Simulation of Space Flexible webs on Capture Process Based on Nonlinear Finite Element Method

Boting Xu¹, Yueneng Yang¹,²*, Bin Zhang⁴ and Ye Yan³

¹ College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China
² College of Intelligence Science and Engineering, National University of Defense Technology, Changsha 410073, China
³ Innovation Research Institute of Defense Technology, Academy of Military Sciences, Beijing, 100071, China

*Corresponding author: yangyueneng_nudt@163.com

Abstract. Aiming at the problem of the space flexible webs collision during the space capture process, the general method of collision detection was given based on the nonlinear finite element method, and the collision dynamic model of the space flexible webs and target was established. In order to verify the versatility of the space flexible webs structure in different capture scenarios, the target capture position and attitude were changed respectively, and different capture scenarios were established to simulate and analyze the working conditions by using the finite element software. The results showed that the target position and attitude during the collision impact process is the key of the results of the flexible webs capture mission, which can provide some reference for the structural design and on-orbit task planning of the space flexible webs system.

1. Introduction

As of May 30, 2019, the total number of on-orbit space targets (diameter greater than 10 cm) catalogued by the Space Surveillance Network (SSN) has reached 19,643, of which 5,134 are payloads (there are 2,315 still in normal working conditions), there are 14509 abandoned rocket body and space debris, accounting for 77% of the total number of targets in the orbital space. Space debris is the potential “perpetrator” of the space collision accident, in the low earth orbit, the space debris runs fast, and the relative velocity of collision between the debris and spacecraft can reach more than 10km/s, which will seriously damage the spacecraft and even lead to catastrophic consequences such as structural disintegration[1,2]. At present, the active debris removal technologies mainly include manipulators capture, flexible webs capture, laser removal and so on. The flexible webs capture technology proceed the debris removal mission by developing a flexible webs to wrap space debris in some corresponding deployment mode. This method has become a research hotspot in the field of space debris removal which can be applied to capture space debris of different shapes and sizes and has great fault-tolerant advantage.

The space flexible webs system is a typical nonlinear dynamic system, which is characterized by variability, relaxation and winding. The capture process of the space flexible webs mainly includes two stages: flexible webs deployment and target capture. Mankala studied the dynamic modeling and simulation of the entire mission process of flexible network systems[3]. Zhai Guang studied the
attitude dynamics during the capture process of flexible network systems[4]. Yu Yang developed the finite element model of the flexible webs projectile deployment process, implemented in the software THUsolver, in order to study the mechanical properties of the webs under different environments[5,6]. Gardsback Tibert developed the finite element model, implemented in the commercial software LS-DYNA, in order to imitate a spinning deployment process of the space webs and verify a robust control method for the spinning deployment[7,8]. Chen Qin established the lumped-mass model and analysed the dynamics problems of the webs deployment process. The above research mainly focuses on the deployment stage of flexible webs, and there are relatively few researches on the collision and wrapping process in the capture stage of flexible webs[9]. During the process of target capture, the collision between flexible webs and target will produce rapid stress and strain, which may lead to the breakage of rope segment or the instability of web configuration, thus causing the target to be escaped from the webs. Therefore, the capture process of space flexible webs also needs to be studied in depth. Yu Yang et al. analyzed the stress and strain of flexible webs with different mesh sizes under impact based on the finite element model[10]. Benvenuto used the penalty function method to simulate the target capture process of the flexible webs[11]. Xu Boting used finite element software to analyze the capture ability of the bionic flexible webs[12].

In this paper, the dynamic modeling and simulation of the collision wrapping process between the flexible webs and the target will be carried out. The general method of collision detection is given based on the nonlinear finite element method, at the same time, the collision dynamic model of the space flexible webs and target is established. In order to verify the universality of the flexible webs in different capture scenarios, we focus on the variation of the collision force and energy of the webs when capture different position/attitude targets, which can provide some reference for the structural design and on-orbit task planning of the space flexible webs system.

2. Dynamic model

2.1. Collision detection

The flexible webs capture process is generally a collision of irregular objects. In this paper, we focus on the simulation analysis of the flexible webs collision process. In order to save the simulation time of the collision detection process, the shape of target is simplified which consider to be a rigid cube.

