Research on Lift Error of Horizontal Tail Based on Component Disassembly Method

Qing Wen[✉], Kangzhi Yang, Zhihang Cheng, and Yuanzhe Zhang

China Aviation Industry General Aircraft Institute Co, Ltd, Zhuhai 519040, China
wenqing0601@163.com

Abstract. It is very important for calculating aerodynamic load and strength design to obtain aerodynamic force of aircraft components accurately. The aerodynamic force of horizontal tail is usually obtained by means of component disassembly in wind tunnel test, That is, subtract the value of non horizontal tail configuration from the value of whole plane configuration to obtain the value of horizontal tail. Using CFD method, through the comparative study of component disassembly method and direct measurement results, it is found that for low Horizontal tail aircraft, the slope of Horizontal tail lift line obtained by component disassembly method is more than 25%. The main reason for the error is that the component disassembly method assumes that the aerodynamic characteristics of the wing and fuselage with/without Horizontal tail configuration remain unchanged, so the interference data of the whole plane Horizontal tail on the fuselage and wing are accumulated on the Horizontal tail components. The error change of component disassembly method when the Horizontal tail is in different positions is studied. When the Horizontal tail is installed on the fuselage, the error is large, and when it is installed on the vertical tail, the error decreases gradually with the increase of height. By using the moment instead of the lift difference method that subtracted from the value of the whole plane configuration, the interference of the Horizontal tail to the wing can be basically eliminated and the interference of the Horizontal tail to the fuselage can be reduced. For the aircraft with T-tail layout, the results obtained by using the component disassembly method combined with the moment inverse calculation are the same as the direct measurement results.

Keywords: Low horizontal tail · Component disassembly method · Wind tunnel tests · Aerodynamic force of horizontal tail

1 Introduction

Among many tail layout forms, low Horizontal tail layout has been widely used in large passenger aircraft and small general-purpose aircraft [1–5]. The aerodynamic characteristics of the Horizontal tail, especially the lift characteristics, are not only related to the shape design and aeroelastic deformation of the Horizontal tail [6, 7], but also directly determine the structural layout, structural stiffness and strength design of the Horizontal tail [8–11]. Therefore, it is of great significance to obtain the accurate lift characteristics of the Horizontal tail [12–14].

In the process of aircraft design, the lift characteristics of the Horizontal tail are generally obtained through the component disassembly method in the wind tunnel test [15, 16], that is, the lift coefficient of the Horizontal tail is obtained by subtracting the lift coefficient of the non Horizontal tail configuration from the lift coefficient of the whole plane. This method assumes that the aerodynamic forces of the wing, fuselage and other components remain unchanged with or without a Horizontal tail. In fact, the installation of the Horizontal tail will inevitably produce aerodynamic interference to the fuselage, wing and other components, and the value of the interference will affect the accuracy of the Horizontal tail lift characteristics obtained by the component disassembly method. When the interference caused by the installation of the Horizontal tail is large, the lifting error of the Horizontal tail will be significantly increased by using the component disassembly method.

The lift of the horizontal tail of a small general-purpose aircraft with low Horizontal tail layout under research in China was initially obtained by component disassembly method. In the aerodynamic load calculation of Horizontal tail in the limit state, it was found that the Horizontal tail load was abnormally large, which was obviously unreasonable. The lift of the horizontal tail of this model is analyzed and studied. Through CFD Research, it is found that at the installation position of the Horizontal tail, the aerodynamic interference of the Horizontal tail to the fuselage and wing cannot be ignored, and the lift characteristic error of the horizontal tail obtained by component disassembly method is large. By moving the position of the Horizontal tail, the error of the Horizontal tail using the component disassembly method with the horizontal tail in different positions is studied.

2   Comparison Between Simulation and Wind Tunnel Test

2.1   Wind Tunnel and Model

The wind tunnel test with the whole plane and component disassembly force measurement was carried out in the fl-12 wind tunnel of the low speed Institute of China Aerodynamic Research and development center. The size of the wind tunnel test section is 4 M × 3 m. Due to the limitation of test conditions, the Reynolds number based on the average aerodynamic chord length of the wing is about 1.42 million and the wind speed is 70 m/s. The wind tunnel test model adopts a 1:5 all metal model. The installation of the whole machine test model in the wind tunnel is shown in Fig. 1.

