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Aerodynamic Impact of Guide Vanes on a Two-Stage Counter-Rotating Lift Fan

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Abstract. The lift fan is a critical component in vertical short takeoff and landing (VSTOL) fighters, enhancing thrust and offering significant applications in aerospace. To streamline airflow and optimize flow field distribution, guide vanes are often incorporated into lift fans to improve efficiency. However, studies on the aerodynamic impact of inlet and outlet guide vanes remain limited. This research examines the effects of inlet guide vane number and deflection angle, as well as the influence of outlet guide vanes on flow characteristics, using a two-stage counter-rotating lift fan as the subject. Findings indicate that fan lift increases steadily with the number of inlet guide vanes until reaching ten, after which additional vanes cause a rapid decrease in lift. The total pressure loss coefficient initially remains constant and then rises with increased inlet guide vane deflection angle. As adjustable vanes, the inlet guide vanes can pivot from approximately 80° to 20° to achieve gradual lift improvement. Compared to configurations without outlet guide vanes, the addition of outlet guide vanes significantly enhances airflow uniformity near the fan's exit, reducing aerodynamic losses and stabilizing the overall flow.

Keywords. Lift fan, aerodynamic analysis, guide vanes, numerical simulation

NOMENCLATURE

CL	Chord length
CH	Culvert height
CBI	Clearance between blade tip and inner wall of culvert

1. Introduction

A lift fan, integrated into an aircraft's fuselage or wings, generates upward lift by creating a pressure differential between intake and exhaust, powered by either the main gas turbine shaft or exhaust gases from the primary engine [1-2]. However, due to constraints such as tip speed limits and boundary layer separation, the aerodynamic load on single-stage fan rotors is restricted, limiting lift generation. To overcome this,

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multi-fan configurations are widely used. For example, the VZ-4 employed twin-ducted fans but achieved only 3,200 lbs of lift[3], while the XV-5, a U.S. prototype, housed multiple fuselage-mounted fans with limited thrust efficiency compared to helicopters in hover mode[4].

The F-35B later introduced a counter-rotating lift fan design that improved aerodynamic loading and contributed approximately 50% of total lift[5].

Despite the advantages of counter-rotating lift fans, they introduce complex flow dynamics that complicate aerodynamic design and practical implementation. The internal flow structures of lift fans critically impact their aerodynamic efficiency, underscoring the need for guide vanes to manage flow behavior effectively.

Early lift fan research abroad led to advancements in fan design and efficiency. Royce D. Moore developed variable inlet guide vanes using the Hamilton standard[6], and JAMES A. FRANKLIN refined a simulation model to evaluate the static and dynamic performance of lift fans and lift-cruise engines[7]. Christopher M. Ostoich et al. improved vane designs with approximate analysis and validated them through high-fidelity CFD simulations[8]. F. C. Kopper's cascade studies, which measured parameters like surface static pressure and exit air angle, demonstrated enhanced performance with profiled endwalls[9]. H. HEALY conducted extensive tests on two 20-inch fan models featuring variable pitch and inlet guide vanes on NASA's compressor test bench, generating data across various operating conditions[10].Conversely, domestic research on lift fans is more recent. Chen Fanbao et al. optimized blade performance using Gaussian processes, concluding that guide vane count and total chord length nonlinearly impact air flow[11]. Mao Zijian's team developed a nonlinear subgrid model for accurate numerical simulations, optimizing guide vane configuration and performing sensitivity analyses[12]. Further studies highlight the influence of guide vane angles on corner flow uniformity[13-14], with optimization largely conducted under fixed expansion ratios.

While global research has extensively examined counter-rotating lift fans, most efforts focus on blade or noise reduction effects, leaving the broader impact of guide vanes on lift fan performance underexplored. This study therefore examines the aerodynamic performance of guide vanes in a custom-designed counter-rotating lift fan through numerical simulations at a target design speed.

