# Design and Dynamic Simulation Analysis of Flexible Swap Device Based on Pro/E and ADAMS

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*Abstract:* - With the development of space science and technology, on-orbit module replacement technology has been more and more attention. Accordance with the requirements of on-orbit spacecraft module replacement, this paper designs the flexible swap device, and analyses the working principle of the insert-pull process. Using Pro/E, the parametric geometry model is established, whose dynamics simulation analysis is realized by ADAMS. First of all, the principle and validation of motion process is analyzed. Then, the impact on the overall devices is discussed when the collision model is under the different working conditions. In order to meet the requirements of damping force and reduce the vibration of the collision, the buffer parameters are adjusted. In the whole simulation process, the important parameters are measured, and the relation between collision force and the entire system are studied. Finally, the paper provides the reasonable design parameters according to the above analysis.

*Key-Words:* - flexible swap device, parameterized geometry model, dynamic simulation analysis

## 1 Introduction

On-orbit service technology is for on-orbit spacecraft, which can enhance the satellite performance, prolong the service life of satellites and reduce the risk of use and maintenance, so as to get more and more attention. Flexible swap device is an important part of on-orbit module replacement in the spacecraft. Its interior carries replaceable module and control unit, which are mainly for on-orbit servicing, firmware upgrades of spacecraft, and fast changing tasks [1]. In the replaceable module flexible swap device, module is in the integration way to complete the insert-pull function of devices, and is controlled mainly by mechanical arm.

The inspection analyses of equipment are completed by virtual prototype. The first step is to form device geometry model which is correspond to the design requirements and product structure. The second step is to analyze the above model, such as the analysis of dynamics and kinematics characteristics. This can effectively improve the design efficiency, shorten the period of development of test institutions, and achieve cost minimization and quality of design optimization. Along with the development of computer technology and virtual prototype technology, the dynamics analysis software such as ADAMS, DADS ANASYS and 3D solid modeling software for example Pro/E, UG, CATIA have been hitherto unknown attention in the field of mechanical design. ADAMS is one of wide range of mechanical system dynamics analysis software in the world, which is widely used in the fields of aerospace, automobile engineering, railway vehicles, equipment, industrial machinery, and industrial machinery etc. ADAMS can realize statics, kinematics, linear and nonlinear dynamic analysis for virtual prototype, and use interactive graphical environment and libraries to establish 3D parametric model of the mechanical system [2-4]. Pro/E is integrated with 3D software including CAD/CAM/CAE function, and the design of the part size is described by parameters in the modeling process, in order to change the shape of a part by means of numerical parameters. Its advantages are using the powerful mathematics operational way, setting up the relation among the size parameters, reducing the size of each modification of the complex and time consuming, and decreasing the occurrence of errors. The combination between ADAMS and Pro/E can maintain the consistency of the data through computer graphics interchange format file, effectively shorten the design cycle, and improve the design efficiency [5-6].

The traditional inserting mechanism is mainly used in the avionics and CNC machine tools. According to the docking and separation can be divided into spring, gear rack, chain link, connecting rod, piston pin, and connecting wedge locking type [7]. The spring connecting forms is completed "insert and pull out" by tension spring, a guide pin, a compression spring. Its application is relatively wide, but the operation is relatively complex, and is require a longer operating time [8]. Gear rack type is mainly composed by vertical transverse rack, rack and pinion. The vertical rack can be passed to the unlocking force structure [9]. Chain type mainly through the chain to transmit force, the structure is relatively complex, and need special locking mechanism to cooperate to use, reliability is not high. Connecting rod type plug body size is relatively large, and there may be coupled phenomenon, leading to even broken connecting rod bending deformation. Piston pin type is mainly composed of a piston pin and spring. It has relatively simple structure, but need the production of high precision machining. The wedge plate is mainly through the wedge plate under the action of external force to move completed [10], but there are some limitations in the locking mechanism.

