Research on Equivalent Tests of Dynamics of On-orbit Soft Contact Technology Based on On-Orbit Experiment Data

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Abstract. Currently, space robots have been become a very important means of space on-orbit maintenance and support. Many countries are taking deep research and experiment on this. Because space operation attitude is very complicated, it is difficult to model them in research lab. This paper builds up a complete equivalent experiment framework according to the requirement of proposed space soft-contact technology. Also, this paper carries out flexible multi-body dynamics parameters verification for on-orbit soft-contact mechanism, which combines on-orbit experiment data, the built soft-contact mechanism equivalent model and flexible multi-body dynamics equivalent model that is based on KANE equation. The experiment results approve the correctness of the built on-orbit soft-contact flexible multi-body dynamics.

1. Introduction
With the rapid development of space technology, the on-orbit maintenance and support have become new strategic commanding heights during international competition, which aim to enhance control and support for space environment by implementing all kinds of space operations. The space contact technology is the basic aspect of on-orbit maintenance and support [1,2]. Currently, the major space contact technology includes manipulator, space fly claw, and space docking. And space advanced countries have already started to discover those technologies. The USA [3], Japan [4] and China [5] have already completed on-orbit experiment on space manipulator. However, those experiments were all based on space hard contact technology, i.e. to directly contact objects by rigid components. Because the spacecraft base and space objects should not generate any abnormal attitude disturbance during on-orbit capturing. This greatly limits the improvement of on-orbit operation ability for space contact technique and limits the application range of space objects. In order to solve the problem of hard-contact technology, this paper proposes a new technology called soft-contact technology. The core idea is to construct a flexible space manipulator model and rigid-flexible compound control method which can make the collision momentum controllable buffering and unloading, and can transfer collision momentum to harmonic collision momentum. [6]

As the idea of space soft-contact technology remains at the stage of theory verification, it still requires verifying the feasibility of collision momentum controllable buffering and unloading implemented by this structure. Currently, most of the similar space robots experiment verifications were implemented by simulation. For example, Zhang developed a set of on-orbit service simulation system for space intelligent operation equipment, which adopted HLA/RTI simulation framework, to
implement abilities like space situation monitoring, mission planning, manoeuvring planning, observation and control resources computation, orbital manoeuvre simulation, on-orbit operation simulation, control instruction generation and dispatch. [7] But its simulation accuracy depends on the accuracy of modelling, which still has a certain gap between the real cases. Air bearing allows us to take experiment on space arm under the condition of simulating 0-G floating in 2D space. In Japan, ETS-VII satellite tested its control algorithm by air bearing table. [8, 9] While another technique to reduce weight is to use pool to implement neutral buoyancy. It can carry out experiment in 6-DOF space, without time limitation. MIT has carried out many tests for long distance operation robots with NBL of NASA. Besides, gravity can be compensated by suspended system or balance mechanism that is used for space manipulator to reduce gravity test [10]. Bai [11] took research on gravity compensation system. Their experiment applied light cable to go through several chain wheels, and ended with the same counterweight with the same valid weight of simulation robot. The above-mentioned method can simulate on-orbit work status of space manipulators in a certain degree, but the simulation results still have a certain error due to the limitation of objective conditions. This paper makes use of current typical space multi-rigid body manipulator system and its space experiment data to develop the multi-body dynamics on-orbit verification for on-orbit soft-contact mechanism, and provides practice data support for the verification of rigid-flexible compound multi-body dynamics model.

The key point of this paper is how to verify the validity of the proposed space flexible robot dynamics model by current space robot on-orbit testing data. Firstly, we set the dynamics parameters for space flexible robot according to the limitations of current space system. In the meantime, we construct dynamics model based on those parameters. Second, this paper designs an equivalent experiment of flexible multi-body dynamics model according to on-orbit testing data, which compares the experiment data with the results given by KANE dynamics equation of flexible space robot, and corrects flexible characteristic parameters by particle swarm algorithm. Finally, this paper carries out test on the validity of the proposed dynamics model by on-orbit testing data.

The rest of paper is organized as follows, section 2 describes experiment demand analysis and on-orbit equivalent experiment framework. Section 3 explains the construction of on-orbit equivalent experiment model. Section 4 verifies flexible multi-body dynamics parameter and shows simulation results. Section 5 gives a brief conclusion on the paper.

2. Experiment Demand Analysis and Equivalent Experiment Framework

On-orbit soft-contact mechanism should have three basic abilities; the first is the ability of having workspace to get the six surfaces of target to carry out maintenance operations. Second is to have a certain degree of flexibility, which can make sure flexible mechanism to operate target satellites in various configurations, in order to meet the requirement of some on-orbit contact task for flexible special configuration. At last, the path plan process of on-orbit soft-contact mechanism should have lower control complexity, to make sure the stability of the control process.

