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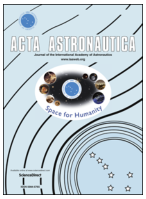

Feedback shape control for deployable mesh reflectors using gain scheduling method

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ABSTRACT

This paper presents a theoretical study on the dynamic shape control problem of deployable mesh reflectors (DMRs) via feedback approaches. The reflector structure is simplified from a nonlinear model to be quasi-static with respect to temperature variations but dynamic with respect to mechanical vibrations. The orbital cycle is segmented into multiple temperature zones, and an H_∞ robust state feedback controller is designed for each zone to guarantee the local stability of the system under the model uncertainty caused by thermal effects and to reject external force disturbances. At the same time, gain scheduling control method is adopted to compensate thermal distortions and to ensure smooth transition response when switching among the local robust controllers. A DMR model is considered in the case study to show the effectiveness of the control approach. The structural vibrations caused by external force disturbances can be sufficiently suppressed in a much shorter time. The closed loop response of the DMR structure shows that much higher surface accuracy is obtained during the orbiting mission compared to the open-loop configuration, and transient focal length and transient de-focus of the reflector are well controlled within the satisfactory bounds, demonstrating the numerical feasibility of the proposed method to solve the dynamic shape control problem of DMRs.

1. Introduction

With the demands to increase their geometric size and shape accuracy, the research on large-scale space structures has encountered new challenges. On one hand, the space structures are usually designed to be light-weighted and deployable to satisfy the requirements of various aerospace tasks; on the other hand, the induced high flexibility makes it hard to precisely maintain the desired structure shape during the mission. Structure shape deformation can largely compromise the effectiveness and performance of the function components; therefore, the shape control problem has gained more and more research attentions.

The technique term “shape control” was first introduced into academic journals by Haftka et al. [1] in 1985 in their analytical study of the static control problem for space reflectors using a force or a thermal actuator under the linear structure assumptions. They focused on the actuator placement problem for static shape control [2], and later discussed the influence of sensing and actuating uncertainties on the shape accuracy [3]. They also concluded that though the optimal locations of actuators could be selected, still a large

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number of actuators are necessary to significantly reduce the shape errors [4]. Balas theoretically studied the optimal control of reflectors on the quasi-static case with discussions on model reduction and controller convergence [5].

Upon research above which laid down the theoretical foundations, the shape control problem has been investigated extensively on various flexible structures for diverse applications. The shape control solutions of static beams were presented by Irschik et al. [6] and the finite element discussion on static composite plates can be found in Ref. [7,8]. For the dynamic shape control, Chandrashekhara and Varadarajan [9] proposed an adaptive algorithm for laminated composite beams and Varadarajan et al. [10] developed an optimal shape control solution on composite plate using piezoelectric actuators and position sensors. A robust controller validated on the flat plate is introduced in Ref. [11] by Kashiwase while Hu and Vukovich suggested a rigorous treatment on the robust stability of dynamic shape control regarding circular plates [12]. A general solution of static and dynamic shape control problems was presented by Ziegler [13] for discrete structures based on the flexibility matrix. Koconis et al. [14] formulated a shape control method for composite beams, plates and shells with piezoelectric actuators embedded. One may also find the literature survey in Ref. [15] regarding the development of shape control theory, especially on applications using piezoelectric actuators.

One of the most important applications of large-scale space structures is the space reflector which has the most stringent requirements on its surface accuracy. Although the space reflector application motivated the foundation of the shape control theory and many shape controllers have been proposed for different structures as listed above, the public research on the surface shape control of deployable mesh reflectors (DMRs) is still mostly limited to static shape control. For the truss-type reflector structures, both the open-loop [16,17] and the closed-loop [18] static shape control were introduced. Several other studies [19,20] investigated the linear static shape control problem specifically for the MUSES-B mission and testified their methods on the experimental models. The optimal distribution of actuators was also discussed for such type of the reflectors [21,22]. Regarding the recent DMR concept, i.e., the cable-truss or tension-truss design, Mitsugi et al. [23] presented a closed-loop shape control approach on linear static model with the experimental validation, and in addition Tanaka and Natori [24,25] proposed the force density approximation of nonlinear static deformation and numerically improved the shape performance of the reflector. Under linear geometry assumption, Tabata and Natori [26] suggested the static shape control algorithm regarding the radiation pattern of the truss-type reflector, and later the extended algorithm was proposed to correct the reflector shape based on the electromagnetic performance gain for the tension-truss reflector [27]. Assuming the small angular deformation during the shape control process, Wang et al. presented two active static shape adjustments by PZT actuators which were used to compensate static force disturbances [28] and static thermal distortions [29]; Du et al. [30] discussed the static shape control problem when the model uncertainty was considered. Shi [31] suggested the static shape control approach to resolve the geometric nonlinearity of the reflector structure, together with its solving algorithm using nonlinear programming techniques. Upon the early studies [32,33] of integrated structural electromagnetic shape control on the truss-type reflector, Zhang et al. [34] further developed the work in Ref. [30] and presented an integrated shape control technique for the cable-truss reflector, showing the improved electromagnetic performance of the reflector surface comparing to the shape control algorithm focusing on the structural accuracy. Beside the previous numerical studies [24–34], Xu et al. performed the static shape adjustment experiment on a double-ring DMR model via photogrammetry [35].

Comparing to static control, the dynamic shape control not only aims to compensate the shape deformation under static environmental and structural assumptions, but more importantly to overcome the surface deviation induced by dynamical environmental variables, such as temperature variations, as well as to suppress the mechanical vibrations caused by external impacts. This work focuses on the dynamic shape control problem of DMRs, which extends the authors' previous initial research [36] by a smooth transient switching control scheme.

A novel schematic for the space application of the cable-type DMR system is presented in Fig. 1, a similar configuration of which could be found in Ref. [37]. The mesh reflector can be simplified to be a 3D truss structure such that the structural elements can only sustain axial tension loads, and the structure is fixed along the boundary with vertical tension loads applied at the nodes. While orbiting Earth, the shape of the DMR surface is influenced by external disturbances, such as temperature variations and impact forces. Temperature variations result in the deformations of the truss elements and, thus, the corresponding dynamic and static behavior of the system. As a result, the nodal positions change along with the temperature even though the same amount of tension loads are applied on each node. It has been reported that the DMR shape error caused by such thermal induced deformations could reach up to 30% of the total shape error on orbits [38]. Additionally, impact forces, either caused by reaction wheels on the satellite, or from space environments, such as solar pressure, impacts of micrometeoroids and debris, aerodynamic drag and gravity gradient in LEO missions [37,39], also have significant impacts on the static and dynamic deformation of the reflector surface.

The two types of dynamical external disturbances mentioned above are addressed in different ways [36]. First, the temperature is taken into consideration within the theoretical dynamic model. Therefore, the model is temperature dependent and time-variant. However, the change of the temperature is respectively slow (usually with a period longer than one hour and changing at a rate less than 0.1 °C/s) compared to the mechanical dynamics (commonly above 0.1 Hz). Thus we can divide the temperature range into multiple zones and obtain a quasi-static model with respect to a predefined nominal temperatures for each zone. On the other hand, the impact forces are treated as external disturbances, which can cause structural vibrations and deviations.

To maintain structural shape accuracy of the mesh surface under the two kinds of disturbances, a nonlinear feedback