This paper presents a drawer type mechanism according to the design requirements of flexible swap devices. Flexible swap device combines spring form, piston pin and wedge type mechanism. On the whole, the device can effectively complete the unlocking process, and the plug process also has a certain degree of security and stability. According to the deformation constraint equations and the conditions of small deformation assumption, and the modeling method based on Lagrange dynamics equation， the system crash consistent linear dynamics equation is established. Through the nonlinear spring damping model to build a meet the contact boundary condition method of collision contact model. The use of the inner shell and the shell method of geometric displacement relationship, we can establish variable topology multi-body system models, and discuses the impact of the collision damping system processes. Analysis of the design and Simulation of flexible plug can effectively understand the movement performance and dynamic characteristics of the structure. First of all, Pro/E is used to establish the 3D geometric model of mechanism, design dimension and position of each main part structural. Then ADAMS is applied to analyze the movement and collision process, determine the collision influence on mechanism performance, and change model through the parameters.

# 2 Flexible Swap Device Modeling

## 2.1 Device design requirements and working principle

Flexible swap devices are mainly used in spacecraft in orbit maintenance, and its hosted replaceable modules can be quickly and effectively completed module replacement and upgrades. Therefore, device design should satisfy with certain design requirements [11]. These specific requirements are as follows:

1) The structure is simple, effective, and has long mechanical life, to prevent incorrect insertion, establish independent locking and rapid unlocking, and be clamped by robot arm etc…
2) The function should have a bearing replacement module, the quick swap device (plug and play), power efficient data transmission, mechanical interface of the precise docking, and temperature control.

According to the structure characteristics and functional requirements, we can establish a drawer type of swap devices. The mechanism is mounted to the outside of the main structure of the spacecraft and is star-shaped distribution, this design advantage is that one can effectively transfer heat and facilitate insertion and removing of the flexible swap device.

Working principle of flexible swap device: Servicing spacecraft or spacecraft carrying its own mechanical arm grasps the clamping mechanism linkage with the remote control. The linkage mechanism transfers the forces to the locking device to complete unlock. After unlock, the mechanical arm drives module free drawing and inserting.

**2.2 Establishment of geometric model**

The flexible swap device geometry is established by Pro/E. In order to study the mating kinematic state better, the parametric modeling agencies, which are defined the size and location, are formed. The agency of flexible device is shown in Figure 1. As can be seen in the picture, the inner shell body is mainly consist of the locking mechanism, the locking pin, a buffer mechanism, linkage mechanism, and manipulator clamping position etc.. The swap device to keep on the spacecraft will be designed with locking device, and installed in the front end module, so it can be easily unlocked and direct feedbacked to unlock state. The unlocking process is complete by mechanical arm control, so the device should ensure not only simple but also efficient and effective. The locking device is mainly composed of lock rod, compression spring and locking sleeve. The action of the compression spring is that the lock rod is pushed down to complete the lock when the external force is removed. The locking mechanism designs a reserved rail unit, which can effectively prevent from abnormal locking. When the module casing pushes inwards, locking pin is designed to play a guiding role, and prevent excessive coupling mechanism. In contact surface of the module, two locking pins are designed and the effect is to guarantee the uniformity of the stress. The role of the buffer can reduce collision loss during the insertion and absorb chief energy from the mechanical arm. Due to assurance of the overall agencies has simple performance, the buffer adopts spring buffer. The spring buffer is mainly composed of the compression spring, the buffer base and cushions the contact lever etc...The buffer can absorb vibration and movement plug impact energy, and has stable performance. The spring buffers is mounted in the forefront of module housing, and can be directly in contact when a collision. It also has two identical spring buffers which are arranged symmetrically. The force of equilibrium mechanism is balanced by four spatial layouts. The linkage mechanism is designed for mechanical arm force applied to the locking mechanism. Linkage is mainly consisted of oriented bolts, positioning guide pin, compression spring, the linkage rod. The movement is mechanical arm force will moves upward along direction of the guide pin, and drive the lock pin to complete the unlock process. Manipulator clamping position mainly is to the mechanical arm reservation interface at clamping, so you can easily clamp to reduce unstable factors. In order to reduce the effect of friction on the device, housing in the module and the shell are designed with oblique contact point rail. The inner shell is provided with a power supply module and a computer module can be replaced, it does not play a decisive role in the simulation and design of experiments, so the geometric model can be ignored in design.