2.2   Simulation Method

The governing equation of the flow field is Reynolds averaged N-S equation. Because the mainstream velocity in the flow field is incompressible flow with low Mach number, the pressure based separation method is selected and the SIMPLEC algorithm is adopted. The pressure term is discretized by the 2nd-order upwind scheme, the convection term is discretized by the 3rd-order MUSCL scheme, and the viscous term is discretized by the 1st-order upwind scheme. The turbulence model adopts transition SST model [17, 18].
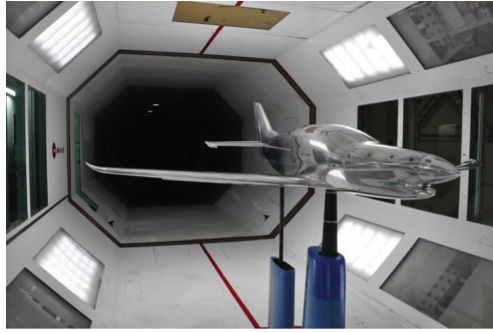
Fig. 1. Wind tunnel test model

The mesh type is a cut volume mesh similar to Cartesian mesh. Since the state of the flow separation near the wing surface is not studied, the wall function model is adopted. The value of the y plus of the first grid layer is set as 30, the boundary layer grid has more than 20 layers, the height of the first layer is about 0.1mm, the growth rate is 1.2, and the total number of cells is 12 million.

The calculation model is a half mode model, the calculation far field is rectangular, and the model ratio is 1:5. The symmetry plane is the symmetry plane boundary condition, the far-field boundary behind the model is the pressure outlet boundary condition, and the other boundaries are the velocity inlet boundary condition.

The value of atmospheric environment calculation condition is 0 km in standard atmosphere, the incoming wind speed is 70 m/s, and the calculated Reynolds number is the same as that in wind tunnel test (Fig. 2).
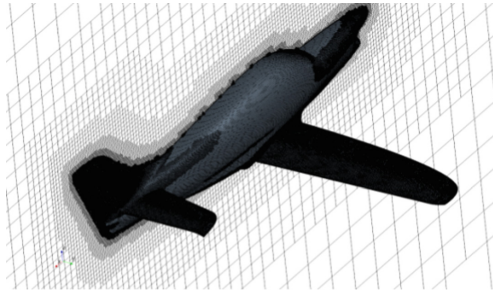

Fig. 2. CFD model

2.3 Comparison Between Simulation and Wind tunnel Test

The CFD simulation state is the same as the wind tunnel test, that is, the aerodynamic characteristics of whole plane and non Horizontal tail configuration are calculated respectively. The cruise configuration is selected as the contrast state, and the angle of elevator is 0°.

The simulation results show that the CFD and wind tunnel test results coincide well, the slope error of lift line is within 1%, and the absolute error of lift coefficient at zero angle of attack is no more than 0.01 (Fig. 3).
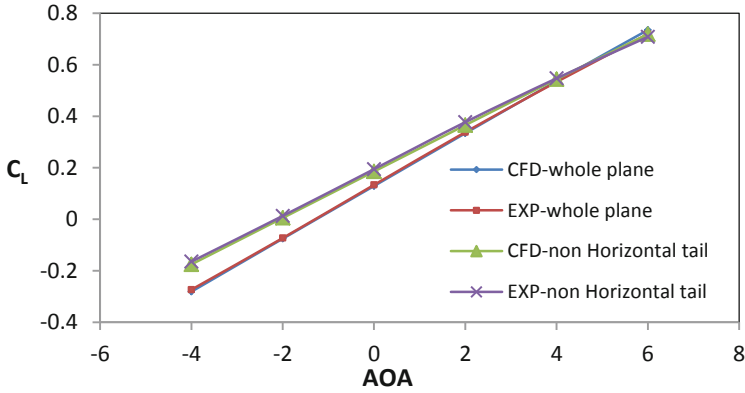

