Performance Evaluation for Optical Measurement-Based Non-Holosymmetric Rocket at Taking-Off Stage

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Abstract. This paper has proposed effective measuring methods for feature points aiming at the unique and particular structure of “non-holosymmetric” carrier rocket, using the rocket imaging information obtained through optical measurement in launch vehicle range, and established a mathematic model about the threaten influence of the carrier rocket on the tower at taking-off stage, and conducted qualitative and quantitative analysis; At the same time, the calculation model of rocket’s posture speed and acceleration established is used for analyzing the carrier rocket’s flying state. Availability of the method has been proved through actual application, which has provided effective technical support for performance analysis of the carrier rocket’s vertical flight stage.

1. Introduction

Some type of carrier rocket is a large-scale three-level liquid bundled carrier rocket; it is consisted of another type of carrier rocket adaptively modified, which is treated as the core level, and two liquid fuel boosters bundled\cite{1}, such unique “Non-holosymmetric” carrier rocket is the sole in long march series\cite{2}. Its carrying capacity has filled a blank of high-orbit capacity in China, and really formed serialization of rocket’s carrying capacity. This type of carrier rocket is mainly used for launching task of GTO orbiting satellite, so that, carrying capacity of GTO orbiting satellite can be up to 2600-5500 KG\cite{3}, which has strong competitive capacity in launching market of international commercial satellite.

As is well-known, in launch vehicle range, the carrier rocket will vertically fly for a long time after the engine being ignited. In theory, vertical flight stage of the carrier rocket is only driven by vertically downward earth gravity along axis of the rocket body, and vertically upward engine thrust, so that the rocket can fly vertically upward. But the carrier rocket is jointly affected by many factors inside and outside of the rocket, such as environmental disturbance, the fuel is uneven; structure of the rocket is imbalance, shaking of the rocket, vortex, and wind power etc. So that the flight path of the carrier rocket at taking-off stage is not completely upward in vertical, there is a gradual drifting with the time. Because the carrier rocket adopts “Non-holosymmetric” structure, at the same time, it shall also leap out of the tower after vertically taking-off and enter the aimed launching direction, and the largest challenge is the balance in flying process. Therefore, it is very important to conduct qualitative and quantitative evaluation, performance evaluation, and evaluation of safety margin to such type of rocket.

In this paper, the performance of “non-holosymmetric” rocket at taking-off stage has been evaluated on the basis of optical measurement. And threat of the carrier rocket at vertical taking-off stage to the tower has been analyzed, in addition, changing trends of the rocket body’s tilt degree, the posture, tilt speed and acceleration of the rocket body have also been analyzed. In order to conduct...
comprehensive analysis to flight process of the “non-holosymmetric” rocket by sufficiently using the means of optical measurement, to provide effective data basis for sizing or modification of such type of carrier rocket.

2. Analysis Methods

A large number of launching tests for carrier rockets at home and abroad have been proved that drifting of carrier rocket at vertical taking-off stage is inevitable, and there also is enormous risk in the drifting. The taking-off period is short, the failure hazard is large, the safety measures often can’t play roles, therefore, in the international spaceflight history, there was the precedent that the carrier rocket upset the launching frame, and there also was the precedent that the carrier rocket fallen near the launching site shortly after taking-off. Therefore, it is very important to find and analyze the reason of the special carrier rocket’s transverse drifting, inspect and eliminate the potential factors resulting in the rocket’s drifting for improving the rocket’s structure, improve performance of measuring and launching system and improving safety of the launching process.

For flight performance analysis to the new type of “non-holosymmetric” rocket, transverse drifting of the rocket body at the stage of vertical taking-off shall be analyzed, in addition, changing trends of the rocket’s tilt degree (especially direction of the tower), tilt speed and acceleration shall also be analyzed, so that flight situations of the rocket can be comprehensively mastered.

2.1. Analysis for Threat of the Rocket to the Tower Direction

The so-called vertical flight stage of the rocket refers to the period from ignition of the rocket’s engine, connection of the taking-off contact to flying out of the tower. The total heights of the tower and lightning - protection tower on top of the tower are about 100 m, the rocket body must safely rise at vertical taking-off stage to exceed the tower, so that the threat to tower can be avoided. In the period of launching, if the rocket needs longer time to fly out of the tower, it may bring larger damage to the tower. If thrust of the two boosters is different, so that the rocket drifts toward the tower, it also may strengthen threat to the tower.

