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Study on conditions of internally carried air-launched launch vehicles based on the virtual prototype technology①

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Abstract

A method based on the virtual prototype technology simulating the separation of a launch vehicle from its aircraft in the aircraft wake was proposed based on the internally carried air-launched launch vehicle program. In this method, the full-scale model of the aircraft, the vehicle and the parachute are constructed. Then, they are imported into the ADAMS software, constraint solutions and driving forces are then added for visual dynamic simulation. The unsteady aerodynamic forces of the vehicle in the aircraft wake are calculated by CFD and the moving grid technique. The forces generated by the parachute can be derived from the Kirchhoff motion equation. Through comparing and analyzing the simulation results under different launch conditions, it has been proven that this method simulates the separation of a launch vehicle from the aircraft in the aircraft wake accurately. It provides the foundation for the aggregate project of internally carried air-launch vehicles, and offers a new referenced method for multi-body dynamic simulation.

Key words: air launch, flight dynamics, virtual prototype, automatic dynamic analysis of mechanical system (ADAMS), parachute

0 Introduction

The technology of internally carried air-launched launch vehicles[1-3] is usually described as follows. When the transport plane arrives at the preset height, velocity, and course, the launch vehicle inside will be released from the cabin through gravity and tension from parachute line. After the vehicle rocket has ignition, the transport plane will return. One of the air-launched launch vehicle's key technologies is providing a way for safe separation between the launch-vehicle and the carrier, all the while allowing for optimal igniting altitude. The main research methods for internally carried air-launched launch vehicle consist of airdrop tests, wind tunnel experiments, ground-based simulations[4], computer simulations, etc. Experiments were conducted mainly abroad[5-8], which eases the stress on theoretical study and computer simulation at home[9-12]. Kang built a mathematical model for the separation between the launch-vehicle and the carrier in three stages. In all the three stages, the existential force generated by the parachute is simplified to a tensile force in the opposite direction of the suspension point' speed[9]. He built the nine degrees of freedom dynamic model for the vehicle-parachute system and carried out the simulation of the separation between the launch vehicle and the carrier. However he didn't factor in the influence of the flow field behind the transport plane[10]. In addition, Zhu disregarded influence imposed by carrier on the launch-vehicle in his flow field simulations[11].

In simplified terms, the separation of the launch-vehicle from the carrier can be defined in terms of typical multi-body dynamic system, but it has special added complexities related to the flow field around the transport plane. Because the parachute is far from the carrier, the wake flow influence on the parachute is negligible[13]. This paper exclusively examines the influence of the carrier on the launch-vehicle and not on the parachute. This paper first computes the launch vehicle's aerodynamic forces behind the flow field of the carrier using computational fluid dynamics (CFD), and then applies the parachute's aerodynamic forces on the virtual prototype model through the dynamic simulation software automatic dynamic analysis of mechanical system (ADAMS). The model will then provide a visual simulation of the separation of the launch-vehicle from the carrier. The framework of this paper is shown in Fig. 1. The goal is to get a new perspective on the interdisciplinary study between multi-body system dynamics and aerodynamics.

