Acta Astronautica 96 (2014) 269–279

Contents lists available at ScienceDirect

Acta Astronautica

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

Nonlinear analysis and vibration suppression control for a rigid–flexible coupling satellite antenna system composed of laminated shell reflector

Bin Di You [a,*], Jian Min Wen [a], Yang Zhao [b]

[a] School of Naval Architecture and Ocean Engineering, Harbin Institute of Technology, Weihai 264209, China
[b] School of Astronautics Engineering, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Article history:
Received 19 May 2013
Received in revised form
8 December 2013
Accepted 10 December 2013
Available online 18 December 2013

Keywords:
Satellite antenna
Shell structures
Dynamic modeling
Vibration suppression
Nonlinear deformation

ABSTRACT

In this paper, a nonlinear dynamic modeling method for a rigid–flexible coupling satellite antenna system composed of laminated shell reflector is proposed undergoing a large overall motion. For the study of the characteristics of the reflector using laminated shell structure, the displacement field description of a point in a 3-noded shell element is acquired in conjunction with the length stretch, lateral bending and torsional deformation. Hence, a nonlinear dynamic model of the satellite antenna system is deduced based on Lagrange's equations. The complete expressions of nonlinear terms of elastic deformation and coupling terms between rigid motion and large deflection are considered in the dynamic equations, and the dynamic behavior of the rigid–flexible coupling system is analyzed using linear model and nonlinear model, respectively. In order to eliminate the system vibration, the PD with vibration force feedback control strategy is used to achieve its desired angles and velocity in a much shorter duration, and can further accomplish reduction of residual vibration. Then, the asymptotic stability of the system is proved based on the Lyapunov method. Through numerical computation, the results show that the linear model cannot capture the motion-induced coupling terms and geometric nonlinearity variations. However, the nonlinear model is suitable for dealing with large deformation rigid–flexible problem undergoing large overall motions. Hence, the satellite antenna pointing accuracy would be predicted based on the nonlinear model. Furthermore, the results also show that the proposed control strategy can suppress system vibration quickly. The above conclusions would have important academic significance and engineering value.

1. Introduction

The dual-axis positioning mechanism of satellite antenna achieves real-time tracking and precise positioning on the target satellite to meet satellite-to-ground and satellite–satellite communication and data transmission in Fig. 1. The mechanism already has been widely used in communications satellites and data relay satellites. The pointing accuracy of the antenna at the free-floating satellite terminal is a key factor that dictates the efficiency of the satellite communication system. However, the satellite antenna system is free-floating in space, and its movement has strong non-linearity. Therefore, the system possesses nonlinear attribute that is responsible for performance degradation and presents special challenges to modeling and control. Thus, the analysis and control dynamic pointing accuracy of the satellite antenna are crucial and challenging tasks [1–3].

The flexible reflector is mounted on the antenna end-shaft. When it operates during on-orbit service undergoing a large overall motion, the system is easily affected by the elastic deformation of the flexible reflector, and the rigid–flexible coupling effect becomes more strong [4,5]. Furthermore, with

* Corresponding author.
E-mail address: youbindi@hitwh.edu.cn (B.D. You).

0094-5765/$ - see front matter
http://dx.doi.org/10.1016/j.actaastro.2013.12.006

the increase of the rotating speed of the antenna shafts, its dynamic behavior becomes more and more complicated. Thus, these factors induced antenna pointing errors not only increase the pointing loss in received signal but also increase interference toward nearby satellites [6].

A review of the previous studies in this area is limited to analysis and measurement of the static antenna pointing error, and structure analyses of antenna system have been of considerable research interest in recent years [7–10]. However, in the vast majority of the investigations in this field, no attempt has been made to study the effect of the coupling between satellite and reflector. And, the deformation of reflector was assumed to be small, and it was considered as a rigid body. Therefore, the performance of antenna pointing error cannot be determined accurately.

