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The Wind Tunnel Test Method of Airframe-propulsion Integration for Rocket-based Combined Cycle Launch Vehicle

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Abstract

The Rocket-based combined cycle (RBCC) engine is effective propulsion for the launch vehicle, but it will produce complex design problems, especially for the airframe-propulsion integration. This paper is mainly on the research on wind tunnel test and test method. The test relationship is established to obtain the performance of the airframe-propulsion integration. The test results are corrected by CFD. The scaling effect and the correction of flight test and ground test are also discussed in this research. The relationship of components' test and integrated test is cleared, and the corrected method will establish the database of the launch vehicle's performance, which can be used to direct the design of such vehicle. The specific works will be given in the full text.

Keywords: *RBCC, Wind Tunnel, Test Method, Airframe-Propulsion Integration*

Nomenclature

F_A - Axial force
T - Trust
I_{sp} - Specific impulse
$I_{sp,eff}$ - Effective specific impulse

1. Introduction

Comparing with rocket engine, air-breathing propulsion has a benefit to carry payloads to space with less fuel. But such engine can't work by itself. Therefore, rocket based combined cycle (RBCC) engine is a more efficient way to take the payloads to the orbit from ground. It's necessary to study RBCC vehicle with the development of space transportation technology. The RBCC launch vehicle works in wide envelope, which contains dense atmosphere and thin atmosphere. The flight speed has a wide range. According to different tasks, propulsion system may include rocket, ramjet or scramjet modes. All these have brought great challenges to the design of launch vehicle. The related technologies needs to be verified by wind tunnel test.

In the Hyper-X program, the United States had used the hypersonic wind tunnel at the Langley Research Center and the Arnold Engineering Development Center, but still cannot cover all the Mach numbers of the aerodynamic database [1]. With the increase of Mach number, it is difficult to correctly simulate the flow state of the real flight conditions by the ground wind tunnel. It is necessary to carry out the correction of the wind tunnel experimental data. From 1860s, Bushnell, Dietzet, McKinney and Sim had carried out a large number of works, including the correction of Reynolds number, tunnel wall, bracket and so on [2]~[5].

NASA and the air force of the United States classified the aerodynamic configuration by the ratio of lift to drag based on wind tunnel test. Therefore, the aerodynamic performance can be related in

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wide range of Mach number and Reynolds number, and the data of ground test can be extrapolated to the real flight condition. Among them, Whitfield and Griffith studied the effect of viscous drag on a blunt configuration by Tsien 'slip parameters', which can associate viscous drag and aerodynamic performance.

For the large scale test model such as NASP [6], it is not realistic to carry out the ground wind tunnel test of the real model completely. It is very important to carry out the study on scale effect problem of the launch vehicle. In addition, it is vital to develop the integrated processing method of the data of all wind tunnel tests.

This paper mainly aims at the problems of the wind tunnel test for RBCC launch vehicle. The various tests are planned, and the method to manage the test data is established for the airframe-propulsion integration of the launch vehicle. All the methods can be used to establish the database of vehicle's performance, and guide the design of the launch vehicle.

2. The problems of airframe-propulsion integration for RBCC launch vehicle

The advantages and disadvantages of the design for airframe-propulsion integration must be evaluated by reasonable performance. The force interface of aerodynamics and propulsion is the key to obtain the performance.

The force interface of 'Top-to-Tail' is shown as Fig.1, which can reduce the coupling of aerodynamics and propulsion, and it's more reasonable for describing the integrated performance.

