Research on Assembly Technology of Complex Flexible Out-cabin Motional Cable for Spacecraft

Chunsheng Yang, Yi Lu, Yu Wang, Feng Xue and Zhenyue Ren
Beijing Institute of Spacecraft Environment Engineering, China

Abstract. Based on the application of flexible cable assembly simulation analysis technology in complex flexible out-cabin motional cable assembly of spacecraft, the working environment and physical characteristics of flexible motional cable are analyzed, reasonable assembly constraints are planned, and cable assembly simulation analysis is described in detail. The research results not only ensure the accuracy and practicability of the design, but also reduce the assembly defects and product failure rate. The actual effect of cable assembly can be accurately judged, the product performance can be improved, the product development cycle can be saved, and the development cost can be significantly reduced.

1. Introduction
Cable assembly technology is widely used in spacecraft assembly integration. There are many factors affecting cable assembly performance. Especially the assembly of large-scale moving cable is basically based on physical prototype test. The simulation assembly test method of prototype is inefficient, with much dependent on manual experience, so it has high cost and long development cycle, which can not meet the development needs of the current aerospace industry. In order to solve these problems, virtual assembly technology of flexible cables has been extensively studied in domestic and foreign institutes to replace the traditional physical model test method. [1] However, in recent years, the research on cable virtual assembly at home and abroad still remains in the aspects of semi-automatic and full-automatic cable, optimization of pipeline layout design algorithm and ergonomics analysis of man-machine interactive wiring in virtual environment, rarely considering cable dynamic assembly process. [2]

Spacecraft cables are complex in variety, with large number and complex laying process. However, cables are always belong to non-linear flexible body with large deformation. [3] Therefore, the assembly technology of flexible moving cables becomes an unpredictable risk point in spacecraft assembly integration design. The assembly effect of cables will directly affect the success or failure of space missions. Relevant research work needs to be carried out. In the stage of process design, detailed process parameters of cable assembly are formed, and the working state of the motional cable on orbit is accurately predicted. Problems such as extrusion, pulling and collision of the cable are avoided, so as to improve the assembly quality and efficiency of flexible moving cable for spacecraft. [4] [5]

Based on the complex flexible cables of a second-generation data relay satellite, this paper studies the simulation analysis technology and application of flexible cables assembly.

2. Analysis of Design Characteristics of Out-cabin Motional Cable

2.1. Structural Characteristics of Extravehicular Motional Cables
The out-cabin cables of a second-generation data relay satellite are fixed as a whole with several cables of different specifications. They are installed outside of the spacecraft. They have the...
characteristics of long-time and large-angle movement around two directions and large span between fixed points. The cable lies along the outer surface of the spacecraft cabin, passes through the fixing bracket, and then extends into the high-frequency module, as shown in the following figure. A large umbrella antenna is installed on the module. Through the movement of the module with antenna, the user satellite can be positioned accurately and the relay communication between the ground station and the user satellite can be ensured. The two-axis driving mechanism is installed on the side of the high-frequency module, and the other end is installed on the fixing bracket. The dual-axis driving mechanism has two rotating functions (rotating around the azimuth axis of X from -20 degrees to +46 degrees, rotating around the elevation axis of Y from -20 degrees to +20 degrees). By controlling and adjusting these two degrees of freedom, the orientation of the high-frequency module can be determined and continuously changed when it is in orbit. The two-axis driving mechanism rotates around its two orthogonal axes, so that the high-frequency module is separated from the surface of the cabin and rotates in two directions accordingly. Movable cables follow the motion of module to achieve long-term complex follow-up in three-dimensional space.

![Figure 1. Schematic diagram of position of extravehicular moving cables](image)

Because out-cabin cables are the only transmission channel connecting spacecraft and high-frequency module for data and power signals, so the cables contain a number of low and high frequency cables of different specifications. At the same time, the thermal control and radiation environment requirements for the cabin are arranged outside the cabin. The cables outside the cabin are inlaid with constantan heating wires, and the cables outside are covered with metal shielding tubes and thermal control multilayers. It can be seen that this cable is a complex combination of various materials. The physical parameters related to the motion characteristics need to be obtained by means of experiments.

2.2. Assembling Process Analysis of Out-cabin Motional Cable

Combining the layout trend, installation position, structural characteristics, movement characteristics and fixed point spacing of the cables outside cabin, it can be judged that the assembly of the cables is very important. It is necessary to ensure that the cables follow freely in the course of driving the high-frequency module by the two-axis driving mechanism, without hindering the movement of the modules and the two-axis driving mechanism, without generating additional resistance. Its structural components should not interfere and scrape with others, while the cable itself is not allowed to be abnormally squeezed and pulled, to ensure that the cable can transmit data and power signals stably in the long-term movement process.