Fig. 3. Comparison of lift curves of the whole plane and non Horizontal tail

The disassembly method obtain the lift of the Horizontal tail by subtracting the lift of the non Horizontal tail configuration from the lift of the whole plane to obtain the lift of the Horizontal tail.

$$C_{L\_Pw\_zc} = C_{L\_All} - C_{L\_YS}$$

where: $C_{L\_Pw\_zc}$ is Horizontal tail lift obtained by component disassembly method, C_{L_All} is the lift of the whole plane,and C_{L_YS} is the Lift of non Horizontal tail configuration.

According to the lift data of the whole plane and the non Horizontal tail configuration with wind tunnel test and CFD method respectively, the Horizontal tail lift comparison curve obtained by the component assembly method is shown in Fig. 4. Due to the small amount of Horizontal tail lift, the percentage error of Horizontal tail lift characteristic data calculated by disassembly method is increased compared with the wing configuration, and the slope error of lift line is 4.24%.

3   Study on the Error of Component Disassembly Method

3.1   Aerodynamic Analysis of Components Obtained by Component Disassembly Method

Component disassembly method: subtracting the lift of non horizontal tail configuration from the lift of whole plane configuration.

The lift of non Horizontal tail configuration is:
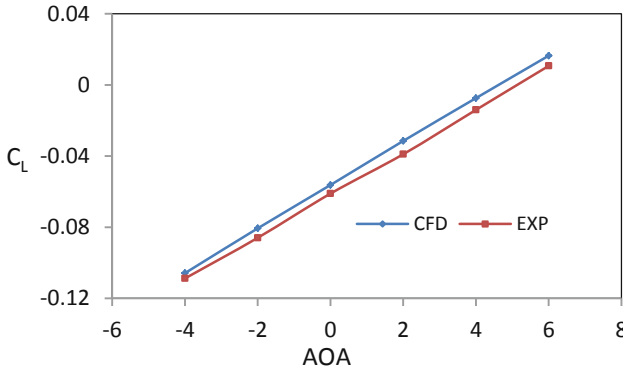
$$C_{L\_NHT} = C_{L\_Wing} + C_{L\_Body}$$

Fig. 4. Comparison of Horizontal Tail lift curves obtained by disassembly method

where C_{L_Wing} is the lift of wing of non Horizontal tail configuration, and C_{L_Body} is the lift of Fuselage of non Horizontal tail configuration (including vertical tail).

The lift of whole planen is:

$$C_{L\_WP} = C_{L\_Wing\_2} + C_{L\_Body\_2} + C_{L\_Pw}$$

where $C_{L\_Wing_2}$ is Wing lift of whole planen, $C_{L\_Body\_2}$ is Fuselage lift of the whole plane configuration(including vertical tail),and C_{L_Pw} is Horizontal tail lift of the whole plane configuration.

Since the lift of the wing in the whole plane state is different from that in the non Horizontal tail state, considering the interference effect of the Horizontal tail, then:

$$C_{L\_Wing\_2} = C_{L_{Wing}} + \Delta C_{L_{Wing\_PW}}$$

$$C_{L\_Body\_2} = C_{L\_Body} + \Delta C_{L_{Body\_PW}}$$

where $\Delta C_{L_{Wing_{PW}}}$ is interference amount of Horizontal tail of whole plane configuration to wing, and $\Delta C_{L_{Body\_PW}}$ is interference amount of Horizontal tail of whole plane configuration to fuselage (including vertical tail).

The Horizontal tail lift coefficient calculated by the component disassembly method is:

$$C_{L\_Pw\_zc} = C_{L\_WP} - C_{L\_NHT} = C_{L\_Pw} + \Delta C_{L_{Wing\_PW}} + \Delta C_{L_{Body\_PW}}$$

It can be seen from the above formula that the Horizontal tail lift obtained by the component disassembly method not only includes the lift of the Horizontal tail itself, but also includes the interference of the Horizontal tail to the wing, fuselage and other components. The magnitude of the interference is directly related to the accuracy of the Horizontal tail lift obtained by the component disassembly method.

