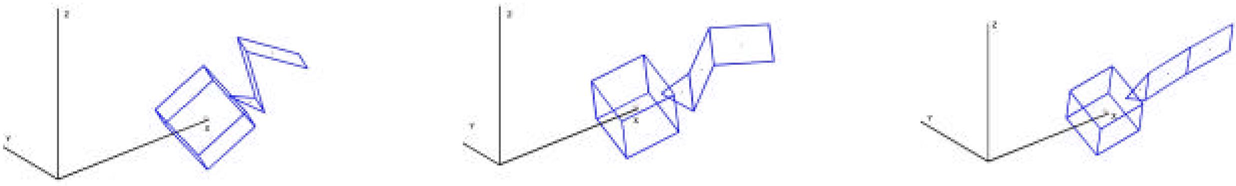

Figure 1. Array deployment

2. Derivation of the Governing Equations of Motion

Figure (2) shows the system considered in this work, where the DC motors are located in each axis.

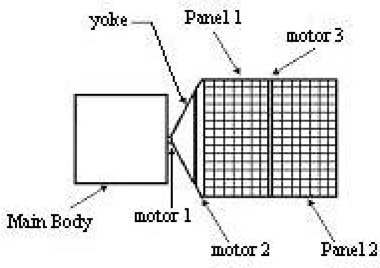

Figure 2. Satellite Model

Table 1. Nomenclature

Symbol	Description
θ_1	Angular position of satellite
θ_2	Opening angle of yoke
θ_3	Opening angle of panel 1
θ_4	Opening angle of panel 2
α	Attitude angle

The governing equations of the motion, obtained applying Lagrange`s equations are given by:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right)-\frac{\partial L}{\partial q}=Q \tag{1}$$

Where:

$$L=T-V \tag{2}$$

The potential energy is considered equal to zero, because the orbit considered is circular.

The total kinetic energy of the system is given by:

$$T=\sum_{i=1}^{4}T_i \tag{3}$$

The energy given by Eq. (3) is composed of two terms: the first related to the kinect energy associated to the orbital and the attitude motion of all (Eq. (4)) and the second related to the kinect energy associated to the appendage motion (Eq. (5)).

$$T_1=\frac{1}{2}m_1r_1^2\dot{\theta}_1^2+\frac{1}{2}\{\dot{\alpha}\}^T[I_1]\{\dot{\alpha}\} \tag{4}$$

$$T_i=\frac{1}{2}m_ir_i^2\dot{\theta}_i^2+\frac{1}{2}\{\dot{\theta}_i\}^T[I_i]\{\dot{\theta}_i\} \tag{5}$$

In Eq. (4) and Eq. (5),

$$\{\dot{\alpha}\}=\begin{Bmatrix}\dot{\alpha}_z\\ \dot{\alpha}_y\\ \dot{\alpha}_x\end{Bmatrix} \tag{6}$$

$$\{\dot{\theta}_i\}=\begin{Bmatrix}0\\ 0\\ \dot{\theta}_i\end{Bmatrix} \tag{7}$$

$$[I_1]=\begin{bmatrix} I_{x1} & 0 & 0 \\ 0 & I_{y1} & 0 \\ 0 & 0 & I_{z1} \end{bmatrix} \quad (8)$$

$$[I_i]=\begin{bmatrix} I_{xi} & I_{xyi} & I_{xzi} \\ I_{xyi} & I_{yi} & I_{yzi} \\ I_{xzi} & I_{yzi} & I_{z1} \end{bmatrix} \quad (9)$$

Substituting Eq. (2) in Eq. (1), results:

$$M(q)\cdot \ddot{q} + f(q,\dot{q})\cdot \dot{q} = \boldsymbol{t} \quad (10)$$

The inertia matrix, *M(q)*, is nonlinear in the variables $(a_1, a_2, a_3, q_1, q_2, q_3, q_4)$ and the vector f is nonlinear in the variables and in the velocities.

The generalized forces Q_i, in the Eq. (1) are the torques (t) necessary to move the appendages. These torques are supplied by the DC motor or used to correct the satellite attitude (in this case the torques are provided by the attitude jets).

The influence of the nonlinearities in the whole system dynamics is investigated multiplying all the nonlinear terms by a small parameter, $\in$, and slowly changing its value from 0 to 1. So the Eq. (10) can be written in this way:

$$[M_l + \in M_{nl}(q)]\cdot \ddot{q} + \in f(q,\dot{q})\cdot \dot{q} = t \quad (11)$$

where: M_l is the linear part of the inertia matrix and M_{nl} is the nonlinear part of the inertia matrix. When $(\in = 0)$ the system is linear.

