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Structural Optimization of Anti-Interference of Small Ducted Aircraft

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Abstract: The small ducted type aircraft has small volume and light weight, and the ducted body occupies a large proportion in the pneumatic surface of the whole machine. The presence of the ducted causes the aircraft to produce momentum resistance and additional resistance moments under the side wind/gust interference. The effect is to produce the rise torque that causes the aircraft to "rise up", which makes the aircraft more susceptible to side wind/gust interference and deviates from the stable equilibrium state. Therefore, compared with the open rotor unmanned aerial vehicle (UAV), the small ducted aircraft itself has worse anti-interference ability. The above analysis shows that the ring structure of the culvert makes the aircraft itself more vulnerable to the side wind/gust interference in the environment and forms an additional resistance moment. Therefore, how to improve the inherent anti-jamming capability of the small ducted aircraft through structural optimization is the problem to be solved in this paper.

Key words: small ducted aircraft; structure; anti-interference
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As a kind of rotary-wing unmanned aerial vehicle (UAV), small ducted aircraft not only has the general characteristics of vertical take-off and landing, air hovering and so on, but also makes up for the problem of poor safety of open rotor aircraft, which cannot work in complex environment such as building, roadway, forest and ruins.

The propeller of the small ducted type aircraft is hidden in the culvert. The combination form of the rudder surface is complex and there are many parameter uncertainties[1]. Moreover, the culvert occupies a large proportion in the pneumatic surface of the whole aircraft, which makes the aircraft have a large force surface under the interference of the side wind/gust wind, which will produce additional resistance moment[2]. The small ducted prototype developed by our group is shown in Fig. 1. In order to ensure the maneuverability of the aircraft, the structure design scheme with the centroid higher than the center of the control rudder surface is adopted, and the diameter of the culvert is 300 mm, which belongs to the small rotor UAV. The ducted body in the small ducted aircraft is named culvert in this paper. We will say "ducted body", "ducted aircraft". Others we called culvert[3-4].

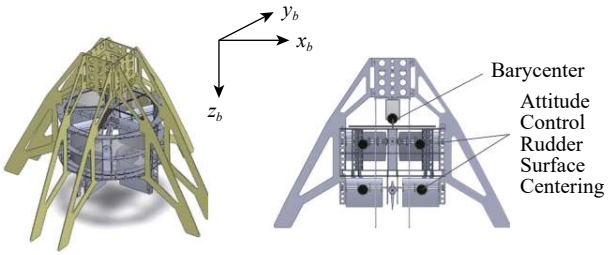

Fig. 1 Pilot prototype of small single-oar ducted type aircraft

According to the stability theory of the control system, the small ducted aircraft itself is a static unstable structure[5]. When the aircraft encounters external interference, it is necessary to control the rudder surface to produce the corres-

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ponding reverse torque to maintain the mechanical balance of the whole machine[6].

For the design process of small ducted type aircraft, it can be called passive flow control by optimizing the aerodynamic structure, making the aircraft achieve the best aerodynamic performance. It is characterized by simplicity and no need for additional drive, but poor strain ability, which can only make the aircraft more controllable through the preset pneumatic structure, and cannot directly control the attitude of the aircraft[7-8]. The purpose of adopting passive flow control scheme is to improve the inherent anti-interference ability of culvert and enhance the control effect of control system[9].

1 Solutions

This paper will start with the overall layout of ducted body, take into account the flow characteristics of culvert around the flow, adopt the whole machine layout optimization and passive flow control to improve the inherent anti-interference ability of ducted body[10]. In the whole structure of the small ducted type aircraft, the ducted body as the main pneumatic structure increases the force surface under the side wind interference of the aircraft, and the aerodynamic relationship between the ducted body and the propeller is coupled to further increase the complexity of the pneumatic characteristics of the whole machine. In order to improve the anti-interference ability of the aircraft itself, the optimal design of its overall pneumatic layout is one of the ways to solve the problem. Through the layout optimization, the flow characteristics of the culvert under the side wind/gust can be improved, and the aerodynamic resistance and the resistance moment can be reduced[11-13].

