Large Eddy Simulation of Boundary Layer Separation and Reattachment in a Turbine Cascade at Different Incidence Angles: Postprint

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Date: 2017-11-07T00:00:00+00:00

Abstract

This study employs the Large Eddy Simulation (LES) method based on the three-dimensional compressible Navier-Stokes equations to investigate the evolution of the boundary layer in the low-pressure turbine cascade T106A, analyzing the influence of angle of attack variations on flow phenomena such as the separation and reattachment locations of the suction surface boundary layer and the separation bubble length. The Reynolds number based on chord length and exit velocity is 1.1×10^5, and the exit Mach number is 0.4. The results show that: when the inflow angle of attack is +7.80°, the cascade surface static pressure coefficient, as well as the separation and reattachment locations of the suction surface boundary layer, show good agreement with experimental results; after boundary layer separation, structures such as Λ-vortices and hairpin vortices form successively under the action of three-dimensional instability, eventually leading to transition; when the inflow changes from positive to negative angle of attack, the separation point of the suction surface boundary layer moves downstream, and the separation bubble length gradually decreases.

Full Text

Compressible LES of Unsteady Boundary Layer Separation and Reattachment in Turbines: Influence of Incidence Angle

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Abstract: A self-developed large eddy simulation (LES) program for the three-dimensional compressible Navier-Stokes equations was employed to investigate the flow field and evolutionary process of the boundary layer in a T106A low-pressure turbine cascade, aiming to predict and analyze separation, reattachment, and separation bubble phenomena at different incidence angles. The Reynolds number based on the exit isentropic velocity and axial chord length is 1.1×10^{5}, and the outlet Mach number is 0.4. Computational results demonstrate that at an incidence angle of $+7.8°$, the time-averaged pressure coefficient on the blade surface and the locations of separation and reattachment on the suction side show good agreement with experimental data. Following separation, the boundary layer undergoes three-dimensional instability, successively forming Λ-vortices and hairpin vortices that eventually lead to transition. As the incidence angle varies from positive to negative, the separation point on the suction side moves downstream and the separation bubble length gradually decreases.

Keywords: large eddy simulation; low-pressure turbine; incidence angle; boundary layer separation

0 Introduction

Aircraft engines must maintain reliable performance across continuously varying operating conditions to ensure superior flight characteristics. As a primary component of aero-engines, low-pressure turbines typically operate under low-Reynolds-number, high-loading conditions where boundary layers are highly susceptible to separation, transition, and reattachment phenomena [1, 2]. The inlet incidence angle represents one of the key factors influencing off-design aerodynamic performance in turbine cascades, making detailed investigation of unsteady flow characteristics at different incidence angles essential.

Numerous experimental and numerical studies have examined incidence angle effects on turbine cascade flow structures and performance. Jouini [3] and Benner [4] experimentally demonstrated that incidence significantly impacts profile losses and secondary flow losses. Dossena et al. [5] showed that incidence variations alter the magnitude, location, and shape of secondary flows. Zhang et al. [6] simulated a turbine cascade at $\mathrm{Re} = 5\times10^{5}$, describing the complete process of suction-side boundary layer separation, roll-up, downstream transport, breakdown, and trailing-edge shedding. Wei et al. [7] employed direct numerical simulation to study two-dimensional turbine cascade flows, revealing that incidence primarily affects near-wall flow in the leading-edge region. Chen [8] and Sun [9] also investigated incidence effects on turbine flow fields, losses, and performance. However, these studies predominantly focused on channel vortices, secondary flow losses, or total pressure losses, with limited attention to the unsteady evolution of flow structures.

Changes in incidence angle modify separation bubble morphology and dimensions, thereby affecting turbine performance. Large eddy simulation offers unique advantages in resolving unsteady flow details. This study employs a self-developed compressible LES code to compute unsteady flow fields in a turbine cascade at various incidence angles, examining their influence on boundary layer separation and reattachment and analyzing boundary layer evolution to provide theoretical foundations for turbine optimization.

1 Governing Equations and Numerical Methods

The governing equations and numerical methods employed herein follow those described in reference [10]. Convective fluxes are computed using a fourth-order central scheme, the subgrid-scale model adopts the dynamic eddy viscosity approach, and time advancement employs a three-step third-order Runge-Kutta method. The computational code is a multi-block parallel LES program (MPLES), with further details available in [10]. Turbomachinery flows represent internal flow problems where boundary conditions typically specify inlet total temperature, total pressure, flow angle, and outlet back pressure, determined using the method presented in [11].

3 Computational Results and Analysis

The T106A cascade profile and geometric parameters are shown in Figure 1 [Figure 1: see original paper] and Table 1 , respectively. Figure 2 [Figure 2: see original paper] illustrates the computational domain and boundary condition configuration, with the inlet located 0.5 Cax upstream of the blade leading edge, the outlet 1.6 Cax downstream of the trailing edge, and a spanwise extent of 0.2 Cax (where Cax denotes axial chord length). The normalized streamwise, pitchwise, and spanwise dimensions are 3.1, 0.93, and 0.2, respectively. The computational grid consists of 320$×180×60*nodesinthestreamwise*, *pitchwise*, *andspanwisedirections*, *withthefirstgridpointmaintainingy*
< 1 and approximately 35 nodes within the boundary layer. The Reynolds number based on axial chord and exit velocity is 1.1$×10^{5}$, the exit Mach number is 0.4, and the incidence angle varies from -10° to +7.8°.

