Study on the Aerodynamic Performance and Internal-External Flow Interaction Effects of Distributed Ducted Fan in the Climbing-Condition

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Abstract. Distributed electric propulsion ducted fans play an important role in saving energy and reducing environmental pollution of the airplanes. In this research, unsteady RANS CFD numerical simulations were used to analyse the possible impact of aerodynamic performance and interaction effects of distributed ducted fan in the climbing condition, which is verified with experimental method. Firstly, this paper will explore the effect of internal/external flow interaction on the flow field of the propulsion system at the same time. Secondly, from the perspective of propulsion efficiency and energy consumption, this paper will find the thrust relationship between the maximum continuous working state and the maximum working state and study the performance of the ducted fan. This paper will aim to reduce energy consumption during the propulsion of ducted fans and obtain longer flight time, and find a balance point between power and propulsion efficiency. The results show that the maximum continuous working state is 85% of the maximum thrust state approximately. By combining the aerodynamic interaction phenomena with the aerodynamic performance of the distributed ducted fan, this research provides an important basis and advice for enhancing the flight time of distributed ducted fans and reducing energy consumption during the process of engineering and flow mechanisms.

1. Introduction

Social development promotes requirements on the safety of civil aviation propulsion systems and environmental protection and prompts scholars to carry out more research [1-2]. Some researchers have conducted internal flow field analysis in the field of axial flow propulsion systems. Bryce's research results suggest that the increase in blade load will promote the separation in blades’ end wall and boundary layer, and the performance will deteriorate [3]. Z Q Wang et al conducted experiments in a wind tunnel, the results showed that curved blades can effectively control the formation of flow channel vortices [4]. Alexej studied the effect of the tip clearance of the axial flow fan on the tip clearance flow through large eddy simulation method. The results showed that the size of the blade tip will affect the
size and shape of the blade tip leakage vortex [5]. Zhen studied the effect of axial clearance on radial flow. The results showed that the radial flow in the moving blade junction area gradually develops toward the blade tip as the flow rate decreases [6]. De-lei Chen studied the effect of setting angle on the performance of axial fans. The results show that at low flow rates, blade setting angle of the fan can be adjusted properly and the efficiency of the fan can be improved, and the appropriate blade setting angle can effectively improve the flow distribution in the fan, reduce flow loss, and delay the fan stall [7]. Hai Xin Chen et al. use genetic algorithm to perform multi-objective optimization designing on rotor blades. The research results show that the optimized propulsion performance can be improved very well [8]. Yang Wei Liu and Li Peng Lu et al. used the DDES method to study the flow structure of the blade tip leakage vortex at different blade tip sizes. The results of the study show that the flow field of small tip clearance is more stable and the anisotropy of the flow vortex is weaker [9]. However, the traditional flight / airplane layout has been limited in reducing fuel consumption and reducing pollutant emissions. There is an urgent need to find an alternative propulsion system to meet the increasingly stringent development requirements [10]. The advantages of circle ducted fan performance at lower incoming Mach number are more obvious [10-11]. Hubbard pointed out in early research that circle ducted fans can increase the safety of the propulsion system and reduce the noise impact of the propulsion system, more and more ducted fans are used in aircraft propulsion systems [12].