Therefore, it is necessary to analyze and study the assembly process of flexible out-cabin motional cables, which mainly includes the following three aspects:

1) Determine the appropriate cable direction, reserved length and fixed mode;
2) To meet the requirement of safe distance, the forces acting on the cables and the clearance between the cables and the rotating structure are analyzed and studied after many times rotation of cables.  
3) Under the excitation of harsh vibration environment at launch stage, the force and swing amplitude of cables outside cables under vibration are analyzed. 
These characteristics bring great difficulties to process design, and can not meet the above requirements through conventional virtual assembly research. It is necessary to use flexible cable simulation technology to get the instantaneous state of cables under dynamic conditions, and then work out the process parameters that meet the requirements, so as to realize the smooth assembly of cables.

3. Simulation and Analysis Technology of Flexible Cable Assembly
In traditional mode, the assembly analysis of cables is generally based on the judgment of the rationality of cable path in three-dimensional modeling software, and the path planning from the beginning to the end does not take into account of the physical properties of cables, such as elastic modulus, density, Poisson's ratio, etc. As a result, the state of the cable can not be effectively evaluated after the design, such as whether to reach the minimum bending radius, whether to reach the maximum pulling force of the cable and so on. It is impossible to analyze the motion state of the cable when it moves with other parts. As for whether the cable meet the target after assembly, can the conclusion be drawn by assembly and test in practice after the physical prototype has been built. In this way, it not only consumes a lot of time and test costs, but also causes certain losses to the quality of cable products.

The simulation analysis technology of flexible cable assembly is to enrich the cable by acquiring the material property parameters of the cable. It is not a simple curve, but a more realistic spatial motion mechanism. At the same time, it sets the motion constraints of the cable, and the virtual simulation obtains the real work and movement process of the cable. The main approaches are as follows:

1) Using physical experiments to test the real material properties of cable, such as external diameter, tensile strength and so on. For cables with different wiring harnesses but the same material properties, it can be obtained from the data base without physical experiments.
2) Using the special simulation analysis software for flexible cables. After importing the cable model, the real material attributes are assigned to the cable in the model, and the connection form of the cable's beginning and end is pretreated. Flexible simulation engine generates flexible cables in virtual reality environment through cable model transformation. The solver can display the safety of cable tension, bending and torsion in real time, and can obtain safe and reasonable flexible layout and length by reflecting the safety of different color materials, and output the cable as a general three-dimensional data model.

3) Restrict the behavior between flexible cable and motion mechanism. The built-in behavioral engine of moving parts in the software can define the constraints of axial displacement, axial rotation,
composite motion and composite motion of a single component in the model. Behavior constraints can define the range of motion of a single component in translation or rotation, or the behavior of components after reaching the constraint limit, so that components can have more complex behavior, so as to obtain more realistic digital virtual prototype. Through this module, the motion relationship between the components of the spacecraft is established, and the motion of the rigid parts is related to the flexible cables. The motion relationship between the flexible cables and the rigid parts is established, and the state of the cables in the process of following the rigid body motion is investigated. 4) The animation module is used to generate the motion simulation animation of the whole component or component related to the cable. The animation of individual components and assembly will be saved and recorded in the form of key frames, which can support editing, modifying and flipping of key frames, and support multi-level composite motion. In the case of lossless shape accuracy, lightweight publishing of models and scenes can be realized to ensure the fluency of large and complex assembly work.

4. Research on Assembly Process Technology of Out-cabin Motional Cable

In this study, the technology described in the second section of this paper is used to conduct physical tests combined with flexible simulation. First, the physical properties of cables, such as elastic modulus and tensile strength, are calculated by experimental tests. Then the measured physical attribute data are input into the ICIDO simulation software, and the overall layout and motion state of the cable are simulated and analyzed by using the powerful flexible pipeline simulation function of ICIDO software.

Firstly, the initial design state of the flexible cables is analyzed and verified. The design length of the cable in the long-term moving section of the initial design state is 1040mm, the outer diameter of the cable is 20mm, the minimum bending radius is 60mm, and the maximum pulling force is 2144N according to the physical test results.

4.1. Assembling Analysis of Initial Design State

Under the initial state condition, Over bending occurs because the bending radius of the cable is less than the critical value of the minimum bending radius. At the same time, the minimum distance between the cable and the left limit rod is 5.54 mm, and the minimum distance between the cable and the right limit rod is 4.75 mm. So there is no interference between the cable and the two limit devices in the natural state.

![Figure 3. Performance analysis of cables in initial design state after assembly](image)

The cable state of flexible motional cables after rotating around X azimuth axis and Y elevation axis respectively is analyzed.
For example, after rotating around Y elevation axis + 20 degrees, the cable overbends at both upper and lower pipe ports, meanwhile the cable collides with the left limit bar(as shown in figure 4).
Figure 4. Performance analysis of cables in initial design state after rotating around Y axis
It can be seen that in the initial design state, the assembly of the cables will not only force the cables, but also affect the movement of the high frequency box and the driving mechanism. So the initial design state needs to be optimized.

