Research on the Key Technology of Propulsion Drag System Division and Performance Analysis of Turboprop-powered Aircraft

Wu Yiting¹, Yuan Zhengzhong¹, Cheng Zhihang², Tao Yang³, *
1 Chengdu Aircraft Design & Research Institute, Chengdu, China
2 AVIC China south China aircraft industry Co., Ltd, Zhuhai, China
3 China Aerodynamics Research and Development Center, Mianyang, China

50323222@qq.com

Abstract. The remarkable characteristic of turboprop-powered aircraft is that its power system has great influence on the aerodynamic characteristics of the aircraft. Due to the action of turboprop slipstream, the airflow velocity after the propeller is obviously increased compared with the velocity of free flow. The turbulence caused by turboprop slipstream affects the aerodynamics of the aircraft, which in turn affects the performance of turboprop blades. In this paper, the layout characteristic and development trend of turboprop powered aircraft are briefly analysed. According to the characteristics of turboprop aircraft, a thrust/drag system division principle and interference characteristics treatment method for turboprop powered aircraft are introduced. Finally the influence of slipstream on a typical turboprop powered aircraft is analysed, It is very necessary to study the influence of propeller slipstream on aircraft aerodynamic performance in the early stage of developmental the effect of propeller slipstream on the aerodynamic characteristics of the whole aircraft is the strongest in take-off state, the influence of climbing state is weakened the influence of cruise state is the lease and the effect of slipstream effect increases with the increase of thrust.

1. Introduction
Turboprop-powered Aircraft is a kind of propeller which converts the mechanical energy on the power output shaft of piston or turboprop engine into forward power of aircraft. Turboprop power system is widely used in many transport aircraft and general-purpose aircraft because of its excellent medium and low-speed fuel economy, such as domestic Y-7, Y-8, Y-12, MA600, AG600 and other series aircraft. However, the propeller of turboprop aircraft will seriously affect the flow structure of downstream fuselage and wing and horizontal tail including flow direction and axial flow velocity and circumferential flow velocity (see Figure 1) which was called "slipstream effect". The influence on the flight performance of turboprop aircraft cannot be ignored, especially for single propeller aircraft, it will cause significant additional left leaning moment on the aircraft.

The rotation effect of propeller slipstream will affect the yaw and roll characteristics of the aircraft. The use of counter rotating turboprop engine can alleviate this problem but it will increase the cost of engine development and operation and maintenance such as Airbus A400M transport aircraft. At present most of the twin engine and multi engine turboprop aircraft still use the same rotating engine and propeller. The rotation effect of slipstream cannot be balanced with each other which requires consideration in aircraft design. Especially for asymmetric flight conditions such as crosswind take-off and landing,
sideslip and roll, the rotation effect of slipstream cannot be ignored. Based on the brief introduction of the layout characteristics and development trend and aerodynamic characteristics of turboprop aircraft this paper summarizes the key technologies of turboprop aircraft such as thrust and drag system division and performance analysis method as well as slipstream effect correction.

2. Layout characteristics and development trend of turboprop powered aircraft

2.1. typical layout of turboprop aircraft

The layout of aircraft is generally limited by take-off weight, operating environment, flight time and range as well as performance parameters of dynamical system. From the energy point of view turboprop aircraft is a kind of propeller with low energy consumption and high efficiency. In some transport aircraft requiring long endurance good take-off and landing performance and low direct operation cost propeller is still the most qualified aircraft[1]. According to the layout of the power system on the aircraft the turboprop aircraft can be divided into two categories. One is the pull-in type (the engine is installed at the head of the fuselage or the leading edge of the wing) and the other is the propulsion type (the engine is installed at the tail of the fuselage or the trailing edge of the wing). In comparison the slipstream effect of the propulsion layout is less than that of the pull-in layout. For the single engine UAV in order to reduce the technical difficulty and control the research and development cost the propulsion type is generally used such as the predator UAV in the United States. For large and medium-sized manned aircraft with large load it is necessary to adopt multiple engines and generally adopt pull-in layout.

The remarkable characteristics of turboprop powered aircraft are large take-off pull coefficient and high economic efficiency in cruise state as well as low cost of operation and maintenance. However, the power system of the turboprop aircraft with pull-in layout has a great influence on the aerodynamic characteristics of the aircraft especially in the low-speed configuration such as take-off or go around which conditions the large pull coefficient are needed [2]. Therefore, excellent take-off and landing performance and low-speed mission and high-speed cruise are always the main targets pursued by turboprop powered aircraft which puts forward high requirements for the power plant and aerodynamic design of turboprop aircraft and needs to achieve a compromise and balance between dynamic performance and aerodynamic layout and noise requirements. Compared with conventional turbojet/turbofan configuration aircraft the main advantages of turboprop aircraft include: more efficient and economical short-range flight; the ability to take off and land on unpaved runways; and lower manufacturing, operation and maintenance costs. The main disadvantages are: low cruise speed, flight Mach number below 0.6, poor flight quality, noise and vibration problems [3][4][5][6][10][11][12].