In recent years, the proposed ‘Green Aviation’ initiative promotes the motivation to reduce the environmental impact of pollutants during aviation flight, which has enhanced researchers in-depth research on distributed electric propulsion systems. Distributed ducted fans are gradually paid attention by researchers because of their advantages of reducing energy consumption and pollutant emissions [14]. A number of small or miniature engines installed on the wing or fuselage replace the current 2 to 4 traditional engines. Fuel consumption and polluting emissions can be reduced effectively with reasonable distribution of thrust, more advantages in aerodynamic stability can also be achieved [13-14]. In order to further explore the effect of internal and external flow coupling effects on the aerodynamic performance of distributed axial ducted fans, some scholars have begun to study the aerodynamic performance of distributed ducted fan power systems. At present, in order to avoid the huge amount of calculation in the integrated numerical calculation process of internal and external flow coupling, the US GLENN research center has developed Chima volume force model for integrated numerical calculation, which is based on a fan with a diameter of 300 mm [15]. Maticiugo simulates the coupling of internal and external flow by setting the inlet and outlet boundary conditions to explore the interaction effect [16]. Kim, H. and Gong, Y. replaced the rotor blades and stator vanes by a circumferential volume force model [17-18]. Cui Rong [19] calculated and analysed a distributed propulsion system using the integrated flight / engine numerical simulation method based on the volume force model along the streamline. Although using volume force model saves a lot of computing resources, it does not reflect the effect of internal and external coupling on ducted fans. Due to the coupling effect of internal and external flow, there is a certain degree of radial inlet total pressure distortion in the distributed ducted fan studied in this paper. Hamed. A conducted experiment to study the effect of distortion location on the ground test of the propulsion system and discussed the effects of total pressure distortion, vortex and turbulence on the flow [20]. Rodriguez J. designed a new type of compressor lip to improve the flow stability. The study also showed that the flow distortion on the surface of the propulsion system mainly originates from the flow separation on the outer wall of the intake system, the internal intake of the propulsion system and the effect on the rotating vortex [21].

In general, most of the previous research works have focused on exploring the internal flow field of the axial flow propulsion system and using the volume force model to study the internal and external flow coupling between the aircraft and propulsion system. Few comprehensive considerations have been given to the coupled internal and external flows of distributed ducted fans. Little attention has been paid on the distributed ducted fan performance under the coupling effect of internal and external flow and the details of the flow field. For the distributed electric ducted fans studied in this paper, on the one hand it is required to reduce energy consumption and get longer flight time, on the other hand, it is expected to work with high propulsion efficiency. The objective of this research is to analyse aerodynamic
performance of the maximum propulsion efficiency and maximum working state, and then understand
the aerodynamic performance difference between them. The unsteady RANS computational fluid
dynamics numerical simulation were conducted in order to acquire the internal and external flow
interaction field. Firstly, by contrasting the numerical results with experimental results, the unsteady
RANS numerical simulation results were evaluated preliminary, which can provide a reference for the
unsteady RANS numerical simulation results. Secondly, the unsteady flow field was analysed to provide
a clear understand of the internal and external flow interaction aerodynamic performance. Finally, the
full passage distributed ducted fan is considered in specific working conditions, numerical simulations
were used to research the performance.

2. Computational setup

In this section, the geometry characteristic of the distributed ducted fan will be introduced and the
numerical simulation methods will be described. Section A will present the geometries that is employed
in this study, section B will describe the solver setup and discuss the uncertainty quantification and
experimental validation, section C will present the domain and boundary conditions that used in this
study.

2.1. Geometry

The current research object is a distributed ducted fan similar to that shown in ‘Figure 1’[22]. The
ducted fan is not embedded in the upper surface of the wing. it is mounted above the wing near the
trailing edge.

![Figure 1: Schematic of Distributed Ducted Fan](image)

The diameter of the ducted fan is 240mm, which is expressed by D. The number of vane, rotor blade
and stator vane is three, eight and seven respectively. The distributed ducted fan rotates in counter-
clockwise direction. The details of the distributed ducted fan are given in table 1.

| Parameter                  | Value  |
|----------------------------|--------|
| Blade tip speed (m/s)      | 115    |
| Flight speed(m /s)         | 10-30  |
| Rotating speed(rpm)        | 0-9100 |
| Thrust range(N)            | 0-80   |

2.2 Solver Setup and Discuss the Uncertainty Quantification

The unsteady RANS equations were solved by using ANSYS, namely, CFD solver CFX. The
compressibility effects have not taken into account, for the inlet wind velocity was 0.1Ma. The fluid was
ideal gas. In the calculation and solution process, second order backward transient scheme is used, and
the time is set to automatic.
2.3 Domain and Boundary Conditions