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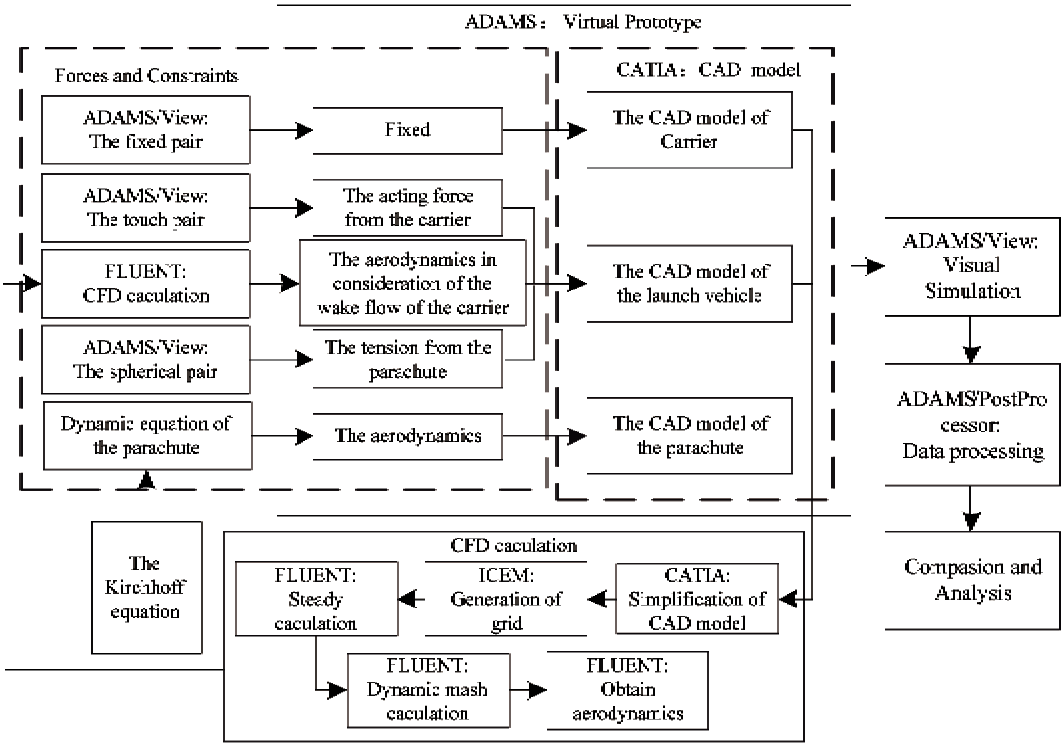

Fig. 1 Framework of simulation and analysis system based on the virtual prototype technology

1 Three dimensional modeling of the virtual prototype

A three dimensional solid model is constructed, and then analyzed in computer-graphics aided three-dimensional interactive application (CATIA) in accordance with the design parameter for the carrier, the launch vehicle, and the parachute. The model is then imported into ADAMS to add quality attributes. Fig. 2 shows three views of the virtual prototype model.

Fig. 2 The three dimensional solid model of internally carried air-launchedLaunch vehicle

2 Physical modeling of the virtual prototype

Physical modeling is done mainly in ADAMS, which allows for the expression of mechanical values. This is done through the addition of kinematical constraints, driving constraints, forces, and moments to the solid model in ADAMS. As a result, relative motions and drives among the components are defined and given mechanical prosperities. The physical model of prototype is shown in Fig. 3.

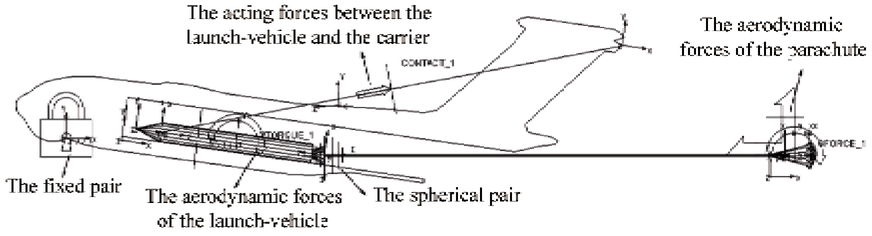

Fig. 3 The physical model of the prototype

2.1 Force analysis of the separation process

The extraction mechanics of internally carried air-launched launch vehicle has two stages: pre-extraction and post-extraction. As shown in Fig. 4, the acting forces imposed on the launch-vehicle in the pre-extraction stage contain the reaction force (N) from hold floor, gravity(G), aerodynamic force(R), the tensile force of the parachute(T), and the frictional force(f) between the launch vehicle and the hold floor. In the post-extraction stage, the launch vehicle is only effected by gravity, aerodynamics, and tensile force of the parachute. Throughout the entire process of extraction, gravity is constant, reaction force, aerodynamic force, and tensile force of parachute are related to the carrier's and the launch vehicle's motion state, and frictional force is associated with friction coefficient and reaction force.

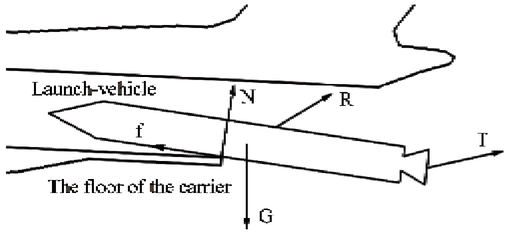

Fig. 4 Free-body diagram of the launch vehicle

2.2 The main constraints and aerodynamic forces

2.2.1 The acting forces between the launch vehicle and the carrier

The acting forces between the launch vehicle and carrier are accomplished by building contact forces on the solid model in ADAMS. The relative parameters refering to the contact forces such as friction coefficient, damping and so on can be set in the creation panel.

