

## Postprint: Effect of Cascade Installation Angle on Performance of Blockerless Cascade Thrust Reverser

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### Abstract

A numerical study was conducted on the flow field of a blockerless cascade-type thrust reverser, with detailed analysis of the effects of different cascade installation angles on reverse thrust performance. Results show that the cascade installation angle influences the mass flow rate, velocity, and flow direction of the air exiting the thrust reverser window, thereby affecting reverse thrust effectiveness. For different fan inlet pressure ratios, there exist different optimal cascade installation angles that achieve the best reverse thrust performance. Due to different fan pressure ratios, the airflow possesses different energy levels; the lower the fan inlet pressure ratio, the less energy the airflow has, the larger the deflection angle entering the thrust reverser window, and the larger the optimal installation angle.

### Full Text

#### Preamble

#### Influence of Cascade Inlet Installation Angle on Performance of Blockerless Thrust Reverser

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**Abstract:** The flowfield of a blockerless thrust reverser is investigated numerically; the effect of cascade inlet installation angle on thrust reverse effectiveness is discussed. Results show that the mass flow, flow velocity, and flow direction through the cascade slot are notably influenced by the cascade installation angle, which consequently changes the thrust reverse efficiency. For different fan inlet pressure ratios, an optimal cascade installation angle exists that maximizes

thrust reverse efficiency. Due to the different fan inlet pressure ratios, the flow possesses different energy levels. The lower the fan inlet pressure, the smaller the flow energy, the greater the deflection angle of the flow entering the thrust reverser window, and thus the larger the optimal installation angle.

**Keywords:** blockerless thrust reverser; secondary flow injection; cascade installation angle; thrust reverse efficiency

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## Introduction

Thrust reversers are commonly used deceleration devices on large commercial aircraft and transport planes. Traditional engine thrust reverser configurations include clamshell deflector doors, bucket-type deflectors, and cascade thrust reversers [1-4]. The primary drawback of these mechanical structures is significant weight increase in the nacelle, increased mechanical moving parts, and high sealing requirements. Fluidic thrust reverser technology based on core secondary flow injection replaces traditional mechanical blocker doors with an “aerodynamic blocker,” substantially reducing the weight of the thrust reverser system and significantly decreasing the complexity of the actuation mechanism. Researchers both domestically and internationally have conducted extensive studies on blockerless thrust reversers based on secondary flow injection, demonstrating that secondary flow injection position and angle substantially affect reverse thrust efficiency [5-7]. Additionally, investigations into the geometric inlet flow angle of cascades in blocked cascade thrust reversers have identified an optimal geometric inlet angle that yields higher air flow rates and axial reverse thrust [8-11]. These findings indicate that the cascade installation angle in the reverser window influences the efficiency of the thrust reverser device.

This study employs numerical simulation to investigate a blockerless cascade thrust reverser, focusing on the influence of different cascade installation angles on reverse thrust efficiency to gain deeper insight into the internal flow mechanisms of blockerless thrust reverser devices.

## 1. Geometric Model

The thrust reverser configuration investigated in this paper is shown in Figure 1 [Figure 1: see original paper][5-7]. This model is a 1/10 scale model based on the CFM56-2 engine (bypass ratio 5:1). In the figure, curve A-B represents the lower wall of the fan bypass duct, with the secondary flow inlet located on A-B as shown. Curve C-D-E-F represents the upper wall of the fan bypass duct, curve G-H-F represents the nacelle outer surface, and curve D-E-H-G-D defines the boundary of the thrust reverser window on the outer bypass wall and nacelle surface. Point F represents the trailing edge of the fairing. Flow boundaries are confined by A-B, C-D-G, and H-E-F. The guide vanes in the reverser window are arranged at equal intervals, with the cascade installation angle illustrated in

Figure 2 [Figure 2: see original paper]. In the calculations, the installation angle was varied by rotating about the center point of the lower arc of the cascade vane at  $5^\circ$  intervals.

**Figure 1. Computational geometry model (unit: mm)**

**Figure 2. Installation angle of the cascade**

Where  $\rho$  represents density;  $V_y, V_x$  represent the velocity components of the fluid at the reverser window exit;  $W_{p, fan}$  denotes fan inlet mass flow;  $T_{t, fan}$  denotes inlet total temperature; and FNPR denotes fan inlet pressure ratio.

The reverse thrust  $F_{rev}$  is the integral of momentum at the reverser window along the X-direction.

## 2. Computational and Performance Evaluation Methods

The commercial software Fluent was used for computations. The governing equations are the Reynolds-averaged Navier-Stokes equations in Cartesian coordinates. The control equations were discretized using the finite volume method with a second-order upwind scheme in space and a steady coupled implicit algorithm. The standard k- turbulence model was employed.

The computational geometry model and boundary conditions are shown in Figure 4 [Figure 4: see original paper]. Pressure inlet boundary conditions were applied at the fan mainstream and secondary injection flow inlets, specifying total pressure, total temperature, and flow direction. Other outer boundaries used pressure far-field boundary conditions. The computational grid was refined near wall surfaces. The grid and boundary conditions are shown in Figure 3.

**Figure 3. Grid and boundary conditions**

Two methods were employed to evaluate thrust reverser performance:

1. **Cascade Flow Ratio (CFR)**, defined as the ratio of flow through the reverser window to total flow:

Where  $W_{cas}$  is the exit flow through the cascade;  $W_{fan}$  is the fan inlet flow; and  $W_{jet}$  is the secondary injection flow.

