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CFD and VLM Simulation of the Novel Twin-body Asymmetric Flying-wing Aircraft

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Abstract. Twin-body aircraft has the advantages of heavy load and long voyage, which make it suitable to execute the task. However, it also has some problems such as high-strength mid-wing requirement and no usable airport in the practical application. In order to solve these problems and promote twin-body aircraft's adaptability, this paper conducts a research of a new type of twin-body asymmetric flying-wing aircraft (TAFA). Two kinds of simulations (CFD and VLM) are conducted to prove the effectiveness of its flight performance. The results show that the flight performance of TAFA is the best among the four different kinds of plane that can perform the same tasks.

Introduction

A twin-body aircraft has the advantages of heavy load and long voyage[1-4]. On May 31, 2017, in Mojave, California, Stratospheric Launch Systems Inc. developed an almost complete a twin-body aircraft model, Stratolaunch 351. It has a wingspan of 117 meters, six engines and a payload of 250,000 kilograms between the two fuselages. The purpose of this aircraft is to deliver rockets, satellites, etc. over 30,000 feet at high altitude, thus reducing the high fuel cost of launching rockets directly from the ground. Richard Vogt, a famous American aeronautical engineer, put forward the concept of two-body asymmetric aircraft and designed BV141 aircraft. BV141 is built for reconnaissance. Vogt designed a smaller cockpit next to the plane body to form an asymmetric layout. Because at that time the engine was in the front-end of a plane, it blocked the sight.

Although the twin-body aircraft has the advantages of heavy load and long range, maneuverability is its weakness. Once the twin-body aircraft is in a complex airflow environment, the stable flight state is likely to be broken[5-8]. In order to maintain the balance of aircraft control force, the dynamical structure and mechanical flight control structure of the twin-body aircraft's each body are basically the same, and pilots operate in both cabins at the same time. However, if the pilot does not synchronize with the control command, the twin-body aircraft will run out of control. This inconsistency of manipulation is a common phenomenon in history. In modern times, with the advent of radio and telex flight control systems, a pilot can complete such complex movements. This phenomenon has been alleviated, but still it is unable to solve the problem of flight under complex weather conditions. Therefore, it is urgent for a twin-body aircraft to solve its maneuverability problem.

A Novel Twin-body Asymmetric Flying-wing Aircraft (TAFA) is designed in this paper. The aerodynamic performance of TAFA in the range of - 4°~8° angle of attack is continuously calculated by the vortex lattice method（VLM）, and the computational fluid dynamics (CFD) is carried out. The results show that the flight dynamic parameters of TAFA model are much better than the three control group plane models that can finish the same task.

Model Design of the Novel Two-body Asymmetric Flying-wing Aircraft

The design process starts with defining the mission requirements of the airplane. Operational requirements such as payloads, endurance and loiter speed need to be determined. Mission requirements and payload requirements are shown in Table 1.

After the requirements are determined, the aircraft gross takeoff weight should be estimated. By using historical data and experience, the initial gross takeoff weight is set as 36kg. Next, calculation need to be done to find out wing area. According to Equation 1[9], Cy is lift coefficient, which is 0.5 in this case. ρis air density, which is 1.2g/m3. V is the loiter speed, which is 25m/s. L is the lift of the aircraft, which is 36×9.8=352.8N. Through calculation, the wing area S is 2.39.

$$L=1/2Cy\rho V2S \tag{1}$$

Table 1. Basic requirements of design.

