Flange balance application in high speed wind tunnel test of BWB aircraft

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Abstract. In order to improve quality and efficiency of Blended Wing-Body (BWB) aircraft’s high-speed wind tunnel test, while verify the reliability and practicability of flange balance in the test of such a layout aircraft. The specific flange-connected balance of BWB aircraft was designed and processed, which was designed under the limits of aerodynamic load and model interspace size. The comparison test results between the flange balance and the traditional cone balance were obtained by conducting a comparison test in the 2.4-meters transonic wind tunnel. The results show that the flange balance has high measurement accuracy and good correlation with the traditional cone balance. Flange balance meets the requirement of BWB layout aircraft high speed wind tunnel test and has a broad application prospect, so that it could be popularized in the future.

1. Introduction

Wind tunnel test is the main means for obtaining the aerodynamic characteristics of aircraft on the ground, and it is also an indispensable key step in the process of aircraft design. During the test, the six-component aerodynamic characteristics such as force and moment are obtained by the balance mounted inside the model. At present, the main wind tunnel test institutes in China adopt cone balance for high speed conventional force test. For the conventional layout aircraft of traditional "cylinder fuselage + wing", the internal space of the model is large enough, the tolerance of the model attitude is high, and the aerodynamic load is relatively low, so that the cone balance can meet the requirements of high speed wind tunnel test. However, more and more modern new aircraft adopt Blended Wing-Body Layout (BWB Layout) design [1-3], which brings great difficulty to the selection of balance in the field of high-speed wind tunnel test. BWB layout aircraft has no obvious fuselage [4-6], and the internal space is limited, while the traditional cone balance has a long length and is difficult to mount. The fuselage and the wing are merged into a lifting surface [7-9], and the small model attitude difference caused by the cone matching will make the aerodynamic data deviation larger, which affects the quality of the test data. The connection and repair of the model cone and the balance cone is the main factor affecting the test efficiency. If there is a defect in the cone surface processing of the model and the balance connecting section, under the excitation of the BWB aircraft with large lift and large rolling moment [10,11], the model oscillation jitter is easily caused, which jeopardizes the test safety. Therefore, it is necessary to carry out in-depth research on the specific balance of the BWB
aircraft high speed wind tunnel in order to improve the quality and efficiency of the test and to ensure the safety of the test.

In this paper, for a typical BWB layout aircraft, a load-matched and properly sized flange-connected balance is designed. The total length of the flange balance is shortened, and the traditional cone surface is changed to the cylindrical surface to avoid the repairing process and the connection is firm, which makes up for the deficiency of the traditional cone balance in the high speed wind tunnel test of the BWB aircraft. From the open literature, there is no precedent for the successful application of flange balance in high-speed wind tunnels in China. In this paper, the measurement accuracy of the flange balance is verified through the comparison test in 2.4-meters transonic wind tunnel. The correlation between the flange balance and the traditional cone balance is obtained. It shows that the flange balance can be used in BWB layout high speed wind tunnel test and has a broad application prospect.

2. Brief introduction of experiment

2.1. Test facility
The experiment was conducted in 2.4-meters transonic wind tunnel of the China Aerodynamic Research and Development Center (CARDC). The 2.4-meters wind tunnel is a semi-return, ejector and temporary-type transonic wind tunnel. As shown in Figure 1, the section size of the test section is 2.4m×2.4m, Mach number range is 0.3~1.2, total pressure range is (1.1~4.5)×10^5 Pa.

The wall of 2.4-meters wind tunnel full-model test section is a wall with 60-degree inclined holes. The performance indexes such as the uniformity of the core flow Mach number in the test section all meet the requirements of the high-speed wind tunnel flow field quality specification.

![Figure 1. Common research test model in the 2.4-meters wind tunnel.](image)

2.2. Test model
The research object of this paper is the BWB layout. The wind tunnel test model chooses a typical BWB aircraft shape, and its layout characteristics are similar to those of the US X-48C aircraft (as shown in Figure 2). The central fuselage of the aircraft is flat, smooth transitioned and high integrated with the outer wing. The engine is mounted on the back of the fuselage and has two tilting tails at the rear. In the 2.4-meters wind tunnel, the model has a wingspan of 1.44 meters.

The experimental model has a small infiltration area and a large aspect ratio, and cruise Mach number is close to the transonic speed range. The experimental results can represent the main aerodynamic characteristics of BWB layout aircraft.
2.3. Test conditions

In the test, the tail sting support was selected as the main support. For the BWB aircraft model, research projects such as longitudinal repeatability test, longitudinal aerodynamic characteristics comparison test and contrast rudder efficiency verification test were carried out. All the tests were carried out under fixed transition conditions. The 0.12 mm height cylindrical transition belt specially designed by CARDC was used for pasting the nose, the leading edge of wing and the inclined tail.

