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Modeling of a space flexible probe–cone docking system based on the Kane method

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Abstract Recent developments in micro- and nano-satellites have attracted the interest of the research community worldwide. Many colleges and corporations have launched their satellites in space. Meanwhile, the space flexible probe–cone docking system for micro- and nano-satellites has become an attractive topic. In this paper, a dynamic model of a space flexible probe–cone docking system, in which the flexible beam technology is applied, is built based on the Kane method. The curves of impact force versus time are obtained by the Lagrange model, the Kane model, and the experimental method. The Lagrange model was presented in the reference and verified by both finite element simulation and experiment. The results of the three methods show good agreements on the condition that the beam flexibility and the initial relative velocity change. It is worth mentioning that the introduction of vectorial mechanics and analytical mechanics in the Kane method leads to a large reduction of differential operations and makes the modeling process much easier than that of the Lagrange method. Moreover, the influences of the beam flexibility and the initial relative velocity are discussed. It is concluded that the initial relative velocity of space docking operation should be controlled to a certain value in order to protect the docking system.

1. Introduction

The application of a flexible beam into a space probe–cone docking system is a novel docking concept. Both theoretical and experimental research is still in the primary stage. A docking system with the effects of a flexible beam considered is a complicated rigid–flexible coupling multi-body system.

The classical Newton–Euler vector mechanics is the first theory introduced to solve multi-body problems. However, it is only for simple situations. Then, the Lagrange analytical method, which gives an easy way to model multi-body systems, is introduced. Based on the Lagrange method, Yoo and Shin[1] derived the motion equations of a rotating cantilever beam. Moreover, the modal characteristics of rotating cantilever beams with a concentrated mass located in an arbitrary position were investigated.[2] Niu et al.[3] developed a mathematical model of a beam using the Lagrange method in order to calculate the electromagnetic control force. A flexible docking dynamic model built by Zhang et al.[4] was also based on the Lagrange method. However, the modeling process of the

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Lagrange method includes a large number of integral differential operations. By taking advantage of vector mechanics and analytical mechanics, the Kane method is presented. Comparing with the Lagrange method, the introduction of vectorial mechanics and analytical mechanics in the Kane method leads to a large reduction of differential operations during the dynamical modeling process. From then on, the Kane method has been widely applied to solve multi-body problems. In 1998, Esmailzadeh and Jalili[5] presented a physically valid, non-linear dynamic model based on the Timoshenko beam theory for axial support motion using the Kane method. Pellicano and Vestroni[6] analyzed the dynamic behavior of a simply supported beam subjected to an axial transport of mass. Feng and Hu[7] established a set of nonlinear differential equations using the Kane method for the planar oscillation of a flexible beam undergoing a large linear motion. Yoo et al.[8,9] derived the equations of beam motion by employing a linear hybrid deformation modeling method along with the Kane method. Cai et al.[10,11] investigated the frequency characteristics of a flexible hub–beam system with an attached mass in an arbitrary position using a first-order approximation coupling (FOAC) model, in which three kinds of damping were considered. In 2008, Liu[12] finished his dissertation by investigating the modeling theory and simulation technique of rigid–flexible coupling systems dynamics. In 2011, Bai[13] investigated the rigid–flexible coupling dynamics and robust control of flexible multi-body spacecraft in his dissertation, which involved the characteristics of complicated dynamics, system uncertainties, input nonlinearity, external disturbances, and precision control requirements.

The modeling methods for the coupled effects of a flexible beam and a rigid multi-body docking system, the equivalent methods for the generalized coordinates of a flexible beam, are our major focus in this paper. The complexity and difficulty of these problems make us be selective in other aspects. Therefore, only the first impact-contact process is investigated in this paper. The purpose of this paper is to propose a modeling method by which the transient response of a flexible beam in a docking process can be obtained. The paper is organized as follows. Section 2 presents the detailed modeling process of flexible docking dynamics using the Kane method. In Section 3, the Hertz contact model is introduced to solve the docking impact problem. Section 4 gives the analysis of simulation and experiment results. Finally, conclusions are made in Section 5.