The biggest difference between on-orbit soft-contact mechanism and current space multi-rigid manipulator is the buffering controlling ability of touching collision momentum. The key to implement this ability is whether the flexible multi-body dynamics model can be built in space environment or not, especially, whether it can accurate construct space object collision dynamics model or not. Thus, it has to discuss about the equivalent experiment, dynamics characteristic parameter and model test and verification of on-orbit dynamics for on-orbit soft-contact mechanism.

On-orbit equivalent experiment and verification of soft-contact mechanism dynamics mainly contain three stages. First, to limit the design of flexible multi-body model in terms of current space multi-body system. Second, to develop the research on equivalent experiment of on-orbit soft-contact mechanism flexible multi-body system. Third, to carry out research on parameter verification of the built flexible multi-body dynamics equations.

The general experiment flow and method are show as figure 1.

3. Construction of On-orbit Equivalent Experiment Model
The basic structure of current on-orbit space multi-rigid manipulator system is consisted of 3 same unified double joints and carbon fibre arms, which has 6 degrees of freedom, and the system basic structure. This paper constructs equivalent model of flexible angular momentum and linear momentum controllable joints of on-orbit soft-contact mechanism by the equivalent design of arms and joints, in terms of the flexible multi-body dynamics characteristics when current space manipulator system’s joint harmonic drive mechanism is under the condition of deadlock, at the moment of capturing space objects.

Based on current space multi-rigid manipulator system, on-orbit soft-contact mechanism does not only have rigidity parameters, but also has flexible joint parameters. Take the space multi-rigid manipulator shown as figure 2 as an example, the flexibility of its joint harmonic drive mechanism under the condition of deadlock can be equivalent to on-orbit soft-contact flexible and controllable joints which have a certain torsional rigidity. Thus, equivalent on-orbit soft-contact mechanism can be treated as a space manipulator system which has 6 DOF flexible joints.

![Figure 2. On-orbit equivalent experiment framework.](image)

The constraints design of soft multi-body model based on existing system

The dynamic model of soft multi-body system

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According to the above equivalent model design, the flexible angular momentum/linear momentum joints can be simplified to torsional spring/spring and damping system, and arms are simplified into rigid-bodies, when doing dynamics modelling on on-orbit soft-contact mechanism. Thus, on-orbit soft-contact mechanism dynamics model can be dispersed to multi-rigid body model that is connected with torsional spring/spring and damping system. The satellite base has six DOFs, which can be considered as a virtual arm which has 6 DOFs. On the basis of the above discussion, according to the construction method of KANE dynamics equation, the floating manipulators which have N joints and 6N DOFs can be considered as a fixed base manipulator system which has (6N+6) DOFs, and also the general dynamics equivalent equation can be constructed as following,

\[
\{\dot{y}_n\} = \left[a_{ny}\right]^T \{f_t\}
\]

Where \(\dot{y}_n\) is the derivative of generalized speed;
\{ f_i \} = \{ F_i \} - \sum_{k=1}^{N+1} \sum_{j=1}^{N+1} \mathbf{y}_k \cdot m_k \cdot V_k \cdot \mathbf{y}_j - \omega_{k\eta} \cdot \left[ \mathbf{A}_{k\eta} \cdot \left( I_k \cdot \omega_k \right) \right] - \sum_{k=1}^{N+1} \omega_{k\eta} \cdot I_{k\eta} \cdot \mathbf{v}_{k\eta} \cdot \mathbf{y}_j \\ \{ a_{i\eta} \} = \sum_{k=1}^{N+1} m_k \cdot V_k \cdot \mathbf{y}_j + \sum_{k=1}^{N+1} \omega_{k\eta} \cdot I_{k\eta} \cdot \omega_{k\eta}

Equation (1) is non-linear simultaneous differential equations, \( K_k \) is the corresponding spring rigidity coefficient, i.e. the flexible joint rigidity parameter which is required to be verified in the equivalent model of on-orbit soft-contact mechanism. The above equations contain 6N+6 generalized coordinates and 6N+6 generalized speed, i.e. 12N+12 unknown variables in total [12].

4. On-orbit Verification of Flexible Multi-body Dynamics Parameter

The docking process of current space manipulator end execution device to space objects is as follows:

(1) By controlling the relative speed of two docking satellites, to make space manipulator end docking mechanism to form a docking envelope area for object satellites.