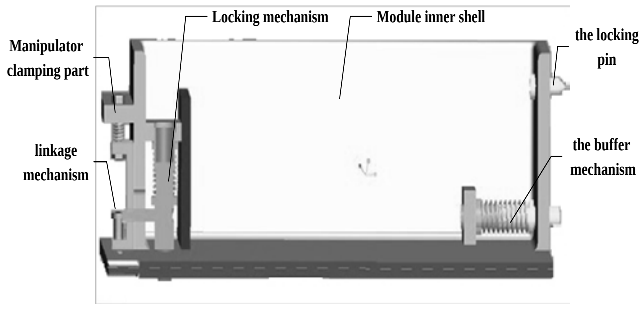


Fig.1 The inner shell structure

After importing the model, the model various parts should be set the steel materials, automatically calculated the center of mass and moment of inertia, and marked the position of the center of mass, so that we can effectively analyze and compare various parameters for the device.

# 3 Dynamic Modeling and Simulation

### 3.1 Equations of collision and systems

The flexible swap devices system is mainly to analyze the impact of collision on mechanism performance. The system dynamic characteristics have a huge change when the spring damper, which is installed in the inner front, collided with module shell. Therefore, the collision process is preferentially analysed when the impact on the dynamic characteristics of the system is considered [12-13]. The flexible plugging mechanism can be simplified as collision model which is shown in Figure 2. M1, M2, $x$, $F$, $k$ and $c$ denote the inner shell of module, the outer shell of module, the relative displacement, the level force exerted by mechanical arm, and non-linear function of the relative displacement, respectively. The Normal collision force:

$$R = f(x, \dot{x}) = F_s + F_d \tag{1}$$

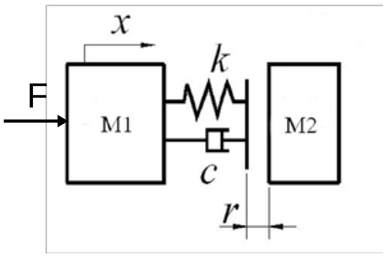


Fig. 2 Collision model

$f(x, \dot{x})$ is relative displacement and the relative velocity of the element. $F_s$ is the equivalent spring force, and $F_d$ is the equivalent damping force.

$$\begin{cases} F_s = kx^n \\ F_d = c\dot{x} \end{cases} \tag{2}$$

$k$ and $n$ are gained from experiment or data calculation.They are the properties of hardened spring generally. $c$ is viscous damping coefficient, determined by the vibration test. Due to the linear system easy to solve, we often convert other forms of damping into the equivalent viscous damping according to their principle of equal energy loss in a cycle in the engineering. Normal collision force $R$ must satisfy the boundary conditions of the collision process and energy loss. As shown in Fig.3, $\Delta E$, the shadow in the figure, is energy loss.

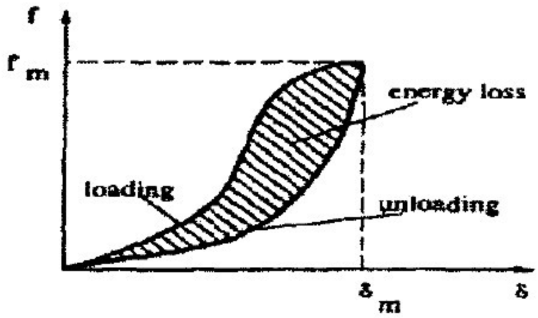


Fig. 3 Energy loss

The collision and relative motion process of kinematic pairs produce friction forces. The friction force $F_f$ and the normal collision force $R$ constitute the total interaction forces in kinematic pairs. Generally, we have two ways of defining collision forces in ADAMS. One is compensation method, and the other is shock function. Since the former is more difficult to set the parameters accurately, we often choose the latter to calculate the collision forces. Shock function method calculates the forces of the collision between two components based on impact function. The main components of shock function are elastic force produced by mutual contact between the two components and damping force caused by relative velocity [14].

