

Investigation of the Aerodynamic Characters of Ducted Fan System

Wang Bo , Guo Zheng , Wang Peng , Shan Shangqiu , Hou Zhongxi

Abstract—This paper investigates the aerodynamic characters of a model ducted fan system, analyses the basic principle of the effect of thrust promotion and torque reduction, discovers the relationship between the revolutions per minute(RPM) of the fan and the characters of thrust, as well as system torque. Firstly a model ducted fan has been designed and manufactured according to the specific structure of flow field, then CFD simulation has been carried out to analyze such aerodynamics, finally bench tests have been used to validate the simulation results and system configuration.

Keywords—ducted fan, free vortex flow, stator blade, screw torque, thrust increase

I. INTRODUCTION

DUCTED fan may have many labels in different kinds of literatures, such as ducted propeller, ducted rotor, shrouded propeller, and so on, while the basic components are duct and fan as the name called. Actually the differences between propeller and fan are largely determined by the number and thickness of rotor blades, propeller usually has thicker blades and much less number, barely more than five blades. Companioned with the technology progress, a considerable variety of new propeller-fans appear based on traditional propulsion system in order to meet all kinds of demands in the field of aviation, aerospace and navigation, the geometry appearance of which are between traditional propellers and fans.

Due to the significant advantage of ducted fan in propulsion, it has attracted plenty of research interests in the last forty years. Such works have obtained lots of results about fundamental aerodynamics theorem and useful method for ducted fan design and experiment. The propulsion system of ships widely adopt ducted propeller, especially large thrust system and high efficiency system. Meanwhile; the tail rotor of helicopter usually employ ducted fan configuration, such as France helicopter *SA342 duiker* and *SA 360 dolphin*, Eurocopter *EC 135*, which not only smaller the diameter of tail rotor, but also reduce the power consumption [1] .

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Last twenty years, many kinds of novel flight vehicles emerge based on the propulsion system of ducted fan, such as GMAV [2] , iSTAR [3] and Hovereye [4] [5] unmanned aerial vehicles. Ducted fan vehicles have outstanding capability of hover, staring, reconnaissance and surveillance, and would be very suitable for special flight missions in complicated environments. That is because the presence of duct not only promotes the efficiency of the fan and the aerodynamic performance of the vehicle, but also protects the fan and power supply system against environment obstacles.

Ducted fan system could be classified as single fan system and coaxially counter rotational system according to the number of the duct and the fan, as well as the arrangement. For detail, the former has a single fan shrouded by a duct, and the latter has two coaxially counter rotating fans shrouded by one duct. Meanwhile, there may be ducted fan systems which are compounds of such two kinds for larger thrust and better controllability.

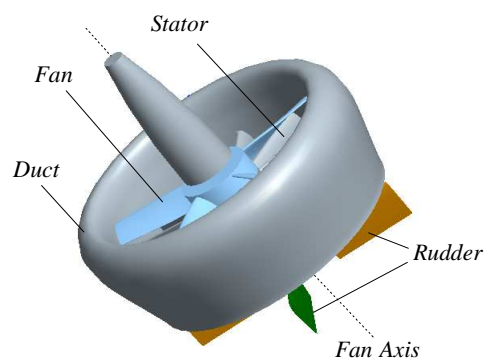


Fig. 1 The configuration of the ducted fan system with control rudders

As shown in Fig. 1, this paper discussed a single fan system, the basic components of which includes a fan, a duct and stator blades, as well as control rudders while the system used for flight vehicles. Investigation of its aerodynamic character aims at obtaining the aerodynamic parameters for modeling and giving valuable suggestions for system design optimization.

II. THE FUNDAMENTAL OF THRUST PROMOTION

For the circumstance of a single open fan, the airflow will be accelerated by rotating fan as crossing the fan disc, and the upper pressure of fan disc will be much lower than the other side, that will lead to three-dimensional flow in the tip region of the fan as Fig. 2 displays. Such free vortical flow may just exist near the tip of the surface if the fan was chosen rectangle blade, while it may be present in a large region of ellipse blades of the fan, then the pressure differential across the fan disc to generate thrust would lose seriously, which may reduce the efficiency of the thrust system obviously.