2.2.2 The aerodynamic forces of the launch vehicle

In this section, we will compute the aerodynamic forces of the launch vehicle behind the flow field of the carrier with CFD and moving-grid technology, in conjunction with dynamic model.

The following provides specific steps for the computation process, as shown in Fig. 5. First, the three dimensional models of the carrier and the launch vehicle are imported into the grid generator software ICEM CFD to mesh initial grid. The flow field around the launch vehicle is meshed by tetrahedron unstructured grid, the surfaces of the carrier and the launch vehicle are meshed by triangular unstructured grid, as shown in Fig. 6. Second, the unsteady aerodynamics of the launch vehicle are computed, and the values are plugged into the six degrees ballistic equations, which compute the position, attitude, and speed of the launch vehicle at any given time during the launch procedure. Next, the launch vehicle's position and attitude are updated, then the grids are regenerated by smooth elastic and constructional remodeling methods. In the next step, the aerodynamic forces of the launch vehicle are computed, then the values are substituted into the ballistic equations to get the ballistic parameters. The cycle repeats until the desired simulated conditions are met.

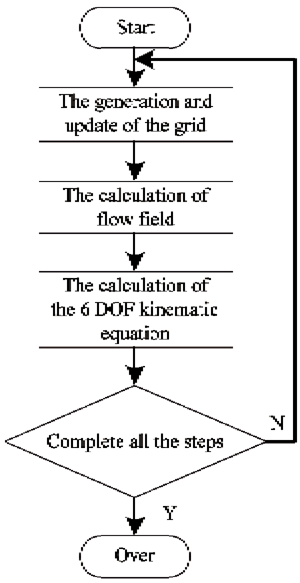

Fig. 5 Flow chart of the computation process

The aerodynamic parameter values are plugged into the equations listed below, with the given reference area, mean value of force arm, air density and velocity of far field, we can get the aerodynamic forces and moments of the launch vehicle.

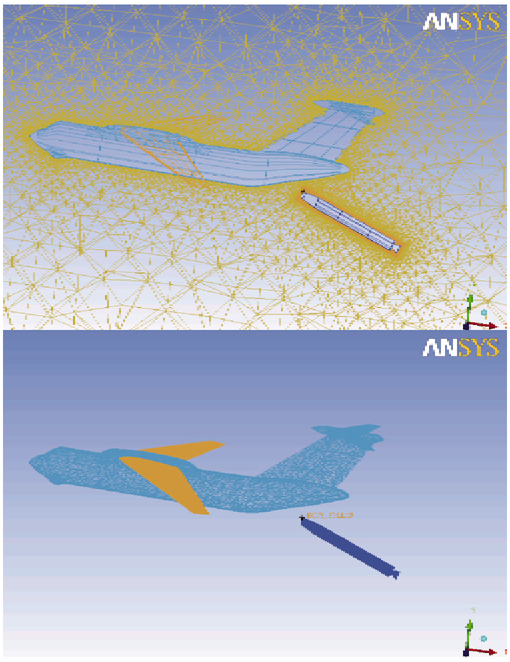

Fig. 6 the computing grid of the separation

$$\begin{cases} F_D = \dfrac{1}{2}\rho V^2 S C_d \\ F_L = \dfrac{1}{2}\rho V^2 S C_l \\ M = \dfrac{1}{2}\rho V^2 S L C_m \end{cases} \tag{1}$$

2.2.3 The aerodynamics of parachute

In this paper, we select the ribless guide parachute as simulation model. The dynamic modeling of the parachute is based on the following hypothesis.

(1) The parachute is axisymmetric.

(2) The origin of parachute-body coordinate system overlaps the center of aerodynamics.