In this paper, the Mach number range is 0.4~0.85, the angle of attack is -4°~10°, and the Reynolds number based on the average aerodynamic chord length of the wing is 4.0×10⁶~5.5×10⁶.

3. Balance

Compared with conventional layout aircraft, BWB layout aircraft has larger lift and roll moment, while the drag, lateral force, yaw moment and pitch moment loads are smaller, so that it is difficult to match each element of the balance design. In addition, the changes in aerodynamic characteristics of such layout aircraft are more sensitive, resulting in higher accuracy requirements for aerodynamic load measurement in wind tunnel tests. Table 1 shows the design requirements for the balance of the experimental model in this paper. In the table, $X$ represents the axial force, $Y$ represents the normal force, $Z$ represents the lateral force, $Mx$ represents the rolling moment, $My$ represents the yaw moment, and $Mz$ represents the pitching moment.

|                      | $Y/N$ | $Mz$/N.m | $X$/N | $Mx$/N.m | $Z$/N | $My$/N.m |
|----------------------|-------|----------|-------|----------|-------|----------|
| Range requirement    | ≥12000| ≥1000    | ≥1200 | ≥1400    | ≥2000 | ≥200     |
| Uncertainty          | 0.3%  | 0.3%     | 0.3%  | 0.3%     | 0.3%  | 0.3%     |

In addition, the BWB layout lacks the conventional cylinder fuselage, and the flat fuselage is highly integrated with the wing. The internal space is narrow, so that the balance size is limited (In the 2.4-meters wind tunnel, the model shrinkage requires the balance diameter $D$$\leq$57mm and the total length $L$$\leq$365mm), which adds extra difficulty to the balance design.

![Figure 2. X-48C validation aircraft.](image-url)
Under the above-mentioned size limitation and load requirements, a special flange connection balance for BWB layout is designed, as shown in Figure 3.

![Flange balance](image)

**Figure 3.** Flange balance.

As shown in Figure 3, the flange and guide cylinder are designed in the front section of the flange connecting balance, and the front connecting cone is eliminated, so that the total length of the flange connecting balance is obviously shorter than the traditional cone balance. Eight screw holes and two pin holes are designed on the flange, while the flange and the model steel sleeve parts can be connected by special screw/pin. In the middle section of the balance, the load is measured by pasting the strain gauge, and the rear section is connected to the support device through the cone, thereby fixing the balance and the model in the wind tunnel test section.

In the designing of the test scheme, a conventional 6-component cone balance is also selected (the range and uncertainty are shown in Table 2, the symbol definitions in the table are the same as in Table 1). The cone balance and the flange balance part have similar measurement load and the same precision. It can be used to compare the measurement reliability and engineering practicability of the calibration flange balance while performing BWB aircraft load measurement. During the test, the steel sleeves were connected by changing the model, and the interchange of the cone balance and the flange balance on the same set of test models was realized.

|                  | Y/N | Mz/N.m | X/N | Mx/N.m | Z/N | My/N.m |
|------------------|-----|--------|-----|--------|-----|--------|
| Measuring range  | 15000 | 800  | 1000 | 1000   | 1500| 200    |
| Uncertainty      | 0.3% | 0.3%  | 0.3% | 0.3%   | 0.3%| 0.3%   |

**Table 2.** Range and accuracy of cone balance.

4. Test verification and analysis

4.1. Longitudinal repeatability test results

In the longitudinal test, the BWB aircraft model was fitted with a flange balance and several repeatability tests were carried out for the same test condition. Figure 4-6 shows the repeatability test results (partial) at Mach number of 0.78. In the figure, RUN=1/2/3 represents the first, second, and third times repeatability results, respectively.

In Figure 4, the BWB aircraft's lift curve repeatability is good, the linear segment basically meets the point-to-point repeatability requirement, the slope of the lift line has no significant difference, and the separation initial angle of attack agrees well. Similarly, the repeatability of the test results in Figure 5 and Figure 6 is high, and the capture parameters such as minimum drag, cruise drag, stability derivative and instability angle of attack are highly accurate.
Table 3 gives the root mean square error results for the longitudinal repeatability test. The results show that within the test angle of attack, the root mean square error of the lift coefficient is between 0.00064 and 0.001916, the root mean square error of the drag coefficient is between 0.00008 and 0.000145, and the root mean square error of the pitching moment coefficient is between 0.000114 and 0.000578. Comparing the accuracy requirements of the national military standard for the high-speed wind tunnel force test (Table 4), the test results in this period are all better than the qualified indicators, and the accuracy of the results under some angle of attack conditions is superior to the advanced indicators. It is proved that the flange balance is highly accurate in the BWB aircraft high speed wind tunnel force test.