For the collision detection between the webs and target, firstly judge the spatial position of the checkpoint and the target, if detected that there is intrusion between the moving bodies, then the quantity of intrusion will be calculated. The contact model calculates the collision force and update the state of collision motion, repeating the aboved process in the next calculation. The detection process is shown in Figure 1. The point-plane detection method is applied in the collision detection process, which by calculate the distance of the checkpoint and detection surface to determine whether the intrusion into the detection surface. Because of the grid of the web unit is sparse, it is necessary to arrange several checkpoints in the unit, and these checkpoint are distributed in the unit evenly.
2.2. Dynamics model of collision

The mechanical process of collision can be described as Lagrange impulse method:

\[
\begin{bmatrix}
M & \Phi^T & \tilde{c} s / \tilde{c} q \\
\Phi & 0 & 0 \\
(\tilde{c} s / \tilde{c} q)^T & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\Delta \dot{q} \\
\dot{\lambda} \\
-\dot{P}
\end{bmatrix}
= 
\begin{bmatrix}
0 \\
0 \\
-(1 + e)(\tilde{c} s / \tilde{c} q)^T \dot{q}
\end{bmatrix}
\]

(1)

where \( M \) is the mass matrix, \( \Phi \) is the Jacobian matrix, \( s \) is the distance between the contact points, \( q \) is the location coordinate, \( \dot{q} \) is the velocity before collision, \( e \) is the coefficient of restitution, \( \dot{\lambda} \) is the counter-force of impact force, \( p \) is the impact force.

2.3. Dynamics model of contact

The contact in the flexible webs system can be divided into two categories: the contact between the flexible webs and the rigid body, and the contact between the rigid body and the rigid body, which regardless of the self-collision between the rope segments of the webs. For a rigid body or particle in contact, \( u_i^j (i = 1, 2) \) is the distance to the vertical contact surface (or point), \( u_i^j (i = 1, 2) \) is the displacement in the contact surface. The contact can generally be divided into several types:

\[
\begin{align*}
u_i^j - u_i^j + a_0 > 0, & \quad P_n = 0 \quad \text{no touch with webs} \\
u_i^j - u_i^j + a_0 = 0, & \quad P_n < 0 \quad \text{in touch with webs} \\
|P_t| < -\mu P_n, u_i^j - u_i^j = 0 & \quad \text{in touch with webs, no slide} \\
|P_t| = -\mu P_n, \text{sgn} P_t (u_i^j - u_i^j) \leq 0 & \quad \text{in touch with webs, slide}
\end{align*}
\]

(2)

where \( a_0 \) is the safe distance, that is the threshold of distance threshold detection, \( P_n \) is the contact force, which is perpendicular to the contact surface, \( P_t \) is the force of friction of contact surface.

3. Numerical simulation and analysis

In order to verify the versatility of the flexible webs system for different capture scenarios, the target capture position and attitude will be changed respectively, and different capture scenarios will be simulated and analyzed by using the finite element method. In the part of the attitude change of target, three typical collision situations of flexible webs in capture process are simulated by designing initial contact states of surface, line and point respectively. In the numerical calculation of different working conditions, only the position and attitude of the target are changed, while the other simulation
parameters remain unchanged. The collision scenarios of initial surface is detailed in the article [12] and will not be repeated here. Simulation parameters are listed in Table 1.

| Parameter                  | Value       |
|----------------------------|-------------|
| Size of webs/m             | $5 \times 5$ |
| Size of target/m           | $1 \times 1$ |
| Size of grids/m            | $0.25 \times 0.25$ |
| Mass of masses/kg          | 0.5         |
| Sectional area of rope units/m$^2$ | $2.73 \times 10^{-5}$ |

Simulation assumptions:
(1) Prior to contact and collision, the flexible webs posture remain stable, the speed of each point is identical, and the webs move at a constant speed;
(2) The flexible webs and target experience straight-line motion; the influence of orbital motion is ignored.
(3) The flexible webs are assumed to be stationary while the target moves relative to the webs.

3.1. Scenarios 1: Capture position change of the target
As shown in Fig. 2, the capture position is not in the center of the flexible webs, but on the left side of the center, the target is 2m away from the surface of webs, and the relative velocity between the target and webs is 100m/s.