Transient flow fields were collected after the flow reached a fully developed state characterized by quasi-periodic variation. Each case yielded more than 3000 instantaneous samples over a total sampling time exceeding 26 periods. Fast Fourier transform was applied to the temporal variation of blade loading in the circumferential direction. Figure 3 [Figure 3: see original paper] presents the frequency spectrum of blade force at +7.8° incidence, revealing a dominant frequency of f = 4.298 and a corresponding dimensionless quasi-period of T = 0.2327. The dominant frequencies and quasi-periods for other incidence angles, summarized in Table 2 , show minimal variation from the +7.8° case.

Figure 4 [Figure 4: see original paper] compares the time-averaged pressure coefficient distribution on the cascade surface at +7.8° incidence with experimental measurements. The pressure coefficient is defined as Cp = $(p - p_2)/(p_1^* - p_2)$, where p_1^* and p_2 represent inlet total pressure and exit static pressure, respectively. The LES results agree well with experimental data, though the pressure plateau on the rear suction side shows slight discrepancies, likely attributable to differences in inlet turbulence intensity between simulation and experiment. This pressure plateau indicates that near-wall fluid decelerates under the combined effects of adverse pressure gradient and viscous forces, leading to boundary layer separation.

Analyzing separation, transition, and reattachment from a vortical perspective aids understanding of boundary layer development. Figure 5 [Figure 5: see original paper] depicts large-scale coherent structures at the rear suction side at two instants for +7.8° incidence, identified using the Q-criterion with an isosurface value of $Q = 120$. A two-dimensional shear layer originating upstream rapidly exhibits three-dimensional characteristics under spanwise velocity perturbations, forming a triangular Λ-vortex structure at time t_1. As the Λ-vortex convects downstream, it grows and quickly assumes a hairpin-like shape (Figure 5(b)). The stretching action of the hairpin vortex progressively destabilizes the laminar boundary layer, causing large-scale vortices to break down into numerous smaller eddies that accumulate near the trailing edge (Figure 5(a)). This process culminates in boundary layer transition and reattachment, with the flow becoming fully turbulent.

Figure 6 [Figure 6: see original paper] presents the spatio-temporal distribution of instantaneous wall shear stress on the suction surface, where the solid black line indicates zero shear stress. Boundary layer separation initiates near 83% Cax, though at certain instants the separated layer immediately reattaches before separating again, resulting in multiple simultaneous separation bubbles.

Figure 7 [Figure 7: see original paper] shows the distribution of time-averaged friction coefficient on the suction surface. The friction coefficient is defined as $Cf = \tau w/(p_2{}^* \times$ [definition incomplete in original]), where $p_2{}^*$ is exit total pressure and τw is the wall shear stress in the axial direction. For the +7.8° case, the friction coefficient decreases from the leading edge to a minimum before increasing, corresponding to the adverse and favorable pressure gradient regions evident in Figure 4. After 60% Cax, the flow encounters another adverse pressure gradient until friction becomes negative at 83% Cax, indicating boundary layer separation. Beyond 97% Cax, friction turns positive and increases sharply, signifying transition from laminar to turbulent flow and subsequent reattachment. The region between 83% and 97% Cax constitutes the recirculation zone, whose length defines the time-averaged separation bubble. Additionally, negative friction between 0% and 5% Cax reveals a small leading-edge separation bubble caused by the large positive incidence. The other four cases exhibit similar friction coefficient trends, though zero and negative incidence cases show no leading-edge separation. As incidence decreases, the separation point moves downstream while the reattachment point remains essentially unchanged near 97% Cax, indicating that separation bubble size diminishes with decreasing incidence.

For incidence angles of -10°, 0°, and +7.8°, tangential velocity profiles were examined at five suction-side locations: 5% Cax, 30% Cax, 70% Cax, 80% Cax, and 90% Cax. Figure 8 [Figure 8: see original paper] presents the time- and spanwise-averaged tangential velocity component normal to the surface. At the leading edge (5% Cax), the three cases show substantial differences, with higher incidence producing greater tangential velocities. The near-wall detail in Figure 9(a) reveals a thin recirculation region for +7.8° incidence, absent in the zero and negative incidence cases. As the profile moves downstream, differences diminish until becoming nearly identical at 70% Cax. From 80% Cax onward, where boundary layer separation occurs at different positions for each incidence (Figure 7), the profiles diverge again. At 90% Cax, Figure 9(b) clearly shows that the -10° case exhibits the smallest negative tangential velocities and thinnest boundary layer.

4 Conclusions

This study employed a self-developed three-dimensional compressible LES method to investigate the evolution of the low-pressure turbine suction-side boundary layer and analyze incidence angle effects on separation and reattachment. The main conclusions are:

(1) At +7.8° incidence, the predicted blade surface pressure coefficient and suction-side boundary layer separation and reattachment locations agree well with experimental data, demonstrating the high accuracy of the present LES method.

(2) Multiple separation bubbles can coexist on the suction-side trailing edge at certain instants. Following separation, the boundary layer successively exhibits Λ-vortices and hairpin vortices; the stretching of hairpin vortices leads to laminar boundary layer breakdown, culminating in transition to turbulence and reattachment.

(3) As incidence varies from positive to negative, the suction-side boundary layer separation point moves downstream while the reattachment point remains essentially constant, resulting in a shorter separation bubble.

(4) Under large positive incidence, a weak separation phenomenon occurs near the suction-side leading edge, and the rear suction-side separation bubble exhibits greater thickness.

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