Table 4. High speed wind tunnel force test accuracy index. ($|\alpha| \leq 4$, $|\beta| \leq 3$)

| 0.4 ≤ Ma ≤ 0.9 | Qualified indicator | Advanced indicators |
|-----------------|---------------------|----------------------|
| CL              | 0.002               | 0.0008               |
| CD              | 0.0005              | 0.0001               |
| Cm              | 0.001               | 0.0003               |

4.2. Longitudinal comparison test results

For the longitudinal aerodynamic characteristics’ comparison test, the aerodynamic measurement was carried out for the same test state using a flange balance and a cone balance, respectively. Figure 7-9 shows the difference curve of flange balance and cone balance under different Mach number conditions.

In Figure 7, the difference of the lift coefficient is less than 0.002 when $Ma=0.6$ and 0.78, the difference is substantially less than 0.005 when $Ma=0.83$. In Figure 8, the difference of drag coefficient is less than 0.0005 under all experimental Mach numbers. In Figure 9, the difference of pitching moment coefficient is within 0.001 when $Ma=0.78$ and is less than 0.002 at $Ma=0.6$ and 0.83. In summary, the difference between the flange balance and the cone balance in the longitudinal aerodynamic measurement of the BWB aircraft in the test range is basically within the range of repeatability accuracy. In view of the early start of the application of the cone balance in the high speed wind tunnel, the technical maturity is high, and it has undergone extensive verification and the test database is abundant. It can be considered that the measurement results of the flange balance in
this test are true and reliable. For the model aerodynamic database established by the cone balance in the early stage, the flange balance can be used for the later test in the future. For the similar layout of the new research aircraft, the flange balance is firmly connected, avoiding the repair and easy to use, so that it can be considered when designing the pre-research selection stage.

4.3. Rudder effect comparison test result

In the comparison test of the rudder surface efficiency, the steering control of the BWB aircraft in the three directions of pitch, yaw and roll is realized by deflecting the camber-type vertical tail and the aileron rudder surface respectively. The rudder results were obtained using a cone balance and a flange balance, respectively. Figure 10-12 show the comparison of the rudder efficiency at a certain angle obtained by the two balances.

The results in the figure show that the curves of the rudder effect results measured by the two balances are in good agreement and the difference in magnitude is small. The maximum difference of the pitch, yaw, and rolling moments are 0.00098, 0.00009, and 0.00017, respectively, which basically represent the repeatability of the measurement of the domestic temporary-type transonic wind tunnel. The difference of measurement results can be neglected in the aerodynamic designing of BWB aircraft. The test results of the yaw moment and the rolling moment in the comparison of the rudder effect can also reflect the measurement accuracy of the transverse direction test to a certain extent.

5. Conclusions

Flange balance has high measurement accuracy in BWB layout aircraft high-speed wind tunnel force test.

The flange balance measurement results of this test are true and reliable, and the flange balance has a good correlation with the cone balance.
The flange balance basically meets the requirements of high-speed wind tunnel test of BWB aircraft and can be promoted and used based on further verification.

References

[1] Liebeck R, Page M and Rawdon B 2013 Blended-wing-body subsonic commercial transport [J]. *AIAA Journal*

[2] Liebeck R 2003 Blended Wing Body Design Challenges [C]. *AIAA International Air and Space Symposium and Exposition: The Next 100 Years*

[3] Okonkwo P and Smith H 2016 Review of evolving trends in blended wing body aircraft design [J]. *Progress in Aerospace Sciences.* 82 1-23

[4] Bolsunovsky A L, Buzoverya N P and Gurevich B I 2001 Flying wing-problems and decisions [J]. *Aircraft Design*, 4 193-219

[5] Thompson D, Feys J and Filewich M 2011 The Design and Construction of a Blended Wing Body UAV [C]. *AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*

[6] Dommelen J V and Vos R 2014 Conceptual design and analysis of blended-wing-body aircraft [J]. *Proceedings of the Institution of Mechanical Engineers Part G Journal of Aerospace Engineering* 228 2452-2474

[7] Ai J Q 2013 Aerodynamic layout and development of typical high lift-to-drag ratio aircraft [J]. *Aviation Science and Technology* 04 1-5

[8] He G Q and Chen L 2013 Analysis of development trend and performance characteristics of next-generation bombers [J]. *Aviation Science and Technology* 04 9-12

[9] Shen L M, Zhong X L and Qin Y H 2007 Preliminary study on aerodynamic characteristics of BWB aerodynamic layout [C]. *High-level Forum on Key Technologies of Large Aircraft and China Aeronautical Society 2007 Annual Conference*

[10] Wu J H and Liu X J 2007 Analysis of aerodynamic characteristics of wing body fusion (BWB) layout passenger aircraft [C]. *High-level Forum on Key Technologies of Large Aircraft and China Aeronautical Society 2007 Annual Conference*

[11] Zhu Z Q, Wang X T, Wu Z C et al. 2008 A New Type of Layout of Civil Aircraft-Wing Body Fusion Aircraft[J]. *Acta Aeronautica.* 01 49-59