Dynamic Modeling and Simulation Analysis of Non-explosive Separation Device

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Abstract. In order to ensure reliable connection and separation between satellites and the launch vehicles, a dynamic modeling method of a certain type of non-explosive separation device based on contact theory is proposed to carry out more accurate results in this paper. After analysis on the actuation principle of the non-explosive separation device, the source of impact response is clarified. Then the contact model is established based on the contact theory and the dynamic simulation model is established. The dynamic simulation results show that the shock acceleration of housing is no more than 300g, it is consistent with the experimental results performed by other workers. The simulation model can be utilized for the design and validation of the non-explosive separation device to provide a reliable basis for subsequent optimization.

1. Introduction
Spacecraft carried by launch vehicles require separation system to accomplish the specified programmatic functions and mission-related tasks such as fairing jettisoning, cabin separation, payload release, deployment of solar arrays and the other appendages separation [1]. Among the modern spacecraft, it is required that the separation of the separation device should be completed within a very short time and the impact force should be decreased to avoid invalidation of important sensitive components and damage of brittle material during the separation process.

Non-pyrotechnic separation device is a new type of device modified based on the limitations of traditional pyrotechnic device, with the main advantages of being reusable, significantly reducing the impact force and being convenient for experimental verification and simulation analysis [2]. The conventional design method is limited, because the original design concept put forward mainly based on experience to judge, using iterative design experience and trial and error to verify. This approach lacks of understanding of the working mechanism of the separation device, thus, resulting in high design cost and waste of resources. Numerical analysis can effectively avoid such problems and it is convenient to design and optimization. Hu et al. [3] carried out dynamics and transient perturbation analysis to obtain separation trajectory and attitude parameters for the helical compression spring mechanism. Jiang et al. [4] used the dynamics and Hertz contact theory to establish the dynamic modeling of the first and second stage swing arms in a certain separation device, then obtained the simulation results in ADAMS software and verified the correctness and reliability of the theoretical model by experiment.

There are numerous researches in the dynamic analysis and separation response analysis with pyrotechnic separation devices due to their explosion characteristics. As for non-explosive separation devices, the studies mainly focused on mechanism design and verification. This paper discusses a certain type of non-explosive separation device based on shape memory alloy (SMA) spring actuator. Firstly,
the configuration and actuation principle of this device is analysed. Subsequently, a multibody dynamics model including contact and impact of non-explosive separation device is presented by using multibody dynamics theory and contact theory for analysing the parameters that influence the impact characteristics. Then, an accurate dynamic simulation model of the non-explosive separation device considering contact parameters is established in the ADAMS software. Finally, dynamic analysis of separation characteristics and shock responses are carried out in aspect of simulation.

2. Configuration of non-explosive separation device

The non-explosive separation device is mainly composed of three sections, the SMA trigger mechanism, connection mechanism and bolt components. The configuration of the device is illustrated in figure 1.

![Model of non-explosive separation device](image)

Figure 1. Model of non-explosive separation device.

The SMA trigger mechanism is consist of SMA spring, buffer spring, heating rod and plunger. The heating rod is contained within the SMA spring, which, when heated by an electrical current to extend SMA spring from compression, and then triggers the plunger to release the radial restraint on the ball pin. This mechanism aims to provide adequate trigger force and displacement to push the plunger to release the ball pin during unlocking.

The connection mechanism includes segment separator, segmented nuts, housing, sleeve and other parts. It is the main bearing structure of the device and connect the bolt components by constraining the axial restraint of the mechanism through threads. It contains two springs, actuation spring and segment separation spring. Before separation, the segmented nut is held in place by compressed actuation spring and segment separation spring in axial direction, meanwhile, it is fastened together by the ball pin in radial direction. When the ball pin was released, the actuation serves as initiator to push the sleeve until hitting the cushion rubber. With the compressing force of segment separation spring, the radial restraint of the segment nut is released and the segment nuts move along the groove of the sleeve in three direction.

The bolt components mainly comprise a bolt, bolt shell, bolt separation spring and the buffer rubber. When the bolt removed the radial constraint on the connecting segmented nut, the bolt components is pushed away from the device by the bolt separation spring during the process of separation.