3.2 Comparison of Component Disassembly Method and Direct Measurement Results

The comparison between the Horizontal tail lift characteristics obtained by component disassembly method and direct measurement is shown in Fig. 5. Direct measurement is to measure the lift characteristics of the Horizontal tail on the whole plane. This method is accurate. It can be seen from the calculation results that there is a great difference between the Horizontal tail lift coefficient obtained by the component disassembly method and the direct measurement. At the angle of attack of 0°, the Horizontal tail negative lift obtained by the component assembly method is 41.8% higher than that obtained by the direct measurement, and the lift line slope is 28.3% higher than that.

The Horizontal tail lift near 0° angle of attack is closely related to the Horizontal tail load during high-speed cruise, and the slope of the Horizontal tail lift line is directly related to the sudden wind load. This error has a decisive influence on the load evaluation of the Horizontal tail.
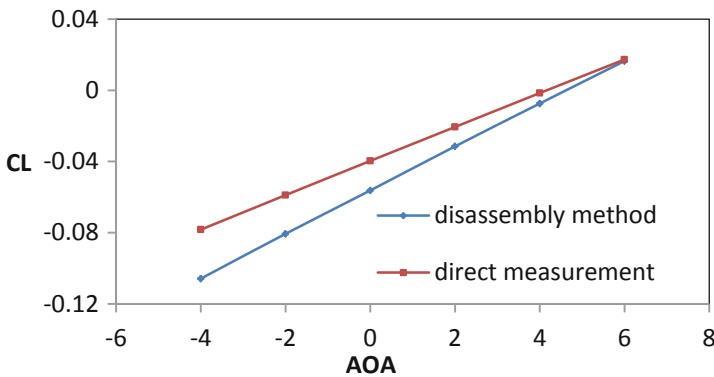

Fig. 5. Comparison of component disassembly method and direct measurement method with CFD

3.3 Analysis on the Error of Component Disassembly Method

According to the comparison of CFD results with/without Horizontal tail configuration, the interference amount of Horizontal tail to aircraft wing and fuselage is shown in Fig. 6. It can be seen from the calculation results that after the Horizontal tail is installed, the lift coefficients of the wing and fuselage are reduced by 0.0052 and 0.0099 respectively at the state of 0° of attack, totaling 0.0151. This part of the force originally acting on the wing and fuselage caused by the interference of the Horizontal tail is calculated on the Horizontal tail when the component disassembly method is adopted, because the aerodynamic forces of the fuselage, wing and other components are assumed to be unchanged, resulting in the increase of the negative lift of the Horizontal tail at zero angle of attack.
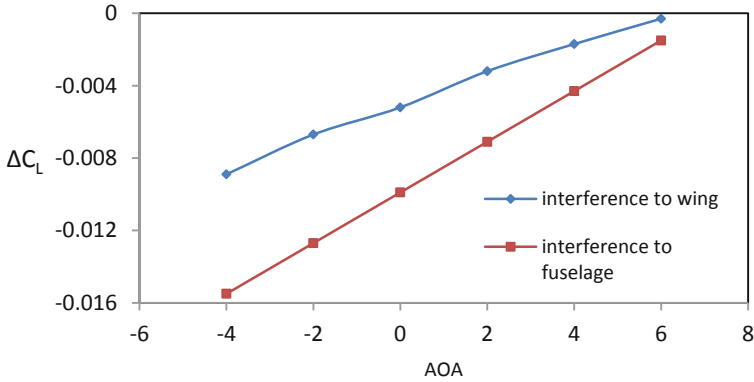
Fig. 6. Lift interference of horizontal tail to fuselage and wing

It can be seen from Fig. 6 that the interference of the Horizontal tail on the fuselage is relatively large. At the angle of attack of 0°, the magnitude of the influence on the wing is about 1/3 and the magnitude of the influence on the fuselage is about 2/3.

