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Investigation of Aerodynamic Characteristics of a Multi-element Wing under Propeller Slipstream

Guopeng Cui, Lihao Feng*

Fluid Mechanics Key Laboratory of Education Ministry, Beijing University of Aeronautics and Astronautics, Beijing, China

*lhfeng@buaa.edu.cn

Abstract

Propeller aircraft has the characteristics of high propulsion efficiency and good economy at low subsonic speed. Thus, propeller has a broad application in transport aircrafts. Especially, because of the high oil price, the propeller attracts more interests of researchers. The propeller slipstream is extremely complex and there are many related researches, including experiments and numerical analysis, to study its characteristics. The fundamental results of these researches provide valuable references to the design of aircraft. In this paper, we firstly summarize the research progress of propeller slipstream in recent years. Then, our recent results of aerodynamic characteristics of a multi-element wing under propeller slipstream are presented. It is indicated that the flap deflection of the multi-element wing can enhance lift of wing. In particular, it can lead to that the resultant force of wing becomes more vertical to the horizontal direction, which is helpful to achieve vertical take-off and landing.

1 Characteristics of Isolated Propeller

In order to investigate the interactions of wing and propeller slipstream, the aerodynamic characteristics of an isolated propeller need to be studied firstly. There are substantial literatures to study the velocity signals and flow field characteristics of the propeller slipstream. Favier et al. (1989) compared the results of numerical and experimental studies of isolated propeller wakes to validate the efficiency of numerical approach. Mast et al. (2004) used a vortex model to estimate the circulation distribution on a rotor blade and the velocity calculated by the vortex model agreed well with the experimental results. Hot wire measurements were used to study the velocity field in the wake of propeller by Mukund et al. (2016). They found that the turbulent level of the wake was very high while the flow in the near-wake did not accelerate at a high advance ratio. The -5/3 power law of Kolmogorov was observed in the spectra of the instantaneous axial velocity signals, as shown in Figure 1.

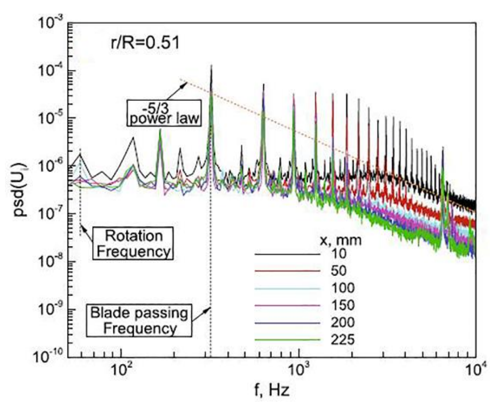


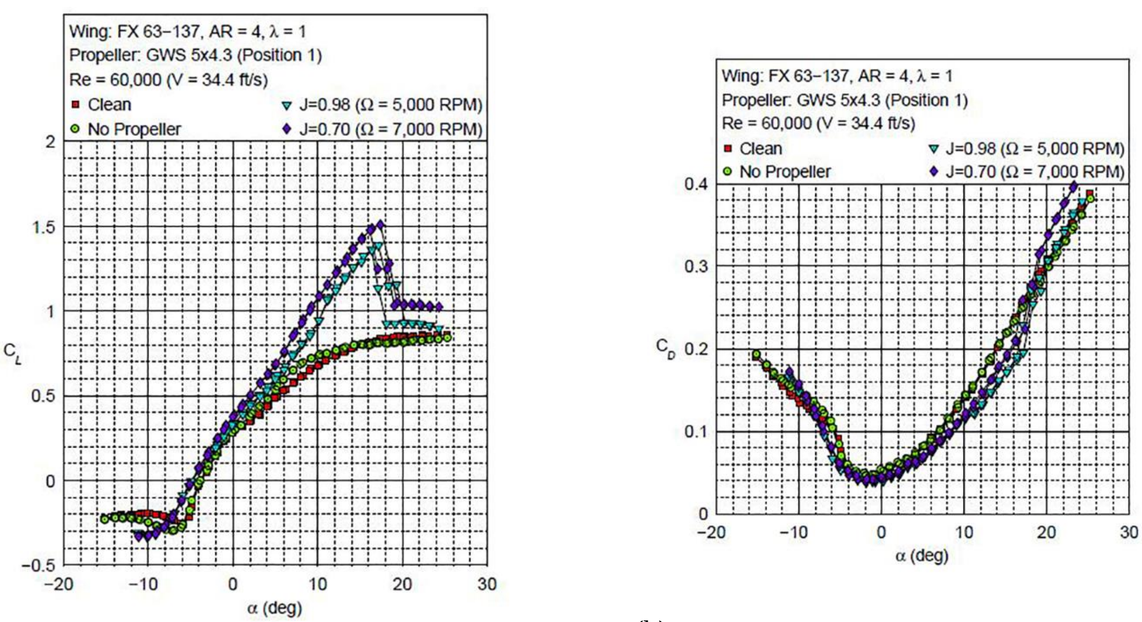
Figure 1: Power spectra of the axial velocity fluctuations at $r/R = 0.51$ for different x positions (Mukund et al., 2016).

