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An integrated control and structural design approach for mesh reflector deployable space antennas

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ABSTRACT

An integrated control and structural design approach for mesh reflector deployable space antennas is presented in this paper. The coupled relationship of the antenna structure, deployment trajectory, and control system is discussed, and then the integrated design model is proposed. A multi-objective function is set to simultaneously minimize the antenna mass, the impact on antenna, and the energy dissipation of control system. The cross section areas of links, Bezier control points, and controller gain parameters are selected as the design variables. With the eigenfrequency, rigidity, stability, rapidity and accuracy constraints, the optimal integrated design is achieved. The highly nonlinear characteristic of this problem is discussed and corresponding solving strategy and methodology are described. Experiments are carried out to verify the rationality and validity of the structural analysis models and the control algorithm. Numerical simulations demonstrate the feasibility of the proposed design method.

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1. Introduction

Extensive activities of aerospace science and technology in the field of communications, navigation, deep space exploration, and environmental monitoring intensify the demand for large-aperture, high-precision space antennas. However, in view of the finite carrier volume and ability of rockets, deployable antennas are widely investigated in recent years. Especially, the mesh reflector deployable antenna is the most primary antenna form on orbit, as shown in Fig. 1, with the advantages of simple configuration, facile folding, good rigidity and thermal stability [1,2].

Deployment, the general expression of antenna deploying movement from stowed state (for launching) to the deployed state (for working on orbit), is a complicated nonlinear dynamics process, which is the conversion from unsteady state to steady state, from mechanism to structure. Smooth and precise deployment is the basis for antenna application, meanwhile, it is a likely process in which malfunction may occur (Fig. 2).

With the trend of large-aperture and light-weight deployable antennas, flexibility becomes one of the most important factors that might influence the deployment. Therefore, the requirements for deployment are not only the deploying precision but also the stability, that is to say, the flexible vibration of deployment should be restrained rapidly to avoid the influence to the satellite attitude. From the 1950 s, there are several cases of spacecraft runaway due to the vibration of flexible appendages, as the Explorer-1(1958) and the Landsat-4(1982) in USA, and the ETS-8(2006) in Japan. The size and complexity of future deployable space structures would be much higher than cases mentioned above. Hence, there is significant theoretical and engineering value for researches to accurately predict the structural and dynamic properties of the deployment and implement reasonable deployment trajectory and control algorithm to achieve precise and stable deployment of deployable antennas.

The control objective of electromechanical systems is to calculate the time history of driven force(or torque) corresponding to desired motions. It is quite related to the physical and geometric parameters of structures whether the objective could be achieved. Therefore, the design of electromechanical systems generally contains two parts: mechanical structure design and control system design. The control system design could be further divided into trajectory and control algorithm design. Thus, the research work on this area includes three aspects: (1) optimization design of the physical and geometric parameters of structures, (2) optimal trajectory design and (3) control force(or torque) determination.

In traditional separated design approach, the structure is generally designed first, then the trajectory, and the control system at last. In this case, optimal sub-systems might be achieved, but the whole system could not be guaranteed to be optimal because of the coupling relationship among three sub-systems. Firstly, the structural design without considering control factors (trajectory and force) might bring about unreliable structures (rigidity and

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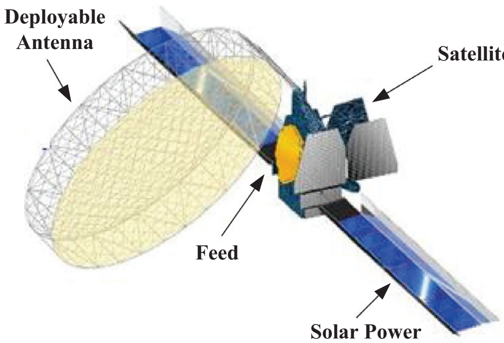

Fig. 1. Satellite-deployable antenna system.

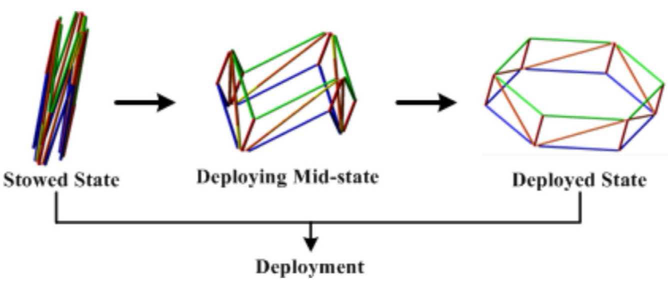

Fig. 2. Deployment of the deployable antenna.

strength). Secondly, the control design without considering structural characteristics might decrease the servo capability, even could not meet the basic index requirement. Thirdly, when designing the trajectory and control system, the more complicated the desired curve is, the more difficult the control design would be. If the interaction between two system is disregardful, the designed trajectory might not be tracked precisely and rapidly. Therefore, it is necessary to design the structure, trajectory, and control system concurrently, for improving the comprehensive performance of electromechanical system.