Great values of angular velocities (both during the attitude control and the solar array deployment phases) strongly feed these nonlinearities.

Fig. (5) shows the behavior of the deployment phase when the torque applied is considered prescribed and the nonlinearities are presented.

When the torques τ, are generate by a DC motor, one more degree of freedom will be included in the formulation. The governing equation of motion for the angular displacement (theta) of the motor is given by:

$$\boldsymbol{t}_{motor} = \left(\frac{k_t}{R_a}\right)\cdot U - \left(C_m + \frac{(k_b \cdot k_t)}{R_a}\right)\cdot \ddot{\boldsymbol{q}}_{motor} \quad (12)$$

where: q = Angular position of the motor axis.

Substituting Eq. (12) in Eq. (11), and considering that the nonlinearities present in the vector f lose their influence because of the DC motor, the array deployment will be controlled in relation to the velocity. So the Eq. (13) is given by:

$$[M_l + \in M_{nl}(q)]\cdot \ddot{q} = \boldsymbol{t}_{motor} \quad (13)$$

Choosing the voltage at the motor terminals carefully, the array deployment can be as smooth as possible, as can be seen in Fig. (4) and Fig. (7). The technical specifications of the DC motor considered in the numerical simulations are shown in Tab. (2).

Table 2. Technical specifications of motor manufactory by Mavilor[1] motors model MSS-6

Characteristics	Symbol	Unit	Value
EMF constant	k_b	V.s/rad	1.98E-3
torque constant	k_t	N.m/A	0.181
terminal resistance	R_a	Ω	0.75
friction torque	C_m	N.m	0.05
rated voltage	U	V	67.8
inertia	J	$kg.m^2$	0.40E-3
maximum torque	T_{max}	N.m	11
mass	M	kg	5.8

1- http://www.mavilor.es/pdf_products/mss_series.pdf

3. Numerical Results

Fig (3) shows the profiles of the voltage applied to the motor terminals. These profiles will turn the deployment soft.

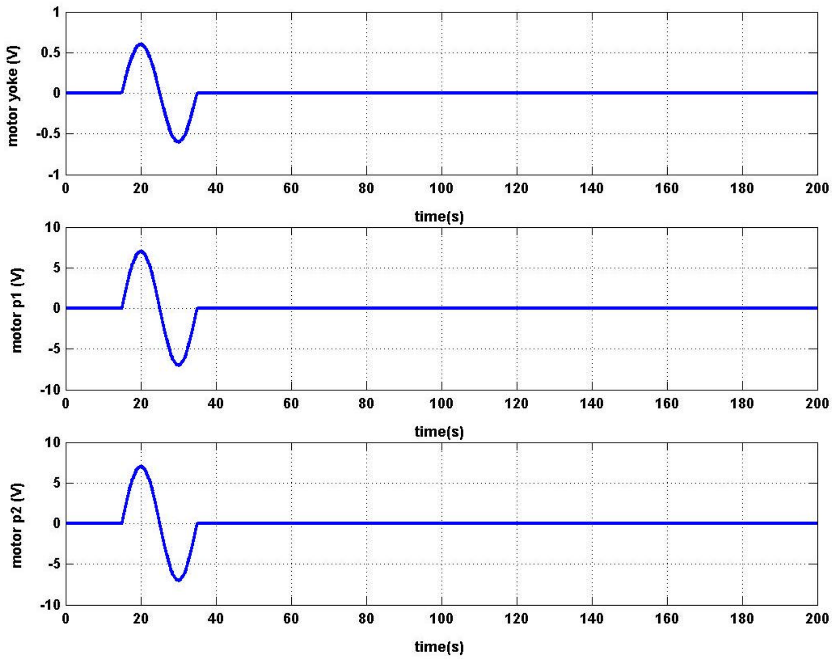

Figure 3. Profiles of rated voltages

Fig. (4) shows the three phases: the first phase (appendages closed) goes from 0 to 15 s, the second phase (array deployment), goes from 16 to 35 s, and the third phase (appendages completely opened), goes from 36s to 200 s. The DC motor controls the second phase.