2. **Thrust Reverser Efficiency ( $\eta_{rev}$ )**, defined as:

Where  $F_{rev}$  is the reverse thrust and  $F_{i, fan}$  is the ideal fan thrust.

**Figure 4. Sketch of the thrust reverser window**

### 3.1 Numerical Method Validation

To verify the computational methodology, the model from reference [6] was simulated to obtain the reverse flow ratio variation curve with fan pressure ratio. A comparison between computational and experimental results is shown in Figure 5 [Figure 5: see original paper]. The computational reverse flow ratio

distribution trend agrees with experimental measurements, with computational results slightly higher than experimental values, demonstrating that the computational method is feasible and can accurately predict the performance of blockerless thrust reverser devices.

**Figure 5. Reverse flow ratio changes with fan pressure ratio**

### 3.2 Numerical Results

Figure 6 [Figure 6: see original paper] presents the variation of cascade flow ratio and thrust reverser efficiency at different cascade installation angles under various fan inlet pressure ratio conditions. Computations were performed at a secondary flow pressure ratio of 6 and fan pressure ratios of 1.3, 1.4, 1.5, and 1.6. At lower pressure ratios, both thrust reverser efficiency and cascade flow ratio exhibit an initial increase followed by a decrease with increasing installation angle, indicating an optimal installation angle that maximizes both parameters. As fan pressure ratio increases, thrust reverser efficiency decreases with increasing installation angle, generally remaining constant at smaller angles before decreasing rapidly at larger angles. In contrast, the cascade flow ratio remains essentially constant with changes in installation angle.

This phenomenon can be explained as follows. At low fan pressure ratios (e.g., 1.3), the bypass flow has relatively low energy. Under the same secondary flow pressure ratio conditions, the deflection angle of the flow entering the cascade channel is relatively large, resulting in optimal reverse thrust efficiency at larger installation angles. At high fan pressure ratios (e.g., 1.7), the bypass flow possesses greater energy, and under the same secondary flow pressure ratio, the deflection angle entering the cascade channel is smaller, requiring a smaller optimal installation angle.

When the installation angle is between  $45^\circ$  and  $60^\circ$ , increasing the angle improves the alignment between the bypass flow entering the reverser window and the cascade channel flow path, resulting in smoother flow. Additionally, as the installation angle increases, the cascade exit area increases, reducing blockage in the front cascade channels and allowing more flow to exit through the cascade, thereby increasing reverse thrust efficiency. Between  $60^\circ$  and  $70^\circ$ , further increases in installation angle cause the flow entering the reverser window to deviate from the cascade channel, significantly increasing flow separation on the blade suction surface and reducing efficiency. Moreover, the increased installation angle enlarges the cascade channel exit area, creating a diffusing channel that reduces the cascade's ability to constrain the flow, further decreasing reverse thrust efficiency.

To further analyze the influence of installation angle on reverse thrust efficiency, Figure 7 [Figure 7: see original paper] shows Mach number and streamline distributions at different installation angles for a low fan pressure ratio of 1.3. For this condition, when secondary flow is injected, the high-speed jet deflects the bypass mainstream, which then exits through the cascade window against the

incoming flow direction. Between  $45^\circ$  and  $60^\circ$ , increasing the installation angle reduces the low-velocity region in each cascade passage, leading to continuously improving reverse thrust efficiency. Between  $60^\circ$  and  $70^\circ$ , the low-velocity region in the first cascade passage increases rapidly with installation angle, and separation zones on the suction surfaces of the second, third, and fourth blades become significantly larger, causing reverse thrust efficiency to decrease with increasing installation angle.

Figure 8 [Figure 8: see original paper] presents Mach number and streamline distributions for a fan pressure ratio of 1.6. The first passage is completely blocked by a recirculation zone. As the installation angle increases, low-velocity regions in subsequent passages grow rapidly, particularly the separation zones on the blade suction surfaces, substantially reducing the effective cascade passage area and causing reverse thrust efficiency to decrease significantly with installation angle. At smaller installation angles, the cascade channels provide stronger flow constraint, resulting in smoother flow. However, as the installation angle decreases further, the cascade channels become very narrow, and even slight low-velocity regions can cause channel blockage. Therefore, it can be inferred that at higher fan pressure ratios, reverse thrust efficiency would decrease with further reduction in installation angle, suggesting that an optimal small installation angle exists for maximum efficiency at high pressure ratios.

As fan pressure ratio increases, the bypass flow energy increases while secondary flow energy remains unchanged, resulting in a smaller flow angle entering the reverser window. With increasing installation angle, the flow incidence angle into the cascade increases, causing larger suction surface separation and flow blockage, thereby reducing reverse thrust efficiency. However, if the cascade installation angle is too small, even slight separation on the suction surface can completely block the cascade channel. Therefore, at higher pressure ratios, a small optimal installation angle exists that maximizes reverse thrust efficiency.

## Conclusions

This paper numerically simulated the flowfield of a blockerless cascade thrust reverser and analyzed in detail the influence of different cascade installation angles on reverse thrust performance parameters. The main conclusions are:

- 1) The cascade installation angle affects the relative angle at which flow enters the cascade channel, influencing flow smoothness within the cascade passage and the exit flow direction, thereby impacting reverse thrust efficiency.
- 2) For different fan pressure ratios, an optimal installation angle exists that maximizes reverse thrust efficiency, and this optimal angle varies with pressure ratio.
- 3) At lower fan pressure ratios, the flow possesses less energy and enters the reverser window with a larger deflection angle, requiring a larger optimal

installation angle. As fan pressure ratio increases, flow energy increases and the entry angle into the reverser window decreases, resulting in a smaller optimal installation angle.

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