2. Structural Composition of Lift Fan

2.1. Introduction to Lift Fan

The lift fan analyzed in this study, shown in Figure1, consists of four main components: fan blades, guide vanes, bypass, and hub assembly, with the following key features:

- The fan is configured with five blade stages, where the second and fourth stages are rotor blades, while the first, third, and fifth stages function as stator (guide) vanes.
- It utilizes a counter-rotating design, with the second-stage rotor spinning clockwise and the fourth stage rotating counterclockwise.
- The first-stage guide vane is adjustable, allowing incremental lift modulation via blade deflection angle adjustments.
- The third and fifth guide vanes are fixed to the duct's inner wall and remain stationary, with unique airfoil profiles at each stage.

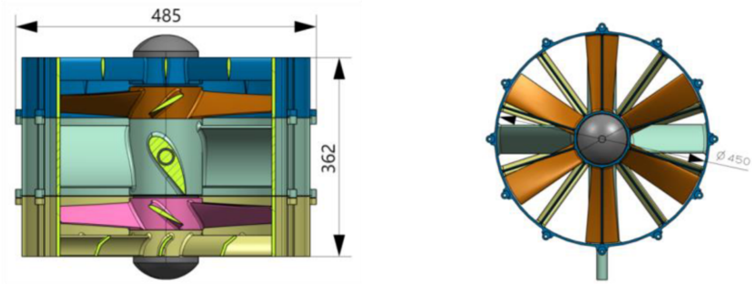


Figure 1. Schematic diagram of lift fan structure

2.2. Structural Parameters of the Lift Fan

The fan blades are driven by a primary bevel gear connected to the drive shaft, which engages two opposing bevel gears to rotate the upper and lower stages.The fan provides approximately 120 kgf of additional thrust, with a duct inner diameter of 450 mm and a blade root radius of 60 mm.Table 1. summarizes the main design parameters of the lift fan.

Table 1. Main design parameters of the lifting fan

	CL c/mm	CH h/mm	CBI L/mm
First stage guide vane	22	71.5	0
The second stage turns the blade	50	85.5	2.5
Third stage guide vane	56	87	0
The fourth stage turns the blade	46	70.5	2.5
Fifth stage guide vane	56	110	0

3. Numerical Simulation Methods

CAE software was utilized for numerical simulation, with CFX employed for post-proces- sing to analyze the internal flow field of the fan duct. The baffle thickness was set to 2 mm, inlet air temperature at 288 K, and blade rotation speed at 9500 rpm. Uniform airflow was introduced at the circular inlet to simulate fan operating conditions. The simulation focused on resolving the internal duct flow field and observing fluid linear velocity at the circular outlet. Performance evaluation metrics included Pressure loss coefficient and lift force[15-16].

Pressure loss coefficient is:

$$\varpi = \frac{P_1^* - P_2^*}{\frac{1}{2}\rho V_1} \tag{1}$$

ρ is the fluid density and V_1 is the inlet flow velocity, P_2^* is the total outlet pressure, P_1^* is the total inlet pressure.

The lift force is:

$$F = A_2(P_2 - P_1) + mV_2 \tag{2}$$

A_2 is the outlet area of the fan, P_2 is the outlet pressure, P_1 is the inlet pressure,m is the mass flow rate through the fan, and V_2 is the average outlet velocity.

3.1. Numerical Verification

Numerical simulations were conducted using CFX, with conditions specified in the accomp- anying table 2. To validate the accuracy of the computational approach, the Rotor67 model from literature[17]was selected as a benchmark.The validation model and computational grid are illustrated in the figure 2.In Verification of the total pressure ratio and efficiency curves shows close alignment with experimental results, as illustrated in the Figure 3and Figure 4.