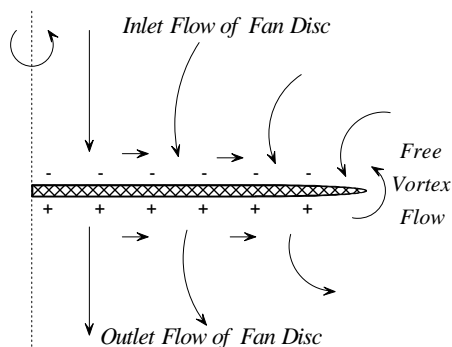


Fig. 2 Scheme of the airflow in the tip region of an open fan

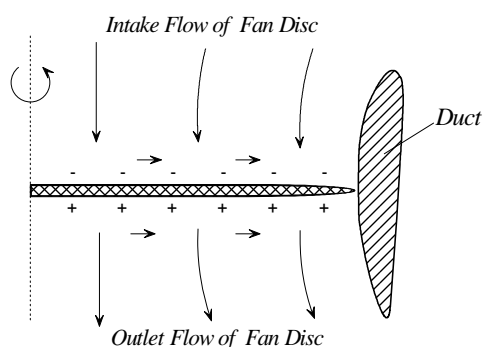


Fig. 3 Scheme of the airflow in the tip region of a ducted fan

However, the presence of duct meliorates the structure of flow field around the ducted fan, as shown in Fig. 3, there is hardly any free vortex flow in contrast to Fig. 2. And significantly increases the system static thrust with uniform fan and power supply associated with the open fan. Improvement details as follows:

A. Reduce tip losses

The duct reduces the free vortical flow in the tip region of fan blades, and the loading on the blades is allowed to extend to the tips. The duct plays a key role in reducing three-dimensional flow [6], and performs like a board in preserving the pressure differential across the fan disc.

B. Improve slipstream

Slipstream contraction will result in air kinetic energy losses, while the duct protects inner flow from outer atmosphere to reduce slipstream contraction, slowing slipstream but increasing the mass flow through the ducted fan system.

C. The advantage of duct lip

In contrast to traditional propellers and fans, optimized ducted fan lip could generate a low pressure region near the duct entrance [7], and then additional thrust could be obtained.

Theoretically, the smaller clearance between the fan blade tip and the duct, the less pressure differential lose, then it would be better that the duct abuts upon the fan disc for better aerodynamic performance.

However, it may be very dangerous to do that in the process of practical engineering applications, because the rotating speed of fan may be as high as 7000 RPM to 8000 RPM and fan may perform distortion as well. Then the model this paper discussed keeps the duct 5 mm apart from the fan tip.

In order to investigate the aerodynamic performance of the designed ducted fan system, CFD analysis was carried out on typical working conditions (fan RPM) without environment wind. Computational domain was divided into four zones and a hybrid grid was generated, then solution of SIMPLEC and $k - \epsilon$ viscous model were introduced to solve such problem based on the inlet and outlet pressure.

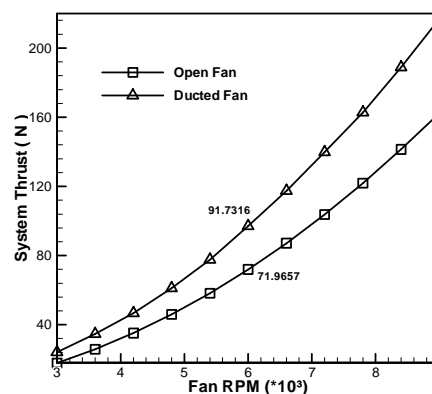


Fig. 4 Comparison of the total thrust of a single open fan with the ducted fan system

As shown in Fig. 4, the model system can provide a total thrust of about 97.13N near the design rotating speed, increasing thrust by 34.97% compared with open fan system's 71.96N. It indicates that the duct weakened the free vortex flow in the blade tip region and reduced the slipstream contraction, which improved the energy conversion efficiency of the power system.

III. INFLUENCE OF THE STATOR BLADE

The airflow will be accelerated by the high speed rotating fan along both radial direction and axial direction while it passes the fan disc, and rotate following the blades. There must be screw torque generated by such rotational airflow according to the theorem of momentum. Then a special stator was designed in the model ducted fan system to generate counter torque by weakening the airflow rotating, which is significant for the control of ducted fan flight vehicles.

