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Effects of tip-gap width on the flow field in an axial fan

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ABSTRACT

The turbulent low Mach number flow through an axial fan at a Reynolds number of 9.36×10^5 is investigated by large-eddy simulation (LES). Computations are performed for a fixed flow rate coefficient $\Phi = 0.165$ and two tip-gap widths, i.e., $s/D_o = 0.01$ and $s/D_o = 0.005$. A finite-volume flow solver in an unstructured hierarchical Cartesian setup for the compressible Navier–Stokes equations is used. To account for sharp edges, a fully conservative cut-cell approach is applied. A periodic boundary condition is used in the azimuthal direction such that only one out of five blades is resolved. The focus of this numerical analysis is on the impact of the tip-gap size on the overall flow field. Special attention is paid to the vortical structures around the tip-gap region and the turbulent transition on the suction side of the blade. It is shown that the reduction of the tip-gap size totally changes the flow field. The blade-wake interaction, which was evident for $s/D_o = 0.01$, vanishes for $s/D_o = 0.005$. Furthermore, depending on the tip-gap width different mechanisms are responsible for the turbulent transition on the suction side of the blade, i.e., for $s/D_o = 0.01$ a cyclic transition is observed which is triggered by the blade-wake interaction, where for $s/D_o = 0.005$ a separation bubble leads to a permanent transition. A reduction of the tip-gap width decreases the amplitude of the tip-gap vortex wandering and as such the region of influence of the turbulent wake and increases the frequencies of the dominant modes. Since this is confirmed by the experimental results of the sound power level, it also shows the dominant role of the tip-gap vortex in the noise emission.

1. Introduction

The tip-leakage flow which is mainly driven by the pressure difference between the pressure and the suction side has a significant impact on the efficiency and noise generation of turbomachines. Complex geometries and highly unsteady flow structures near the tip-gap make the understanding of the flow field phenomena in this region very difficult. Its strong impact on aerodynamic losses, rotating instabilities, and blockage, which highly affect the performance of turbomachines (Mailach et al., 2001; Storer and Cumpsty, 1991, 1994) and their contribution to the broadband noise emission (Camussi et al., 2010; Jacob et al., 2010) make the investigation and understanding of the complex flow phenomena in the tip-gap region an important task.

The tip-leakage flow has been extensively studied in the past. Many experimental studies have been conducted in this area (Goto, 1992; Inoue et al., 1986; Kang and Hirsch, 1993a, 1993b, 1994; Lakshminarayana et al., 1995; Muthanna and Devenport, 2004; Stauter, 1993; Wang and Devenport, 2004; Wenger et al., 2004), encountering huge difficulties inside the tip gap due to access and safety reasons. To numerically investigate the flow field near the tip-gap region, methods based on the Reynolds-averaged Navier–Stokes (RANS) equations have been primarily applied (Gourdain et al., 2012; Khorrami et al., 2002; Storer and Cumpsty, 1991, 1994). Due to their low computational costs, these methods became very popular in the past, especially for complex industrial applications. However, since the fundamental RANS formulation in conjunction with standard closure models suppresses the resolution of the relevant temporal and spatial length scales of the turbulence spectrum, which is determined by the highly complex and unsteady nature of the flow field, e.g., the interactions of the vortical flow structures caused by the tip gap with the boundary layer of the outer casing wall or the neighboring blades, RANS results are not reliable to capture this class of highly unsteady flows (Carolus et al., 2007; Pogorelov et al., 2015b; Tyacke et al., 2013).

Only a few other authors applied large-eddy simulations (LES) to investigate the complex flow phenomena inside the tip-gap

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Nomenclature

Greek symbols

$\boldsymbol{\alpha}$	vector with Runge–Kutta coefficients
γ	heat capacity ratio
η	dynamic viscosity
λ	thermal conductivity
ξ	primitive variable
ρ	density
$\overline{\boldsymbol{\tau}}$	stress tensor
τ	time shift
Φ	flow rate coefficient
χ	dissipation factor
Ψ	pressure coefficient
$\boldsymbol{\Omega}$	angular velocity vector