The domain for the numerical simulation of the distributed ducted fan is presented in ‘Figure 3’. The flow direction, total pressure and total temperature were specified at the inlet. In the far-field boundary, opening boundary was prescribed, apart from velocity, static temperature is applied in the opening boundary. At the outlet, the static pressure was prescribed. The unsteady simulation physical step is 50, the loop is 5. The grids were generated with ANSYS ICEM. NUMECA (Auto-grid and IGG) software. Both structured mesh and unstructured mesh were used in the domain. Furthermore, Turbulence has been modelled with the standard two equations k-ε model. With the full blade model, the unsteady numerical simulations were performed. Near the no slip walls, a scalable wall model has to be employed, the first layer height is specified in order to achieve in a maximum y+ lower than 50, more than 30. ‘Figure 3’ shows the schematic of grid computing domain for internal/external flow of ducted fans, the interface in the figure is set as the transient rotor stator interface. Transient rotor stator interface model should be used, which is important to account for transient interaction effects at a sliding interface and can predicts the true transient interaction effects of the flow between a stator and rotor passage. The interface between the internal and external flow field can be connected “General”. According to the software CFX. A general connection can be applied to fully transient sliding interfaces between domains. Assuming that the diameter of the ducted fan is D, the upstream distance is 15D, the downstream distance is 15D, and the far field distance is 15D. ‘Figure 2’ is based on the grid-independent verification of the distributed ducted fan thrust coefficient. Based on the expected error on thrust coefficient when choosing the suitable value, and CPU computing power, the total number of grids is about 8.5 million, considering the number of calculation grids and calculation accuracy.

![Figure 2](image2.png)

Figure 2. Grid independence.

![Figure 3](image3.png)

Figure 3. Schematic of grid computing domain.

3. Experimental methods

3.1. A Wind Tunnel Model and Data Acquisition Device

Experimental wind tunnel testing of the distributed ducted fan model was conducted in a 15mx6.85m subsonic speed, opened-environment, low-turbulence wind tunnel, which is located in the Beijing 35 Middle School, as shown in the ‘Figure 4’. The wind tunnel is equipped with data acquisition device, including Pitot tubes, model angle of attack, sideslip angle mechanism control system, six-component strain balance and signal conditioning system, digital DC speed control system, etc. The maximum wind speed which is able to be measured is 55m/s. All experimental data recorded in this paper is based on blade diameter, the Reynolds number is 5E5 approximately.

The test wind tunnel contains the test section, diffusion section and other parts of the structure. This test is conducted in the test section. The test equipment used in the test process is shown in the ‘Figure 5’, which mainly includes the distributed full-scale test model and measuring elements of the distributed ducted fan. The distributed full-scale test model of the distributed ducted fan is installed on the six-component balance through the installation hole and the fixing belt. The full-scale test model of distributed ducted fan consists of fan, motor, electronic speed controller, cooling channel and
photoelectric sensor. The motor drives the fan to provide power, and the electronic speed controller controls the fan rotating speed.

Figure 4. Schematic of Low-Speed Wind Tunnel.

In order to study the aerodynamic performance of the distributed ducted fan propulsion system and the influence of design parameters on the aerodynamic performance through experiments, the ducted fan was tested. The experiment results are compared with the numerical simulation results to verify the reliability of the numerical simulation results, and analyze the numerical results of the flow field and explore the effect of internal and external flow coupling on the aerodynamic performance of distributed ducted fans and flow mechanism.

Table 2 Wind tunnel test conditions.

| Parameter                  | Value   |
|----------------------------|---------|
| Inlet flow speed (m/s)     | 5-55    |
| Rotating speed (rpm)       | 0-9100  |
| Height (m)                 | 0-3     |
| Temperature (K)            | 292     |
| Pressure (Pa)              | 100200  |

4. Analysis and discussion

4.1. A The Validation

The numerical simulation results were compared with the experimental data. That qualitative comparison is developed to increase the reliability in the simulation results in the ‘Figure 6’.

Figure 6. Advanced Ratio-Thrust Coefficient.
The atmospheric pressure measured by the device is 100200 Pa, and the atmospheric temperature is 292 K. The horizontal measurement device maintains the axial intake of the ducted fan at 0 ° angle of attack. During the test, different inflow velocity $V_{in}$ and corresponding rotating speeds were obtained to obtain different advanced ratio $J$. In general, regarding the ducted fan performance, there is an error of less than 5% between the calculated results shown in the figure and the results obtained from the experiment based on the thrust coefficient. The difference may be results from the number of grids, the selection of turbulence models, and the interface and calculation method and so on. The stability of the measurement during the experiment and the reading of the data of the sensor's measuring point, including post-processing, will lead to the appeal result.