From the perspective of momentum, the stator depresses the radial velocity of the airflow behind the rotating fan, so that the induced flow actually has been accelerated along axial direction when it passed through such duct fan system, and there are not screw torque any more. Then by the view point of energy, the rotational kinetic energy of the induced flow will eventually be transformed into heat without the presence of stator, that will result in energy lose partially. While the stator could transform such kinetic energy into useful pressure energy. Meanwhile, the reduction of rotating makes the airflow become straight in the duct tail region, uniform and orderly, thus greatly improving the aerodynamic efficiency of the tail control surface.

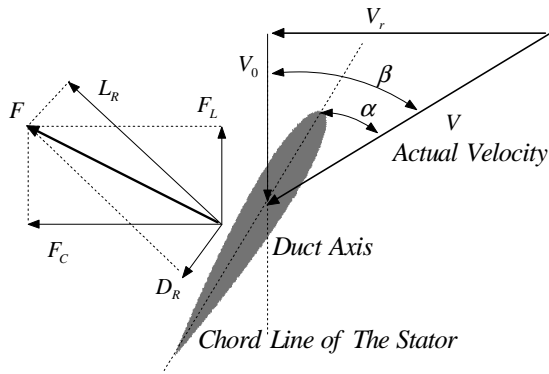


Fig. 5 Scheme of the airflow on a section of the stator in radial orientation

The flow detail around a section of the stator blade which is arranged in radial orientation is shown in Fig. 3, high-speed rotating fan makes the airflow gain a tangential velocity V_r and an increase in axial velocity at the entrance of duct, then the real velocity of induced flow is V which has a angle β with the duct axis. If the local flow angle of attack α on such section is greater than zero and less than the stall angle of attack of the airfoil, control force F_C as well as airfoil lift F_L would be generated. And then each section of the stator blade should be arranged properly to generate both lift component and control component. In other words, a optimized stator could provide counter torque balance most of the screw torque and generate additional thrust that consists of airfoil lift of each section to the ducted fan system [8]. In order to examine the feasibility of such program and analyze the performance of the design of such ducted fan system, CFD simulation was carried out under the static condition of zero environment wind. Gain the torque of the ducted fan system on different fan RPM, the simulation results as Fig. 6 shows.

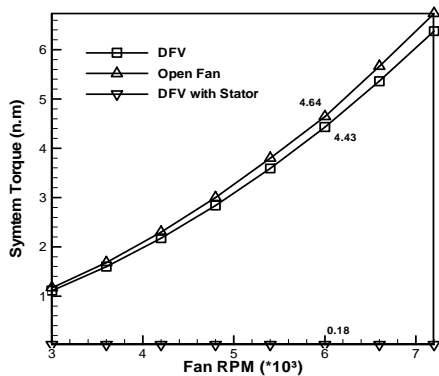


Fig. 6 Comparison of the torque performance of three kinds system

Fig. 6 demonstrates that the installation of the stator blade reduced the total screw torque by 95.8%, down to 0.18n.m relative to no stator case of 4.43n.m. And the simulation result displays that the flow field has become regularly almost axial flow, illuminating the induced flow rotate has been restrained efficiently and the stator blade design satisfied the original requirements. Substantially reduction of anti-torque is favorable for structure design and control system development.

However, not all stator blades could bring an increase to the total thrust of the system. In some circumstance, the stator blades may lead to the flow channel blocked and the original flow field disturbed, if the blades were too thick or blade sections were twisted too much. Mass flow rate of the system decreasing results in total thrust fallen, although the stator provides the ducted fan system for additional thrust.

The ducted fan has not been further optimized in the early design process about this paper. The simulation result indicates that the total thrust of the ducted fan system with stator is 80.6125N while the engine is working on the typical operation speed (6000RPM), as shown in Fig. 7, which is increased by 13.41% rather than open fan system's 71.9657N, thrust performance improved visibly. However, the installation of the stator blade leads to a thrust decrease of 17.01% in contrast to the ducted fan system's 97.1316N without stator, thrust performance worsened obviously.