Beams and plates are common structural elements in many mechanical systems, such as spacecraft appendages and helicopter blades. Therefore, the dynamics of rotating beams and plates have been a subject of several investigations. A few investigations included the interaction of large overall motion accompanied by large elastic displacements and elastic deformations. The dynamic analysis of flexible structure often called as the conventional linear modeling method is widely used, and the dynamics of flexible beams undergoing large overall motions have been a topic of many recent publications. During the period, the linear modeling method employs a non-Cartesian deformation variable which is approximated to derive the equations of motion [11,12]. However, it often provides erroneous results when structures undergo overall motion such as rotation, and it has not been extended to plates. In order to solve the problem of the conventional linear modeling method, the geometrically nonlinear formulations are put forward [13–15]. Due to the large rotations, the nonlinear displacement–strain relationships are used for deriving the dynamic equations, and the geometric nonlinearities are included via the stiffness terms. Yoo and Chung [16] extended the investigation on dynamic problem from beams to plates. A set of linear equations of motion for rectangular plates undergoing prescribed overall motion is derived [17–19]. The flexible rectangular plates are discretized by means of finite element method (FEM) and the nodal displacement of rectangular plates is obtained in the body coordinate system. It was found that the modeling method failed to capture proper motion-induced stiffness variation effects. Therefore, all of the previous analyses are limited to isotropic beams and plates suffer from loss of additional motion-induced stiffness undergoing a large overall motion. However, the flexible reflector with characteristic of large and thin in thickness can be regarded as shell structure. Due to rapid operational motions of antenna pointing, large and rotational maneuvers induce the coupling among length stretch, lateral flexible deformation and torsional deformation. The coupling effect of bending, stretching and twisting in composite shell structure further complicate the dynamic behavior. Thus, in order to predict the dynamic behavior of the antenna pointing precisely, the coupling effect due to large and rotational maneuvers must be taken into account. In addition, the vibration of the appendage (flexible reflector) can cause degradation of the system performance such as the attitude or antenna pointing accuracy. Thus, in actual dynamic systems, large deformation of flexible appendages can have a significant impact on the dynamic response of the system. These effects can result in uncertainties in the geometric and physical parameters of the system. Accordingly, there are some significant literatures discussing the treatment of uncertainties of attitude control in a satellite with large flexible appendages by the methods provided by Gasbarri et al. [20,21]. The techniques verify that the design is robust enough to meet the system performance specification in case of uncertainties.

The objective of this paper is to capture the motion-induced dynamics stiffness variations by explicitly including the nonlinear displacement–strain relationships and coupling among length stretch, lateral flexible deformation and torsional deformation. Also, the coupling effect inducing the vibrations on the reflector degrades the performance of the antenna pointing. Thus, an effective control strategy for vibration suppression is proposed, and rigorous stability and performance analyses of the control strategy are also conducted.

The organization of this paper is as follows: the description of motion based on a 3-noded triangular element is presented for geometrically nonlinear analysis of laminated shell reflector in Section 2. Lagrange's equations are utilized to derive the dynamical formulations for satellite antenna system, which include complete nonlinear terms of elastic deformations and coupling terms in Section 3. Then in Section 4, an effective control scheme is proposed for vibration suppression of flexible reflector, and rigorous stability of the proposed controller is proved based on the Lyapunov method. Then, some numerical examples including linear and nonlinear analyses of laminated shell reflector are given in Section 5. Also, other numerical simulations are presented in this section to illustrate the effectiveness of the vibration suppression control strategy. Finally, Section 6 presents the conclusions of this study.

2. Description of displacement field for the flexible reflector

The mechanism of satellite antenna is shown in Fig. 1, where the reflector is mounted on the end-shaft. A flexible

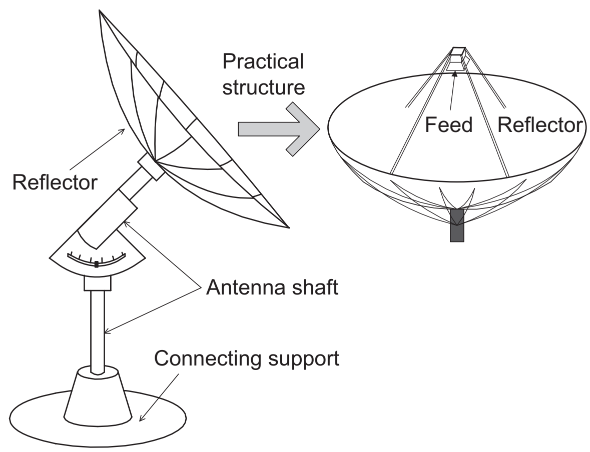

Fig. 1. The mechanism of satellite antenna.