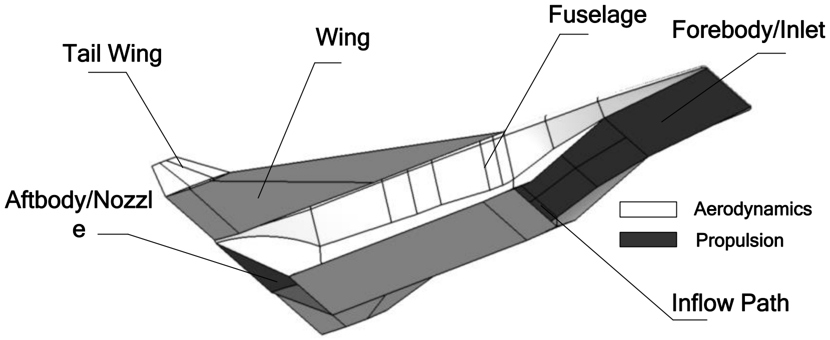

Fig 1. The force interface of aerodynamics and propulsion

The aerodynamic performance contains axial force, normal force, and pitch moment. The performance of propulsion contains the net thrust of inner flow path, the axial force of the inlet and the nozzle, the normal force of the inlet and the nozzle, the pitch moment of the inlet and the nozzle, and the pitch moment produced by thrust misalignment of the engine.

The final performance of airframe-propulsion integration is

$$I_{sp,eff} = I_{sp}\left(1 - F_A / T\right) \tag{1}$$

3. The relationships of the wind tunnel tests

The typical ground wind tunnel tests of the RBCC launch vehicle include the test of the components and the test of the whole vehicle, which include the inlet test, direct connection test of the engine, test of the aerodynamic configuration, integrated free jet test, flight test and so on. The relationships of the experiments are related to each other, which are shown in Fig.2.

Based on the results of the tests and CFD simulation, the test results are corrected, and the integrated database of the large scale launch vehicle can be established.

4. The method of the wind tunnel test for airframe-propulsion integration

4.1. The correction of test results based on CFD

It's a feasible method to correct the test data based on the difference which is obtained by CFD. The vehicle are analyzed in the real wind tunnel state and the state without any disturbance, then the difference is obtained as the correction factor, which is used to corrected the test data. That is

$$\Delta F_{CFD} = F_{CFD2} - F_{CFD1} \tag{2}$$

$$F = F_{test} + \Delta F_{CFD} \tag{3}$$

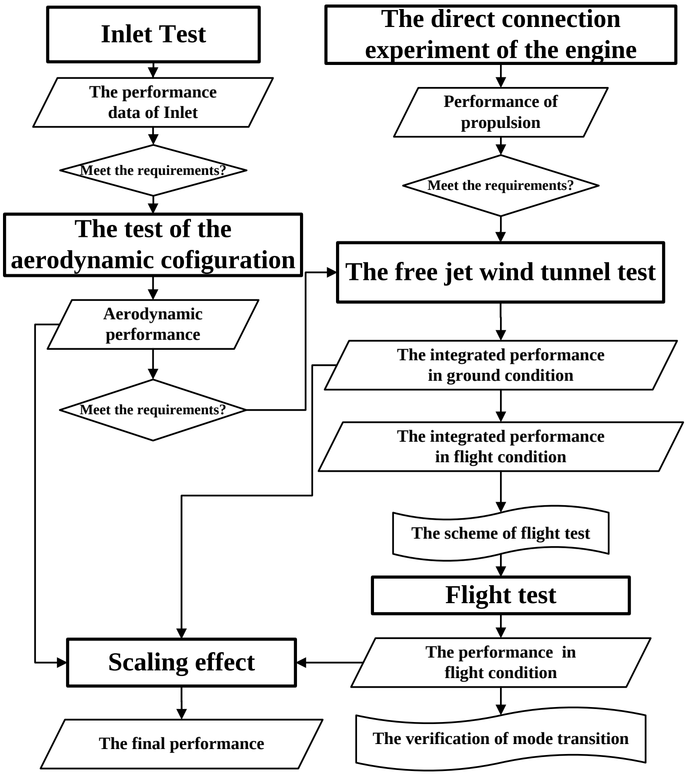

Fig 2. The Relationships of the Test for RBCC Launch Vehicle

4.2. The problem of scale effect for the wind tunnel test

The scale effect of the airframe-propulsion integration for the launch vehicle is mainly reflected in the aerodynamics and the propulsion.