Table 2. Calculate condition setting

Boundary condition	Import border, export border,
Total temperature	288K
Total inlet pressure	101325Pa
Rotational speed	16043r/min
Design tip clearance	1.01
Outlet mass flow	33.25kg/s
Number of blades	22 pieces

（a）roter67 Validation model （b）Schematic diagram of grid

Figure 2. Schematic diagram of the verification model

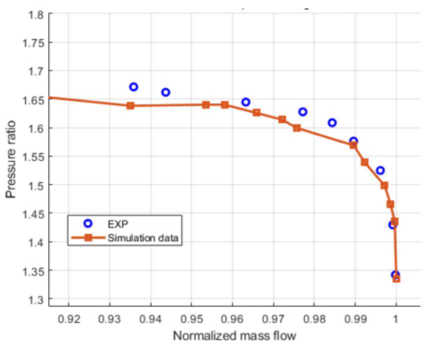


Figure 3. Rotor67 Total pressure ratio curve

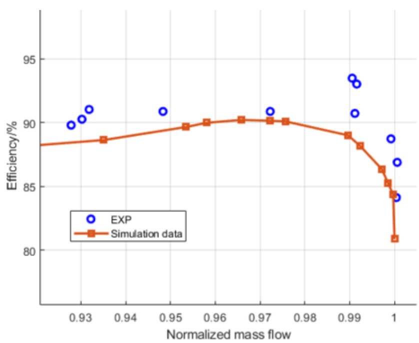


Figure 4. Rotor67 Efficiency curve

3.2. Grid Independence Verification

To minimize grid-related impacts on accuracy, a grid independence study was conducted using three mesh densities for the Rotor67 model:1 million, 2 million and 3 million cells. Figure 5and Figure 6,displays the meridional and blade-to-blade grids for the 1million-cell mesh. The resulting performance curves indicate that while the 1 million-cell mesh is slightly insufficient, the results from the 2 million and 3 million meshes show minimal differences. Thus, the 2 million-cell mesh was selected for subsequent calculations.

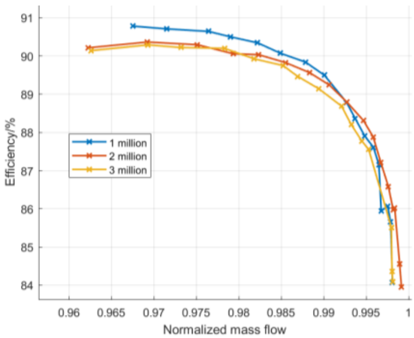


Figure 5. Efficiency comparison

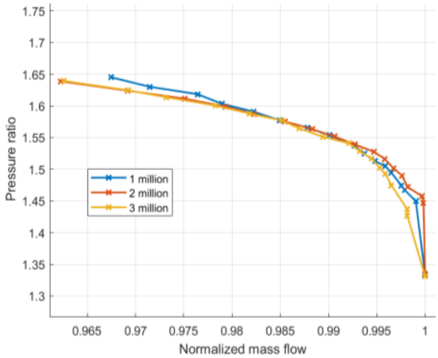


Figure 6. Pressure ratio comparison

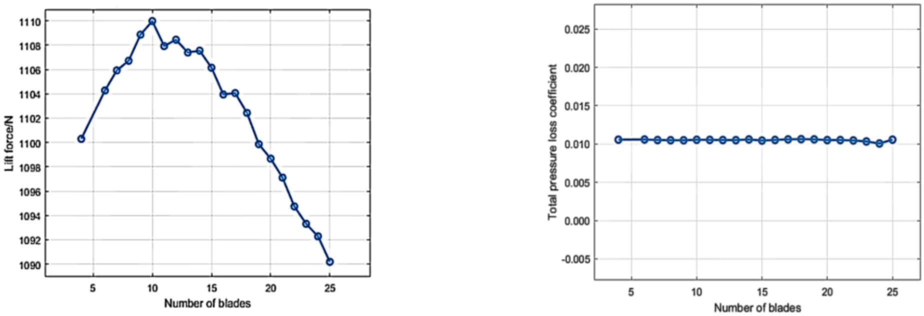
4. Study on Vane Performance

In vertical takeoff and landing operations, lift fans aim to maintain axial flow within the duct. However, at low flight speeds, the inflow direction at the duct entrance is significantly influenced by surrounding conditions, creating an angle between the inflow and the hub axis. Inside the duct, interactions with high-speed rotating fan blades introduce tangential velocity components, further altering the airflow angle as it progresses through subsequent fan stages. To mitigate thrust loss caused by these directional changes, it is essential to design guide vanes to reorient the airflow within the duct and improve flow field distribution. The effects of vane installation angle and blade count must be individually assessed to optimize performance[18].