2. Docking dynamic model based on the Kane method

A simplified space probe–cone docking model is shown in Fig. 1.[4] In Fig. 1, $\boldsymbol{iOj}$ is the inertial coordinate system. O_1 is the mass center of chaser satellite and O_2 is the mass center of target satellite. $\boldsymbol{i}_1O_1\boldsymbol{j}_1$ is the body frame of chaser satellite and $\boldsymbol{\omega}_1$ is its angle velocity. $\boldsymbol{i}_2O_2\boldsymbol{j}_2$ is the body frame of target satellite and $\boldsymbol{\omega}_2$ is its angle velocity. In the model, the aims of the chaser and target satellite counterweights are to simulate their masses and principal inertia moments. The flexible docking probe is studied by using a linear elastic model. The docking system will be departed as two sides, which are respectively the docking probe side and the docking cone side. Through this way, the impact force during the docking process is easy to be considered in the dynamic model. Because the normal and tangential directions of the impact force are easily determined by the docking cone, analysis will be firstly developed from the docking cone.

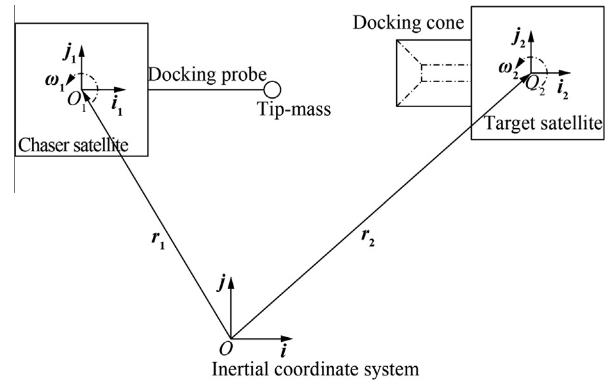

Fig. 1 Simplified space probe–cone docking model.

2.1. Dynamic equations of the docking cone

Firstly, the force analysis of the docking cone is shown in Fig. 2, in which the impact force has been decomposed as the normal contact force F_N and the tangential friction force F_τ.

In Fig. 2, b denotes the distance from impact point to the inner edge of docking cone, R_2 is the radius of the inner edge. What c represents can be known easily through observing Fig. 2. β is the included angle between cone generatrix and axial direction of the cone, θ_2 is the angle between axis direction of target satellite and horizontal direction.

From Figs. 1 and 2, the displacement vector of the mass center of the docking cone system in the inertial frame is known as follows:

$$\boldsymbol{r}_2 = u_2\boldsymbol{i} + v_2\boldsymbol{j} \tag{1}$$

where u_2 and v_2 are respectively its horizontal coordinate and vertical coordinate.

The corresponding velocity vector is given by

$$\dot{\boldsymbol{r}}_2 = \dot{u}_2\boldsymbol{i} + \dot{v}_2\boldsymbol{j} \tag{2}$$

The angular velocity vector is given by

$$\dot{\boldsymbol{\omega}}_2 = \dot{\theta}_2\boldsymbol{k} \tag{3}$$

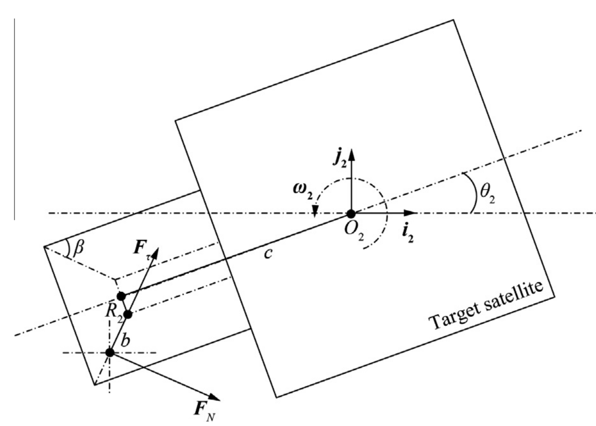

Fig. 2 Force analysis of the docking cone.