2 Optimization of Culvert Layout

Because the flight stability of culvert under the side wind/gust disturbance is not taken into account, this paper will optimize the overall layout of culvert under the premise of taking into account the enhancement effect of culvert and anti-jamming ability to enhance the inherent anti-jamming capability and maneuverability of ducted body.

The main contents and ideas of this section are shown in Fig. 2.

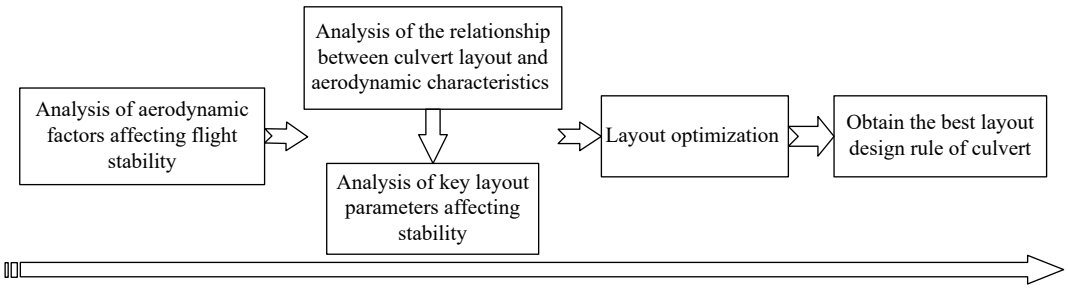


Fig. 2 Research process

2.1 Analysis of ascension effect of culvert

Culvert propeller can produce a larger thrust/pull at the same power and the same diameter compared to the isolated propeller; at the same power, the diameter required to produce the same thrust/pull is smaller[14]. The aerodynamic principles that make this difference are as follows:

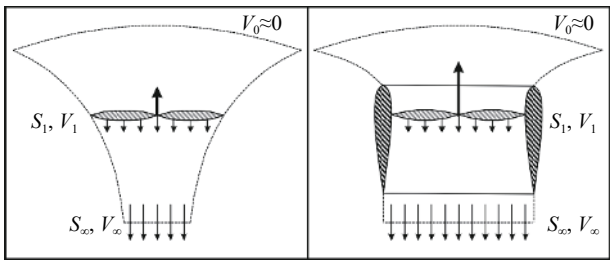
①The existence of the culvert changes the sliding state under the propeller, increases the sliding cross section area, reduces the sliding velocity and the loss of the sliding kinetic energy, and therefore converts the kinetic energy of the propeller into the pressure energy, as shown in Fig. 3;

②The wall of the culvert improves the flow characteristics of the propeller tip and reduces the energy loss of the propeller tip;

③The inlet leading edge of the mouth of the culvert has formed a large negative pressure

zone, resulting in additional lift;

Due to the shrinkage effect of the open propeller on the sliding flow, the aerodynamic efficiency of the propeller has been reduced to a certain extent, and its thrust has a great loss.



(a) Open propeller (b) Culvert propeller

Fig. 3 Schematic diagram of sliding flow of open propeller and culvert propeller

For ducted type aircraft, the sliding outlet area is

$$S_{\text{e-duct}} = \sigma S \tag{1}$$

Mass flow is

$$\dot{m} = \rho S v_{\text{i}} = \rho \sigma S v_{\text{e-duct}} \tag{2}$$

$$v_{\text{i}} = \sigma v_{\text{e-duct}} \tag{3}$$

At this point, the total thrust of the system consists of two parts are

$$T = T_{\text{FAN}} + T_{\text{DUCT}} \tag{4}$$

based on the derivation

$$T_{\text{FAN}} = (p_2 - p_1) S = \frac{1}{2} \rho v_{\text{e}}^2 S \tag{5}$$

$$\frac{T_{\text{FAN}}}{T} = \frac{1}{2\sigma} \tag{6}$$

For the open propeller, the coefficient, for the ducted type aircraft, the corresponding value of different culvert structure is different, the larger the value, the more obvious the increase effect of culvert.

