Research on The Construction of Flexible Multi-body Dynamics Model based on Virtual Components

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Abstract. Focus on the harsh operation condition of space manipulator, which cannot afford relative large collision momentum, this paper proposes a new concept and technology, called soft-contact technology. In order to solve the problem of collision dynamics of flexible multi-body system caused by this technology, this paper also proposes the concepts of virtual components and virtual hinges, and constructs flexible dynamic model based on virtual components, and also studies on its solutions. On this basis, this paper uses NX to carry out model and comparison simulation for space manipulator in 3 different modes. The results show that using the model of multi-rigid body + flexible body hinge + controllable damping can make effective control on amplitude for the force and torque caused by target satellite collision.

1. Introduction

With the rapid development of space technology, space on-orbit maintenance and support have become the hottest topic among different countries, which aim to enhance control and support for space environment by implementing all kinds of space operations. The space capture technology is an basic aspect of on-orbit maintenance and support. Currently, the world's major space powers have already completed space contact technology on-orbit tests, such as NASA's "Orbital Express" [1] and Japan’s ETS-VII [2]. However, these tests basically adopt "hard-contact technology", that is, directly contacting with rigid components in orbit capture technology. This technology’s space target operating condition is very harsh. The main reason is that the main spacecraft’s space capturing device is generally composed of a single rigid arm or multi-rigid arm cascade, and the space target relative attitude requires keeping highly stability during operating. This requires that any abnormal disturbance should not happen when the main spacecraft and space targets are contacting with each other, otherwise a great impact collision momentum may be generated. This greatly limits the space contact technology to improve on-orbit operational capacity and the range of applications of space target.

To resolve the problem of on-orbit hard-contact technology, this paper proposes a new concept called soft-contact technology. Its core idea is to build up a soft-capture mechanism model and rigid-flexible compound control method, in order to achieve transformation from stepped collision momentum to harmonic attenuation momentum. And the key parameters, such as harmonic amplitude, phase and convergence time, can be controlled according to the desired function. This idea can make collision momentum controlled buffering and unloading come true. [3]

On-orbit soft-contact mechanism constructed by this idea is a complex multi-flexible body system consisted of multiple joints and multiple arms, which has multiple inputs and multiple outputs, and
they have coupling relations in between with strong non-linear characteristic in the meantime. This research on flexible multi-body system collision dynamics of on-orbit soft-contact mechanism aims to design the control strategy. The key to solve flexible multi-body system collision dynamics is to build accurate rigid-flexible compound dynamics model and correctly deal with collision process, and then find out effective and stable solutions. According to the different hypotheses of collision process, the multi-body system collision dynamics model methods can be classified into impulse momentum method, continuous contacting force method, contact constraint method, etc. [4] The above mention methods have their own advantages and limitations. Zhang etc. brought the idea of impulse potential energy, and obtained the collision dynamics equation out of flexible-hinge rigid-arm robot system, which can calculate the mutations of system general velocity after collision [5]. However, this method has certain constraints in the research on complex flexible multi-body system. Fang adopted contacting theory and non-linear damping theory to build contacting collision model, and exported flexible variables and rigid-flexible compound dynamics equation of collision. [6] The biggest problem of this method is how to select collision model and how to recognize the parameters in the selected model. Han adopted contacting constraint to process collision process, and proposed multi-variable method for the problem of flexible multi-body system collision. In the stage of collision, use floating reference system method to solve the problem in non-collision area, and use non-linear finite element method to solve the problem in the local area of collision. [7] Wang built attached contacting constraint according to the idea of objects that are not embedded in each other, unified dynamics equation of flexible multi-body dynamics before, during, and after collision, brought collision testing mechanism, and implemented the auto changes of topology model. [8] However, similar to the hinge constraint equation in multi-body system, contacting constraint equation and dynamics equation have constructed differential algebra equations, which lead to the difficulty in numeric.

This paper mainly introduces a solution of collision rigid-flexible compound dynamics under Cartesian Coordinate System. On the basis of using contacting constraint method, this paper constructs flexible dynamics model based on virtual components, by bringing the idea of virtual components and virtual hinges. The proposed method makes flexible components without the limitations of all motion conditions except flexible hinge, which reduces the effort to process attached flexible body algorithm. This paper carries out modeling and comparison simulation of three different modes by NX, including multi-rigid body, multi-rigid body + flexible hinge, and multi-rigid body + flexible hinge + controllable damping, according to the proposed idea.

2. Flexible dynamics model based on virtual components
The algorithm structure of flexible multi-body dynamics is shown as figure 1. The old hinge module and force module are only suitable to rigid body, which can be processed to a system consisted of rigid body and flexible body by adding a flexible hinge in the hinge base.