If some type of “non-holosymmetric” carrier rocket takes longer time for flying out of the tower, and flies by climbing over the tower, it will strengthen the threat to the tower. Therefore, for the launching of new-type of rocket, it is necessary to conduct modeling calculation and analysis to drifting of the rocket in OT (The original point is the launching point of the carrier rocket, it points to axis direction of the tower) direction.

2.1.1. Measuring methods

In launch vehicle range, tracking measurement to the carrier rocket at vertical taking-off stage is completed with high-speed TV measuring system. Figure 1 is the outside view of “non-holosymmetric” carrier rocket. From the figure, we can find that there are many blue measuring rings on the rocket body, purpose of such spraying design is to measure the carrier rocket’s transverse drifting and posture at vertical taking-off stage.

![Figure 1. Outside View of Some Type of “Non-full symmetric” Carrier Rocket](image-url)
For the rocket body with many measuring rings, the rocket’s overall rigid body effect must be considered when the measuring points for rocket’s transverse drifting and posture are selected; the rocket can’t be evaluated as an approach mass point. Therefore, for the imaging situations of carrier rocket taken with optical tracking and measuring according to actual combat tasks, two measuring rings that the interval between them is the largest shall be selected as far as possible, thus can possibly achieve complete evaluation to the carrier rocket’s overall rigid body’s drifting and posture.

2.1.2. Calculation model
The calculation methods about the carrier rocket’s transverse drifting have been described in detail in the literature [4], here not describes them again. For threat of the rocket body to the tower at vertical taking-off stage, the general formula of (1) is got according to the geometrical relationship between the rocket body and tower, with calculation derivation, as well as calculation and analysis to different situations of the four quadrants:

\[
\Delta OT = \Delta r \cos (A_0 - A_{OT} + A)
\]  
(1)

Where,
- \(A\) refers to the drifting azimuth angle (recorded in clockwise) in launching coordinates;
- \(A_0\) refers to the launching azimuth angle;
- \(A_{OT}\) refers to the included angle between true-north direction and the plane of original point and tower’s axle line, with original point of the launching coordinates as the vertex, the direction in clockwise is positive direction;
- \(\Delta r\) refers to the drift distance,
- \(\Delta OT\) refers to the component of the drift distance in OT direction.

2.2. Analysis for Changing Trends of the Rocket Body’s Tilt Speed and Acceleration
The trend analysis for changing trends of the rocket body’s tilt speed and acceleration mainly means to the evaluation and analysis conducted according to the carrier rocket’s parameters in pitching and tilting postures. For specific determination methods about the carrier rocket’s posture, see the detailed description in the literature[4]. This section mainly describes the calculation and analysis of the carrier rocket’s speed and acceleration changing with the time.

In general, the speed and acceleration are analyzed with polynomial fitting differential method. Using orthogonal polynomials \(\{P_k(i)\}\) and its L derivative \(\{P_k^{(1)}(i)\}\):

\[
P_{k+1}(i) = P_1(i)P_k(i) - \frac{K^2(N^2 - K^2)}{4(4K^2 - 1)} P_{k-1}(i)
\]
(2)

\[
P_{k+1}^{(1)}(i) = P_1(i)P_k^{(1)}(i) + LP_k^{(1-1)}(i) - \frac{K^2(N^2 - K^2)}{4(4K^2 - 1)} P_{k-1}^{(1)}(i)
\]
(3)

Where,
- \(K = 0,1,\ldots, m\);
- \(i = 1,2,\ldots N\);

Central differential smoothing calculation:

\[
\frac{\bar{s}^{(1)}}{N+1, \frac{N}{2}} = \frac{1}{[(l+1)h]^h} \sum_{i=-l}^{N-l} W_{N-1}^{(0)} s_{i+(i-1)h}
\]
(4)

Where,
\[ W^{(0)}_{N-i} = \sum_{K=1}^{m} P_K(i) P_K^{(L)} \left( \frac{N+1}{2} \right) s(N, K), \]

\[ S(N, K) = \frac{(K!)^4}{(2K)! (2K+1)!} \prod_{j=K}^{K} (N - j) \]