2.2 Analysis of momentum resistance of culvert under lateral wind/gust disturbance

For a small ducted aircraft, shortening the distance between the center of gravity and the center of mass is an effective method to reduce the momentum resistance. The decrease of the force arm can effectively reduce the pitch torque and then reduce the influence of the momentum resistance on the stability of the aircraft.

In a crosswind/gust environment, the incoming flow deflects under the induction of the ducted fan and accelerates through the duct body, causing the static pressure distribution in the lip plane to change, and the static pressure on the downwind side is higher than that on the upwind side, and then generate momentum resistance D_{m} and pitching moment M_y, as shown in Fig. 4.

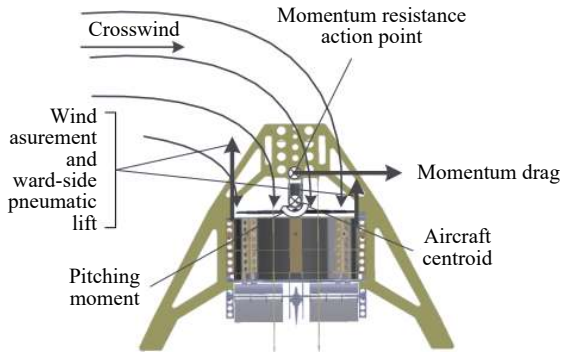


Fig. 4 Aerodynamic force of small ducted aircraft under crosswind interference

The momentum resistance of the aircraft is zero when it hovers under the condition of no lateral wind:

$$D_{\text{m}} = \dot{m}_{\text{duct}} V_{\text{b}} = \rho V_{\text{b}} S_{\text{e}} V_{\text{e}} = \rho V S_{\text{e}} V_{\text{e}} \tag{7}$$

When a ducted type aircraft flies with a certain angle of attack, $\alpha < 0°$. The projection of the velocity in the direction is $V\cos\alpha$:

$$D_{\text{m}} = \rho V S_{\text{e}} V_{\text{e}} \cos\alpha \tag{8}$$

It can be seen from the above formula that the momentum resistance acting on the ducted is the wind velocity, the outlet area of the culvert and the culvert outlet slip velocity is proportional.

3 Numerical Calculation of Ducted Body Around Flow

In the overall layout of culvert, culverts and propellers are the main pneumatic components of the whole machine. In this paper, computational fluid dynamics (CFD) is used to study the aero-

dynamic characteristics of small culvert type vehicles.

The turbulence model used in this paper is the shear stress transport (SST) k-ω model.

3.1 Pneumatic relationship analysis of the interaction between culvert and propeller

According to the aerodynamic analysis, the aerodynamic relationship between propeller and culvert is a problem that must be considered in the design of aircraft structure and control system.

Through the aerodynamic characteristic curve, we can get the following aerodynamic relation between the ducted body and propeller of small ducted type aircraft:

① In the small angle of attack, the coupling between the culvert and the propeller improves the lift characteristics of the aircraft, and the culvert still has a significant lift effect.

② When the aircraft is flying with a small angle of attack, the aerodynamic coupling between the ducted body and the propeller increases the aerodynamic resistance of the aircraft.

③ The pitching torque is closely related to the momentum resistance. Therefore, the pitching torque change curve is close to the aerodynamic resistance change trend. During the small angle of attack flight, the action of the propeller increases the static pressure difference between the windward side and the downwind side of the culvert lip, resulting in the increase of the pitching torque. In this case, the control system needs to produce a larger reverse torque to ensure the stable flight of the aircraft.

Therefore, how to reduce the adverse effect of culvert and propeller through layout optimization is the next research focus.

3.2 Pneumatic characteristics of small ducted aircraft maneuvering process

In different stages of maneuver flight, the lift, drag and pitch torque of the aircraft show different changing trends. In the process of the aircraft changing from vertical hovering to high-speed forward flight, the aerodynamic lift of the ducted body increases with the increase of the inclination angle, reaching the maximum value of angle of attack about α=–45°, then gradually decreases, the aerodynamic drag of the ducted body decreases with the increase of inclination angle, and the pitching torque decreases gradually in the process of aircraft maneuvering.