Fig. 3 shows the movement of the flexible webs and the target at different times during the collision process. The target is wrapped by the flexible webs after collision, and the two will form a rigid-flexible coupling body to move together. Fig. 4-Fig. 6 are the changes of deformation, strain and stress of flexible rope segment during collision when the initial collision position is changed. It can be seen from the simulation results that although the flexible webs can successfully capture the target, the target is not completely wrapped by the network, which increases the difficulty of the next step of the off-track control process of the complex, and there is a risk of failure of the capture task. Therefore, in order to ensure the success of the capture task, the initial development angle of the webs is designed to ensure that the acquisition position is the center area of the flexible network.
3.2. Scenarios 2: Capture attitude change of the target (Initial line collision)

Fig. 7 shows the movement of the flexible webs and the target at different times during the collision process. The target is wrapped by the flexible webs after collision, and the two will form a rigid-flexible coupling body to move together. Fig. 8-Fig. 10 are the changes of deformation, strain and stress of flexible rope segment during initial line collision. It can be seen from the simulation results that the target is completely wrapped by the flexible network, and the initial line collision can also ensure the success of the capture task.
3.3. Scenarios 3: Capture attitude change of the target (Initial point collision)

Figure 11 shows the movement of the flexible net and the target at different times during the collision process. In the case of initial point collision, the simulation results are not ideal, the flexible webs does not capture the target and the capture task fails. Fig. 12-Fig. 14 are the changes of deformation, strain and stress of flexible rope segment during initial line collision. It can be seen from the simulation results that in the initial stage of the collision between the target and the flexible webs, the excessive stress on the flexible webs is the main reason for the failure of the capture task.
4. Conclusion

Based on the non-linear finite element method, the dynamic modeling and simulation of the capture process of the space flexible webs are carried out. The influence of the position/attitude change of the target on the capture results of the flexible webs is analyzed. The results show that under the condition of the same relative collision speed, the initial surface collision and the initial line collision can ensure the success of the capture mission. In the case of initial point collision, the capture failure occurs due
to the excessive stress on the flexible webs at the initial moment of the collision. Therefore, in the structural design process of space flexible webs system, the configuration analysis and verification of the energy dissipation of the flexible webs should be emphasized. In the process of space on-orbit mission design, the deployment angle of flexible webs structure can be adjusted by the attitude of the target, and the appropriate initial contact and collision position should be selected to ensure the success of the capture mission.

It should be pointed out that in this paper, the capture process of space flexible webs is qualitatively analyzed, but the accuracy of the model in this paper still needs to be corrected and modified by means of ground test. For the analysis of the capture process of space flexible webs, further verification and improvement are needed.

Acknowledgement
The work reported in this paper was partially sponsored by the Science and Technology Committee of China (No. 02-ZT-005-021-01), National Science Key Lab Project of the Technology of Space Intelligent Control(No. HTKJ2019KL5022016).

References
[1] J.-C. Liou, Nicholas L. Johnson 2009 Asensitivity study of the effectiveness of active debris removal in LEO, Acta Astronautica, 236–243.
[2] J.-C. Liou, Nicholas L. Johnson, N.M. Hill 2010 Controlling the growth of future LEO debris populations with active debris removal Acta Astronautica, (66) 648-653.
[3] Mankala K K, Agrawal S K 2004 Dynamic modeling and simulation of impact in tether net/gripper systems, Multibody System Dynamics, (11) 235-250.
[4] Zhai G, Qiu Y, Liang B 2009 On-orbit capture with flexible tether–net system, Acta Astronautica, (65) 613-623.
[5] Yu Y, Baoyin H X, Li J F 2010 Modelling and simulation of space webs projecting dynamics, Journal of Astronautics, 1289–1296.
[6] Yu Y, Baoyin H X, Li J F 2011 Dynamic modelling and analysis of space webs, Science China Physics, Mechanics and Astronomy, (54) 783-791.
[7] Gärdsback M, Tibert G 2009 Deployment control of spinning space webs, Journal of guidance, control, and dynamics, (32) 40-50.
[8] Gärdsback M, Tibert G, Izzo D 2007 Design considerations and deployment simulations of spinning space webs, in: AIAA (Ed.) Proc. of 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference.
[9] Chen Q, Yang L P 2008 Dynamic modeling and simulation of orbital net-capture systems, in: The 14th CASI As-tronautics Conference, Montreal, Quebec Canada.
[10] Yu Y, Baoyin H X, Li J F 2011 Dynamic modelling and analysis of space webs. SCIENCE CHINA Physics, Mechanics & Astronomy, 54(4): 783-791.
[11] Benvenuto R, Salvi S, Lavagna M 2015 Dynamics analysis and GNC design of flexible systems for space debris active removal. Acta Astronautica, 110: 247-265.
[12] Boting Xu, Yueneng Yang, Ye Yan, Bin Zhang 2019 Bionics design and dynamics analysis of space webs based on spider predation[J]. Acta Astronautic, 159: 294-307.