4.2. Aerodynamic Coupling Performance and Interaction Phenomena

In this section, we firstly analyse the performance of the electric propulsion distributed ducted fan causes of different working conditions, afterwards, we analyse the internal and external flow coupling flow field in the maximum working state and the longest continuous working state. Finally, based on the above results, we further analyse the aerodynamic performance from the fluid flow contour. We have made a regulation that the electric propulsion distributed ducted fan is at its maximum working state when it works at Rated rotating speed.

Figure 7 Ratio of Thrust- Aerodynamic Efficiency/ Propulsion Efficiency.

‘Figure 7’ and ‘Figure 8’ will analyse the effects of different rotating speed and internal/external flow coupling effects on the aerodynamic efficiency and propulsion efficiency of electric propulsion distributed ducted fans at the same flight velocity. This paper defines a new dimensionless parameter, which is expressed to the ratio of thrust between working state corresponding to random rotating speed and the maximum working state ($T/T^*$) in flight.

Figure 8 Ratio of Thrust-P/Propulsion Efficiency.

The ratio of thrust represents the magnitude of the thrust value when distributed ducted fan rotating speed changes. In this paper, firstly: as shown in ‘Figure 7’, as the ratio of thrust increases, aerodynamic efficiency increases. Secondly: as shown in ‘Figure 8’, as the ratio of thrust decreases, the electric
propulsion distributed ducted fan rotating speed decreases, the propulsion efficiency first increases, and then decreases. For the research object of this paper, there is a ratio of thrust corresponding to the optimal propulsion efficiency. Regarding of the working state, the maximum aerodynamic efficiency is not consistent with the maximum propulsion efficiency. Finally, as shown in ‘Figure 8’, as the ratio of thrust increases, the power consumption also increases. For the distributed electric propulsion ducted fan studied in this paper: This paper chooses the longest continuous working state from following three reasons: low power consumption, high propulsion efficiency and high aerodynamic efficiency. Based on the above three reasons, for the electric propulsion distributed ducted fan that researched in this paper, the working state of the highest efficiency point is the longest continuous working state discussed in this paper, and the ratio of thrust of the longest continuous working state is 85%. At this time, the propulsion efficiency is the highest, and the energy consumption and aerodynamic efficiency meet the requirements that defined earlier in this paper.

4.3. An Aerodynamic Efficiency and Power Consumption

Distributed ducted fan works near the design point, the change influence of unsteady flow fields between the highest propulsion efficiency point and maximum energy consumption point is small, therefore, one of the same moments is selected for analysis and discussion. The internal flow of the rotor blade has a significant influence on the aerodynamic efficiency. Overall, the aerodynamic efficiency of the maximum energy consumption point in ‘Figure 7’ is higher than the aerodynamic efficiency of the longest continuous working state. In the following discussion, the flow mechanism of different working states on aerodynamic efficiency will be analysed in detail from the rotor blade flow field and angle of attack.

‘Figure 9’ is an entropy contour of rotor blades at 90% of the blade height about different working states. ‘Figure 10’ is an entropy contour of rotor blades at 10% of the blade height in different working states. At the rotor tip, the entropy in the longest continuous working state is much larger than the entropy area in the maximum working state; The entropy distribution of the blade root is not significantly different. Generally speaking, the high entropy of the longest continuous working state is greater than that of the maximum working state, hence, the aerodynamic efficiency of the maximum working state is higher than that of the longest continuous working state.

The Highest Propulsion Efficiency Point
Maximum Energy Consumption Point
Figure 9 Rotor Tip Entropy Distribution.

The Highest Propulsion Efficiency Point
Maximum Energy Consumption Point
Figure 10 Rotor Root Entropy Distribution.