4 Optimization of Culvert Layout

In this paper, four main structural parameters, such as length ratio of culvert, cone angle of culvert, depth of propeller disc and clearance of inner wall of propeller disc and culvert, are calculated and analyzed.

4.1 Effect of length ratio of culvert on aircraft stability

With the increase of the aspect ratio, the aerodynamic lift, aerodynamic drag and pitching torque of the ducted body are increasing gradually. Obviously, increasing the culvert length may provide beneficial effects for small ducted type aircraft in terms of aerodynamic lift, but it also results in the increase of aerodynamic drag and pitch torque.

The larger the aspect ratio of ducted body, the more obvious its increasing effect, but the increase of resistance and pitch torque will also lead to the decrease of its stability and maneuverability. Therefore, in the design of the aircraft layout, we can consider sacrificing the lifting effect of the culvert, and choose the structure of the ducted body with relatively small length, so that the aircraft itself has stronger anti-interference ability and maneuvering ability.

4.2 Effect of cone angle on stability of aircraft

Based on simulation the results show that the larger the cone angle is theoretically, the stronger the anti-interference ability is, and the stronger the maneuverability is. However, the continuous increase of β will increase the blocking effect of culvert on the under wash flow, and the additional resistance of culvert wall in the under wash flow field will also increase, so β can-

not increase without restriction.

4.3 Effect of paddle disc position on aircraft stability

The pressure difference between the inlet and outlet of the culvert is caused by the ring of the propeller, so the longitudinal position of the propeller in the culvert will have a great influence on the static pressure distribution inside the culvert. The simulation results show that when the inlet distance between the paddle plate and the culvert is about one third of the height of the culvert, the pitch moment of the culvert is the least.

As the propeller plate moves from the inlet of the culvert to the outlet, the influence of the propeller on the flow characteristics of the inlet air is gradually weakened, but its inductive effect on the forward flow still exists, which makes the uneven distribution of static pressure in the plane of the mouth of the culvert more serious, and then leads to the increase of the pitching torque.

4.4 Effect of clearance between propeller disc and culvert on stability of aircraft

The results show that it is the general rule for the structure design of small ducted type aircraft to minimize the gap between the oar and the inner wall, whether considering the increasing effect or the stability and maneuverability of the aircraft.

4.5 Summary of influence of culvert structure layout on aircraft stability

The rules affecting the stability and maneuverability of aircraft are as follows:

① An increase in the ratio of length to diameter of the culvert will result in a decrease in the anti-interference capability of the aircraft as well as a decrease in the maneuverability of the aircraft.

② The stability and maneuverability of the vehicle are the best between –3° and 3°. Considering the aerodynamic characteristics of the aircraft, it is more reasonable to choose the cone angle between 0° and 3°.

③ The propeller has the best stability and maneuverability when the propeller disc is at the inlet of the culvert at a third altitude.

④ Reducing the clearance between the inner wall of the propeller disc and the culvert can improve the anti-interference and maneuverability of the aircraft.

5 Conclusions

In this paper, the aerodynamic characteristics and numerical calculation methods of small ducted aircraft under side wind interference are analyzed in detail. The variation of lift, resistance and pitch moment of the aircraft in the maneuvering process is obtained by analysis, and the overall layout of the culvert is optimized.

Firstly, the influence of the coupling of the culvert and propeller on the aerodynamic characteristics of the whole machine is verified by theoretical analysis and numerical calculation. The results show that the anti-jamming ability of the aircraft is reduced by the mutual influence and provides reference for the layout optimization and future aircraft structure design.

Secondly, the optimization of the overall layout of the culvert can effectively change the pitching torque of the aircraft. By reducing the chord ratio of the culvert, increasing the cone angle of the culvert and setting the proper position of the propeller can effectively improve the pitching torque of the aircraft under the side wind interference or in the process of maneuvering.

After layout optimization, reasonable layout can enhance the anti-interference ability of ducted body to a certain extent, which is of great significance to improve the overall stability and maneuverability of ducted aircraft.

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