Acta Astronautica 94 (2014) 515–526

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Effects of uncertainties and flexible dynamic contributions on the control of a spacecraft full-coupled model

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ARTICLE INFO

Article history:
Received 31 May 2012
Received in revised form
12 July 2012
Accepted 16 August 2012
Available online 29 September 2012

Keywords:
Very large flexible space structures
Flexible uncertainties
Attitude control
Finite elements

ABSTRACT

One of the most important problems for performing a good design of the spacecraft attitude control law is connected to its robustness when some uncertainty parameters are present on the inertial and/or on the elastic characteristics of a satellite. These uncertainties are generally intrinsic on the modeling of complex structures and in the case of large flexible structures they can be also attributed to secondary effects associated to the elasticity. One of the most interesting issues in modeling large flexible space structures is associated to the evaluation of the inertia tensor which in general depends not only on the geometric 'fixed' characteristic of the satellite but also on its elastic displacements which of course in turn modify the 'shape' of the satellite. Usually these terms can be considered of a second order of magnitude if compared with the ones associated to the rigid part of a structure. However the increasing demand on the dimension of satellites due to the presence for instance of very large solar arrays (necessary to generate power) and/or large antennas has the necessity to investigate their effects on their global dynamic behavior in more details as a consequence. In the present paper a methodology based on classical Lagrangian approach coupled with a standard Finite Element tool has been used to derive the full dynamic equations of an orbiting flexible satellite under the actions of gravity, gravity gradient forces and attitude control. A particular attention has been paid to the study of the effects of flexibility on the inertial terms of the spacecraft which, as well known, influence its attitude dynamic behavior. Furthermore the effects of the attitude control authority and its robustness to the uncertainties on inertial and elastic parameters has been investigated and discussed.

1. Introduction

The study of Very Large Space Structures, from the structural point of view, implies the need to use standard and well-established tools such as commercial Finite Element Software (MSC.Nastran, MSC Patran, etc.). As a matter of fact these tools are deputed to perform structural analyses and generally they are not suitable for the design of orbital and attitude motion. This is true above all if we consider that a spacecraft may be represented by thousands of degrees of freedom. It is not easy to handle the high number of degrees of freedom from flight mechanics and attitude dynamics point of view. On the contrary mathematical models of spacecraft, developed to design the guidance, navigation and attitude control laws, are not meant to represent the flexibility effects and the structural behavior of a complex large structure. It is worth to note that the flexibility effects of large appendages may in turn influence the attitude motion and may be influenced themselves, too. In fact the flexible behavior

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http://dx.doi.org/10.1016/j.actaastro.2012.08.018

of an orbiting spacecraft is influenced not only by the space environment, such as the space-varying gravity forces, but also by the orbital and attitude perturbations and the relevant counteracting control forces. Several methods and formulations devoted to the modeling of flexible bodies undergoing large overall motions have been developed in the last decades [1–3].

Most of these different formulations were aimed (a) to face one of the main problems concerning the analysis of spacecraft dynamics namely the reduction of computer simulation time and (b) to have a good even if simplified representation of its flexible elements. In general these formulations are based on a kinematics suitable to represent flexible displacements via a modal superposition technique [4–6]. On account of this, it is mandatory to compute the modal shapes of the structure as better as possible. Furthermore, since the equations of the elastic vibrations are defined into a modal domain, it is necessary to evaluate the eigen-frequencies of the structures and to select the most significant ones, in terms of the modal masses and eventually of the modal participation factors, to represent the overall free motion of the spacecraft [7]. It is also worth to note that sometimes dynamics of complex structures can be described only with the help of experimental campaigns necessary to correlate numerical data with the experimental ones [8,9]. This is especially true when dealing with structural eigenfrequencies and damping ratios of an orbiting spacecraft. As far as an orbiting flexible-spacecraft is concerned it is important to observe that gravity, gravity gradient and the perturbation of the gravitational field interact with the structure itself in different ways. Gravity influences the motion of the center of mass whereas the gravity gradient acts on the motion around the center of mass. Furthermore the gravity local forces, depending on the local elastic displacements, must be defined in order to correctly identify the generalised forces acting on the elastic terms that appear on the equation of motion of a flexible space structure. Another important aspect relevant to the large flexible structures is the one associated to the effects of the elastic displacement on the moment of inertia tensor. If a body undergoes a large deformation its moment of inertia tensor cannot be considered constant with respect to time. For studying correctly the attitude behaviour of a flexible structure it is necessary to introduce the flexibility effects on the inertia tensor associated to the rotational motion. Of course, elastic terms also affect the gravity gradient torque since it depends on the moment of inertia. The full coupled equations of motion will be derived and discussed and the robustness of the attitude control law will be analyzed. Several numerical simulations have been introduced and discussed in the paper. In Fig. 1 a schematic of all test cases provided in the section Numerical Simulations has been reported.