3. Modeling of contact

The non-explosive separation device generates two shocks due to the release of sleeve and bolt in the separation process, thus, the contact relationships between the components of device is discussed. The distinct characteristic of contact problem is highly nonlinear, reflecting in material nonlinearity, geometric nonlinearity and contact interface nonlinearity. Therefore, it is important to choose the appropriate contact model according to different occasions.
Generally speaking, the contact process can be considered as two stages, namely the compression stage and the restitution stage. In the compression stage, the contact deformation of two spheres increases along the normal direction of the impact surface, simultaneously, the relative velocity of the two spheres decreases to zero [5]. As the foundation of contact force model, Hertz contact model performs a pure elasticity and has no energy dissipation in the contact process, this continuous contact force model cannot be used to describe the two stages of contact change.

Hunt and Crossley purposed a contact model based on the Hertz contact model and expressed the energy dissipation as a nonlinear damper [6-7]. Its dissipation component is a nonlinear function of the contact indentation and the normal relative approaching velocity, the contact force $F_n$ can be calculated as the following form

$$ F_n = K\delta^n + D\dot{\delta} $$  \hspace{1cm} (1)

Where $K$ is the contact stiffness, which is related to the material and shape of the object, $\delta$ is the relative indentation between the two contacting parts, $n$ is the nonlinear power exponent mainly determined from the material and the geometric shapes of the contact bodies, the parameter $D$ represents the energy dissipation coefficient during the contact process, $\dot{\delta}$ is the relative velocity, which is to take the derivative of the relative indentation $\delta$.

Hunt and Crossley state that the energy dissipation coefficient depends on the penetration depth and the hysteretic damping factor, and the exponent of damping is equal to the exponent of the relative indentation, the contact force has the form

$$ F_n = K\delta^n + \mu K \delta^n \dot{\delta} $$  \hspace{1cm} (2)

Where, $\mu$ is the hysteretic damping coefficient which depicts the energy loss.

A commonly used assumption is to express the energy dissipation in the form of the internal damping of the material presented by Lankarani and Nikravesh [8]. The hysteretic damping coefficient $\mu$ can be determined by the impulse-momentum equation and the principle of energy. The damping coefficient can be calculated as follow

$$ \mu = \frac{3K(1-e^2)}{4\delta(-)} $$ \hspace{1cm} (3)

Where, the restitution coefficient $e$ is the ratio of the approaching velocity and the separation velocity along the normal direction of two contact objects, $e = (V_{i(i+)} - V_{j(i+)} / (V_{i(i)} - V_{i(i+)} )$, and it is only related to the material of the contact object.

The contact force expressed by combined damping can be written in another form as

$$ F_n = K\delta^n \left[ 1 + \frac{3(1-e^2)}{4} \frac{\dot{\delta}}{\delta(-)} \right] $$  \hspace{1cm} (4)

The expression shows that continuous contact force model is actually an equivalent spring damping model, the contact force depends on the equivalent spring stiffness and damping coefficient. The model involves the calculation of some parameters, and the appropriate value of damping coefficient and stiffness coefficient can be used to calculate the contact force more accurately, so the application of effective spring-damper contact model is relatively common.

The developed model can be used for general contacts in mechanical systems with low velocity, especially when the impact velocity is negligible compared to the velocity of the stress wave propagating in the solid [9].

**4. Simulation analysis**

Numerical simulation technology can greatly decrease the design cycle and production quality of the separation device to avoid long development cycles that cause new technologies to fail to be applied. According to the provided three-dimensional model of the non-explosive separation device, the dynamic modeling work is carried out to establish the virtual prototype model of the non-explosive separation device, which can effectively simulate the whole process of its connection, action and separation.
4.1. Modeling in ADAMS

Smart material shape memory alloy is widely used in separation devices as an actuator or trigger due to its shape memory effect. In this paper, the non-explosive separation device employs shape memory alloy spring as an actuator. Shape memory effects include two categories, one-way shape memory effects and two-way shape memory effects. The one-way memory alloy has more application at present because the two-way memory effects are unstable [10]. The SMA spring is shaped at high temperature, then it is loaded when the ambient temperature is lower than its phase transition temperature. When the temperature rises, the residual deformation in the SMA spring disappears and it automatically returns to its original shape at high temperature. The SMA spring is heated to restore its original length through the heating rod in the middle of spring.