2.2. Aerodynamic characteristics of turboprop aircraft

The aerodynamic force of aircraft is mainly determined by aerodynamic configuration and wing shape parameters. Among them the aerodynamic layout must meet the overall layout requirements and strive to reduce the fuselage drag (about 20%-40% of the zero lift drag of the whole aircraft). As the main part
of the lift force of the aircraft the shape parameters of the wing directly determine the lift drag characteristics of the aircraft (its drag accounts for about 50% of the total drag of the aircraft). The horizontal tail is mainly to meet the requirements of the aircraft’s control and trim which also has some contributions. As the wing, tail and fuselage of the pull-in turboprop aircraft are just in the slipstream of the propeller, the air flow passing through the wing and horizontal tail will generate large additional lift and moment which can make the aircraft take off quickly or land at low speed and reduce the take-off and landing distance which is the unique advantage of turboprop aircraft \[1\][7]. However, the working state of the turboprop power system has a more serious influence on the aerodynamic characteristics of the whole aircraft and the coupling effect between the aerodynamic force and the power system is more obvious.

2.3. Development trend of turboprop aircraft

When the cruise Mach number is higher than 0.6 the efficiency of traditional propeller decreases rapidly. In 1975 the United States first put forward the idea of high-speed propeller such as reducing the diameter of propeller to reduce the tangential speed of the blade tip and increasing the number of blades and solidity to absorb the huge power of the engine, reducing the thickness of the blade, adopting the form of backward sweep or forward sweep to slow down the influence of air compressibility, etc. In 1982 NASA published a number of reports on the concept of counter rotating propeller, which systematically expounded the advantages of counter rotating propeller \[8\][9]:

1. The reaction torque transmitted by the engine to the aircraft is approximately zero which can eliminate many torque balancing measures.
2. In the high-speed flight state the total efficiency of the coaxial propeller with the same total number of blades is higher than that of the non-coaxial propeller.
3. For the high-power engine the take-off performance of the coaxial propeller is better than that of single stage propeller. Based on these advantages the modern open rotor engine adopts double row counter rotating propeller as the main propulsion component the maximum flight Mach number can reach 0.8 and the influence of slipstream is more complex which brings more uncertainty to aircraft performance analysis. So, more attention should be paid to the influence of slipstream in aircraft design.

3. Thrust/drag system division and performance analysis method for turboprop powered aircraft

3.1. Thrust and drag system of turboprop powered aircraft

Flight performance analysis is a process to obtain the height, speed, distance, time and other parameters of the aircraft by solving the dynamic and kinematic equations under the action of external forces. For turboprop powered aircraft, its takeoff and landing performance, climbing performance and endurance performance are usually used as the main indicators to evaluate its performance level. When the weight of the aircraft is determined, the factors that affect the flight performance of the aircraft mainly include aerodynamic force, engine thrust, aircraft control logic, atmospheric and runway environmental conditions. Among them, aerodynamics and engine thrust are the key factors to determine the flight performance of aircraft and the basis of flight performance calculation and analysis. It is necessary to establish a clear thrust and drag calculation system through reasonable thrust and drag system division, and scientifically determine the available thrust and aerodynamic drag of the aircraft, so as to ensure the reliability of performance analysis. For turboprop aircraft, the key point is to evaluate the impact of blockage effect of fuselage and wing on propeller propulsion efficiency and thrust, and the influence of propeller slipstream on aerodynamic characteristics of the whole aircraft as shown in Fig. 2.

3.2. Thrust calculation of turboprop aircraft

The thrust calculation shown in Fig. 2 is a modified calculation process from engine bench characteristics and free flow characteristics of propeller to available thrust of power plant. Among them, the turboprop engine bench characteristic shaft power and nozzle thrust (if any) are obtained by the engine manufacturer through cycle calculation or test. According to the requirements of national military standards, they are usually provided in the form of height velocity characteristics, which cannot be directly used for performance calculation and analysis. Therefore, the engine installation influence
(intake, nozzle, bleed, accessory power extraction, etc.) must be deducted or corrected. The available power and thrust characteristics for performance analysis can only be obtained after the influence of atmospheric conditions. The free flow characteristics of the propeller are usually obtained by the propeller Research Institute through experiments or aerodynamic calculation. After the propeller is installed, the body will affect the flow field passing through the propeller, so it is necessary to modify it to obtain the installed characteristics of the propeller. In addition, there is an optimal propeller speed and blade angle at any operating point of the turboprop engine, which makes the shaft power conversion efficiency reach the highest, which needs to be determined by propeller generator matching calculation. For turboprop aircraft, compared with turbojet/turbofan engine, the difficulty of installation correction lies in the determination of the influence of airframe flow on the aerodynamic performance of propeller. Compared with the pull-in layout, the propulsive propeller is in the complex wake of the front block, with poor uniformity of incoming flow, even with flow separation and serious boundary layer low-energy flow. The correction amount of influence is generally larger than that of pull-in type. It should be studied and determined by detailed CFD simulation or wind tunnel test.