4.1. Simulation Results and Analysis

4.1.1.The influence of the number of first stage deflectors

The effect of first-stage guide vane count on lift performance was analyzed numerically. Figure 7(a) shows that as the number of guide vanes increases, lift initially rises gradually, reaching a 1% increase at the optimal configuration. Beyond n=10, however, further vane additions result in diminishing lift, with a progressively higher reduction rate. Figure 7(b) indicates that the total pressure loss coefficient remains largely unaffected by vane count, holding steady around 1% with minimal fluctuation. Increasing the number of adjustable inlet guide vanes can improve airflow mixing at the culvert entrance, thereby enhancing lift, though it also incurs localized flow losses due to airflow interactions with the vanes.

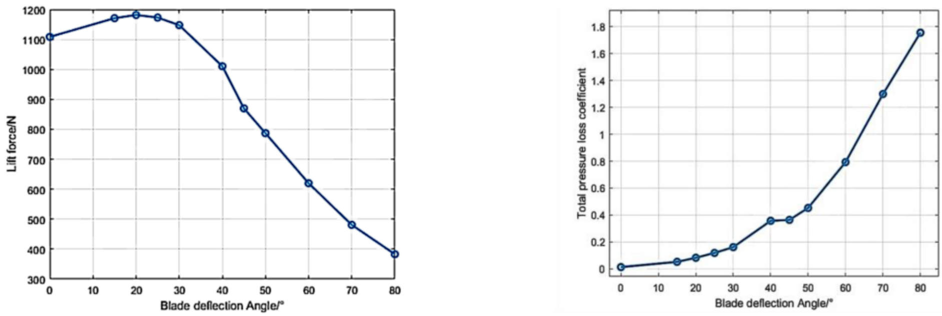


(a) Lift force (b) Total pressure loss coefficient

Figure 7. Inlet Guide Vane Count Effects on Lift and Pressure Loss in Lift Fans

4.1.2.Influence of deflection Angle of the first stage guide plate

Figure 8(a) presents the lift distribution across various deflection angles of the vane at n=10. The results indicate an optimal deflection angle range, where a gradual increase from 20° to 70° in the first-stage adjustable vane maximizes fan lift, achieving a 5% improvement. Figure 8(b) shows that as the deflection angle increases, the total pressure loss coefficient initially remains stable due to minimal flow separation, with losses primarily attributed to boundary layer friction. Beyond 40°, however, pressure losses start to rise as trailing-edge flow separation begins, leading to increased total pressure loss and greater flow instability at higher angles.

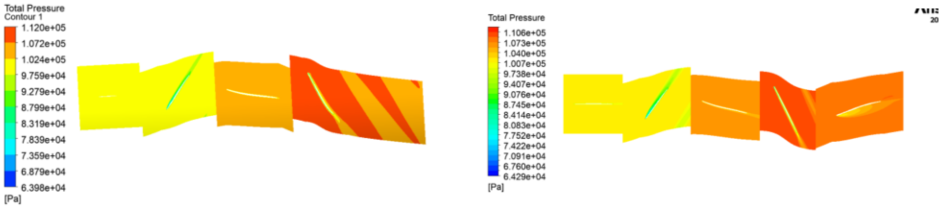


(a) Lift force (b) Total pressure loss coefficient

Figure 8. Effect of Inlet Guide Vane Deflection on Lift and Pressure Loss in Lift Fans.