![Figure 1. Program structure of flexible multi-body dynamics.](image-url)
The virtual component connects with the original flexible body through the virtual hinge as shown in Figure 2.

**Figure 2.** The flexible hinge between flexible body and virtual components.

$s'_{0(i-1)i}$ and $u'_{0(i-1)i}$ are unreformed position vector and deformed vector of virtual component origin point relative to flexible reference system. Assuming $s'_{(i-1)i} = s'_{0(i-1)i} + u'_{0(i-1)i}$, the wave symbol represents oblique symmetric matrix, which can get the velocity recursive equation of flexible hinge as follows,

$$Y_i = B'_i ({i-1}) Y_{i-1} + B'_i ({i-1}) q'_{(i-1)i}$$  \hspace{1cm} (1)

In (1), The superscript $f$ of $q'_{(i-1)i}$ is the modal coordinate vector, and subscript $i$ and $i-1$ are the generalized coordinate in reference system.

$$B'_i ({i-1}) = \begin{bmatrix} A'_{(i-1)i} & -A'_{(i-1)i} s'_{(i-1)i} \\ 0 & A'_{(i-1)i} \end{bmatrix}, B'_i ({i-1})_{2} = \begin{bmatrix} A'_{(i-1)i} \Phi^R_{i-1} \\ A'_{(i-1)i} \Phi^\theta_{i-1} \end{bmatrix}$$ \hspace{1cm} (2)

$\Phi^R_{i-1}$ is modal matrix, which columns is consisted of translation modal vibration mode. Matrix $B'_i (i-1)$ and $B'_i (i-1)_{2}$ are only the modal coordinate function of flexible body $i-1$, $A'_{(i-1)i}$ is the attitude matrix of flexible body reference system. (1) defines the kinematics relation between an inner flexible body and an external flexible body, which relation can be deduced. Similarly, the virtual displacement recursive relation between a flexible body and a virtual component is as follows,

$$Y_i = B'_i ({i-1}) Y_{i-1} + B'_i ({i-1}) q'_{(i-1)i}$$ \hspace{1cm} (3)

In (3),

$$B'_i (i-1) = \begin{bmatrix} A'_{(i-1)i} & s'_{(i-1)i} A'_{(i-1)i} \\ 0 & A'_{(i-1)i} \end{bmatrix}, B'_i (i-1)_{2} = \begin{bmatrix} -s'_{(i-1)i} \Phi^\theta_{i-1} - \Phi^R_{i-1} \\ A'_{(i-1)i} \Phi^\theta_{i-1} \end{bmatrix}$$ \hspace{1cm} (4)

The recursive relation of rigid hinge velocity between two rigid bodies can be deduced by (5).

$$Y_i = B'_i (i) Y_{i-1} + B'_i (i) q'_{(i-1)i}$$ \hspace{1cm} (5)

In (5), the superscript $r$ is the generalized coordinate of rigid hinge.

$$B'_i (i) = \begin{bmatrix} A'_{(i-1)i} & -A'_{(i-1)i} s'_{(i-1)i} + \hat{d}''_{(i-1)i} - A'_{(i-1)i} s''_{(i-1)i} A'_{(i-1)i} \\ 0 & A'_{(i-1)i} \end{bmatrix}$$ \hspace{1cm} (6)

$$B'_i (i)_{2} = \begin{bmatrix} A'_{(i-1)i} + \left( \hat{d}''_{(i-1)i} A'_{(i-1)i} \right) + A'_{(i-1)i} s''_{(i-1)i} A'_{(i-1)i} H'_{(i-1)i} \\ A'_{(i-1)i} H'_{(i-1)i} \end{bmatrix}$$

In (6), $H'_{(i-1)i}$ is fixed by rotation axis. Matrix $B$ is the function of $q'_{(i-1)i}$.

Constraint mechanical system dynamics equation can be obtained by velocity transfer method.

$$F = B'( MT + \Phi T / \left( Z^\lambda - \tilde{Q} \right) )$$ \hspace{1cm} (7)
In (7), $\Phi$ and $\lambda$ represent the Lagrange multipliers of cut hinge, $M$ is the mass matrix, and $\bar{Q}$ is force vector, which includes external force, force generated by strain energy and the force caused by velocity. Differential algebra equation (DAE) is consisted of motion equation, constraint equation, $\dot{q}=v$ and $\ddot{q}=a$. For the DAE, the following non-linear equation system can be obtained by “cutting space method”.

$$H(p_a) = [U_0^T(q_a + \beta_0v_a + \beta_1) U_0^T(q_a + \beta_0a_a + \beta_2) F(q_a, v_a, a_a, \lambda_a, t_a)]^T$$

$$\Phi(q_a, t_a) \Phi(q_a, v_a, a_a) \Phi(q_a, v_a, z_a, t_a)]^T$$

In (8), $p_a^T = [q_a^T, v_a^T, a_a^T, \lambda_a^T]$, $\beta_0$, $\beta_1$ and $\beta_2$ are decided by the coefficients of Fractional Backward Differential Method (BDF) method. $U_0$ is selected to make sure the augmented matrix $[U_0^T \Phi_q]^T$ is a nonsingular matrix. The given non-linear system can be solved by Newton method.