The shape memory effect of SMA spring in the separation device is replaced by displacement drive, and the input is set as a displacement function \(\text{STEP}(\text{time}, 0, 0, 0.02, 5.5)\). The action point is applied to the bottom of the plunger, and the direction is upward. There are four spring parts in the separation device, and they are in the form of spring force in ADAMS, so spring force should be added in the corresponding position of the model. Spring parameters as shown in table 1 can be obtained according to calculation.

| Spring   | Name                  | Stiffness (N/mm) | Damping (N/(mm/s)) | Preload (N)  |
|----------|-----------------------|------------------|--------------------|--------------|
| Spring1  | Segment separation spring | 2.571            | 0.003              | 74.556       |
| Spring2  | Buffer spring         | 0.967            | 0.003              | 9.944        |
| Spring3  | Actuation spring      | 2.629            | 0.003              | 176.143      |
| Spring4  | Bolt separation spring | 0.930            | 0.003              | 39.046       |

According to the spring arrangement of the separation device, in order to reduce the influence of clearance on unlocking and separation, the movement of the sleeve in the housing is defined as a moving pair, and the two components without relative movement are connected by a fixed pair. In ADAMS, constraints and materials are added to the parts according to the motion relationship and actuating principle of the separation device. The main motion pairs are shown in Table 2.

| Joint   | Joint type | PART1       | PART2               |
|---------|------------|-------------|---------------------|
| Joint1  | Fix        | bolt        | connect plate       |
| Joint2  | Transition | sleeve      | housing             |
| Joint3  | Fix        | cushion rubber | head cover      |
| Joint4  | Fix        | bottom cover | housing             |

There are a lot of behaviours such as gap friction and contact in the motion process of the separation device, and the connection pair can hardly simulate the real actuating effect. ADAMS has a certain ability to capture and analyse the process of impact and contact, and its impact force model is defined by statement CONTACT.

In order to ensure the reliable connection of the separation device, pre-tightening force should be applied to the bolts. The preload will disappear quickly after the bolt is released, and the time for the bolt begins to move is the time when the preload starts to release. The step function is used to simulate the preload, and the displacement time of the bolt is 13.4ms calculated through the pre-simulation. Preload can be set as \(\text{STEP}(\text{time}, 0.0134, 1400, 0.014, 0)\).

4.2. Contact in ADAMS

There are two methods to calculate contact force in Adams, contact algorithm based on regression and contact algorithm based on impact function. Generally speaking, the impact function method is numerically smoother and the simulation speed is faster. In ADAMS, according to the Hertz contact theory, the impact function algorithm is adopted to equate the object contact process to the nonlinear
equivalent spring and damping model based on penetration depth. The calculation formula of normal contact force is

\[
\text{IMPACT} = \begin{cases} 
  k(x_i - x)^n - \text{STEP}(x, x_i - d, c_{\text{max}}, x_i, 0) \cdot \dot{x}, & x < x_i \\
  0, & x \geq x_i
\end{cases}
\]

Where STEP presents the step function, \( n \) is the force exponent which represents the nonlinearity of materials and depends on the surface geometry of the contact bodies, \( x \) is the penetration depth, and \( x_1 \) is the free distance, the two objects are in contact when \( x \) is greater than \( x_1 \). The difference between \( x_1 \) and \( x \) is equal to relative indentation \( \delta \) in equation (4). \( c_{\text{max}} \) is the maximum of damping coefficient and \( d \) defines the maximum penetration depth in fully damping, \( k \) depicts the contact stiffness which can be calculated by Hertz contact theory.

The contact between the sleeve and the cushion rubber can be considered as the elastic deformation of a semi-infinite boundary under the action of surface force regardless of the microscopic situation, It is assumed that the external force is distributed on the circular area, the contact force is linear

\[
F = K\delta
\]

The contact stiffness between two plane surfaces can be

\[
K = \frac{\pi a}{2(h_1 + h_2)}
\]

For which, \( a \) is the radius of the contact area, \( h_1 \) and \( h_2 \) are the material parameter, \( h_i = (1 - v^2) / \pi E_i^2 \), \( i = 1, 2 \). Where \( E \) is the elastic modulus of the material, and \( v \) is the Poisson's ratio of the material.