(2) To gradually close the end docking mechanism, to make the collision momentum between the two docking satellites reach rigid connection, and do not cause too much collision momentum to satellite base which carries manipulator. During the process of capturing object satellite, two docking satellite bases stay in floating state.

After analysis the collision dynamics response data of space arm system for the two satellites in the docking process, we can obtain important dynamics response characteristics from the docking process of manipulator system, which can provide on-orbit experiment data support for developing multi-body dynamics characteristic test verification of on-orbit soft-contact mechanism.

We use the current space manipulator system on-orbit data to develop flexible multi-body dynamics experiment, parameter verification and test verification based on KANE equation. More details about the flow chart is shown as figure 3.

**Figure 3.** Flow of flexible multi-body dynamics parameter verification of soft-contact mechanism.

Step 1: Acquire of equivalent parameters of on-orbit soft-contact mechanism flexible joints.

Making the twisting stiffness of the harmonic reducer of current space manipulator system as the basic parameter of flexible multi-body dynamics in KANE equation of flexible multi-body system.

Step 2: Analyse and select dynamics response data of space experiment of on-orbit space manipulator system.
On-orbit experiment data is divided into two parts. One part is used for flexible dynamics parameter verification, and the other part is used to test the results of model verification.

Step 3: The equivalent experiment process design of on-orbit soft-contact mechanism flexible multi-body dynamics.

Step 4: Comparing the experiment data of current space manipulator system with the results of KANE dynamics equation. And using their differences to correct the flexible characteristic parameter of KANE dynamics equation.

Step 5: Using the other experiment data of on-orbit contacts experiment test the correctness and effectiveness of the verified soft multi-body dynamics model.

The location of collision point, and joint angular changes between no collision and the moment of collision can be obtained by on-orbit data during the docking process between two satellites. The collision force of space manipulator end can be obtained by Jacobi equation. The angle of each joint response of space manipulator can be obtained by corresponding collision point on-orbit data, and Euler angle can be got by coordinate transformation equation. Then, bring the end collision force of above mentioned collision points and corresponding joint response Euler angles to equation (1) for solution. Finally, comprehensively make use of particle swarm algorithm and damper positive-inverse model, to implement the momentum control of on-orbit soft-contact mechanism, more detailed flow is show as follows,

1) When the end of on-orbit soft-contact mechanism is collided, the displacement $x(t)$ of damper at $t$ moment can be tested by motion sensor.

2) Joint damper displacement $x(t)$ at $t$ moment, particle swarm algorithm, and KANE dynamics model can be used to get optimized damping force at $t$ moment by iteration.

3) We use damper positive-inverse model to output the expected optimized damping force $u(t)$ to act on flexible controller of multi-arm joints. And then to obtain damper displacement $x(t+1)$ of each joint at $t+1$ moment tested by sensor. We reuse step 2 to compute the optimized damping force at $t+1$ moment, and get the torsional rigidity, and we repeat the same procedure again and again.

We use the above verified torsional rigidity of harmonic reducer as the equivalent flexible parameter for on-orbit soft-contact mechanism dynamics equations, and bring other collision sample data obtained by space manipulator on-orbit experiment to the equivalent KANE equation of on-orbit soft-contact mechanism, and obtain the angle of each joint in the collision process, to compare with the response data of each corresponding on-orbit joint, so as to verify the correctness of the built flexible multi-body dynamics of on-orbit soft-contact mechanism. After the flexible joint parameter verification of on-orbit soft-contact mechanism dynamics and the test of current on-orbit space manipulator system, the results are as figure 4-7. The dash lines represent the joint response original data at the collision moment in on-orbit experiment, and the solid lines represent the response data of flexible multi-body equivalent model joint at the collision moment of on-orbit soft-contact mechanism. The tendency of two lines are almost the same. The equivalent experiment comparison results show that compared with current on-orbit experiment data, the accuracy error of on-orbit soft-contact mechanism flexible multi-body dynamics model has been controlled to within 35% after being verified.

![Figure 4. Rotation degree of joint 1 at collision moment.](image1)

![Figure 5. Rotation degree of joint 2 at collision moment.](image2)
5. Conclusion
This paper firstly develops equivalent experiment requirement analysis and equivalent experiment basic framework and its contents based on current space manipulator system. Secondly, this paper implements space flexible multi-body dynamics modelling based on current space manipulator system, which mainly focuses on the building up of space flexible multi-body dynamics equivalent model based on KANE equation. Finally, according to the above research, this paper develops equivalent parameter verification using on-orbit data, and the results show that the correctness of the built up on-orbit soft-contact mechanism flexible multi-body dynamics.

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