![Figure 2. Schematic diagram of thrust and drag calculation method for turboprop aircraft](image)

### 3.3. Drag calculation of turboprop aircraft

The aircraft drag equation expressed in the form of coefficient is called polar curve equation

\[
C_D = C_{D0} + AC_L^2
\]

\[
A = (C_D - C_{D0})/C_L^2
\]

The general polar curve equation is used to describe the drag of the aircraft with a curved or twisted wing design or a deflected trailing edge and maneuver flap

\[
C_D = C_{Dmin} + A(C_L - C_{Lmin})^2
\]

Here:

\[
C_{D0} = C_{Dmin} + AC_{Lmin}^2
\]

\[
A = (C_D - C_{Dmin})/(C_L - C_{Lmin})^2
\]

Here \(C_D\) is the total drag of the aircraft which is composed of zero lift drag \(C_{D0}\) and induced drag \(AC_L^2\). A is the induced drag factor which is a function of flight \(M\) number and lift coefficient \(C_L\). That is the induced drag is determined by flight attitude and speed. For subsonic aircraft there are two parts for \(C_{D0}\) including friction drag and pressure drag which are determined by airframe shape and flight speed. From the above analysis of aerodynamic characteristics of turboprop aircraft, it is necessary to accurately evaluate the influence of propeller slipstream on the lift drag characteristics of turboprop aircraft in order to accurately predict the aerodynamic drag of turboprop aircraft. However, due to the effects of acceleration, rotation and turbulence instability in the slipstream flow field, the simplified methods such as panel method and equivalent disk model (excitation disk) which have been developed in the industry all have the disadvantages of inaccurate flow field simulation and low credibility; the full three-dimensional numerical simulation also has some practical problems such as turbulence model and computational efficiency. Therefore, in engineering practice, in the early stage of aircraft conceptual
design, the unpowered state without propeller is generally regarded as the "aircraft reference state", and the aerodynamic characteristics of aircraft reference state are obtained by mature and reliable numerical or experimental methods, and then the influence of propeller slipstream on aircraft aerodynamic characteristics is determined through wind tunnel test with dynamic model, which can be obtained by adding it to the reference state. The actual drag characteristics of the aircraft are obtained. Performance analysis of typical turboprop aircraft under the influence of slipstream. Based on the idea and method proposed in this paper, combined with CFD calculation, wind tunnel test and flight test results, the drag characteristics and polar curve of a turboprop aircraft under the influence of slipstream are analysed.

4. Performance analysis of typical turboprop aircraft under slipstream

Based on the ideas and methods proposed above, combined with CFD calculation, wind tunnel test and flight test results, the drag characteristics and polar curve of a turboprop aircraft under the influence of slipstream are analyzed.

4.1. Analysis of drag characteristics

In this paper, the reliability of CFD calculation results is verified by comparing the results of CFD calculation and wind tunnel test under different Reynolds numbers of the whole aircraft. The data show that the Reynolds number has a great influence on the drag characteristics (Fig. 5). Therefore, it is necessary to revise the Reynolds number in the aircraft drag calculation. Based on the above calculation model, CFD calculation and wind tunnel test show that the wing accounts for about 60% of the whole aircraft drag during cruising; the fuselage and vertical tail basically do not produce lift, and their friction drag and differential pressure drag are basically equivalent; as the main lifting component, the differential pressure drag is the main factor. Due to the influence of downwash, the real wind axis of the flat tail is different from that of the whole fan, so the differential pressure drag is negative, and the main drag contribution comes from friction drag, as shown in Fig. 3 and Fig. 4.
4.2. Analysis of slipstream effect

Firstly, through the wind tunnel test of the whole aircraft with dynamic slipstream, the polar curve after longitudinal trim is given.

In this paper, the aerodynamic parameters of the aircraft are identified and verified by the simulation results. The flight test data processing method is as follows:

Firstly, the mathematical expressions including drag coefficient $C_D$, tension coefficient $C_T$ and asymmetric tension coefficient $C_{T,ASY}$ are established as $C_D = f(C_L, C_T, C_{T,ASY})$.