According Hertz theory, when two spheres are in contact, the contact area is circle. The relation between the indentation \( \delta \) and the contact normal force \( F \) during impact is

\[
\delta = \left( \frac{9}{16} \frac{R_1 + R_2}{R_1 R_2} (h_1 + h_2)^2 F^2 \right)^{1/3}
\]

The contact stiffness \( K \) of the two spheres can be calculated as

\[
K = \frac{4}{3(h_1 + h_2)} \left[ \frac{R_1 R_2}{R_1 + R_2} \right]^{3/2}
\]

Where \( R_1 \) and \( R_2 \) are radii of two spheres respectively. The equivalent radius is the sphere radius, when the sphere contacts the concave sphere, the concave sphere radius is negative.

The calculation results of main contact pair parameters according to equation (7) and equation (9) are shown in Table 3.

### Table 3. The parameters of contact.

| CONTACT | PART          | PART          | Stiffness       | Force exponent | Damping |
|---------|---------------|---------------|-----------------|----------------|---------|
| Contact1| Ball pin      | Plunger       | 205743N/mm      | 1.5            | 10      |
| Contact2| Ball pin      | Housing       | 205743N/mm      | 1.5            | 10      |
| Contact3| Ball pin      | Sleeve        | 205743N/mm      | 1.5            | 10      |
| Contact4| Sleeve        | Cushion rubber| 260 N/mm        | 1              | 0.57    |
| Contact5| Bolt          | Buffer rubber | 162 N/mm        | 1              | 0.35    |

5. Results and discussion

After repeated simulation calculation, the model parameters and solving accuracy are adjusted to determine the appropriate solving duration and step length. The simulation duration is 0.03s and the simulation step length is 3000.
Figure 2. The acceleration of the housing in X, Y and Z axes.

Figure 2 shows the acceleration curves of the housing in the X, Y and Z axis which define by Cartesian coordinates, Y-axis is the radial direction of the device, X and Z axes are the axial direction of the device. It can be seen from the structure of the separation device that the release of the sleeve and bolt can generate two shocks at 16.7ms and 21.5ms respectively. The peak values of the two impact accelerations are 246g and 287g respectively, which meet the unlocking performance requirements of not more than 300g and the maximum of the release impact in ground test results is 246.8g [11].

Figure 3. Time history curve of velocity with the sleeve.

Figure 4. Time history curve of velocity with the bolt.

Figure 5. Time history curve of contact force with the sleeve.

Figure 6. Time history curve of contact force with the bolt.

The time history curves of velocity the sleeve and bolt are shown in figure 3 and figure 4. It can be seen that the velocity of the sleeve and bolt fluctuate from zero to 0.5ms, because there is a certain gap between the pin ball and the plunger. With the unlocking of the pin ball, the sleeve accelerates upward
and reaches the peak velocity of 1535mm/s at 16.7ms, contact with the sleeve and then decreases. With the movement of the sleeve, the radial constraint of the segmented nuts is gradually released at 13.4ms, and then the bolt begins to release. It reaches the peak velocity of 6617mm/s at 21.5ms. Figure 5 and figure 6 illustrate the time curves of contact force on the sleeve and bolt respectively. The maximum is reached at the same time as the velocity, respectively 684N and 2132N.

6. Conclusion
The traditional design method for the separation device is the way of experience and test to perform prediction and analysis which can basically satisfy the requirements of initiation device, but the traditional design method cannot accurately obtain kinetic parameters during the separation, so it is difficult to effectively evaluate the separation performance of the separation device. This paper mainly studies the contact dynamic modeling and simulation of the connection and unlocking process of a non-explosive separation device. The separation actuation process of the non-explosive separation device contains various nonlinear factors which can make the system even weaker and it is difficult to obtain the analytical solutions of shock response. The contact parameters have great influence on the simulation results, so determining more accurate parameters can establish a precise dynamics model. The simulation model in this paper can be used as a reference for optimization design combined with subsequent experiments.

Acknowledgments
The work is supported by the National Key Research and Development Project of China (No.2019YFB2006404).

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