The general Impact function expressions:

$$F\_impact = \begin{cases} 0 & x > x_0 \\ k(x_0 - x)^e - c_{\max} \dfrac{dx}{dt} step(x, x_0, -d, 1, x_0, 0) & x \le x_0 \end{cases} \tag{3}$$

$x_0$, $x$, $\dfrac{dx}{dt}$, $k$, $e$ and $c_{\max}$ denote the initial distance of two colliding objects, the actual distance in the process of collision of two objects, the relative velocity, the stiffness coefficient, the collision index, and the maximum damping whose value is normally set to 0.1 to 1% stiffness coefficients, respectively. $d$ is the contact depth, which determines when the damping force reaches the maximum value. Until the maximum damping force, the general value is 0.1mm. In order to prevent the damping force is not continuous in the process of impact, step function is often used.

After the flexible swap device collision model and the linear equation are set up, ADAMS defines center of mass coordinates and reaction of rigid body azimuth rigid Euler angle (or generalized Euler angle) as the generalized coordinates through Descartes。 $q_i = \left[x, y, z, \psi, \theta, \varphi\right]_i^T$ , $q = \left[q_1^T, \cdots, q_n^T\right]^T$ . Lagrange multipliers are used to establish the motion equation of the system:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}}\right)^T - \left(\frac{\partial T}{\partial q}\right)^T + {\varphi_q}^T \rho + {\theta_{\dot{q}}}^T \mu = Q \qquad (4)$$

Complete constraint equation:

$$\varphi(q,t) = 0 \qquad (5)$$

Nonholonomic constraint equation:

$$\theta(q,\dot{q},t) = 0 \qquad (6)$$

$T$ , $q$ , $Q$ , $\rho$ and $\mu$ denote the kinetic energy, the generalized coordinates system array, the generalized array, the correspond to the complete constraint Lagrange multiplier array, and the incomplete constraints Lagrange multiplier array, respectively.

The equations of collision and systems are formed to analyze the contact-impact influence on the system. While dealing with contacts - collision phenomenon, we treat them as continuous dynamic problems and determine the collision force by recovery coefficient method of impulse theorem, which can be more realistic simulation of the collision process. The contact-impact process should be taken into account the friction on system convergence effect, the equation is solved mainly by the modified Newton-Rap Son iterative algorithm. The detailed are in [15].

### 3.2 Adding Constraints and Motion

Comprehensive consideration for the influence of device constraints on the devices is needed when adding constraints. Flexible swap device is mounted on the maintenance spacecraft or service spacecraft. The spacecraft is restrained by the space and weightlessness conditions, so the device should be satisfied the movement requirements as follows:

(1) The pin, guide pin, buffer among various components and the interconnecting pieces should be fixed or moved in the axial direction.
(2) Linkage mechanism is driven by a mechanical arm and along a vertical direction with no skew. So the pin hole corresponding linkage mechanism is connected with the lock mechanism and the module shell is coaxial.
(3) Inner shell lower surface is parallel to the outer shell inner surface, the inner shell is driven by mechanical arm free insertion and removal so that we can ensure that it is unlocked before pulled out horizontally or pushed.