‘Figure 11’ and ‘Figure 12’ show the distribution of the inlet airflow angle and geometry inlet angle and outlet airflow angle along the blade span from the rotor blade root to the tip (the airflow is
circumference averaged in the blade passage, and the relative inlet airflow angle is defined as 
\[\text{arctan}(W_z/W_t) \times 180/\pi\], where \(W_z\) is the axial velocity of the inlet and \(W_t\) is the tangential component of the relative velocity). It can be found from ‘Figure 11’ that by comparing the inlet flow angle distribution of the rotor blade root to the rotor blade tip, the airflow angle in the longest continuous working state is smaller than that in the maximum working state. ‘Figure 12’ shows outlet flow angle at the rotor blade has little difference under two different working state. This shows that the radial distortion of the blade tip and blade root in this paper has the same degree of influence on the under different rotating speeds.

\[\text{Figure 11: Rotor Inlet Angle.}\]
\[\text{Figure 12: Rotor Outlet Flow Angle.}\]

In the ‘Figure 13’, \(C_{1i}\) and \(W_{1i}\) (\(i=1,2\)) express the absolute and relative inlet velocity of the rotor blade in the longest continuous working state and the maximum working state, respectively, \(C_{2i}\) and \(W_{2i}\) (\(i=1,2\)) express the absolute and relative outlet velocity of the rotor blade in the longest continuous working state and the maximum working state, respectively, \(U_{i}\) (\(i=1,2\)) represents the longest continuous working state and the maximum working state rotor blade circumferential rotating speed, respectively. Make a regulation: The angle between \(C\) and \(U\) is \(\alpha\), and the angle between \(W\) and \(U\) is \(\beta\).

Combining ‘Figure 11’ and ‘Figure 13’ to analyze the mechanism of aerodynamic efficiency. When the electric propulsion distributed ducted fan works at different rotating speeds and the same flight inlet velocity, the ducted fan rotating speed increases, in the same time, the relative airflow angle increases. As the fan rotating speed increases, the rotor leading edge relative airflow angle is closer to the design geometric airflow angle, the angle of attack is smaller. In this paper, the electric propulsion distributed ducted fan works at different conditions, rotor inlet axial velocity increases faster than rotor inlet rotating speed. The angle of attack in the maximum working state is smaller than that in the longest continuous working state. And the aerodynamic efficiency in the maximum working state is higher than that in the longest continuous working state.

\[\text{Figure 13 Velocity Triangle Distribution.}\]
4.4. Propulsion Efficiency

The external resistance has a significant effect on the effective propulsion power. This paper will discuss the influencing factors of propulsion efficiency from two aspects: differential pressure resistance, friction resistance.

First, the streamline and the static pressure of the lip distribution are discussed to analysis the lip flow field of the electric propulsion distributed ducted fan. ‘Figure 14’ shows the streamline of the lip. As can be seen from ‘Figure 14’, the density of red streamlines at the highest efficiency point is fewer than that at the maximum working point. For the electric propulsion ducted fan studied in this paper, under the conditions of the same inlet wind velocity and different rotating speeds, as shown in the ‘Figure 14’, the separate position of the lip streamline is basically the same, located at the upper of the lip wall surface, and the fluid flows through the surface of the lip, the actual fluid flow into the ducted fan is more than the ideally defined fluid flow. When the rotating speed is higher, the fluid ingests into the ducted fan faster. By comparing ‘Figure 15(a)’ with ‘Figure 15(b)’, the airflow accelerates on the lip surface and the static pressure also decreases. The static pressure of the front of the lip on the highest efficiency point is greater than in the maximum working state, the maximum working state produces an obvious semi-circular low static pressure area on the lip.

![Figure 14. Axial Streamlines Distribution of Lip.](image1)

![Figure 15. Pressure Distribution of Lip.](image2)

The following part will analyse the propulsion efficiency of the electric propulsion distributed ducted fan at the same flight velocity and different fan rotating speeds. For the research object in this paper, the location where the geometric curvature has obvious change is the lip wall of the ducted fan. We define the lip geometry as follows: as shown in ‘Figure 16’ Lip geometric BAC surface is the main part of lip, which is researched on the mechanism of influence on propulsion efficiency in the subsequent research and discussion.
In the following discussion, two dimensionless parameters defined in this paper will be introduced, namely, the dimensionless static pressure coefficient, the axial velocity gradient coefficient. The reason for choosing the two dimensionless parameters is that for the electric propulsion distributed ducted fan studied in this paper, the inlet flow velocity is the same, the ducted fan works at different rotating speeds, in order to eliminate the interaction effects on different rotating speeds.

\[
C_p = \frac{P}{0.5 \rho U^2} \tag{1}
\]

\[
C_{VG} = \frac{VG}{U} \tag{2}
\]