Symbols

$\overline{\mathbf{A}}$	reconstruction weights tensor
A	area
a	speed of sound
$\mathbf{b}$	body force vector
$\mathbf{C_l}$	reconstruction constants of neighboring cell l
C_p	pressure coefficient
D_i, D_o	inner and outer casing wall diameter
E	total specific energy
$E_{*,*}$	energy spectra
e	specific energy
$\mathbf{F}$	vector with surface values
$\mathbf{f}$	flux vector
f	frequency
$\overline{\mathbf{H}}$	flux tensor
h	length of smallest uncut cell
k	turbulent kinetic energy
$L_{w45-spec}$	specific sound power level
M	Mach number in the rotating reference frame
N_c	number of all direct neighbors of cell c
$\mathbf{n}$	normal vector
n	rotational speed
$\mathbf{P}$	vector of primitive variables
Pr	Prandtl number
p	pressure
$\mathbf{Q}$	vector of conservative variables
$\mathbf{q}$	vector of heat conduction
$R_{*,*}$	autocorrelations
Re	Reynolds number
r	radius
S	Sutherland's constant
Sr	Strouhal number
s	tip-gap width
T	temperature
t	time
$\mathbf{u}$, u_i	velocity vector in the rotating reference frame
V	volume
$\dot{V}$	volume flow rate
W_l	reconstruction weight of neighboring cell l
$\mathbf{x}$, $\mathbf{r}$, x_i	Cartesian coordinates
x, r, θ	cylindrical coordinates

Subscripts and superscripts

+	wall units
′	fluctuations
0	state of rest
c	cell
L/R	left/right values
n	time level in the Runge-Kutta scheme
s	surface
t	tangential

region. The LES generally gives a more accurate prediction of this intricate flow field which is defined by a strong variation of the temporal and spatial scales. You et al. (2004, 2006, 2007a, 2007b) investigated the tip-leakage flow of a linear cascade with a moving end wall. The underlying mechanisms for low-pressure fluctuations downstream of the rotor near the end wall were analyzed. They observed a good agreement of their numerical results with experimental data in terms of velocity, Reynolds stresses, and energy spectra. Furthermore, they showed the mechanisms for the generation of vorticity and turbulent kinetic energy to be independent of the tip-gap size and identified the velocity gradients to be the major causes for viscous losses in the cascade end wall region. They also described a pitchwise low frequency wandering motion of the tip-gap vortex. Boudet et al. (2015, 2010, 2007) performed computations for a single blade focusing on flow spectra and noise generation. Using a zonal RANS/LES approach, the tonal and broadband content of the flow could be captured. A Fourier decomposition over the whole domain highlighted the existence of a wandering motion of the tip-gap vortex, which they assumed to be a major contribution to noise radiation.

The LES method has already been successfully used by Pogorelov et al. (2015a) for the same configuration at the flow rate coefficient $\Phi = 0.165$ and the tip-gap width $s/D_o = 0.01$. A detailed grid convergence study on four computational grids proved the capability of the method to accurately capture the temporal and spatial development of the tip-gap vortex. Two dominant frequencies were shown to be related to an interaction of the turbulent wake generated by the tip-gap vortex with the downstream blade and a cyclic transition forced by this interaction. The analysis evidenced those phenomena to be major sources of the noise emission.

The study aims at getting a better understanding of the unsteady flow phenomena inside the tip-gap region and demonstrating the sensitivity of the flow field with respect to the tip-gap size. Compared to previous investigations, the current LES computations are applied to more complex geometries using an extremely high resolution to capture the temporal and spatial generation of the intricate flow structures. A computational grid with approximately 1 billion cells is used. The number of required time steps is approximately 0.65×10^6 and about 80 TB of disk space is needed to store data for two full rotations of the rotor. Furthermore, the investigated flow field is more complex compared to previous investigations, including transitional effect and interactions of the turbulent wake with the blade. In this study, it will be shown that a reduction of the tip-gap size may change the mechanism which triggers the turbulent transition on the suction side of the blade. In addition, the major role of the tip-gap vortex wandering motion in the noise emission, which is highly influenced by the tip-gap size, is demonstrated.

Numerical results of two computations at a fixed flow rate coefficient $\Phi = 0.165$ and tip-gap widths $s/D_o = 0.01$ and $s/D_o = 0.005$ are compared. The impact of the tip-gap width on the vortical structures near the tip-gap region and the turbulent transition on the suction side of the blade is analyzed in detail. As in the previous study (Pogorelov et al., 2015a), computations are performed for a single blade using a periodic boundary condition in the azimuthal direction to reduce the computational costs. The use of the periodic boundary condition has been justified by Pogorelov et al. (2016) for this configuration. The time-averaged and spectral quantities of a 360° full-fan and a 72° single-blade computation were in good agreement.