The dynamic equations of the parachute are derived from the Kirchhoff equations. The vector form of the Kirchhoff equations can be written as

$$\begin{cases} \dfrac{d}{\mathrm{d}t}\left(\dfrac{\partial T}{\partial \boldsymbol{V}}\right) + \boldsymbol{\omega} \times \dfrac{\partial T}{\partial \boldsymbol{V}} = \boldsymbol{F} \\ \dfrac{d}{\mathrm{d}t}\left(\dfrac{\partial T}{\partial \boldsymbol{\omega}}\right) + \boldsymbol{V} \times \dfrac{\partial T}{\partial \boldsymbol{V}} + \boldsymbol{\omega} \times \dfrac{\partial T}{\partial \boldsymbol{\omega}} = \boldsymbol{M} \end{cases} \tag{2}$$

In Eq. (2), $\boldsymbol{T}$ is the kinetic energy of the parachute-flow system, $\boldsymbol{V}$ is the velocity, $\boldsymbol{\omega}$ is the angular velocity, $\boldsymbol{F}$ is the external force, and $\boldsymbol{M}$ is the external moment. Ref. [8] has deduced scalar dynamic equations in parachute-body coordinate system according to the equations above. According to the results, combined with the hypothesis listed previously, the dynamic equations of the parachute can be deduced as follows.

$$\begin{cases} F_x = (m + \alpha_{11})\dot{V}_x - (m + \alpha_{33})(V_y\omega_z - V_z\omega_y) \\ F_y = (m + \alpha_{22})(\dot{V}_y - V_z\omega_x) + (m + \alpha_{11})V_x\omega_z \\ F_z = (m + \alpha_{33})(\dot{V}_z + V_y\omega_x) - (m + \alpha_{11})V_x\omega_y \\ M_x = I_x\dot{\omega}_x + (I_z - I_y)\omega_y\omega_z \\ M_y = (I_y + \alpha_{55})\dot{\omega}_y + (I_z - I_x - \alpha_{56})\omega_x\omega_z \\ M_z = (I_z + \alpha_{66})\dot{\omega}_z + (I_y + \alpha_{55} - I_x)\omega_x\omega_y \end{cases} \tag{3}$$

where m is the mass of parachute, I_x, I_y and I_z are rotational inertias relative to the axis of parachute. α_{11}, α_{22} and α_{33} are associated mass along the axis of X_b, Y_b and Z_b in the parachute-body coordinate system, $\alpha_{22} = \alpha_{33}$. α_{55} and α_{66} are associated with rotational inertias along the axis of Y_b and Z_b in the parachute-body coordinate system, $\alpha_{55} = \alpha_{65}$. The constants above can be solved in accordance with Ref. [14], the others can be measured with measuring tool in ADAMS/View, with the survey point being the center of aerodynamics.

3 Simulation and analysis

In the separation process, the movement of the launch vehicle is affected by multiple factors. We select three main influencing factors to carry out the simulation based on the virtual prototype above, the pitch angle of carrier, the condition determining whether it is necessary to use the parachute, and the resistance characteristic of the parachute. The set altitude of the carrier is 10km, and the speed is 210m/s.

3.1 The influence of carrier pitch angle to the separation of a launch vehicle from the carrier

The pitch angle of the carrier adopted by the reshipment dropping technology is usually 3° – 8°. We select three pitch angles (3°, 5°, 8°) to simulate the varying effects on the launch-vehicle. Fig. 7 ~ Fig. 10 show the differences in launch-vehicle behaviors exhibited by different carrier pitch angles.