Khan et al. (2015) used a propeller slipstream model, which considered both the acceleration and diffusion effects, to predict the velocity in the propeller slipstream. They divided the propeller slipstream into two different regions, namely, the near-field region which was characterized by slipstream contraction and the far-field region which was characterized by slipstream expansion. The velocity predicted by the propeller slipstream model compared well with the experimental results. The effects of advance ratio on the evolution of propeller wake were numerically investigated by Baek et al. (2015). The results showed that increasing the advance ratio could delay the merging of tip vortex of propeller. Cotroni et al. (2000) investigated the flow field behind a marine propeller using particle image velocimetry (PIV). They found that the propeller slipstream contracted in the region near propeller and began to expand about one diameter from the propeller, which proved the rationality of the two propeller slipstream regions pointed out by Khan et al. (2015).

2 Interactions between Propeller and Wing

The interactions between propeller and wing have an effect on the aerodynamic characteristics of wing, thus, the performance of aircraft. The effects of propeller slipstream on the wing have been studied by many researchers to understand the mechanism of the interactions between propeller and wing. These works are important to the optimum design of propeller aircraft.

The wing performance, including lift and drag, etc., can be changed in the propeller slipstream. Witkowski et al. (1989) investigated the influence of advance ratio of propeller on the characteristics of wing. The results showed that the propeller could increase the lift and reduce the drag of wing. The effects of some parameters on the wing performance at low Reynolds number of *Re* = 60000 were experimentally investigated by Ananda et al. (2013). They equipped propeller and wing separately so as to investigate the effect of propeller position with respect to wing. They found that the wing performance was improved under the propeller slipstream with the benefits of lift augmentation, lift-to-drag ratio improvement and pressure drag reduction, as shown in Figure 2.



(a) (b)

Figure 2: Effect of propeller advance ratio on the lift and drag curve of the wing at *Re* = 60000 (Ananda et al., 2013).

The wake of propeller is complex and turbulent, thus, it affects the flow over the wing surface. The temperature sensitive paint technology was used to study the flow characteristics of wing under propeller slipstream by Makino et al. (2014). The results showed that the propeller could prevent the formation of the laminar separation bubble and the stalling characteristics were also changed. Catalano (2004) studied the boundary layer characteristics of two propeller/wing configurations, namely the pusher and tractor configurations. The flow visualization results showed that the pusher configuration could delay boundary layer transition and separation, while the tractor configuration could promote the boundary layer transition.

The flow field information is important to understand the mechanism of propeller slipstream. The wake of propeller is complex and the vortex shedding from the propeller impinges on the wing surface, thus changes the boundary layer condition of wing. Roosenboom et al. (2009, 2010) used both PIV measurement and numerical simulation to investigate the propeller slipstream development. They captured the evolution of tip vortices and found the secondary boundary layer vortices formed in the slipstream.