The influence of the Horizontal tail on the wing is mainly due to the change of the wing angle of attack caused by the wash flow generated by the lift force of the Horizontal tail in front of the Horizontal tail. In the state of angle of attack 0 degrees, the Horizontal tail causes negative lift, and there is a counterclockwise circulation on the Horizontal tail from the left side of the fuselage, which reduces the effective angle of attack and lift coefficient of the wing.

The interference effect of the Horizontal tail on the fuselage is more complex and has the effect of up washing. More importantly, the Horizontal tail is installed on the fuselage, and the Horizontal tail has an obvious influence on the pressure distribution of the fuselage. Figures 7 and 8 are side views of the pressure distribution in the rear section of the aircraft with and non Horizontal tail configuration at zero angle of attack. It can be seen from the Fig that the pressure distribution at the root of the Horizontal tail obviously affects the pressure distribution of the fuselage. A high-pressure area is formed on the upper side of the leading edge of the Horizontal tail wing root and a low-pressure area is formed on the lower side. Figure 9 shows the comparison of the pressure distribution of the fuselage profile at the leading edge of the Horizontal tail between the whole plane and the non Horizontal tail configuration at zero angle of attack. The area enclosed by the pressure distribution curve of the whole plane configuration is significantly larger than that of the non Horizontal tail configuration, indicating that there is an obvious lift change in the fuselage profile due to the installation of the Horizontal tail.
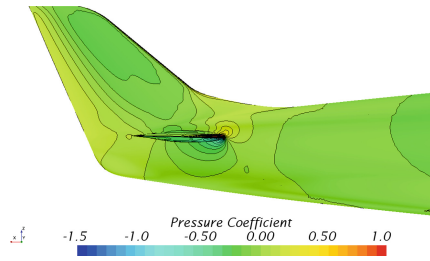
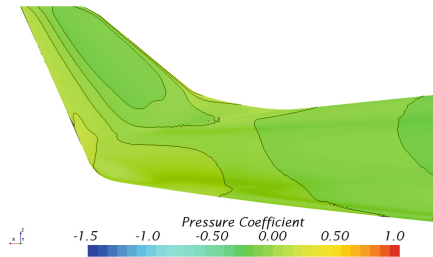**Fig. 7.** Pressure distribution in the rear section of aircraft

Fig. 8. Pressure distribution in the rear section of tailless aircraft
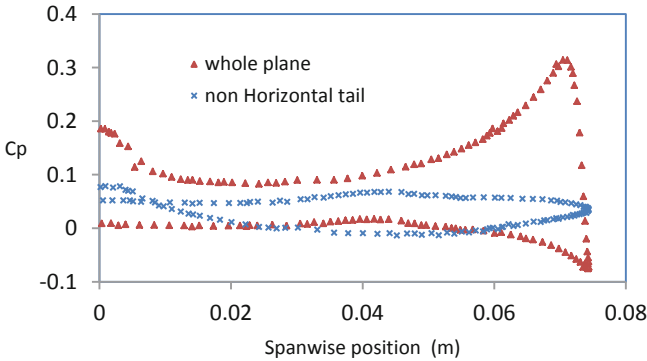

Fig. 9. Comparison of pressure distribution in fuselage section with/without horizontal tail configuration

4 Influence of Horizontal Tail Position on the Accuracy of Disassembly Method

Because the installation of the Horizontal tail has a great influence on the aerodynamic force of the fuselage, the influence of the Horizontal tail at different installation positions on the accuracy of the Horizontal tail aerodynamic force obtained by the component disassembly method is studied.

(1) The Horizontal tail is installed in the upper position of the fuselage, so the Horizontal tail moves downward in the vertical direction on the fuselage. According to the height limit of the rear fuselage, the Horizontal tail moves down 100 ~ 400 mm on the fuselage at an interval of 100 mm (the corresponding size of the full-size aircraft, the same below).