The models are added Joints and motion according to the above requirements. The module housing is connected to the ground by a fixed joint. The linkage mechanism is connected to the guide bolts by a translational joint. The guide pin is connected to the module box by a translational joint. The locking pin of the locking mechanism is connected to the modules by a translational joint, and to the module housing by a fixed joint. The linkage is connected to the rod linkage and to the locking lever by fixed joints. The buffer is connected to the module housing and to the module box by translational joints. The whole model is composed of 14 rigid bodies, 6 Translational Joints, 5 Fixed Joints, 2 Contact Joints and 2 spring dampers. The model is the Joints are shown in Table 1.

There are two motions often used in ADAMS. One is Translational Joint Motion; the other is Rotational Joint Motion. The two motions are often associated with the constraint Joints [16]. In the paper, the Translational Joint Motion which is added on the kinematic pairs of horizontal and vertical direction is used in the emulation motion. Motion is mainly defined by mechanical arm $F$ and Time functions. Since large impact on the influence of device, the collision model is respectively constructed between buffer and module housing, locating pin and outer shell.

Table 1 Joint constraints in ADAMS

| Joint | Type | Body i | Body j |
|---|---|---|---|
| ① Joint_1 | Translational Joint | . module housing | . Module box. |
| ② Joint_2 | Fixed Joint | . module housing | . the ground |
| ③ Joint_3 | Fixed Joint | . the linkage | . guide bolts |
| ④ Joint_4 | Fixed Joint | . module housing | . locking pin |
| ⑤ Joint_5 | Fixed Joint | . linkage | . rod linkage |
| ⑥ Joint_6 | Fixed Joint | . linkage | .locking lever. |
| ⑦ Joint_7 | Contact Joints | .buffer | .module housing |
| ⑧ Joint_8 | Contact Joints | .Positioning pins | .module housing |
| ⑨ Joint_9 | Translational Joint | . guide pin | . Module box. |
| ⑩ Joint_10 | Translational Joint | . locking pin | . Module box. |
| ⑪ Joint_11 | Translational Joint | . guide plate | . guide bolt |
| ⑫ Joint_12 | Translational Joint | . module housing | . buffer |
| ⑬ Joint_13 | Translational Joint | .module box | . buffer |

The model is two degree of freedom and the Joints are shown in Fig.4. In the following figure, we can learn various motion pair, constraints, and driving force.

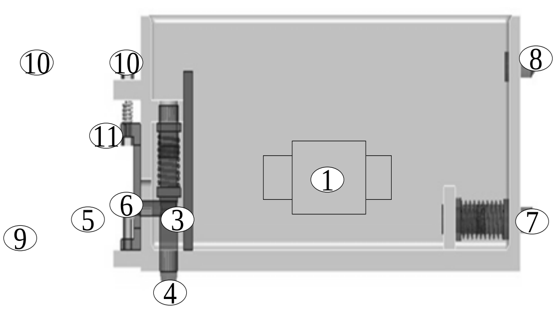


Fig. 4 Model motion

### 3.3 Model Device Simulation

The flexible swap device is mainly divided into two kinds of motion states including inserted the lock and unlock separation according to the actual functions. The working process is shown in Fig.5. The multi-body model is shown in Fig.6. Mechanism within the housing is actually integrated modules, including the power supply module and the computer module. When the component is damaged in the spacecraft, servicing spacecraft will get replaceable module through the robotic arm. Then the new module is inserted into the damage spacecraft. The process must be ensured complete replacement comfort and stability.

The movement process of flexible swap device is implemented in outer space, so we set the gravitational acceleration $g = 0$. There are a total of three springs and two spring buffers in insertion agencies. We can set $k = 200, c = 1.20$ meeting the Hooke's law for spring buffer. K and c denote the spring stiffness coefficient, and damping coefficient, respectively. The main functions are design process and motion process functions in ADAMS. During the simulation, horizontal and vertical direction driving forces are created to replace the effect of robot arm. The driving force is established by the motion process function which is the STEP function [17].