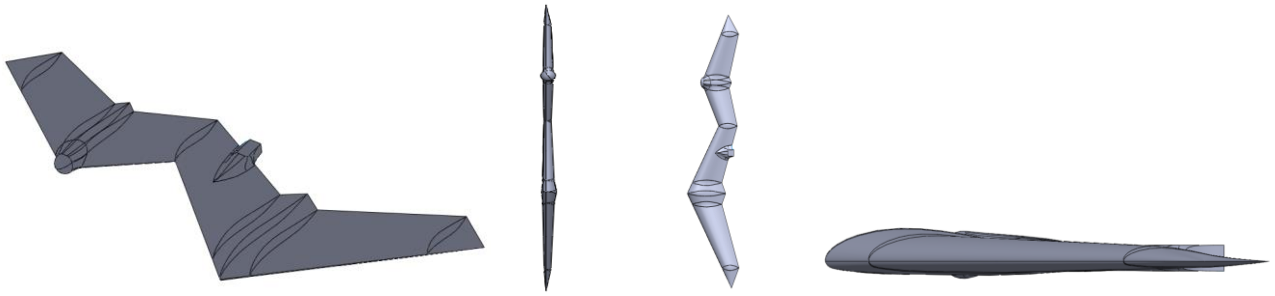
Mission Requirements	Payload Requirements
Flight Requirements Payload weight: 9.24kg Endurance: 8h(Battery)/24h(fuel) Loiter Speed: 25m/s	Synthetic aperture radar (contains radar, antenna, and imaging processor): Radar: 203*165*76mm, 2.44kg Antenna: 127*127*38mm, 0.29kg Lidar: 142*70*230mm, 2.2kg Data link: 290*179*161mm, 1.5kg Multispectral camera: 127*177.1mm, 1.4kg Imaging processor: 152.5*152.5*76mm, 1.41kg Engine: 60*161*93mm, 0.62 kg

The aircraft adopts and combines three features: twin-fuselage, all-wing structure, and asymmetry distribution. Twin-fuselage plane is a kind of plane that has two main fuselages. All-wing plane is a special kind of aircraft that consist of wings and has no tail or fuselage. Asymmetry distribution plane has unequal sides.

Despite the reason that can increase lift, load, endurance and voyage, twin-fuselage aircraft also has significant advantages. In this task, the aircraft need to load both multispectral camera and radar. However, this two equipment interfere with each other. Usually the solution would be putting multispectral camera on the top of radar, but it would make the plane too thick and increase its air resistance, so the solution influences its flight performance negatively. By employing twin-fuselage aircraft layout, multispectral camera and radar can be put on two plane heads respectively.

The use of all-wing structure can substantially increase the lift of an aircraft and increase the stability and strength of the connection area of twin-fuselage airplane. The lift is proportional to wing area. By using all-wing structure, all parts of the plane can contribute to the lift. Thus, lift is maximized. In addition, all-wing structure reinforces the fragile connection part between the two fuselages. It changes previous long rectangular easy-broken off structure into a nearly square shape to reduce the force moment by reducing the moment arm. Also, it increases the connection area to prevent being easily damaged during the flight.

The basic diagrams of this novel TAFA are as follows:



(a) 3D (b) X direction (c) Z direction (d) Y direction

Figure 1. Design diagram of the novel twin-body Asymmetric Flying-wing Aircraft.

Simulation Principle of Vortex Lattice Method and Computational Fluid Dynamics

The feedback method is used to design the aircraft model. Firstly, according to the main points of aircraft design, the aircraft model is drawn, and the parameters of the aircraft model are substituted into VLM simulation calculation program. If the results are not appropriate, the aircraft model is redesigned according to the feedback information obtained from the calculation until VLM results are appropriate. According to the above method, the model of TAFA is obtained.

In order to test the airplanes' performances, modelling and simulation process is necessary. The airplanes' properties are measured by two different kinds of simulations [10-11]: VLM and CFD. VLM is quicker and easier than CFD, so it is used to design prilimilary plane model. CFD simulation is used for testing rationality of the designed plane.

VLM simulation

The main formula of VLM is as follows[10]:

$$\omega(x,y)=-\frac{1}{4\pi}\iint_{S}\frac{(x-\xi)\gamma(\xi,\eta)+(y-\eta)\delta(\xi,\eta)}{\left[(x-\xi)^2+(y-\eta)^2\right]^{3/2}}d\xi d\eta-\frac{1}{4\pi}\iint_{W}\frac{(y-\eta)\delta_{\omega}(\xi,\eta)}{\left[(x-\xi)^2+(y-\eta)^2\right]^{3/2}}d\xi d\eta \tag{2}$$

Where (x,y) represent coordinate; ω (x,y) represents normal velocity; γ represents the spanwise vortex strength of per unit length; (ξ,ζ) represents coordinate points; represents ; δ represents chordwise vortex strength per unit length.