(2) Because the vertical tail has a certain sweep angle, when moving on the vertical tail, the Horizontal tail moves along the 45° angle direction, that is, moving upward and moving backward at the same time, and the moving amount is the same. The Horizontal tail moves up/back 400 mm, 600 mm, 800 mm, 1500 mm on the vertical tail.

The moving direction and partial position of the Horizontal tail on the fuselage and vertical tail are shown in Fig. 10.
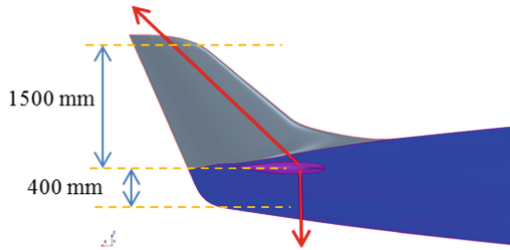

Fig. 10. Horizontal tail position diagram

4.1 The Horizontal Tail Moves on the Fuselage

When the Horizontal tail moves downward on the fuselage, the lift characteristic results of the Horizontal tail obtained by CFD method based on component disassembly method and direct measurement method are shown in Table 1. The calculation results show that when the Horizontal tail moves on the fuselage, due to the certain differences in the downwash characteristics of the wing at different heights and the different exposed areas of the Horizontal tail, the CLA and CL0 of the Horizontal tail are obviously different. However, at all Horizontal tail positions, the slope of the Horizontal tail lift line obtained by the component disassembly method is more than 25% greater than that obtained by the direct measurement method.

4.2 The Horizontal Tail Moves on the Vertical Tail

When the Horizontal tail moves on the vertical tail, the lifting characteristic results of the Horizontal tail obtained by CFD method based on component disassembly method and direct measurement method are shown in Table 2. The results show that the difference between the two method comparing that on the fuselage obviously decrease, the difference can be controlled below 10%, and gradually decrease by the moving up of the horizontal tail.

Table 1. Comparison of lift between component force measurement and component disassembly with different horizontal tail positions

The position of the horizontal tail	Component disassembly method		Direct measurement		Error	
	C_{L0}	C_{La}	C_{L0}	C_{La}	C_{L0}	C_{La} (%)
Designed position	−0.0563	0.01230	−0.0397	0.00959	−0.01660	28.3
Down 100	−0.04262	0.01189	−0.03048	0.00920	−0.01214	29.2
Down 200	−0.03004	0.01169	−0.02217	0.00906	−0.00787	29.0
Down 300	−0.01731	0.01151	−0.01364	0.00902	−0.00367	27.6
Down 400	−0.00633	0.01131	−0.00615	0.00905	−0.00018	25.0

After the horizontal tail is moved up by 1500 mm, the overall layout of the aircraft is changed from the conventional layout to the T-tail layout. At this time, the error of the component disassembly method is significantly reduced, and the slope error of the horizontal tail lift line is only 3.7%. Since the Horizontal tail is far away from the fuselage, the main reason for this error is the interference effect of the Horizontal tail on the wing, as shown in Fig. 11.

Table 2. Comparison of lift between direct measurement and component disassembly with different horizontal tail positions

The position of the horizontal tail	Component disassembly method		Direct measurement		Error	
	C_{L0}	C_{La}	C_{L0}	C_{La}	C_{L0}	C_{La} (%)
Designed position	−0.0563	0.0123	−0.0397	0.00959	−0.0166	28.3
Up 400	−0.0581	0.0126	−0.0496	0.0114	−0.0085	10.5
Up 600	−0.0523	0.0122	−0.0455	0.0111	−0.0068	9.9
Up 800	−0.0483	0.0124	−0.0428	0.0115	−0.0055	7.8
Up 1500	−0.0396	0.0140	−0.03657	0.0135	−0.00303	3.7

5   The Lift Obtained by Moment Inverse Calcultion Method

The lift coefficient can also be inversely calculated according to the pitching moment coefficient of the Horizontal tail, but the following two assumptions need to be met:

(1) When the horizontal tail lift is 0, the pitching moment coefficient is also 0;
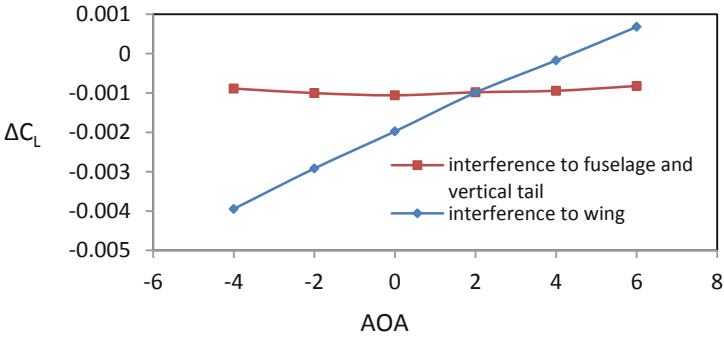(2) The lift of the Horizontal tail acts on 25% of the average aerodynamic chord point of the Horizontal tail.

Fig. 11. Inverse calculation of lift by pitching moment

The above conditions are basically satisfied when the Horizontal tail is a symmetrical airfoil.

Ignoring the influence of the drag of the horizontal tail on the pitching moment, the lift and pitching moment coefficients of the Horizontal tail meet the following relationship:

$$C_L \frac{L_{pw}cos(\alpha)}{C_A} = C_m$$

where: L_{pw} is the tail force arm with Horizontal tail; C_A is the average aerodynamic chord length of wing; α is the fuselage angle of attack.

When the Horizontal tail is at the designed position, according to the CFD results, the lift characteristics of the Horizontal tail are obtained by using lift difference and the reverse calculation method of pitching moment according to the component disassembly method and, and compared with the results obtained by the direct measurement method. The results are shown in Fig. 12.

Using the component disassembly method, the aerodynamic force of the Horizontal tail is obtained by subtracting the non Horizontal tail configuration from the whole plane configuration. There is an obvious difference between the value obtained by lift difference method and the value obtained by moment inverse calculation method, and the result of moment inverse calculation method is closer to the result of direct measurement. The moment inverse algorithm helps to reduce the error, but compared with the direct measurement method, the slope of the Horizontal tail lift line obtained by moment inverse calculation is still 14.3% more than that using direct measurement.

There is an obvious difference between the component disassembly method, the direct measurement and the moment inverse calculation. The main reason is that the Horizontal tail aerodynamic force obtained by the component disassembly method includes three parts: the Horizontal tail aerodynamic force, the interference of the Horizontal tail to the wing and the interference of the Horizontal tail to the fuselage. The force arms of these three parts relative to the moment reference point are different, and the contribution of the same lift to the pitching moment is different. For example, the interference part of the wing, although the installation of the Horizontal tail has obvious interference to the lift of the wing, because the moment reference point is located on the wing, The force arm of the wing interfering with the lift is small and has little influence on the
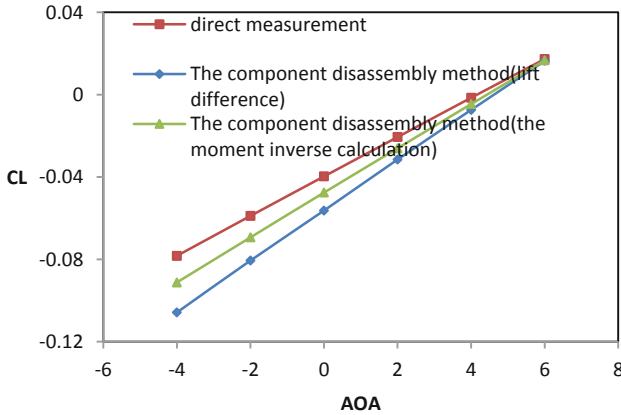
Fig. 12. Comparison of moment inverse method and lift difference method