STEP function applied to the holding part of mechanical arm is as follows:

$$\mathrm{Step}(\mathrm{time},0,0,3,9) + \mathrm{Step}(\mathrm{time},4,0,8,320) \quad (7)$$

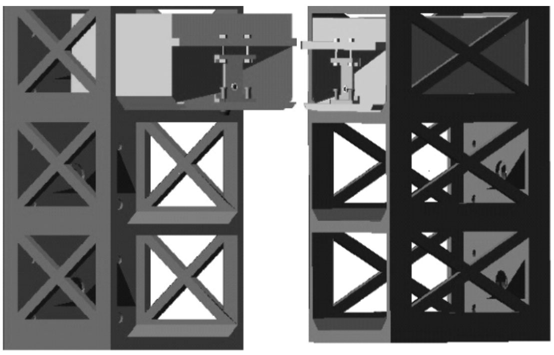

Fig. 5 Flexible swap device process

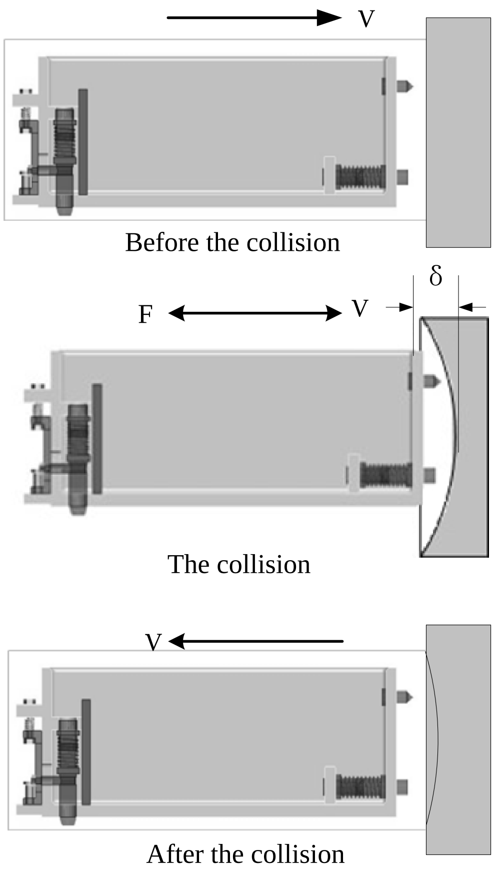


Fig. 6 The multi-body model

The most important is the insertion and pull out of the module in the module replacement process. The quality of the completion directly affects the entire on-orbit module worse task success, therefore we should chief analyses pulled out and inserted into the locking motion of process. According to the driving force of step function to load in the vertical direction, the linkage is moved along the vertical direction. At the same time the linkage rod on the linkage moves upward with linkage locking pin, makes devices is in the unlocking state. The motion trajectory of the inner shell is shown in Fig.7 and Fig.8. The buffer device is installed in front of the flexible swap device, and contacted with the shell in the movement process. The force of the buffer suffers cannot be too large, otherwise it will lose effectiveness. The simulation results of the collision force of the model and the collision torque is shown in Fig.9, and Fig.10, respectively. The guide pin is installed at the distal end of the inner casing, and its accurate position is helpful to the connection with data Electrical Interface Expertise docking. The friction is generated between the guide pin and the guide hole corresponding to the outer shell during the collision. The collision movement amplitude is shown in Fig.11. When the module inner shell is moved to the specified location, sensors decide whether the position is certain or not. If device reaches the designated position, sensors feedback to the control center and the center issues a command to stop applying mechanical arm drive. At the same time inner shell without external force will lock up to complete the whole insertion process.