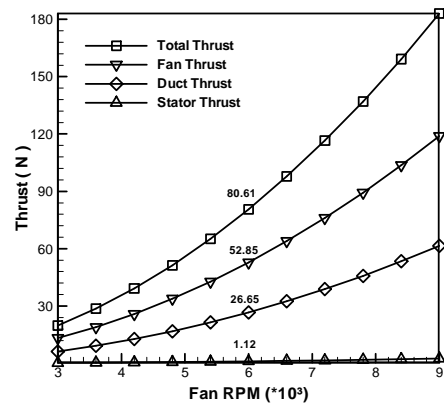


Fig. 7 The thrust components of the ducted fan system with stator

Model measurements tell the truth that the flow channel on the inner side of duct was narrowed by stator installation, as shown in Fig. 8, the cross sectional area along the duct axis were decreased in varying degree while the narrowest place constricted by 8.98%, that may cause airflow obstruction. And the CFD simulation result shows that the mass flow rate of the system reduced to 3.21372 kg/s from 3.47179 kg/s, with a decrease of 7.43% after the stator installation.

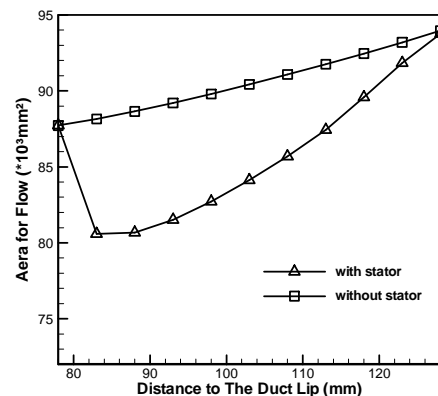


Fig. 8 Comparison of the area of flow channel with stator to without stator

Theorem of momentum shows that the value of total system thrust equals the value of total force that the airflow suffered, which equals the increased momentum of the airflow per unit time as well, namely

$$T = \dot{m}\Delta V$$

Where T is the total thrust, \dot{m} and ΔV represent the mass flow rate and the axially increased velocity of the induced airflow separately. It is known that the stator installation won't increase the axial velocity augment ΔV , then the decrease of mass flow rate \dot{m} will inevitably result in a total thrust T decline.

Therefore, special attention should be paid to avoiding the inner airflow channel obstructed, and overall consideration should be made about the thrust increase design and torque decline design in the process of optimization and improvement.

IV. EXPERIMENTAL PERFORMANCE OF THE DUCTED FAN SYSTEM

In order to examine the performance of the designed ducted fan system, a novel test bench was devised with several kinds of sensors and data collection equipment.

The thrust and torque were measured under different RPM condition of the fan, and comparisons with simulation results were given. The total thrust comparison was shown in Fig. 9, while the torque of the system with stator was so small that the actual value cannot be directly obtained with the presence of measurement noise, so here don't discuss it any more.

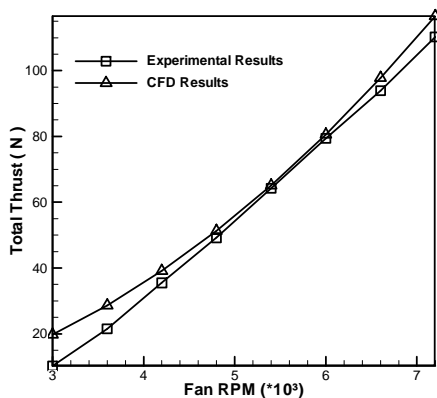


Fig. 9 Comparison of simulation results with experimental values

As shown in Fig. 9, the total thrust of simulation results are basically accords with experimental values, and the two values near the design condition agree with each other well. There are deviations in the phrases of low fan RPM as well as high fan RPM. Because the measurement noise introduced obviously relative error while the system thrust was little during the engine's idle period, and engine vibration during high RPM brought about errors as well.

V. SUMMARY

This paper briefly discussed the fundamental principles of thrust increase and torque decrease of a model ducted fan system based on the specific flow characteristic, then numerical

simulation was carried out to quantitatively analyze the aerodynamic performance and the restricting relationship between thrust increase and torque decrease by a stator was discovered. Finally experimental measurements verified the simulation results and provided aerodynamic parameters for modeling and control system design, as well as guidance for further optimization of such ducted fan system.

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