Researches on integrated control and structural design of electromechanical systems began in the 1980 s and mainly went through three stages of development: (1) structural design for control and optimal controller design [3–5], 2) two-stage iterative optimization of structure and control system [6] and (3) integrated design of control and structural parameters of mechanism [7–10]. Starting with the transfer function, Zhu propose an integrated optimal model for a flexible manipulator based on the pole assignment method [7]. Asada discussed the relationship between the zero-pole points and the structural parameters and presented an integrated design approach for a non-uniform beam [8]. Xiao established a synthetical optimization model of the flexible arms and solved the problem with an improved genetic algorithm method [9]. However, research objects of three references above are all flexible beams, which are a kind of mechanism with invariant structure. For complicated variant-structure mechanisms, the transfer function or analytical dynamics model are difficult to obtained, thus leading to application limitations. In reference [10], the AKP(Adjust Kinetic Parameter) method is proposed based on the complete balance theory, the objective of minimum dynamic tracking error and control energy dissipation was pursued via the optimization of cross sectional area of mechanical links, balanced counterweight, and the control parameters. However, it was mainly concentrated in the rigid multi-body system, which did not consider the influence of component flexibility to dynamic properties, meanwhile the eigenfrequency constraint of the mechanism and the stability constraint of control system. In view of the integrated control and structural design for deployable antennas, Duan gave systematically discussion of the concept of integrated design, the symbol representation, optimization model, and the solving strategy [11]. On this basis, for the radar servo system, Li achieved the objective of both the light-weight and the control accuracy, via adjusting the structural size and controller gains [12]. Besides the constraints of stress, overshoot, adjusting time, and steady error, the eigenfrequency and stability of controller are considered. However, the eigenfrequency factor does not actually effect the control design, since the controller in this optimization model did not adopt a model-based control algorithm, thus hardly associating the control design sub-system and the structure design sub-system.

Authors have proposed a decoupling control method for the controlled deployment of flexible deployable antennas [13]. A filter is used to decouple the motion feedback signals into two parts: the rigid movement and flexible vibration. Then, two corresponding controllers are designed separately. Based on the instantaneous structural modal analysis of the mechanism, the eigenfrequency affiliation between the mechanism and the structure is discussed, which provides a criterion for determining the decoupling frequency of the filter. Therefore, the evaluation of the eigenfrequency would make a great influence on the stability and precision of the controlled deployment. On the one hand, the weight and eigenfrequency of the mechanism would generally decrease with the reduction of cross sectional areas of links, thus, the decoupling frequency would also decrease. Via filtering, the rigid movement energy would be truncated meanwhile the vibration energy would increase, which makes the control design more complex. On the other hand, for good control properties, the eigenfrequency should be higher, which also meets general design concepts of mechanisms. However, it would lead to mass addition meanwhile. To sum up, depending on this model-based control algorithm, the control design sub-system and the structure design sub-system could be associated.

In this paper, an integrated control and structural design approach for mesh reflector deployable space antennas is presented, based on the model-based control algorithm. Firstly, in view of the multi-state of the deployable space antenna, static and dynamic structural performance is analyzed and the independent structural design is concluded to an optimization problem. The deployable mechanism is transformed into several instantaneous structures for modal analysis. Via investigating the variation law of the instantaneous structural eigenfrequency with the deployment, the selection criterion of key positions is decided, and the decoupling frequency of control system is determined simultaneously. Then, the independent trajectory design and controller design approaches are discussed respectively. Based on a 2-meter-aperture experimental model, the validity and accuracy of the mathematical analysis model and the control system are verified. Finally, the coupled relationship of the antenna structure, deployment trajectory, and control system is discussed, and then the integrated design model is proposed. The optimization objective is simultaneously minimize the antenna mass, the impact on antenna, and the energy dissipation for control system. The design variables consist of the cross section areas of links, Bezier control points, and controller gain parameters. The constraint functions are summarized, as the eigenfrequency and rigidity of the mechanical structure and the stability, rapidity, and accuracy of the control system. The highly nonlinear characteristic of this problem is discussed. Therefore, the problem is transformed into a separated quadratic programming problem (SQP) and Lemke method is used to solve it. Numerical simulations demonstrate the feasibility and validity of this design approach.

2. Multi-state structural analysis and design

The development of the structural design for deployable antennas went through three stages: the structural optimization based on natural characteristic analysis [14], the dynamic optimization of

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