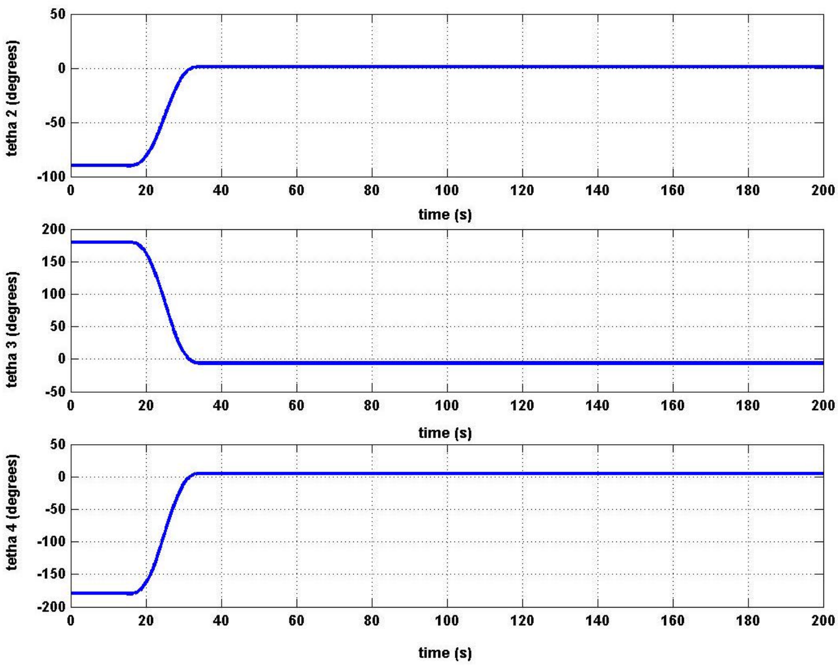

Figure 4. Deployment Angles considering the DC motor

Fig. (5) shows the array deployment, considering the prescribed torque. Three cases were considered: a) the dash-dotted line represents the behavior of the deployment angle when the nonlinearities have strong influence, thus when the parameter $\in$, presented in Eq. (11) has value equal to 1 the system dynamics is completely nonlinear; b) the solid line represents the behavior when the parameter $\in$, has the intermediate value, equal to 10^{-1}; c) the dotted line represents the behavior when the parameter $\in$, has value equal to 0. In this case the system dynamics is completely linear.

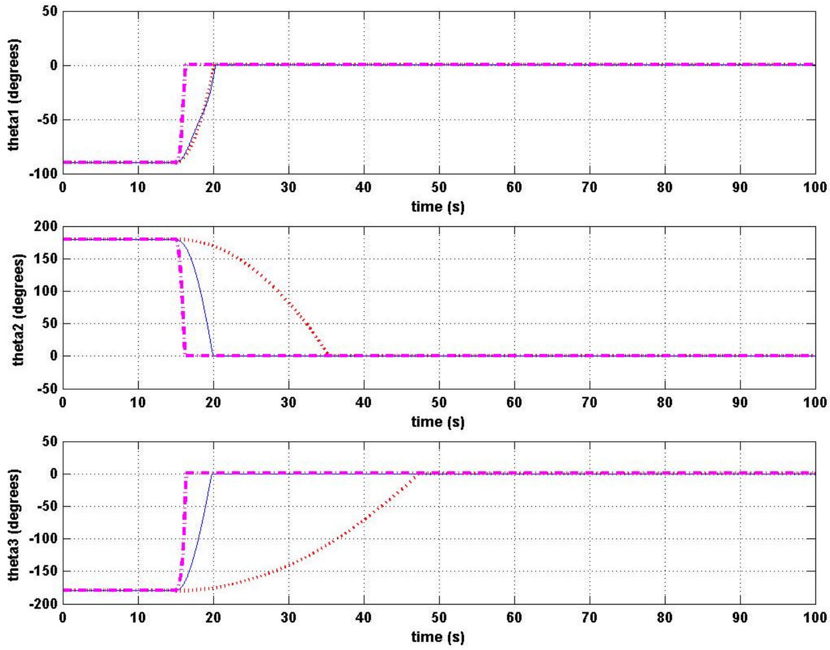

Figure 5. Deployment Angles considering the Prescribed torque

In Fig. (6) the behavior of the attitude angle alpha 1 and alpha 2 has the amplitude modulated by the nonlinearities and the behavior of the attitude angle alpha 3 has that shape because the velocity becomes constant with a value different from zero. The attitude has no control.