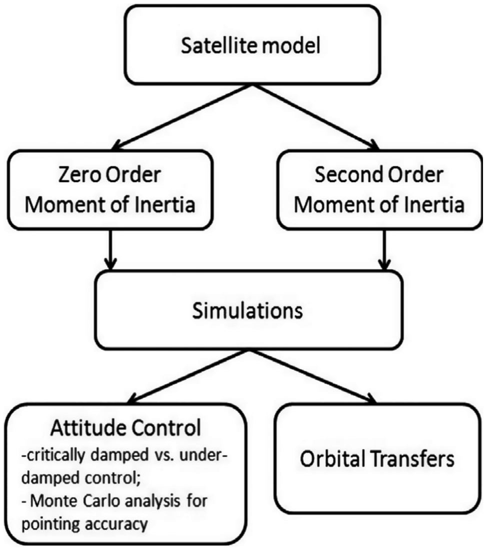

Fig. 1. Schematic of numerical simulations.

2. Kinematics and dynamics of a flexible space structure

This section deals with the description of the kinematics used to derive the full equation of motion of a flexible orbiting satellite [10]. The equations of a flexible body in a space environment—although well known—are derived by using a classical Lagrangian formulation which needs (a) the definition of kinematic parameters; (b) the definition of the kinetic, elastic and gravitational functionals; (c) the definition of the Lagrangian; and (d) finally the writing of the equilibrium equations;

2.1. Kinematics

As far as the kinematics is concerned we will use a classical formulation

$$\mathbf{X}(P) = \mathbf{X}_0 + \mathbf{T}\left(\xi + \sum_{k=1}^{N} A_k(t)\boldsymbol{\phi}_k(\xi)\right) \tag{1}$$

where the vector $\mathbf{X}$ represents the position in an inertial, Earth-centered, frame of a point P, whose position in the body-fixed reference frame is given by the vector ξ; the body-fixed frame is centered in a properly chosen point of the considered body which in most cases can be the center of mass. The $\boldsymbol{\phi}_k(\xi)$ is the set of the first N eigenmodes of the structure (to be properly chosen), where N must be prescribed according to the required accuracy, whereas $A_k(t)$ are their relevant amplitudes. The position of the body in the inertial reference frame (I_0) is further defined by the position vector $\mathbf{X}_0$ of its reference point, and by the rotation matrix $\mathbf{T}$, describing the rotation from body-axes (I_2) to the inertial ones. This rotation is accomplished into two steps. In the first one we move from body-axes to orbital reference frame (I_1) by means of the rotation matrix $\mathbf{T}_1$. This matrix is written in terms of rotational motion parameters, such as Euler's angles $[\varphi,\theta,\psi]$ or quaternions $\mathbf{Q}$. The second step is accomplished by using a matrix $\mathbf{T}_2$, depending on the orbital parameters (right ascension, inclination and true anomaly).

The rotation $\mathbf{T} = \mathbf{T_2}\mathbf{T_1}$ has the property

$$\dot{\mathbf{T}} = \mathbf{TR} \tag{2}$$