Journal of Sound and Vibration 432 (2018) 549–568

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Boundary control of flexible satellite vibration in planar motion

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A R T I C L E I N F O

Article history:
Received 7 January 2018
Received in revised form 30 May 2018
Accepted 22 June 2018

Handling Editor: D. J. Wagg

Keywords:
Flexible satellite
PDE-ODE system control
Vibration control
Boundary control
Asymptotic stability
Partial differential equation

A B S T R A C T

In this paper, the planar maneuver of a flexible satellite with regard to its flexible appendages vibration has been studied. The flexible satellite translates and rotates in a plane; in addition, the flexible appendages can also vibrate in that plane. The system governing equations, which are coupled partial and ordinary differential equations, are obtained based on Hamilton's principle. Then the original system converts to three equivalent subsystems, two of which contains one partial differential equation and one ordinary differential equation along with four boundary conditions, by using change of variables. Employing control forces and one control torque which are applied to the central hub, control objectives, tracking the desired angle and suppressing the satellite and its flexible appendages vibrations, are fulfilled. Furthermore, to eliminate spillover instability phenomenon and to exclude in-domain measurement and actuator usage problem, these control torque and forces are designed based on boundary control method. Lyapunov's direct method is employed to prove the asymptotic stability in absence of any damping effect in modeling the vibrations of flexible appendages. Eventually, in order to demonstrate the effectiveness of the designed boundary control, numerical simulations are presented.

1. Introduction

Communicate with earth, remote sensing, and satellite imagery are the most important reasons of using satellites in past decades [1]. Flexible satellites, a large group of satellite, comprise interconnection between a rigid structure and flexible appendages such as large solar arrays or antennae. Consequently, the system governing equations are coupled partial and ordinary differential equations. Due to the coupling between appendages vibration and the rigid body dynamics of the satellite, appendages vibration affects on satellite maneuvers and causes the satellite translation and rotation; in addition, the satellite rotation or translation leads to the appendages vibration. Therefore, tracking the desired angle along with suppressing the satellite and its flexible appendages vibration must be accomplished simultaneously.

Dealing with the control design of systems whose governing equations consist of PDEs and ODEs, such as a flexible satellite system, has always been elaborated. Usually, such a system is discretized into a set of ODEs; afterward the obtained ODEs are

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https://doi.org/10.1016/j.jsv.2018.06.052

Nomenclature

A	cross-sectional area of the panels (m^2)
c	velocity of wave propagation in cantilever beams
E	Young modulus of the flexible panels ($kg/m/s^2$)
f	control force in x_b-direction
J	inertia of central hub ($kg\,m^2$)
I	area moment of inertia of the flexible appendages cross-section (m^4)
l	length of each flexible appendages (m)
L	Lagrangian function of the system ($N\,m^2$)
m	hub mass (m)
r	each appendage distance from the hub center (m)
t	time (s)
T	Kinetic energy
u	control force in y_b-direction
U	Potential energy
V	Lyapunov function
W	work of control torque on the satellite
x	space independent variable (m)
$\dot{x}_{hub}, \dot{y}(t), \dot{X}(t), \dot{Y}(t)$	satellite velocity in i-, j-, I- and J-axis, respectively
τ	boundary control torque (N m)
ρ	density of the panels (kg/m^3)
θ	pitch angle (radian)
θ_d	desired pitch angle (radian)
e_θ	pitch angle tracking error (radian)
e_y	displacement tracking error in the special case (m)
w_R, w_L	elastic deformation of right and left appendage element (m)
E_a	a summation of the potential and Kinetic energy of the flexible appendages
E_{as}, E_s	a summation of the potential and kinetic energy of the flexible appendages in special cases
V_s, V_{as}, Δ_{as}	some terms in Lyapunov function
$\alpha_0, \alpha_1, \beta_1, \beta_2, k_1, k_2, c_x$	constant coefficients in Lyapunov function and the controller
q_{s-i}, q_{as-i}	generalized coordinates
φ_i	the normal modes for clamped-free Euler-Bernoulli beam
S_i	invaiat set
M_g	couple in z-direction due to angular velocity in x_b- and y_b-direction
$I_{x_b x_b}, I_{y_b y_b}$	inertia of satellite in x_b- and y_b-direction ($kg\,m^2$)
ω_{xb}, ω_{yb}	angular velocity in x_b- and y_b-direction ($kg\,m^2$)

controlled by various control methods of ordinary differential equations [2,3]. In the field of the flexible satellite dynamic modeling and control based on discretizing model, the satellite hub along with the flexible appendages are considered as a rigid body and Euler-Bernoulli beam, respectively [4,5]; moreover, in some other investigations, Euler-Bernoulli beams with tip masses are considered as the flexible satellite appendages [6,7].

In Ref. [8], flexible orbiting space systems are modeled and a formulation suitable for synthesizing optimal control strategies during the deploying maneuvers of robotic arms or solar arrays is presented. In Refs. [9,10], the satellite rotational motion and anti-symmetric vibration in a plane are controlled. In Refs. [11,12], the three-axis maneuver control and vibration suppression of a flexible satellite in a circular orbit are studied. In Ref. [13], the three-axis maneuver control of the flexible satellite in the face of faulty actuators, system uncertainties, actuator saturation and external disturbances are studied. In Ref. [14], disturbance effects like gravity gradient torque are investigated. In Ref. [15], system uncertainties in the flexible satellite control are studied. In Refs. [16,17], in addition to the control torque used for the flexible satellite maneuver control, the surface piezoelectric layer is used for active vibration suppression. Furthermore, different control methods are addressed in previous investigation, such as sliding mode [6], robust control [18], variable structure control [19], adaptive control [20], and non-linear PD control [21].

In some discretized model, the proposed controllers are difficult to implement, for expensive distributed actuator and sensor instruments or a large set of properly located sensors and actuators are required. Moreover, in some cases, some sensors are needed to feedback information in the domain and an observer must be used to estimate the required information. Furthermore, the high order modes are ignored in the discretized model for the distributed system and as a result, these neglected modes will cause spillover instability that should be avoided in the control design. All aforementioned