Research of Dynamics Simulation Platform for Spacecraft Container

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Abstract. Transportation is an important part of spacecraft launching mission. Container is the most important equipment to ensure transportation tasks. In order to overcome the shortcomings of the physical dynamic test of spacecraft container, based on the theory of rigid-flexible coupling dynamics, the dynamic model of the container-based spacecraft transport system is established. External excitation of the dynamic model is determined by obtaining track spectrum and identifying track condition. Using modular design, C/S architecture and navigation process, a simulation platform is built, which is designed for whole container lifecycle used in spacecraft missions.

1. Introduction
Spacecraft container is an electromechanical tooling device that realizes the functions of transit and transportation of spacecraft (figure 1 shows a Chinese spacecraft and its container). It is composed of multiple subsystems. In the process of design and use, it involves the cooperation of many specialized subjects such as force, heat and electricity. A large number of analytical simulations are performed during the formulation of the plan. Current physical transit test for functions is difficult to meet the growing spacecraft transportation safety requirements. In order to overcome the shortcomings of limited physical running test conditions and fewer measuring points, digital simulation and verification platform for the spacecraft transportation container urgently needs to be researched and developed.

There are many studies on the dynamics properties of spacecraft container. Bai et al. established the physical model of the container suspension system and established the model by dynamic energy method [1]. Tan et al. analyzed the spectrum analysis of the collected data by using the virtual instrument and developed the vibration test system of the spacecraft container, which can highlight the key point, retrieve the polar value and so on [2]. Based on the airlift package of a certain type of spacecraft, Xiao et al. introduced the design and development characteristics of the container and the test results of airlift test, which proved the rationality of the design of the container [3].

At present, the mechanical analysis model of the packaging box established during the container design and simulation process has potential shortages such as lack of unified management of simulation data, un-reusability of single simulation project. Simulation analysis method to optimize the container design and working condition environment is also lacked [4-5]. As a result, it is still necessary to evaluate the performance of the spacecraft container through a physical running test to see if it meets all required quality requirements. Based on the demand for improvement of design technology of spacecraft container, it is necessary to develop a digital container simulation verification
platform. In this paper, the dynamic simulation model of the container is established on the basis of structure of the spacecraft container and working condition of spacecraft, and the simulation analysis of the loading conditions of the spacecraft container during the railway transportation is realized.

![Spacecraft and its container.](image)

**Figure 1.** Spacecraft and its container.

### 2. Dynamic Simulation Model of the Container

#### 2.1. Container Dynamic Model

The spacecraft transport packing box system consists of a number of subsystems, including box, bracket, shock absorber, spacecraft and railway transporter (as shown in figure 2). The dynamics model of the system are described as follows:

![Modeling process of rigid-flexible coupling dynamics model.](image)

**Figure 2.** Modeling process of rigid-flexible coupling dynamics model.
The container system has complex structure and different stiffness components. For example, the stiffness of the box structure is large, while the structural stiffness of the bracket and the star is low. Therefore, in dynamic modeling, the components with large structural stiffness are equivalent to rigid bodies, and the structure with low stiffness and large elastic deformation is equivalent to a flexible body. The container system finally forms a rigid-flexible multi-body system. And the complete system equation is:

\[ \dot{p} = T(p)\dot{v} \]  

\[ M(p)\ddot{v} = F(p,v,c,s,t,u,\lambda) - G'(p,c,s,t,u)\dot{\lambda} \]  

\[ \dot{\dot{e}} = F_e(p,v,c,s,t,u,\lambda) \]  

\[ 0 = g(p,c,s,t,u) \]  

\[ 0 = b(p,v,c,s,t,u,\lambda) \]  

The p is a state vector of hinge position. The T is an angular transformation matrix. The v is a state vector of hinge velocity. The M is mass matrix. The F is force and moment vector produced by force element. The c is dynamic state vector of force element and control element. The s is algebraic state of the displacement and acceleration. The t is the time. The u is external input of the displacement and velocity. The \( \lambda \) is constraint force and moment. The G is Jacobian matrix of the constraint equation. The \( F_e \) is dynamic state equation of force element and the control element. The \( g \) is a constraint-dependent constrained algebraic equation. The \( b \) is a constrained algebraic equation dependent on algebraic state.

2.2. Modeling of Rigid-flexible Coupling Dynamics

Due to the relatively small rigidity of the bracket and the spacecraft, the bracket and the spacecraft need to be considered as flexible bodies in order to more accurately reflect the dynamics of the container system. The rigid-flexible coupling dynamic system equation of container-based spacecraft transportation system is rigid differential algebraic equation, which usually difficult to solve. The key issue is to choose a reasonable modality.