‘Figure 17(a)’ shows the static pressure distribution along the axial direction of the lip BAC wall surface. In “Figure 17(b)” shows wall static pressure with dimensionless, ‘as in equation (1)’. In the upper wall surface AB, regarding of the wall static pressure, there is no difference between the maximum working state and the longest continuous working state. In the lower wall AC, the static pressure of the wall in the maximum working state is lower than that of the longest continuous working state. For the lip wall BAC, the resistance of the wall pressure difference in the maximum working state is greater than that of the longest continuous working state. The ‘Figure 17(b)’ is the dimensionless wall static pressure coefficient distribution. Through numerical integration, the area surrounded by the black line area is 2.33, and the area of the red line area is 2.40. The pressure resistance coefficient of the longest continuous working state is smaller than that of the maximum working state.

Figure 18(a)’ is the velocity gradient distribution of the lip BAC wall surface in the axial direction. In “Figure 18(b)” shows wall velocity gradient with dimensionless, ‘as in equation (2)’. In the upper
wall surface AB, the wall velocity gradient in the maximum working state is greater than that in the longest continuous working state. In the lower wall surface AC, the wall velocity gradient in the maximum working state is similar to the longest continuous working state.

![Image of Velocity Gradient Distribution](image1)

**Figure 18 Lip Axial Velocity Gradient.**

For the lip wall surface BAC, the wall surface friction resistance in the maximum working state is greater than the wall surface friction resistance in the longest continuous working state.

‘Figure 19’ is an entropy contour. The airflow does not produce an obvious high entropy area on the upper wall of the lip, while the airflow produces a relative high entropy area on the lower wall of the lip. The maximum entropy loss in the maximum working state is higher than in the longest continuous working state. The flight velocity remains unchanged, and the rotating speed of the electric propulsion distributed ducted fan changes. The fluid on the wall of the lip separates, resulting in frictional resistance. At the same time, the subsonic fluid decelerates and increases pressure on the concave surface of the lip, and the pressure on the convex surface accelerates to reduce pressure, resulting in differential pressure resistance.

![Image of Static Entropy Distribution](image2)

**Figure 19 Static Entropy Distribution of Lip.**

Differential pressure resistance and fluid friction resistance together affect the lip loss of the ducted fan. The greater the friction resistance and differential pressure resistance are, the lower the propulsion efficiency is.

As we all know: propulsion efficiency has a significant impact on the aircraft. This paper analyses the factors affecting the propulsion efficiency of electric propulsion distributed ducted fans to exclude the impact of different rotating speed. Including friction drag coefficient, differential pressure drag coefficient and have an impact on propulsion efficiency. In the future, from the perspective of reducing frictional resistance and differential pressure resistance, the researches should be taken measures to reduce the frictional resistance and differential pressure resistance of the electric propulsion distributed ducted fan, and in the same time, the researches should be taken measures to reduce power consumption, to expand the peak range of propulsion efficiency and increase the low-loss range of angle of attack. The researchers can optimize the lip profile, reducing frictional resistance and differential pressure resistance is an effective way to achieve the above objectives.
Conclusions and outlook

As the ratio of thrust increases, the aerodynamic efficiency increases, and the propulsion efficiency increases first and then decreases. For the research object of this paper, there is a best ratio of thrust corresponding to the maximum propulsion efficiency. As the ratio of thrust increases, the power consumption also increases. The ratio of thrust in the longest continuous working state is 85%, and the propulsion efficiency at this time is the highest.

The main factor affecting aerodynamic efficiency is the airflow angle of attack. When the rotating speed of the electric propulsion distributed ducted fan increases, the relative inlet angle of the airflow increases, which is closer to the design geometric inlet airflow angle, the airflow inlet angle of attack decreases, and the aerodynamic efficiency increases.

The determination of the propulsion efficiency are the values of frictional resistance, differential pressure resistance. The differential pressure resistance, friction resistance in the maximum working state are greater than in the longest continuous working state. Differential pressure resistance, fluid friction resistance together affects the ducted fan lip loss. The key step to improve propulsion efficiency is to reduce the influence of resistance. The researchers should be taken measures to expand the peak range of propulsion efficiency and increase the low-loss range of attack angle. The researchers can optimize the lip profile, reducing frictional resistance and differential pressure resistance is an effective way to achieve the above objectives.