3. Simulation computation and verification

The dynamic model based on virtual components contains two parts which are multi-rigid body dynamics modeling and rigid-flexible compound body dynamics modeling. Multi-rigid body dynamics modeling considers all components as rigid units. While rigid-flexible compound body dynamics modeling analyzes flexible multi-body dynamics of virtual components and hinges. The dynamics modeling framework is shown as figure 3. The modeling scheme is shown as Table 1.

![Figure 3. Rigid-flexible compound dynamics modeling framework of virtual components.](image)

**Table 1.** Modeling scheme.

| Model | Explanation |
|-------|-------------|
| Model 1: Multi-rigid body | All rigid connections between base and joints, and among joints |
| Model 2: Multi-rigid body + flexible hinge | Based on model 1, add flexible joints |
| Model 3: Multi-rigid body + flexible hinge + controllable damping | Based on model 2, add controllable damping |

We build up a three joints model of on-orbit soft-contact mechanism in NX software, shown as figure 4.

![Figure 4. Three joints model.](image)

Assuming the typical collision between space targets and on-orbit soft-contact mechanism has 3 situations as follows,

Collision 1: space targets collide with manipulator with the linear velocity of 1250mm/s along the direction of Z axis.

Collision 2: space targets collide with manipulator with the linear velocity of 1250mm/s and angular velocity of 90deg/s along the direction of Z axis.

Collision 3: space targets collide with manipulator with the linear velocity of 1250mm/s and angular velocity of 90deg/s along the direction of oblique 45 degree.
We carry out simulation analysis on model 1, 2, 3 in table 1 in terms of the above collision situations. We mainly compare the disturbance of rigid-flexible dynamics characteristics of soft-contact mechanism on satellite base, under the same collision conditions.

1) The disturbance dynamics simulation analysis caused by satellite base under the condition of collision 1 (the target satellites collide with the linear velocity along the direction of Z axis) are shown as figure 5.

(a) Changes of satellite base disturbance force.  (b) Changes of satellite base disturbance torque.

Figure 5. The changing curve of disturbance force and disturbance torque for satellite base.

2) The disturbance dynamics simulation analysis caused by satellite base under the condition of collision 2 (the target satellites collide with the linear velocity + angular velocity along the direction of Z axis) are shown as figure 6.

(a) Changes of disturbance force for base.  (b) Changes of disturbance torque for base.

Figure 6. The changes of disturbance force and disturbance torque for base.

3) The disturbance dynamics simulation analysis caused by satellite base under the condition of collision 3 (the target satellites collide with the linear velocity + angular velocity along the direction of oblique 45 degree) are shown as figure 7.

(a) Disturbance force changing curve of base.  (b) Disturbance torque changing curve of base.

Figure 7. The changes curve of disturbance force and disturbance torque of base.

From figure 5 to 7, in the aspect of disturbance force and torque acted on satellite base, the dynamics simulation results of 3 models are as follows. On the starting moment, compared with model 2, 3, model 1 has several continuous pulsed large amplitude disturbance force, followed by model 3,
and the force of model 2 is the smallest. In the following stage of disturbance force, model 3 first implements stable convergence on disturbance force, and the amplitude is the smallest, followed by model 1, while model 2 appears small amplitude of shock state. For the disturbance torque of satellite base, model 1, 2, 3 appear different pulsed peaks, where the peak value of model 2 is the largest, followed by model 1, and the peak value of model 3 is the smallest. In the following stage of disturbance torque, the amplitude of model 1 is quickly stabilized, model 3 appears micro shock, and model 2 appears several big continuous peaks of amplitude. Thus, under the condition of collision 1, model 2 has smallest disturbance force peak on satellite base, followed by model 3, and the model 1 is the largest. And model 3 has the smallest disturbance torque peak on satellite base, followed by model 1, and model 2 is the biggest.

4. Conclusion
This paper involves the idea of virtual components, which use the idea of contacting constraints to build a flexible dynamics model, and takes research on its solution. On this basis, this paper uses NX software to implement flexible dynamics model based on virtual components, and carries out comparison simulation analysis on 3 different model of multi-body, multi-body + flexible hinge, multi-body + flexible hinge + controllable damping. The analysis results show that using the mode of multi-body + flexible hinge + controllable damping can make effective amplitude control on the force and torque caused by target satellites.

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