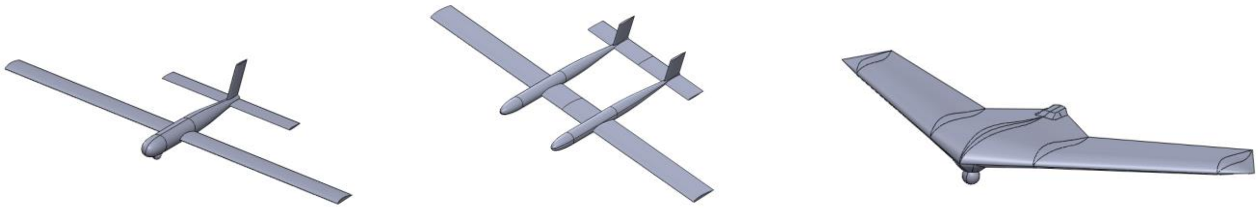
The basic dada for VLM is from Table 1. Aerodynamic forces at angles of attack ranging from -4 ~8° are continuously calculated by using VLM. Since the basic assumption of VLM is that the aircraft has no thickness, the drag must pass through the reference point and no moment is produced. The position of lift center in wingspan direction can be deduced by rolling moment coefficient and lift force. The relationship between rolling moment coefficient and rolling moment is as follows:

$$L=qsBCl \tag{3}$$

Where L is the rolling moment, q is the dynamic pressure, s is the wing area, B is the wingspan, Cl is the rolling moment coefficient.

Rolling moment is the product of the vector from the reference point to the lifting center and the lifting vector. The other one can be obtained from either of the three known vectors. Through the above formulas and the data in the table, the spreading position of the lift center corresponding to each angle of attack can be obtained.

For comparing the properties between this novel plane and others model，flying-wing aircraft, a twin-body symmetric flying aircraft and normal aircraft are also designed in this paper, shown in Figure 2. These types also underwent VLM at the same flight speed.



(a) Normal airfraft (b) Twin-body symmetric flying aircraft (c) Flying-wing aircraft

Figure 2. Design diagram of the others' aircrafts.

CFD Simulation

For CFD simulation, fluid dynamics was used. The main equations are as following[10]:

Continuity equation

$$\frac{D\rho}{Dt}+\rho\nabla\cdot V=0 \tag{4}$$

Momentum conservation

X direction

$$\rho\frac{Du}{Dt}=-\frac{\partial p}{\partial x}+\frac{\partial\tau_{xx}}{\partial x}+\frac{\partial\tau_{yx}}{\partial y}+\frac{\partial\tau_{zx}}{\partial z}+\rho f_x \tag{5}$$

Y direction

$$\rho\frac{Dv}{Dt}=-\frac{\partial p}{\partial y}+\frac{\partial\tau_{xy}}{\partial x}+\frac{\partial\tau_{yy}}{\partial y}+\frac{\partial\tau_{zy}}{\partial z}+\rho f_y \tag{6}$$

Z direction

$$\rho\frac{Dw}{Dt}=-\frac{\partial p}{\partial z}+\frac{\partial\tau_{xz}}{\partial x}+\frac{\partial\tau_{yz}}{\partial y}+\frac{\partial\tau_{zz}}{\partial z}+\rho f_z \tag{7}$$

Conservation of energy

$$\begin{aligned}\rho\frac{D}{Dt}\left(e+\frac{V^2}{2}\right)=\rho\dot{q}+\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}\\+\frac{\partial(u\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z}+\frac{\partial(v\tau_{xy})}{\partial x}+\frac{\partial(v\tau_{yy})}{\partial y}+\frac{\partial(v\tau_{zx})}{\partial z}+\\\frac{\partial(w\tau_{xz})}{\partial x}+\frac{\partial(w\tau_{yz})}{\partial y}+\frac{\partial(w\tau_{zz})}{\partial z}+\rho f\cdot V\end{aligned} \tag{8}$$

Where τ is Shearing force, f is external force, p is pressure, u,v,w represent velocity of x,y and z direction respectively, e is energy.