The rigid-flexible coupling dynamics modeling process of the container-based spacecraft transportation system is as follows (shown as figure 3):

Firstly, 3D CAD models of both bracket and spacecraft are properly simplified. In order to reduce the difficulty of meshing, small holes, chamfers, and minor structures that do not affect the modal frequency are eliminated. Then, a finite element model is established and meshed based on shell unit. Secondly, the finite modal analysis is performed according to the connection point between the bracket and its external structure. The resulting file is used to generate flexible input file by SIMPACK and used for dynamic modeling.

Finally, according to the modal file, a flexible body file of the package system is generated.
2.3. Simulation of Rigid-flexible Coupling Dynamics
The external excitation of dynamics is mainly determined by track spectrum and railway conditions. The track spectrum is a random excitation with a certain power spectrum distribution. As the track spectrum of the existing railway in China is not confirmed, the American track spectrum is generally used as track excitation. This paper adopts the power spectral density function referenced to the US five-level spectrum. According to the acceleration record of train, combined with the container-based transport system dynamics simulation, the power spectral density function coefficients of the US five-level spectrum are amended. This work makes sure the simulation results and the actual measurement results are close in probability and statistics. The specific process is shown in figure 4.

Railway conditions include information such as curve radius, superelevation, slope and so on. It is generally difficult to obtain data directly from relevant departments for research. In order to solve this problem, we used the known measured acceleration response information to obtain these data indirectly. The specific methods are as follows (shown as figure 5):

**Figure 3.** Modeling process of rigid-flexible coupling dynamics model.

**Figure 4.** Track spectrum acquisition method.
Firstly, according to the GPS longitude and dimension information, the corresponding railway line is found out from the map.

Secondly, interpolation points are defined for the curve part of the line in the map, and curve fitting is performed to derive the curvature radius.

Thirdly, according to the public railway design standards, two kinds of railway design rules can be found: (1) the corresponding relation between the radius of the curve and the superelevation. (2) The relationship between the radius of curvature and the length of transition curve. According to the above rules, we can deduce the actual railway's superelevation and length of transition curve of each curve.

Fourthly, according to the elevation information of GPS and the longitudinal acceleration of the container body, the slope parameter can be derived. As there is a certain tolerance in the GPS, more precise information of slope is available by analysis on the component of gravity in the longitudinal acceleration caused by climbing.

Finally, the dynamics simulation is carried out by using the line information combined with the track irregularity, and the obtained simulation results are compared with the actual test results to further correct the line conditions.

3. Development of Simulation Plantform

3.1. Plantform Requirement
The functional requirements of the platform include the following aspects:

- Management of the simulation projects.
- Management of simulation model library.
- Management of simulation template library.
- Fast building dynamics simulation.
- Silent action mechanics of analysis.
- Visualization of simulation result.
- Automatic generation of simulation report document.
- Management of the simulation working condition.
- Query, processing and management of test data.
- Management of the user information.

3.2. Platform Architecture
The final application of the simulation platform will involve the whole life cycle of spacecraft container, including its design, analysis, manufacture and application. At present, the expansion requirements of the various functional modules need to be taken into consideration in the design of the platform. In order to complete the modular design of the framework and build a strong data association, it is
necessary to have a deeper understanding of the business processes of product design, simulation, optimization, manufacturing, and testing. Aiming at the versatility, maintainability and extensibility of the simulation platform architecture, the following solutions are adopted:

Firstly, the system adopts the modular design idea and uses the matching management of user role - privilege - function module to establish the mapping relationship between the user and the function module.

Secondly, because of the diversity and complexity of the platform application, the platform adopts the C/S architecture. The client deploys the application for different users and the server centralizes management of most data. This architecture can solve the localization problem of complex commercial software.

Thirdly, considering ease of use, the design adopts navigation method and structure tree to make it easier for the user to understand and master the operation process. The Tab page is convenient for users to jump between operations.

The overall simulation process provided by the platform is shown in Figure 3. The modules of design, optimization and manufacturing are the interfaces for the simulation of the whole process of container in the future.

3.3. Platform Interface

Figure 7 and 8 are the dynamic simulation interface of the spacecraft container system. The selection of simulation topologies for new dynamic simulation conditions is shown in figure 5, and the results are viewed as shown in figure 6. Users can choose the corresponding results according to their own requirements.

![Figure 6. Navigation method for simulation.](image)

Figure 9 and 10 shows the package system dynamics test management interface. By reading the test data, the data can be visualized, and the test data can be used for time domain charts, statistical indicators, spectrograms, and filter analysis functions.
Figure 7. Interface of selection of simulation topologies.

Figure 8. Interface of display of simulation.

Figure 9. Visualization of test data.
4. Conclusion

Based on the information of the container and spacecraft structure, materials, and transportation, a rigid-flexible dynamic simulation model of container-based spacecraft transportation is established. By combining the dynamic environmental incentives collected from the actual railway test, the simulation analysis of the loading conditions during the railway transportation of the container was realized, and an easy-to-use dynamic simulation platform for the spacecraft container was built.

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