References

[1] Greitzer E M et al 2010 N+3 Aircraft Concept Designs and Trade Studies NASA/CR-2010-216794 Glenn Research Center
[2] Smith L H 1993 Wake Ingestion Propulsion Benefit J. Propul. Power 9 74-82
[3] Bryce J D, Cherrett M A and Lyes P A 1995 Three-Dimensional Flow in a Highly Loaded Single-Stage Transonic Fan J. Turbomach 117 22-28
[4] Shang E and Z Q Wang 1993 The Experimental Investigations on the Compressor Cascades with Leaned and Curved Blade ASME International Gas Turbine and Aeroengine Congress and Exposition
[5] Alexej P, Matthias M and Wolfgang S 2018 Large-Eddy Simulation of the Tip-Leakage Flow in an Axial Fan Chinese J. Turbomach 60
[6] Zhen Y, Tao P, Bin J and Qun Z 2018 Effect of Axial Clearance on Radial Flow in Axial Compressor Near to Stall Condition Chinese J. Turbomach
[7] Delei C, Huashu D, Hantao M, Jiong Z, Zhenhai L 2019 Effect of Front Blade Mounting Angle on Performance of Counter-rotating Axial Flow Fan Chinese J. Turbomach
[8] Yincheang N and Haixin C 2019 Rapid Aerodynamic Design of Prop-rotor Blade with Optimization Chinese J. Turbomach 61
[9] Luyang Z, Yangwei L and Lipeng L 2019 Unsteady Behavior of Tip Leakage Vortex in an Axial Compressor with Different Rotor Tip-gap Sizes Using DDES Chinese J. Turbomach 61
[10] Black D M, Wainauski H S and Rohrbuch C 1968 Shrouded Propellers A Comprehensive Performance Study AIAA 5th Annual Meeting and Technical Display
[11] Bogdanski K, Krusz W and Rodzwicz M 2014 Design and Optimization of Low Speed Ducted Fan for a New Generation of Jointed Wing Aircraft 29th Congress of Interational Council of the Aeronautical Sciences (Saint Petersburg)
[12] Hubbard H H 1950 Sound Measurements for Five Shrouded Propellers at Static Conditions Tech NACA-TN-2024
[13] Sehra A K and Whitlow W 2004 Propulsion and Power for 21st Century Aviation Prog. Aerosp. Sci 40 199-235
[14] Amir S G, Georgios D and Riti S 2011 Challenges of Future Aircraft Propulsion: A Review of Propulsion Technology and Its Potential Application for the All-Electric Commercial Aircraft Prog. Aerosp. Sci 47 369-391
[15] Chima R V, Arend D J and Castner R S 2010 CFD Models of a Serpentine Inlet, Fan and Nozzle AIAA

[16] Mantic L, Doulgeris G and Gohhardani A 2012 Computational Analysis of Aerodynamic Performance of a Jet-flap Airfoil in Transonic Flow J. Aerosp. Eng. 226 664-678.

[17] KIM H and LIOU M S 2015 Mail-slot Nacelle Shape Design for N3-X Hybrid Wing-body Configuration AIAA

[18] Gong Y and Greitzer E M 1999 A Computational Model for Short Wavelength Stall Inception and Development in Multistage Compressors J. Turbomach

[19] Cui R, Li Qiushi and PAN Tianyu 2016 Streamwise-body-force-model for Rapid Simulation Combining Internal and External Flow Field Chinese J. Aeronaut 29 1205-12

[20] Hamed A and Numbers K 1997 Inlet Distortion Considerations for High Cycle Fatigue in Gas Turbine Engine Joint Propulsion Conference and Exhibit

[21] Rodriguez J, Klumpp S and Biesinger T 2013 A New Inlet Distortion and Pressure Loss Based Design of an Intake System for Stationary Gas Turbines ASME Turbo Expo: Turbine Technical Conference and Exposition

[22] Hugo F M, Bento, Reynard de V, Leo L M and Veldhuis 2020 Aerodynamic Performance and Interaction Effects of Circular and Square Ducted Propellers AIAA SciTech Forum (Orlando)

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