VLM Results

Computational meshing for this novel plane is shown in Figure 3[11]. Figure 4 shows computational meshing for others aircrafts such as single-wing aircraft, twin-body symmetric flying aircraft, and flying-wing aircraft. Matlab is used for VLM.

In order to prove the effectiveness of the new type of airplane, it is compared with single-wing aircraft, twin-body symmetric flying aircraft, and flying-wing aircraft for the same task.

L/D is the lift-drag ratio and an important parameter to represent the aerodynamic efficiency of an aircraft. The bigger it is, the better the performance of the aircraft. As shown in Fig.5, at the same flight speed and lifting, the L/D of TAFA is the largest, which is 25.5, much higher than 23.3 of the normal aircraft, 23 of the twin-body aircraft and 22.7 of the flying-wing aircraft. Under the same fuel and lift conditions, due to the small drag of the two-body asymmetric flying-wing aircraft, the flight time and range will increase, which is more suitable for tasks.

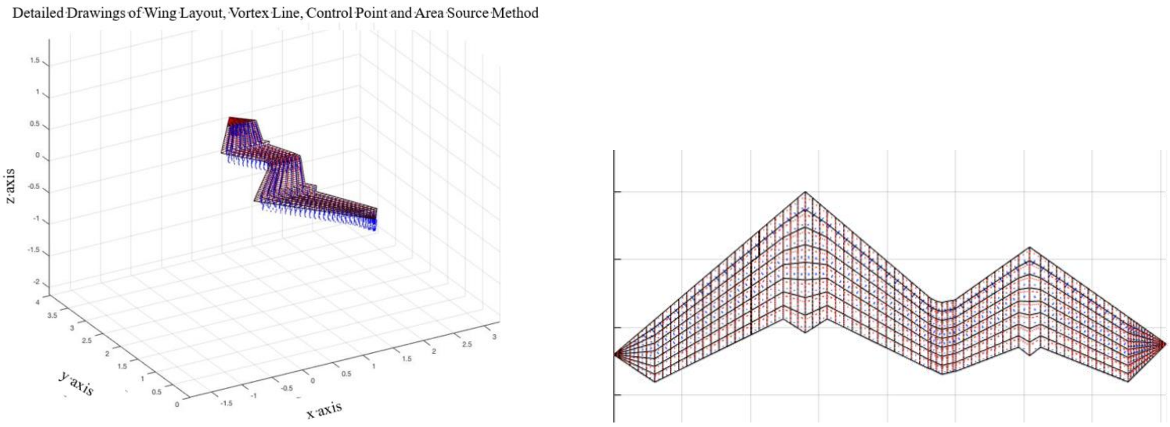
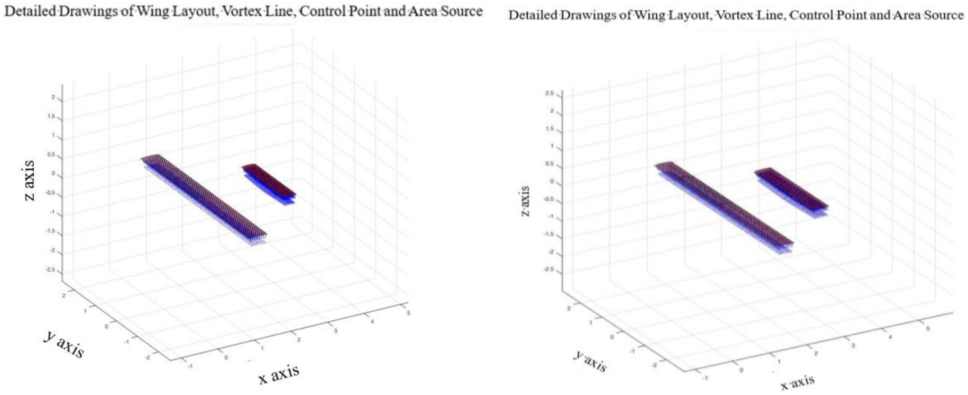
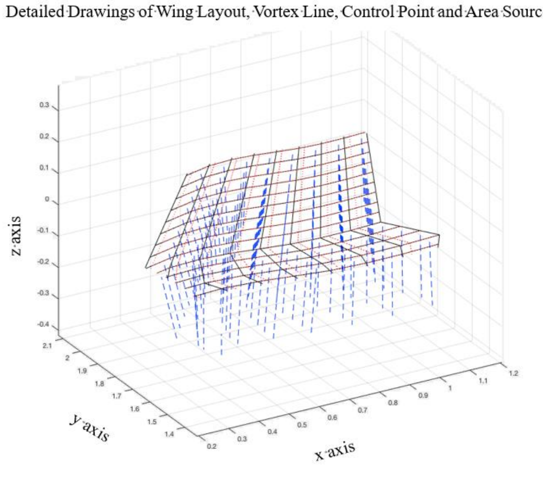

