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Dynamics analysis of flexible space robot with joint friction

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ABSTRACT

It is well known that friction is an inevitable phenomenon existing in almost all mechanical systems including robotic systems. Friction can harm dynamic characteristics of mechanical systems as well as the accuracy of manual control. In this paper, we have comprehensively investigated the dynamic process of a flexible space robot with joint friction. Dynamic equation of the system is established based on the Jourdain's velocity variation principle and the single direction recursive construction method. The Coulomb friction model and LuGre friction model are adopted to describe the joint friction. The calculation method for joint friction is discussed in detail. Moreover, an active controller is designed by the computed torque control method for trajectory tracking control. Simulation results indicate that the proposed model is effective in describing the dynamics response of the system. Joint friction can cause oscillation of the joint response and vibration of the flexible link, as well as affecting the precision of position control of the system. From the results we present, it can also be inferred that the Coulomb friction model is limited in describing the nonlinear features of friction.

1. Introduction

Flexible space robot is one of the typical unrooted tree dynamic systems with strong nonlinear coupling and time-variant features. This kind of robot has been widely used in space missions due to the advantages such as large load-to-weight ratio and low energy consumption. However, the large load-to-weight ratio will lead to this space robot manipulator to large deformation and considerable amplitude of vibration [1–3]. Although researchers have conducted many investigations on modeling and control of flexible space robot, many of them do not consider the effect of joint friction that cannot be ignored in the space robot system. From the perspective of controller design, joint friction may be regarded as an external disturbance. One can neglect the nonlinear characteristics of joint friction by enhancing the robustness and adaptability, paying the penalty of decreasing control performance. However, the nonlinear characteristics of friction, such as hysteresis, stick–slip and limit cycle are becoming more standing out when it comes to cases where the space robot is moving in low speed, since the coupling characteristics between joint friction and manipulator deformation would be amplified. These nonlinear characteristics could cause complex dynamic behaviors and notable inaccuracy in control result. So the effect of joint friction on the space robot system should not be neglected.

Ambrose and Askew [4] experimentally studied the joint friction of space robot system. Their results showed that static friction of joint was found to increase by a factor of 5 over the Extra-Vehicular Activity temperature ranging from 223 K to 373 K, and the kinematic fiction, mapped in a speed–torque curve, was found to vary by 10 or more. The experiment results of ROKVISS, a German space robotics technology experiment, showed that the joint friction of space robot would increase notably in space in comparison with the value on ground [5,6]. Comparing with the ground measurement results, the total frictions increase by 50% and 20% in two different joints of a space robot, respectively. The results of these experiments indicate that joint friction could more negatively affect the dynamics of the system in the severe space environment than that on ground. So the necessity to investigate the effect of joint friction on space robot is obvious. Today some researchers have already carried out studies on this friction problem. For example, Katoh et al. [7] proposed a real time path planning method of a space robot in saving the energy consumed by the mechanical viscous friction forces and the armature's resistances of motors. But the frictional force adopted is only related with velocity, making the model exercise limited in practice. Breedveld et al. [8] used a new friction model, which is based on a hypothesis that friction tries to stop the system, to simulate the effects of friction on a flexible space manipulator. The friction model simulated the effects of the friction accurately in only little computing time and without numerical instability problems. It can also be used to simulate Stiction and fluid friction, as well as serving as a useful aid to model friction in a discrete simulation model of a position or

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velocity controlled mechanical system. Zavrazhina and Zavrazhina [9] established the dynamic equations of a space manipulator considering the flexibility and friction of hinge joint based on the Euler–Lagrange and Lagrange 2nd kind equations, and analyzed the influence of elastic and friction of hinge joints on the space manipulator. Martins et al. [10] proposed an adaptive neural network control design method for trajectory tracking control of space robot manipulators considering the influence of friction and payload. Xue et al. [11] derived the dynamic model of a space robot, as well as the low speed friction model, and applied two different distributed variable structure control methods for a space robot. The analysis has shown that a proper variable structure control law can not only have better robustness and adaptability, but also reduce the complexity of computation. Zhao and Bai [12] presented a computational methodology for analysis of space robot manipulator system considering the effects of the joint clearances and joint friction, which is modeled by the Coulomb friction model. Krzyzak et al. [13] derived the dynamics of two-link flexible space manipulator based on the Euler–Lagrange formulation, where the nonlinear stiffness and friction components of joints are considered. Liu et al. [14] derived the dynamics of a space robot with a 6-DOF manipulator considering joint friction, and studied the influence of joint friction on the system. From above we can see that the friction in a space robot has gained attention in the field of space robot and some research results have been published. However, there are still some problems worth further exploring. For example, in the above studies for joint friction, the dynamic equations of space robot are often established by the conventional Lagrangian formulation or Newton–Euler method, making the dimensions of the dynamic equations bigger than the degrees of freedom of the system, which increases the difficulty in solving the dynamic equations. Besides the friction model adopted cannot fully describe frictional behaviors, and the detailed calculation of joint friction was not given. The expression of revolute joint in the above studies is overly simplified, or alternatively, planar model of joint is adopted, both leading to the result that the calculated frictional force cannot reflect the true value in actual situation. Considering the flexibility of the space robot manipulator, the effect of joint friction on the space robot system becomes complex. So it is necessary to investigate the problem mentioned above in detail.