4.2. Optimizing Process and Analysis of Flexible Cable Assembly Research
According to the analysis results of the previous section, it is necessary to gradually enlarge the length of the moving section of the motional cable, and then carry out multi-state analysis and testing according to the items of the previous section. When the length of the moving section of the cable is gradually adjusted to 1070 mm, according to the analysis of the same items mentioned above, the cable has no over-bending state and has not collided with the two limit poles.

Figure 5. Analysis results after optimizing the moving section of cable with 1070mm length
### Table 1. Structural comparison of cables after optimization of design status

| No. | Analysis content                  | Cable movable length                                                                 |
|-----|----------------------------------|--------------------------------------------------------------------------------------|
| 1   | Initial assembly, no rotation    | 1040mm (initial value before optimization)                                           |
|     |                                  | 1070mm (final value after optimization)                                              |
|     |                                  | The whole cable is in normal condition. The cable has no contact with the two limit poles and no over-bending occurs. |
| 2   | Rotate - 20 degrees around X axis | The current state of the cable is consistent with the initial assembly state.       |
|     | Rotation around X axis + 46 degrees | The cable is partially over-bended and touches the right limit rod.                 |
| 3   | Rotation around Y - 20 degrees   | The minimum distance between the cable and the left limit rod is 6.79 mm and the right limit rod is 1.58 mm. |
|     | Rotation around Y + 20 degrees   | The cable collides with the left limit rod.                                        |
|     |                                  | There is no over-bending phenomenon and cable don’t contact with the limit rod.      |
|     |                                  | The cable does not touch the limit rod without over-bending phenomenon.              |

4.3. Analysis and Research on Vibration Environment of out-cabin Motional Cable

When the cables are launched, the high-frequency module and the two-axis driving mechanism do not rotate. Under the same vibration excitation conditions as the actual situation, the vibration analysis of the cables with the high-frequency module and the two-axle drive mechanism is shown in the following figures.

![Figure 6. Analysis effect diagram of cables outside cabin under vibration condition](image-url)
The green area in the figure is the envelope area formed by the cable sweeping with the high-frequency module during vibrating. As shown in the figure, the maximum position width of the envelope is 44.10mm, and there is no interference with other structural mechanism components.

4.4. Application Results for Actual Assembly

According to the above research results, through the analysis of cable status of out-cabin motional cables under different working modes, the corresponding measures in the actual assembly process can be obtained.

(1) If the reserved length of the moving section of the cable is not less than 1070 mm, the collision between the moving cable and the right limiting rod occurs when the cable rotates around the X axis + 46 degrees, and the repeated scraping and collision with the left limiting rod when the cable rotates around the Y axis + 20 degrees. Therefore, when transplanting, assembling and binding the fixed cable (moving section), it is necessary to ensure that the length of this section should not be less than 1070 mm.

(2) Considering the possible errors in the assembly process, it is necessary to take corresponding protective measures for the right side of the metal outlet of the moving cable within 126 mm, as shown in the following figure.

5. Concluding Remarks

In this paper, the assembly process of complex out-cabin motional cables is analyzed and studied. Obtain the physical properties of cables, design the route of cables, specify constraints, construct the simulation environment for cable assembly and dynamic analysis, and carry out flexible simulation research. In the course of this research, the selection of fixed points, protective measures, the stress condition under each limit state, the permissible bending radius, the range of motion under dynamic conditions, the analysis of the surrounding safety clearance and the oscillation amplitude of the
vibration environment of the cable are studied. Then a reasonable and feasible series of technological parameters are formed, and the effect of the cables after assembly can be done. Then we can make accurate analysis and judgment. Through the research of flexible cable assembly technology, it can effectively ensure the accuracy and practicability of design, reduce assembly defects and product failure rate, ensure product assembly quality, significantly save development cycle and reduce development costs. [6] [7] The successful application of this technology in laying complex flexible out-cabin motional cables for second-generation data relay satellites can provide reference and guidance for assembly design of other spacecraft products.

References

[1] Huang Yixin. Research on wiring of spacecraft and virtual prototyping of deformable objects[D]. Harbin Institute of Technology, 2012
[2] Du Hongwang. Physical modeling and configuration simulation for flexible cable[D]. Dalian Maritime University, 2014
[3] Wang Tongsu, Du Baorui. Research on Aircraft Cable Assembly in Virtual Environment. Aeronautical Manufacturing Technology, 2015(19): 52~55
[4] Feng Wei, Zhang Yanlei, etc. The Virtual Simulation Technology in Assembly Process Design of China’s Lunar Exploration Project II. Spacecraft Environmental Engineering, 2014 (6): 326-331
[5] Shen Zhong, Zheng Hongtao. Application of digital assembly simulation technology for complicated vehicle based on DELMIA. Missiles and Space Vehicles, 2015(6): 42~45
[6] Ritchie J M, Dewar R G, Simmons J E L. The generation and practical use of plans for manual assembly using immersive virtual reality [J]. Proceedings of the Institution of Mechanical Engineers (Part B), 1999, 213: 461-474
[7] Han Bing. Research on digital layout design of cable harness in aerospace products [D]. Harbin Institute of Technology, 2014