pitching moment, and the result of rhe lift inverse calculation is close to 0. It can be seen from Fig. 13 that the moment inverse calculation basically eliminates the interference of the Horizontal tail to the wing and reduces the interference of the Horizontal tail to the fuselage.
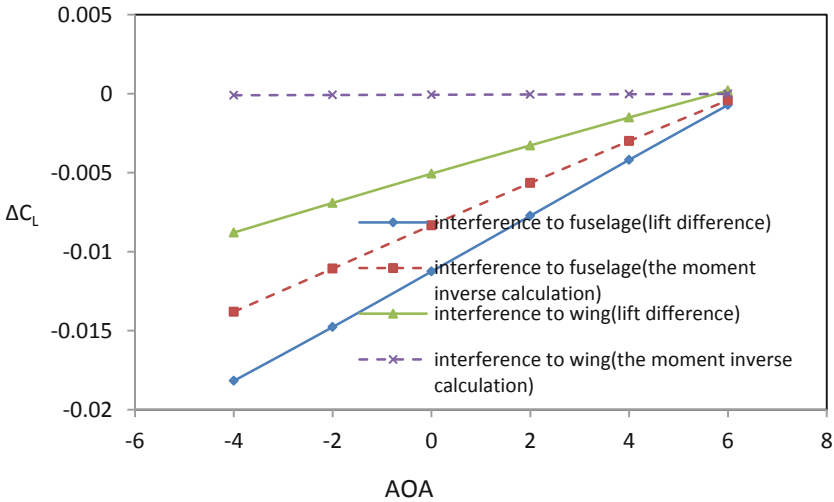

Fig. 13. Comparison of interference lift corresponding to lift difference and reverse from moment

When the Horizontal tail moves on the vertical tail, the research shows that after the Horizontal tail moves up 1500 mm, the overall layout of the aircraft changes from the conventional layout to the T-tail layout. At this time, the error of the component disassembly method is significantly reduced, and the slope error of the Horizontal tail lift line is only 3.7%. The main reason for this error is the interference effect of the Horizontal

tail on the wing, as shown in Fig. 13. Because the interference of the Horizontal tail to the wing can be eliminated by using the moment inverse calculation, for the aircraft with T-tail layout, according to the component disassembly method and combined with the moment inverse calculation, the result is basically the same as that of the component disassembly method, and the error is only—0.3% (Table 3).

Table 3. Lift of Horizontal tail with different methods for T-tail

Method	C_{L0}	C_{La}	C_{L0} error	C_{La} error
The component disassembly method-using lift difference	−0.0396	0.01397	−0.003	3.5%
The component disassembly method-the moment inverse calculation	−0.0375	0.01346	−0.0009	−0.3%
Direct measurement	−0.0366	0.01350	–	–

6 Conclusion

The component disassembly method theoretically assumes that the aerodynamic characteristics of the fuselage and wing remain unchanged with or without a Horizontal tail. In fact, for the low Horizontal tail layout with a Horizontal tail installed on the fuselage, the installation of a Horizontal tail will significantly affect the aerodynamic characteristics of the fuselage and wing, which is mainly reflected in two aspects: after adding a Horizontal tail, the lift of the Horizontal tail will change the flow field of the wing, and the pressure distribution of the aircraft which can cause to change of the lift of the wing. The installation of the Horizontal tail on the fuselage changes the pressure distribution of the fuselage. Therefore, for aircraft with low Horizontal tail layout, the Horizontal tail aerodynamic data obtained by component disassembly method has large error.

The differences between the component disassembly method and the direct measurement method when the Horizontal tail is installed at different positions of the fuselage and the vertical tail are studied. When the Horizontal tail is on the fuselage, the error of the component disassembly method is large, and when the Horizontal tail is on the vertical tail, the error decreases gradually with the increase of the installation height.

The moment inverse calculation method can basically eliminate the interference of the Horizontal tail to the wing and reduce the interference of the Horizontal tail to the fuselage. Compared with the method using the substration of the lift, it can effectively reduce the error of the component disassembly method.

For the T-tail layout of high Horizontal tail, the error of Horizontal tail aerodynamic data obtained by component disassembly method is relatively small. With the moment inverse claculation, the results are basically the same as that of direct measurement method.

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