Detailed Drawings of Wing Layout, Vortex Line, Control Point and Area Source Method

Figure 3. Mesh generation of TAFA simulated by vortex lattice method.


Detailed Drawings of Wing Layout, Vortex Line, Control Point and Area Source

Detailed Drawings of Wing Layout, Vortex Line, Control Point and Area Source

(a) Single-body aircraft (b) twin-body symmetric aircraft


Detailed Drawings of Wing Layout, Vortex Line, Control Point and Area Source

(c) Flying-wing aircraft

Figure 4. Mesh generation of others aircrafts.

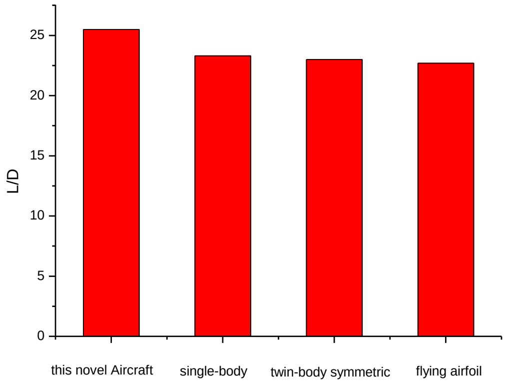


Figure 5. Comparison of Lift-drag ratio.

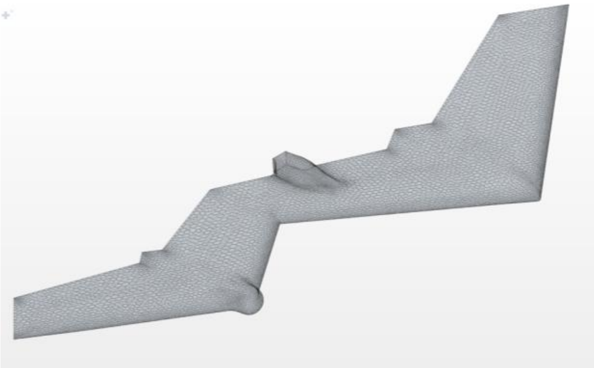


Figure 6. Mesh generation for CFD.

CFD Results

VLM can quickly calculate the main aerodynamic parameters such as lift and drag generated by aircraft wings. However, it cannot accurately calculate the parameters of an aircraft with a fuselage. Compared with the vortex lattice method, CFD can calculate lift, drag and lift-drag ratio more accurately. Mesh generation for CFD calculation is shown in Figure 6. The calculation condition is shown in Table 1. STAR-CCM+ software is used. The simulation results are shown in Figure 7~Figure 9.