In this paper, dynamics modeling and active control of a flexible space robot considering joint friction are investigated. The influence of the joint friction on the flexible space manipulator is analyzed. This paper is organized as follows. Section 2 briefly presents the expressions of dynamic model of the system, including the kinematic and dynamic equations of single flexible body, the kinematical recursive relations of the system, the calculation of joint friction and the establishing of dynamic equations of the system. The controller design for trajectory tracking is given in Section 3. Section 4 provides simulation and comparison studies. Finally, a concluding remark is given in Section 5.

2. Dynamic model of the system

In this paper, a simplified flexible space robot shown in Fig. 1 is used to study the effect of joint friction on the system, which consists of a spacecraft base and a manipulator. The manipulator is composed of Link 1 and Link 2, where Link 1 is rigid and Link 2 is flexible. A payload is fixed on the tip of Link 2 and it is regarded as a lumped mass in this paper. In this section, the dynamic equations of this system are established by the Jourdain's velocity variation principle and the single direction recursive construction method [15].

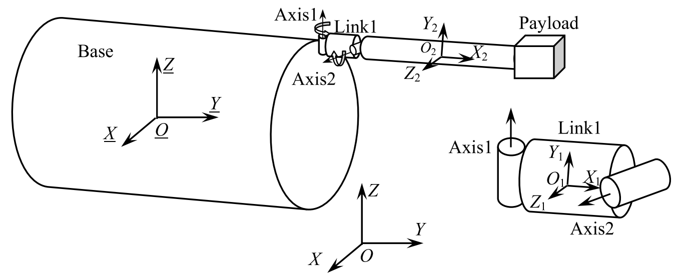

Fig. 1. Structural model of space robot.

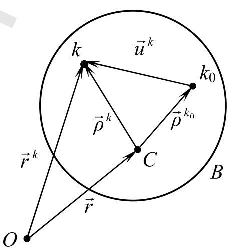

Fig. 2. Single flexible body.

2.1. Kinematic and dynamic equations of single flexible body

Fig. 2 shows a single flexible body B. The lumped mass finite element method is used to divide the body B into l elements. The mass matrix of the k-th node can be expressed as

$$\boldsymbol{M}^k = \begin{bmatrix} \boldsymbol{m}^k & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{J}^k \end{bmatrix} \in \Re^{6\times 6}, \quad k = 1, \dots, l_n \tag{1}$$

where $\boldsymbol{m}^k \in \Re^{3\times 3}$ and $\boldsymbol{J}^k \in \Re^{3\times 3}$ are the translational mass matrix and matrix of moment of inertia of the k-th node, respectively; l_n is the amount of nodes of the body B.

As shown in Fig. 2, the point C is the mass center of the body B before the deformation, and the floating frame $\vec{\boldsymbol{e}}$ is established on it. The relative position vector of the node k is $\vec{\rho}^{k_0}$ before the deformation and $\vec{\rho}^k$ after the deformation. The vectors $\vec{r}$ and $\vec{r}^k$ are the absolute position vectors of the mass center C and the node k, respectively. The vectors $\vec{u}^k$ and $\vec{\varphi}^k$ are the translational and rotational deformation vectors of the node k, respectively. They can be described by the modal coordinates, given by

$$\vec{u}^k = \vec{\boldsymbol{\Phi}}^k \boldsymbol{x} \tag{2}$$

$$\vec{\varphi}^k = \vec{\boldsymbol{\Psi}}^k \boldsymbol{x} \tag{3}$$

where $\vec{\boldsymbol{\Phi}}^k$ and $\vec{\boldsymbol{\Psi}}^k$ are the translational and rotational modal vector arrays of the node k, respectively; $\boldsymbol{x}$ is the modal coordinate vector of the body B. Choosing the s modes of the body B, we have $\vec{\boldsymbol{\Phi}}^k = [\vec{\varphi}_1^k, \dots, \vec{\varphi}_s^k]$, $\vec{\boldsymbol{\Psi}}^k = [\vec{\psi}_1^k, \dots, \vec{\psi}_s^k]$ and $\boldsymbol{x} = [x_1, \dots, x_s]^{\mathrm{T}}$. The coordinate matrices of $\vec{\boldsymbol{\Phi}}^k$ and $\vec{\boldsymbol{\Psi}}^k$ in the absolute reference frame are $\boldsymbol{\Phi}^k$ and $\boldsymbol{\Psi}^k$, respectively, which can be expressed as

$$\boldsymbol{\Phi}^k = \boldsymbol{A}\boldsymbol{\Phi}'^k, \qquad \boldsymbol{\Psi}^k = \boldsymbol{A}\boldsymbol{\Psi}'^k \tag{4}$$

where $\boldsymbol{A}$ is the direction cosine matrix relating the floating frame $\vec{\boldsymbol{e}}$ and the absolute reference frame; $\boldsymbol{\Phi}'^k$ and $\boldsymbol{\Psi}'^k$ are the coordinate matrices of $\vec{\boldsymbol{\Phi}}^k$ and $\vec{\boldsymbol{\Psi}}^k$ in the floating frame $\vec{\boldsymbol{e}}$, which are both constant matrices.

As shown in Fig. 2, the absolute position vector of the node k can be expressed as

$$\vec{r}^k = \vec{r} + \vec{\rho}^k = \vec{r} + \vec{\rho}^{k_0} + \vec{u}^k \tag{5}$$