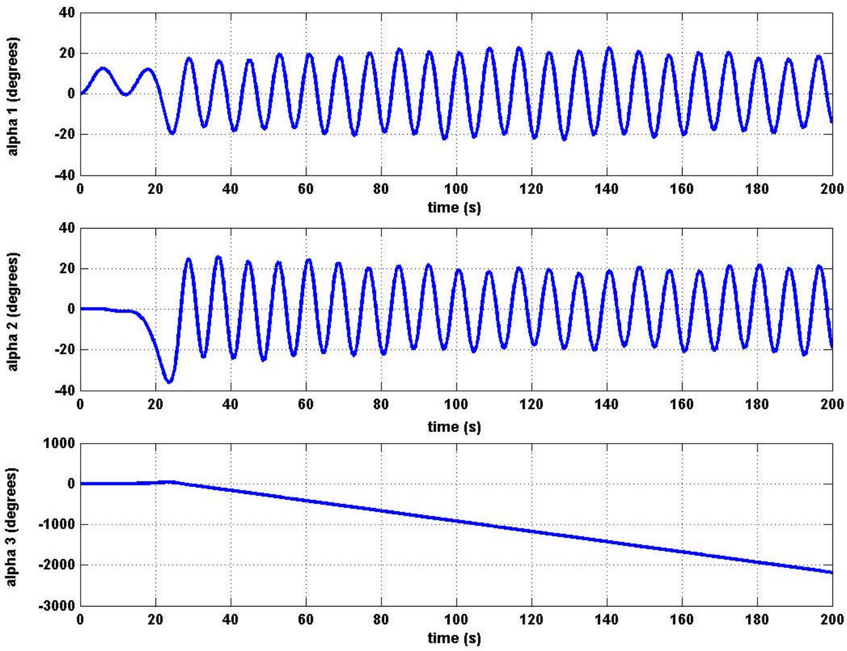

Figure 6. Attitude Angles

Fig. (7) shows the comparison of the deployment angles considering that phase with and without the DC motor. When the motor supplies the torque for the deployment, it occurs softly and the time is bigger than when the motor is not used.

The solid line represents the opening angles supplied by the prescribed torque. Thus the system is completely nonlinear. The dotted line represents the torque supplied by the DC motor, considering the time for the opening equal to 20s and the dash-dotted line represents the time for the opening equal to 40s.

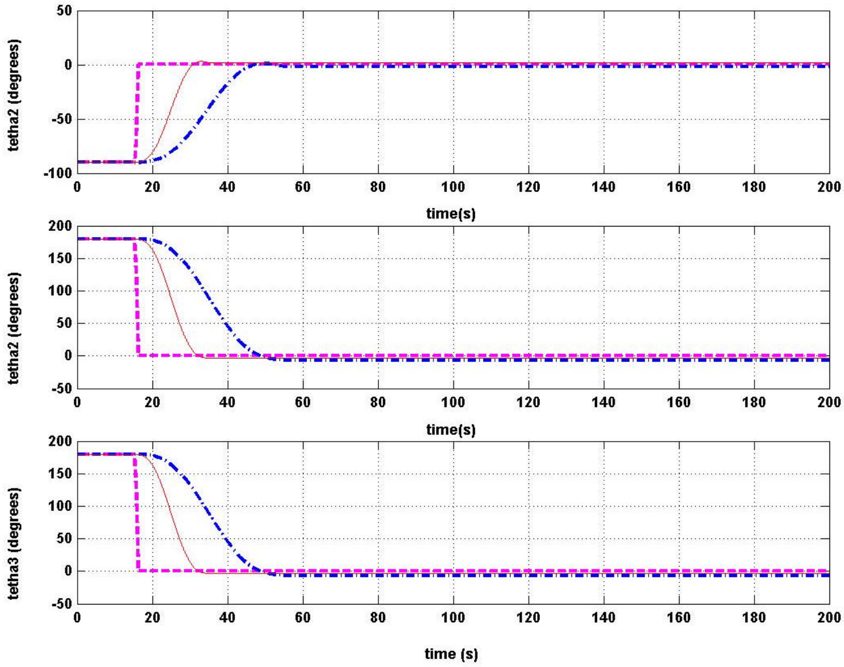

Figure 7. Comparison of the opening angles with and without the DC motor

4. Conclusion

The nonlinearities show strong influence in the behavior of the attitude and opening of the appendage angles, causing instability in the same ones. In some cases these terms are more representative than the prescribed torques used, determining the dynamic behavior of the system.

An important aspect of this work is the study about the introduction of a small parameter, $\in$, in the governing equations of motion multiplying all the nonlinear terms. This parameter is used to verify the contribution of the nonlinearities in the system behavior. When this parameter is considered equal to 0, the system is linear and when it is considered equal to 1, the system becomes strongly nonlinear. Any intermediate value between 0 and 1 will indicate a bigger or a smaller influence of the nonlinearities in the dynamic behavior of the system. This influence will depend on the deployment velocities and on the involved panel masses and inertias.

Without the inclusion of the DC motors to control the solar array deployment, the system is completely unstable (unless some precaution is taken regarding the velocities involved, for instance).

5. Acknowledgement

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