Here $C_D = \text{DRAG}/(qS_w)$ and $\text{DRAG}=$total drag + acceleration force + gravity component parallel to flight path, dynamic pressure $Q=1/2\rho V^2$, $\rho$ is atmospheric density, $V_T$ is aircraft true speed, $S_w$ is wing area, $W$ is aircraft weight, $C_T = \text{total pull }/(qS_w)$, $C_{T,ASY} = \text{asymmetric pull }/(qS_w)$. Then, according to the data obtained from flight test, the relationship curve of lift and drag is fitted by multiple linear regression method as $C_D = A_1C_L + A_2C_L^2 + A_3C_T + A_4$.

Figure 5 shows the difference of polar curves obtained from wind tunnel test and flight identification under the influence of slipstream of typical turboprop aircraft. The polar curves obtained from flight test identification and wind tunnel test are consistent, but the wind tunnel test data tend to be conservative. Therefore, the correlation correction between wind tunnel test and flight is necessary to improve the accuracy of performance analysis based on wind tunnel test data.

5. Main conclusions

1) Turboprop powered aircraft is widely used in low subsonic transport aircraft and Reconnaissance UAV in pursuit of economy and long endurance due to its remarkable advantages of good cruise economy and low maintenance cost; in the future, open rotor engine can be considered as propulsion device for high-speed turboprop powered aircraft, so as to better achieve short-range take-off and landing, low-speed and high-speed flight performance indicators requirement.

2) The performance analysis of turboprop powered aircraft needs to consider the relevant characteristics of both turbine engine and propeller aircraft; compared with the turbojet / turbofan aircraft, its performance analysis adds the key technologies such as the influence of slipstream on aerodynamic force, the influence of airframe on propeller efficiency and propeller matching, which has higher complexity and thrust drag coupling characteristics, and needs more in-depth research and exploration.

3) The slipstream effect is a key factor affecting the flight performance of turboprop aircraft, and the strength of the effect is related to the angle of attack and propeller pull / thrust. In the early stage of model development, the mutual interference between the vortex force and the aircraft aerodynamic force must be considered, and an effective correction method should be formulated.

4) Wind tunnel test with dynamic model is a reliable method to determine the influence of slipstream. However, the results of performance analysis based on wind tunnel test data tend to be conservative, and the accuracy of performance analysis can only be improved by correcting the correlation between wind tunnel and flight.

6. Reference

[1] Kundu A K. Aircraft design[M]. Cambridge: Cambridge University Press,2010.
[2] Marinus B G, Pope J. Data and design models for Military Turbo-propeller aircraft[J]. Aerospace Science and Technology, 2015(41):63-80.
[3] Paul Jackson FRAeS. Jane’s all the world’s aircraft.2014-2015[M], Cambridge: Cambridge University Press,2014.
[4] Sha Zhengping, Aircraft design manual volume 4[M]. Beijing, Aviation Industry Press,2005. (in Chinese)
[5] Chen Bushi, Aircraft design manual volume 5[M]. Beijing, Aviation Industry Press,2005. (in Chinese)
[6] Liu Jicang. Aircraft design manual volume 7[M]. Beijing, Aviation Industry Press,2010. (in Chinese)
[7] Li Shangbin, Jiao Yuqin. The investigate development of propeller slipstream’s effect[J]. Science Technology and Engineering, 2012, 12(8) : 1867-1873. (in Chinese)
[8] Veldhuis L L M. Review of propeller-wing aerodynamic interference[C]. ICAS2004, 2004.

[9] Bronsw Uk N. The effects of propeller power on the stability and control of a tractor propeller powered single-engine low wing monoplane[D]. Sydney: University of Sydney, 2001.

[10] Yury I. Dimitrienko, Mikhail N. Koryakov, and Andrey A. Zakharov, "Computational Simulation of Conjugated Problem of External Aerodynamics and Internal Heat and Mass Transfer in HighSpeed Aircraft Composite Construct," International Journal of Mechanical Engineering and Robotics Research, Vol. 6, No. 1, pp. 58-64, January 2017. DOI: 10.18178/ijmerr.6.1.58-64

[11] Masoud Jahanmorad Nouri, Habibollah Sayehvand, and Abolghasem Mekanik, "Numerical Investigation of Aerodynamic Characteristics of NACA 23018 Airfoil with a Gurney Flap," International Journal of Mechanical Engineering and Robotics Research, Vol. 1, No. 3, pp. 341-349, October 2012.

[12] Kakumani Sureka and Satya Meher, "Modeling and Structural Analysis on A300 Flight Wing by Using ANSYS," International Journal of Mechanical Engineering and Robotics Research, Vol. 4, No. 2, pp. 123-130, April 2015.