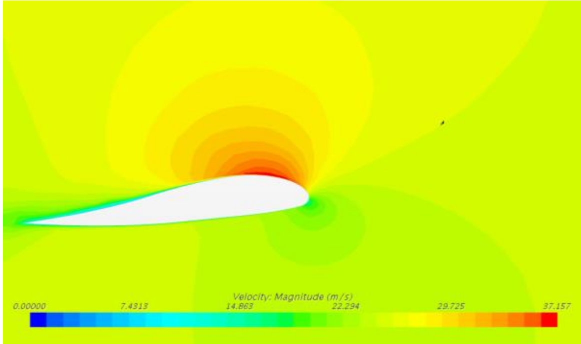


Figure 7. Sectional velocity.

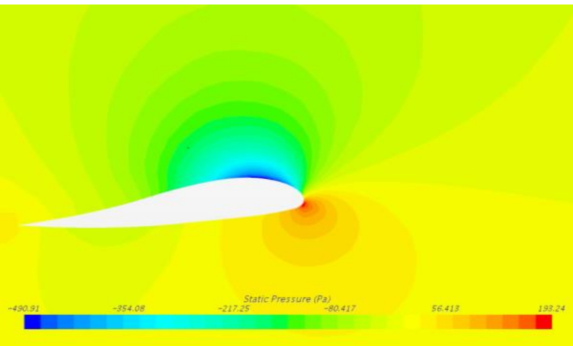


Figure 8. Sectional pressure.

If the aircraft is in an abnormal state, it can be clearly shown by Figure 9. For example, if an aircraft goes out of control, the CFD simulation graph will show that there are many areas under the same pressure. However, the pressure distribution in this graph has a gradient, which proves that there is no stalled problem. In addition, turbulence is one of the main factors affecting flight, which makes the aircraft out of control and causes malignant flight accidents. In the Figure 9, the pressure in the second half of the aircraft in the turbulent zone is much greater than that in the front, like a rainbow. This means that no large-scale flow separation problem. In summary, the airflow of the aircraft is in an adherent state, and there are no obvious design problems.

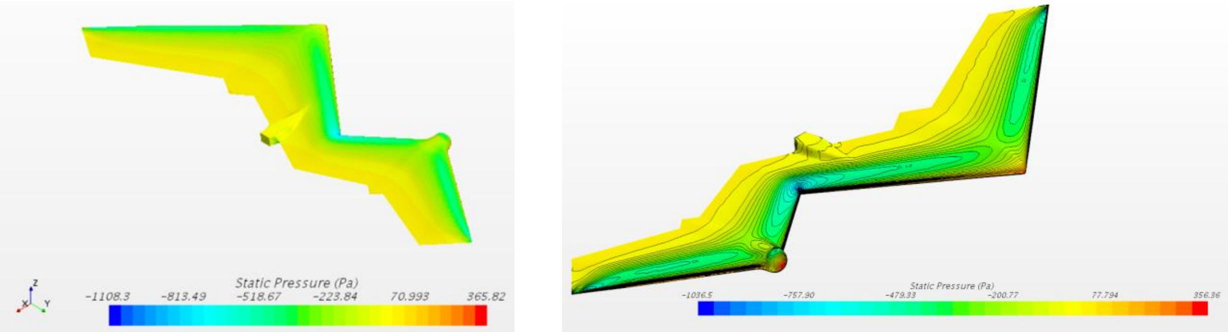


Figure 9. Distribution of pressure.

Summary

In this paper, the model of an novel TAFA is designed. The aerodynamic performance of TAFA in the range of - 4°~8° angle of attack is continuously calculated by VLM, and CFD simulation is carried out. The results show that the flight dynamic parameters of the novel TAFA model are much better than the three control group plane models that can finish the same task. CFD simulation shows the TAFA model is well designed. The lift-drag ratio of TAFA is significantly higher than that of other three types of aircraft. TAFA has its advantages of fuel-saving and long range.

Acknowledgement

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