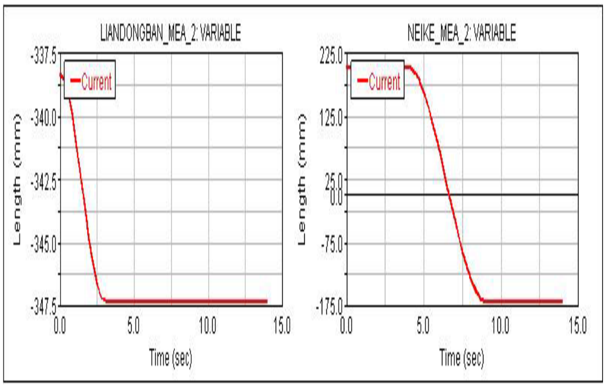


Fig. 7 Insert into the lock pin and the inner trajectory

Figure 6 is the motion state that the module is inserted. The locking lever on the left is the center of mass trajectory. When the linkage mechanism is driven by the vertical direction, the locking lever is to the vertical flat mobile. The center of mass moves to a specified location and will remain the same as the level of the curve. The right picture shows the trajectory of the center of mass within the module. Because step function is not applied in the horizontal direction within 3 seconds, the center of mass position remains unchanged. When the horizontal drive is applied, the center of mass begins gently inward movement relative to the module housing. When the internal module is inserted, the simulation center of mass motion curves to remain the level.

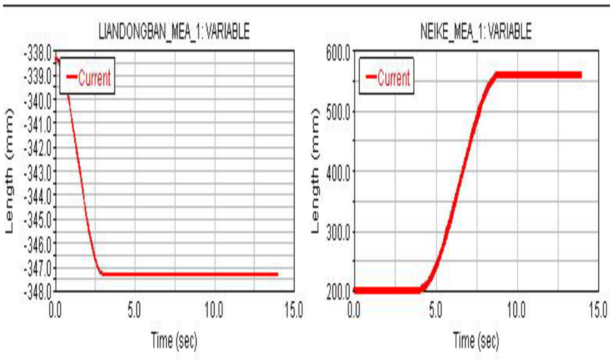


Fig. 8 when separation lock pin and the inner center of mass center trajectory

Figure 8 is the separate state of motion modules. The locking lever on the left is the center of mass trajectory. The whole process is divided into unlocking movement and separation. In the first place is the device is applied in a direction vertical drive, the locking bar starts to move up, and the center of mass movement as the curve of 0 ~ 3 seconds. When the locking bar is moved to the specified position, the housing and the unlock process are finished. The center of mass is shown in right picture. When the horizontal direction is not applied to drive within 4 seconds, the center of mass is maintained in a stable position. From 4 ~ 8 seconds, the center of mass within the module housing began to outward. After 8 seconds, mechanism is completely separated. And process of the unlock separation is completed.