3 Multi-element Wing's Performance under Propeller Slipstream

3.1 Experimental Setup

The multi-element wing with large chord flaps can induce the propeller slipstream downward, which results in the resultant force of wing more vertical to the horizontal direction. It is helpful in the fields of vertical take-off and landing. Thus, the aerodynamic characteristics of multi-element wing under propeller slipstream were experimentally investigated here.

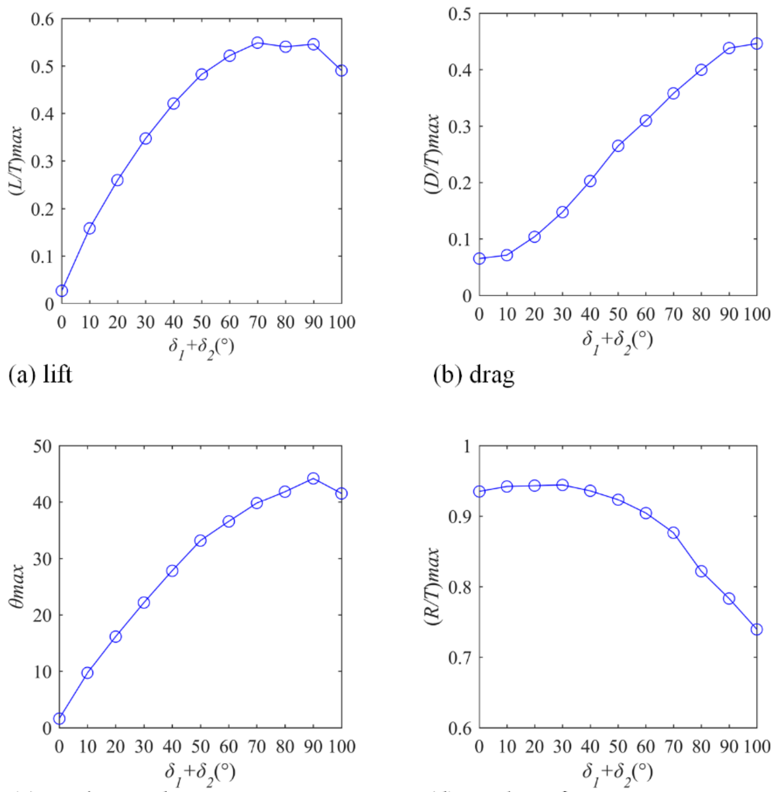
The experiment was conducted in the D1 wind tunnel at Beijing University of Aeronautics and Astronautics. The aerodynamic performance of wing was firstly investigated under static thrust condition, namely the tunnel speed was zero. The experimental setup is shown in Figure 3. The multi-element wing had two large flaps and was made of aluminum. The chord and span of the multi-element wing were 260 mm and 650 mm, respectively. The two flaps could be adjusted individually and the deflection angles of the two flaps were represented by δ_1 and δ_2, respectively.

Figure 3 The experimental setup.

A wooden made propeller with a diameter of 457.2 mm was mounted in a platform in front of the wing so that the position of propeller with respect to wing can be adjusted. The propeller was driven by brushless electrical motor and the rotational speed of propeller was 2700 revolutions per minute (rpm) with an accuracy of ±10 rpm. The horizontal distance between propeller and wing was 0.25 times of propeller diameter.

The aerodynamic forces were measured by load cells which were mounted as shown in Figure 3. The lift of wing was represented by *L*, the drag was represented by *D*, the propeller thrust was represented by *T*, the resultant force of wing was represented by *R* and the symbol θ represented the turning angle between resultant force vector and horizontal direction. The forces in this experiment were normalized by propeller thrust.