4.1.3.Influence of the fifth stage deflector on the flow field

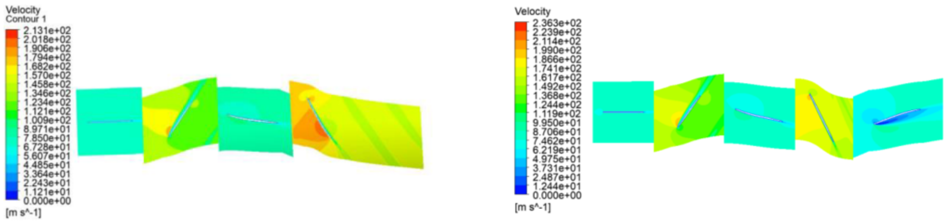
Figure 9 presents the total pressure distribution of the cross-sectional profile for the l-ift fan, comparing configurations with and without the fifth-stage baffle. Without the baffle, high-velocity airflow impacts the outer wall, creating a localized high-pressure region at the outlet due to accelerated airflow from blade rotation. The transition from low to high pressure is abrupt, particularly near the blade surface, where the rapid shift from yellow to red zones indicates significant airflow acceleration. This pressure distribution suggests strong localized thrust but also heightened aerodynamic losses due to flow separation and vortex formation. With the addition of the baffle beneath the rot-or, airflow is better guided, reducing the extent of high-pressure zones and providing as-moother pressure gradient. This indicates more uniform acceleration across the blades, reduced aerodynamic losses, and a more stable overall flow.



(a)No fifth guide baffle (b)With fifth guide baffles

Figure 9. Total Pressure Distribution Contour of Lift Fan.

Figure 10 presents the velocity contour of the lift fan. Distinct high-velocity zones (in orange and red) near the blades indicate rapid acceleration of airflow across the blade surface. The large velocity gradients in these regions contribute to potential vortex formation, causing flow instability and substantial aerodynamic losses. With the addition of guide vanes, the velocity gradient transitions become more gradual, leading to a more uniform acceleration profile across the blade's midsection and improved flow stability. Compared to Figure 10(b), the guide vane in Figure 10(a) effectively reduces localized vortex formation, enhancing overall flow stability.



(a)No fifth guide baffle (b)With fifth guide baffles

Figure 10. Speed cloud image of a lift fan

Figure 11 illustrates the 3D velocity field of the lift fan. In Figure 11(a), the flow lines at the bottom exhibit a pronounced helical structure, with airflow pushed outward by centrifugal forces due to blade rotation, indicating strong aerodynamic control by the blades. This helical structure also suggests localized instability due to accelerated, rotating airflow. In Figure 11(b), while the helical flow persists, the flow lines appear tighter and more uniform, indicating enhanced rotational control and greater flow stability. The addition of a bottom baffle effectively consolidates the airflow, significantly reducing vortex formation and separation, thereby improving fan efficiency and stability.

(a)No fifth guide baffle (b)With fifth guide baffles

Figure 11. Lift fan 3D velocity field flow diagram

5. Conclusion and Follow-up Research Direction

Numerical analysis was conducted to assess the aerodynamic performance of guide vanes in a lift fan, leading to these key findings:

- The lift exhibits a monotonically increasing trend with the increase in the number of inlet guide vanes. However, after reaching ten vanes, further increases in the number of vanes lead to a decrease in lift. This indicates that while the inlet guide vanes adjust the airflow direction, they also contribute to a certain extent in enhancing lift; nonetheless, their impact on the total pressure loss coefficient of the fan system is minimal.
- Lift increases with the angle of deflection of the inlet guide vanes up to a certain point before decreasing. The maximum lift occurs at an angle of approximately 20°, with an approximate 5% increase compared to the angle of 0°. Additionally, the total pressure loss coefficient of the fan system shows a slow increase with rising deflection angles.It shows that the deflection Angle of the vane will cause a certain aerodynamic loss while increasing the lift force.
- Without guide vanes at the lift fan outlet, the transition from low-pressure to high-pressure regions is abrupt. In contrast, the addition of guide vanes smooths this transition and reduces aerodynamic losses, resulting in a more stable overall flow.
- The installation of guide vanes at the lift fan outlet improves the uniformity of the mixed airflow near the fan exit, enhances flow integration, and significantly reduces vortices and separation phenomena, thereby improving the fan's efficiency and stability.

The guide vanes investigated are positioned near the upper and lower regions of the rotor, and the results indicate that they can effectively facilitate flow diversion and increase exit flow rates. Future design optimizations could be based on factors such as blade angle to reduce weight and enhance thrust and efficiency.

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