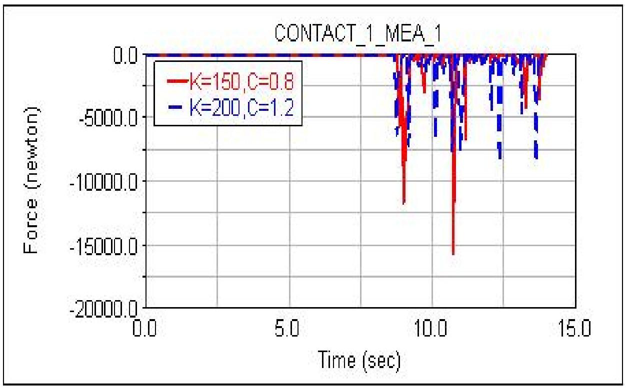


Fig. 9 Buffer impact force simulation results

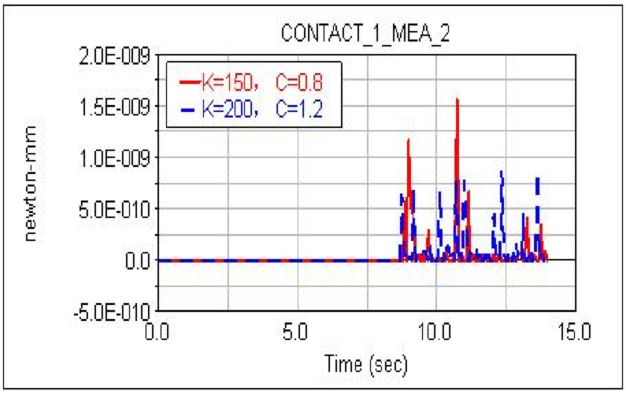


Fig. 10 Buffer impact torque simulation results

Figure9, Figure10 is simulation results that the impact force and the collision torque of the swap device spring buffer collision model in a different spring and damping. From 0 to 8 seconds， the figure can be seen that the collision force and moment are zero without contact. As the depth of the mutual coupling increasing, the maximum impact force becomes greater. We can see from the figure that the highest point is changed over time. The damping is to absorb great force and energy, so the collision force appears sharp point in just contact, and becomes gentle with time. From the contrast of the blue and red line graph can be seen that the collision force and torque becomes smooth with the damping and spring stiffness changes great. The optimal value is selected as the size of the mechanical arm, so not is changed the bigger and better. From this we can see that the flexible swap device installed buffer can reduce the collision force and energy absorption effectively.

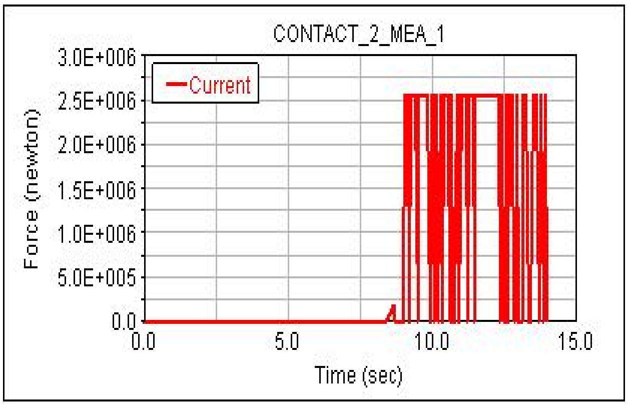


Fig. 11 Positioning pins collision amplitude of movement

The picture shows the amplitude of the positioning pins is changed with the collision force in the collision process. From the chart we can see that the force of the positioning pin is not immediately changed but produced a relatively small on initial contact. The positioning pin is not reduced the size of the force only plays the positioning and guiding role. In the collision process, the spring buffer can absorbs the impact force so that the force of the positioning pin is maintained very small.

## 4 Conclusion

Research on structure design in flexible swap device, model by parameter can improves the efficiency of structural design. The design process enables quick evaluation of multiple design alternatives and optimization of spatial layout, while improving cost and safety. The flexible swap device for the parametric geometry model is mainly through Pro/E to rapid model. So we can design dimension and position of each main part structural, built the flexible swap device meeting functional requirements, and help designers via geometric relations to define design principle.

ADAMS dynamics simulation software is applied to analyze the movement and collision process. In order to study the mechanism of the feasibility of performance index and operation mechanism, we can establish a suitable collision model, use the Lagrange structure to establish the motion equation of the system, determine the coalitional influence on mechanism performance, and judge the practicability of mechanism design. According to Hertz's contact theory and nonlinear damping law, the contact with the collision model is established. In order to study the impact of the organization structure of the collision, structural stiffness in different situations is simulated. As can be seen from the simulation results, the buffer can reduce the energy loss and reduce the role of the collision caused the collision play a significant effect.

In the mechanism design analysis process, we should build the model parameters and find out the influence factor in the mechanism. Through the analysis of the flexible plug mechanism kinematics and mechanism performance stability, this paper provides the basis for meeting the maximum force of space state mechanical arm, and offers reference for the flexibility analysis of mechanism. Design of virtual instrument simulation can reduce mission risk and the cost of production, while providing a significant improvement on-orbit replacement task operating environment. With the flexible swap device developed in industry to the latest spacecraft technology, we can improve the task performance and security, and reduce the cost of development and operation.

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