3.2 Results and Discussion



(a) lift (b) drag

(c) turning angle (d) resultant force

Figure 4 The aerodynamic performance of multi-element wing under propeller slipstream.

Figure 4 shows the aerodynamic characteristics of multi-element wing under propeller slipstream. It can be seen from Figure 4a that the maximum lift at different combinations of δ_1 and δ_2 increases with the total deflection angle of the first and second flaps ($\delta_1+\delta_2$) when $\delta_1+\delta_2 \leq 70°$. However, it remains nearly unchanged when $70° \leq \delta_1+\delta_2 \leq 90°$ and begins to decrease when $\delta_1+\delta_2 \geqslant 90°$. It is indicated that the flap deflection improves the lift of wing for most cases. The maximum drag of wing increases with the total deflection angle of the first and second flaps for all cases. It is meaningful that the turning angle also increases with the total deflection angle of the first and second flaps, which means that the aircraft can achieve the vertical take-off and landing with a small initial attitude angle. The maximum turning angle can reach 44°. It can be seen from Figure 4d that the resultant force changes smoothly when the total deflection angle of the first and second flaps is small, while it begins to decrease when $\delta_1+\delta_2 \geq 30°$.

4 Conclusion

The interactions between propeller slipstream and wing are complex. The propeller slipstream can change the aerodynamic forces and boundary layer condition of wing. Substantial researches about the flow fields of propeller slipstream and aerodynamic forces of wing under propeller slipstream provide important information to the propeller aircraft design. The aerodynamic characteristics of a multi-element wing under propeller slipstream was further experimentally investigated. It is indicated that the flap deflection of the multi-element wing could enhance the lift and turning angle of wing, which can improve the ability of aircraft to achieve vertical take-off and landing.

Acknowledgements

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References

[1] Favier D, Maresca C, and Ettaouil A (1989) Numerical and experimental investigation of isolated propeller wakesin axial flight. Journal of Aircraft 26:837-846
[2] Mast E, Vermeer LJ, and Van Bussel GJW (2004) Estimation of the circulation distribution on a rotor blade from detailed near wake velocities. Wind Energy 7:189-209
[3] Mukund R, and Kumar AC (2016) Velocity field measurements in the wake of a propeller model. Experiments in Fluids 57:154
[4] Khan W, and Nahon M (2015) Development and validation of a propeller slipstream model for unmanned aerial vehicles. Journal of Aircraft 52:1985-1994
[5] Baek DG, Yoon HS, Jung JH, Kim KS, and Paik BG (2015) Effects of the advance ratio on the evolution of a propeller wake. Computers & Fluids 118:32-43
[6] Cotroni A, Di Felice F, Romano GP, and Elefante M (2000) Investigation of the near wake of a propeller using particle image velocimetry. Experiments in Fluids 29:S227-S236
[7] Witkowski DP, Lee AKH, and Sullivan JP (1989) Aerodynamic interaction between propellers and wings. Journal of Aircraft 26:829-836
[8] Ananda GK, Deters RW, and Selig MS (2013) Propeller Induced Flow Effects on Wings at Low Reynolds Numbers. 31st AIAA Applied Aerodynamics Conference, San Diego, AIAA-2013-3193
[9] Makino F, and Nagai H (2014) Propeller Slipstream Interference with Wing Aerodynamic Characteristics of Mars Airplane at Low Reynolds Number. 52nd Aerospace Sciences Meeting, Maryland, AIAA-2014-0744
[10] Catalano FM (2004) On the effects of an installed propeller slipstream on wing aerodynamic characteristics. Acta Polytechnica 44:8-14
[11] Roosenboom EWM, Stürmer A, and Schröder A (2010) Advanced experimental and numerical validation and analysis of propeller slipstream flows. Journal of Aircraft 47:284-291
[12] Roosenboom EWM, Heider A, and Schröder A (2009) Investigation of the propeller slipstream with particle image velocimetry. Journal of Aircraft 46:442-449