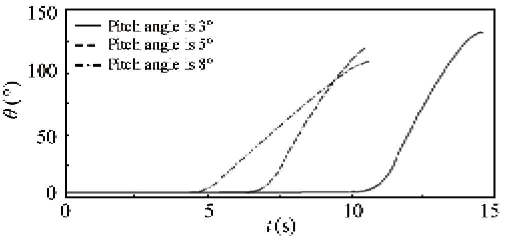

Fig. 7 The launch vehicle pitch angle variation curve

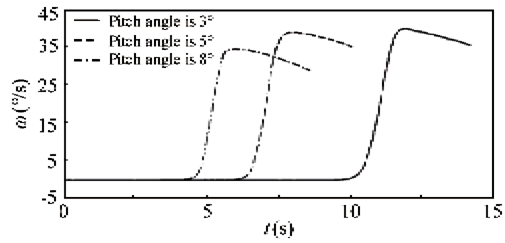

Fig. 8 The launch vehicle pitch angular velocity variation curve

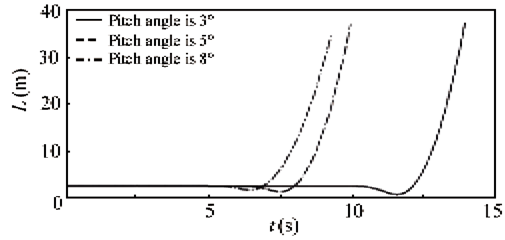

Fig. 9 The pallet distance variation curve

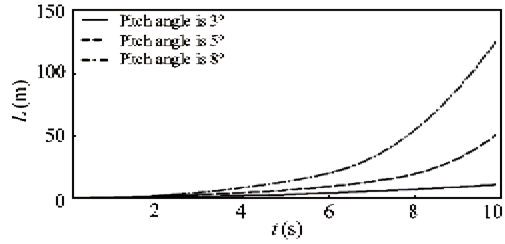

Fig. 10 The variation curve of the distance between the launch vehicle and carrier

These results show clearly that increasing the carrier pitch angle improves separation rate, reduces probability of launch-vehicle collision with the cargo celling, and optimizes the ignition altitude of the launch vehicle. However it is more difficult to drop the launch vehicle at a higher angle, and it places higher demands on the carrier's performance and flight crews' skills. So we need supplementary means to make the launch vehicle get the best igniting attitude.

3.2 The influence of parachute on the separation of launch vehicle from carrier

The parachute is strapped to the nozzle of the launch vehicle to decrease the angular velocity of the launch vehicle as it pitches during the extraction process and after the extraction. As the pitch angle of the launch-vehicle reaches a range of 75° ~ 90°, the angular vehicle should be near zero, as facilitated by the parachute. At this point, the launch-vehicle blasts off, burning the parachute cord. Fig. 11 ~ Fig. 14 show the simulation results of the separation of the launch vehicle from the carrier, the carrier pitch angle is set to 5°, the resistance characteristic of parachute is set to 3m^2.

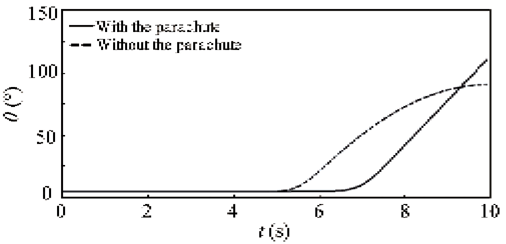

Fig. 11 The launch vehicle pitch angle variation curve

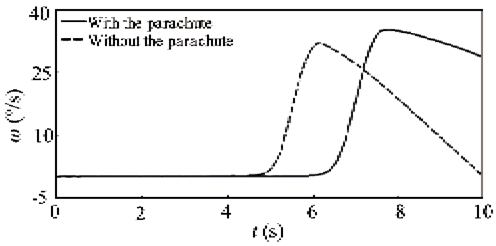

Fig. 12 The launch vehicle pitch angular velocity variation curve

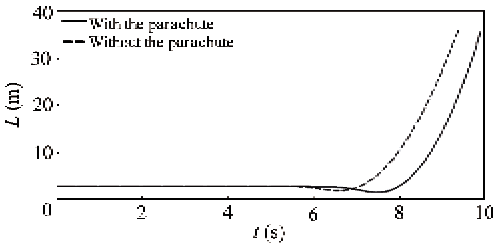

Fig. 13 The pallet distance variation curve

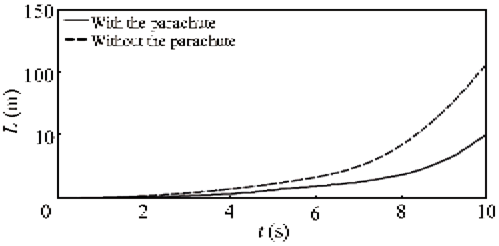

Fig. 14 The variation curve of the distance between the launch vehicle and carrier

The simulation results show that it will improve the separation rate, reduce the possibility that the launch vehicle hits the carrier ceiling as well as restrains the pitch angular velocity of the launch vehicle effectively to assure the launch vehicle reach to the best igniting attitude.

3.3 The influence of resistance characteristic of the parachute to the separation of a launch vehicle from the carrier

Three resistance characteristics of the parachute CA (2m^2, 3m^2, 4m^2) are tested to simulate what different effect resistance characteristic has on launch-vehicle behaviors. Fig. 15 ~ Fig. 18 show the simulation results of the separation of launch vehicle from carrier.