End point differential smoothing calculation:

\[ \overline{\xi}_{N+(N-1)l}^{(L)} = \frac{1}{[(l+1)h]^l} \sum_{l=1}^{N} W^{(1)}_{N-i} \xi_{l+(i-1)l} \]  

Where,

\[ W^{(1)}_{N-i} = \sum_{K=1}^{m} P_K(i) P_K^{(L)}(N) \frac{s(N, K)}{s(N, K)} \]

3. Data Analysis

In more than 10 times of launching of “non-holosymmetric” carrier rocket, the same launching direction was used, and station distributions of the high-speed TV measuring system were the same, therefore, for description, this paper adopts simulation data of some task to calculate the drifting of the rocket body relative to the tower direction at the stage of taking-off for analyzing threat to the tower; while, the calculation to changing trend of the rocket’s tilt speed and acceleration is used to analyze the influence of power on the carrier rocket’s posture.

3.1. Data Case Analysis for Threat of the Rocket Body to Tower Direction

Figure 2 and 3 refer to the drifting of two measuring rings selected on the carrier rocket relative to OT direction.

![Figure 2. The Data Figure for Drifting of Measuring Point 1 in OT Direction](image1)

![Figure 3. The Data Figure for Drifting of Measuring Point 2 in OT Direction](image2)

The station clearance value (the distance between the launching point and the tower’s first two supporting columns) of the “non-holosymmetric” carrier rocket used for launching is more than 10 meters wide, and height of the tower is about 100m. The drifting data in OT direction of Figure 2 and 3 evidently shows that: Before about 1.6s, the carrier rocket showed slight swing in OT’s positive and negative direction, and then, there was drifting without exceeding 1 meter in OT direction before the rocket flying out of the tower, which is far less than the clearance value, therefore, the rocket can’t cause threat to the tower, meeting design results for flying of the rocket. And the whole rocket body
flew out of the tower within 7.6 s. The results show that dynamic design of the two boosters at vertical taking-off stage is scientific, reliable and safe.

3.2. Data Case Analysis for Changing Trends of the Rocket Body’s Tilt Speed and Acceleration

Similarly, the simulation data of some task is used to calculate and analyze the carrier rocket’s changes in speed and acceleration. Figure 4 ~ Figure 5 respectively are the data figures of pitch angle speed and acceleration; Figure 6~Figure 7 respectively are the data figures of yaw rate and acceleration.

![Figure 4. The Data Figure of Pitch Angle Tilt Speed of the Rocket Body](image1)

![Figure 5. The Data Figure of Pitch Angle Tilt Acceleration of the Rocket Body](image2)

![Figure 6. The Data Figure of Yaw Angle Tilt Speed of the Rocket Body](image3)

![Figure 7. The Data Figure of Yaw Angle Tilt Acceleration of the Rocket Body](image4)

Figure 4-Figure 7 show that the rocket body’s pitch angle and yaw angle were changed slightly before 7s, and the speed was stable; while, 7s later, the rocket body’s pitch angle, yaw rate, and acceleration were changed evidently, which showed changes of the rocket body’s posture and meant that the rocket would transferred to programmed turning stage after completing the vertical taking-off task. Flying state of the carrier rocket at the whole vertical taking-off stage from ignition to flying out of the tower completely met the design requirements.

4. Conclusion

Through utilization of the methods above, and through calculation and analysis for the carrier rocket’s transverse drifting in OT direction, the rocket body’s tilt degree and posture, the following conclusion can be obtained: From actual flying situations, the two boosters of “non-holosymmetric” carrier rocket
met flying performance design and requirements at vertical taking-off stage, that is, from ignition of the rocket, taking-off to completely flying out of the tower. Successful application of “non-holosymmetric” carrier rocket has established a technique foundation for development of non-axisymmetric carrier rocket in China, and it has also made the distribution gradient of high-orbit carrying capacity of China more reasonable, and made posture stability and control technology of carrier rocket of China up to advanced level all over the world, and met the development demands of space technology in the future.

The evaluation technology research based on optical tracking and measuring is always the exploratory direction of external trajectory data processing. We believe that the more and better evaluation methods and technical means will be expanded though continuous profound research.

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6. References
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