(1) The scale effect of aerodynamics

The scale effect of aerodynamics for RBCC launch vehicle is consistent with the common aircraft, which is mainly reflected in the Reynolds number. The wind test can be conducted by the equal scaling of the model of the vehicle.

(2) The scale effect of RBCC engine

The influence of scale effect on engine thrust can be transformed into the influence of scale effect on total temperature and total pressure on the outlet of the engine. Combined with the operation modes of RBCC engine, there are four main mechanisms of the RBCC combustor, which are jet mixing, shock waves, viscosity and combustion. Under the condition of uniform mixing, the jet mixing is characterized by scale independence. Therefore, the influence of the scale effect on jet mixing is mainly reflected in the uniformity. If the jet mixing is uniform, the difference of the thrust for the different scales will be small.

The related research is still being carried out, which is to obtain the conversion principle of the engine scale effect for the background vehicle. For the engine performance $T\left(Ma,q,H,L\right)$ in test scale, the real performance can be obtained under the real scale ($L^{'}$). It can be represented as

$$T\left(Ma,q,H,L\right) \xrightarrow{f} T\left(Ma,q,H,L^{'}\right) \tag{4}$$

Through the analysis and transformation of scale effect, the performance of aerodynamics and propulsion for the real launch vehicle can be obtained, which can be used to guide the analysis and demonstration of the RBCC launch vehicle.

4.3. The performance correction of the flight and the ground test

The wind tunnel test cannot fully reflect the real flight environment of the launch vehicle. In order to ensure the availability of the experimental data, the correlation problems between the experimental data and the real flight data must be clearly defined.

(1) The correction of aerodynamics

The correlation between the wind tunnel data and the flight data is realized by finding a correlation parameter, which is to realize the conversion of the ground test data to the aerodynamic performance of the real flight environment. It can be expressed as

$$C = f\left(\alpha, \bar{V}_{\infty}^{'}\right) \tag{5}$$

Where, C is the coefficients of the aerodynamic force, $\bar{V}_{\infty}^{'}$ is the third viscosity interference parameter. The parameter takes into account the influence of Mach number, Reynolds number, wall temperature, environment temperature and so on.

(2) The correction of propulsion

The results of the ground test and real flight are connected by the correction method of the test and flight. For the ground test and flight test which meets the third Da number, the specific impulse is the same. For the launch vehicle adopting the configuration of airframe-propulsion integration, the specific impulse is the ratio of the thrust to the fuel. However, the force is the combined force of the fuselage and engine, therefore, the engine's specific impulse can be defined as

$$I_{sp} = \frac{T + F_{\text{A, fuselage}}}{m_f} \tag{6}$$

For ground test and flight test, the specific impulse is coincident. That is

$$\frac{T_{\text{flight}} + F_{\text{A, fuselage, flight}}}{m_{f,\text{flight}}} = \frac{T_{\text{ground}} + F_{\text{A, fuselage, ground}}}{m_{f,\text{ground}}} \tag{7}$$

After finishing, we can get the thrust value of the launch vehicle in the real environment in Eq.8.

$$T_{\text{flight}} = \frac{m_{f,\text{flight}}}{m_{f,\text{ground}}} T_{\text{ground}} + \frac{m_{f,\text{flight}}}{m_{f,\text{ground}}} F_{\text{A, fuselage, ground}} - F_{\text{A, fuselage, flight}} \tag{8}$$

The drag $F_{\text{A, fuselage, flight}}$ in the flight environment can be obtained by CFD.

The specific work will be described in detail in the full text.

5. Conclusion

In this paper, the contents and relationships of the ground wind tunnel tests for the RBCC launch vehicle are studied, and conduct the research on the test data correction, scale effect and the correlation of ground test and the test in flight environment. Such work can be used to establish the performance database of airframe-propulsion integration for RBCC vehicle, and direct the design of the launch vehicle.

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