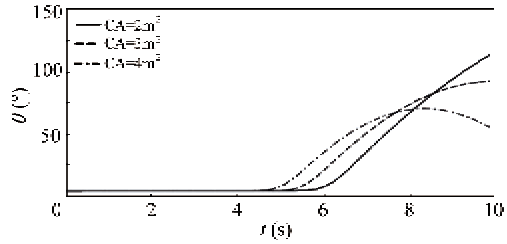

Fig. 15 The launch vehicle pitch angle variation curve

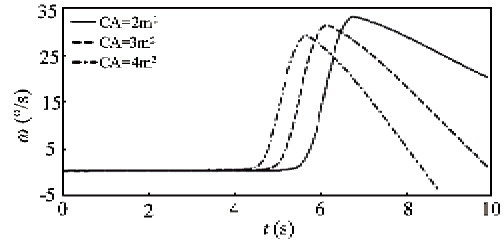

Fig. 16 The launch vehicle pitch angular velocity variation curve

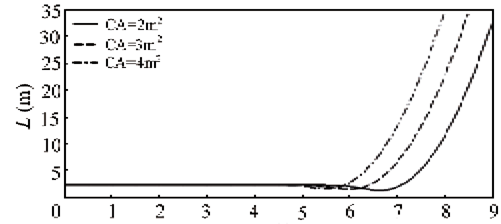

Fig. 17 The pallet distance variation curve

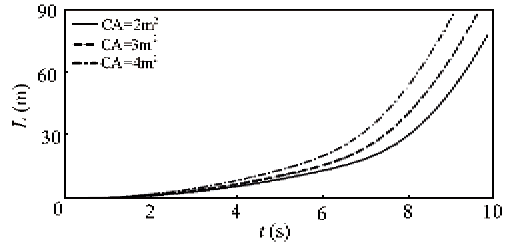

Fig. 18 The variation curve of the distance between the launch vehicle and carrier

The simulation results show that the increase of resistance characteristic can increase resistance to the pitch motion of the launch vehicle, decrease the maximum pitch angle and the pitch angular velocity, improve the separation rate, and reduce the possibility of the launch vehicle hitting the carrier ceiling.

4 Conclusion

In this paper, a virtual prototype platform has been built based on the three dimensional CAD software CATIA, CFD software Fluent, and dynamic simulation software ADAMS to simulate the separation process of internally carried air-launched launch vehicle from the carrier. The dynamic simulation depicts the influence of carrier pitch angle, parachute and resistance characteristic of parachute on the behavior of the launch vehicle during the separation process.

This article more thoroughly explores the research method for the internally carried air-launched launch-vehicle technology on the basis of the previous research. In this exploration process, we found that there are still several problems to be perfected and improved. These problems include:

(1) This paper doesn't consider the movement of the carrier, but assumes the carrier maintains the initial pitch attitude the entire time. During the actual process of extraction however, the barycenter of launch vehicle-parachute system changes significantly, which influences the carrier's attitude, even has a significant impact on the safety and success of the separation.

(2) In this paper, we don't take the influence of the carrier wake flow on the parachute into account. There is a lot of nonlinear hydro-mechanical phenomenon in the study of the parachute flow field which is needed to build the high-real model and it is important in obtaining a more precise result in the algorithmic calculation. We plan to carry out a numerical simulation of the dropping process in the carrier flow field based on the SIMPLE algorithm.

(3) The air-launch launch-vehicle system is a multi-body system which contains flexible components. After extraction, the parachute will move extensively. So, we need to consider the contradiction between the distortion of the flexible components and large motion to build high precise models. This is also a difficult issue in the study of multi-body system rigid-flexible coupling dynamics.

(4) The launch vehicle is simplified as a rigid in this paper, and the effects caused by the sloshing of the fuel on the launch-vehicle are ignored. However, the low frequency vibration of the liquid fuel can easily resonate to the structural vibration caused by the parachute. Also, the sloshing of large amount of fuel can cause unsteadiness of the carrier, which can cause impact to the launch-vehicle with adjacent contact surface. This could potentially have a great effect on the attitude control and the stability of the launch-vehicle. So, we will scrutinize this issue further in future research project.

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