Chinese Journal of Aeronautics, (2016), **xxx**(xx): xxx–xxx

CSAA

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Experimental investigation of flow field in a laboratory-scale compressor

Ma Hongwei [a,b,*], **Wei Wei** [a,b,d], **Xavier Ottavy** [c]

[a] *Key Laboratory of Science and Technology on Aero-Engine Aero-Thermodynamics, School of Energy and Power Engineering, Beihang University, Beijing 100191, China*
[b] *Collaborative Innovation Center of Advanced Aero-Engine, Beijing 100191, China*
[c] *Laboratoire de Mécanique des Fluides et d'Acoustique (LMFA), Groupe Turbomachines, Ecole Centrale de Lyon, 36 av. Guy de Collongue, 69134 Ecully cedex, France*
[d] *China Academy of Aerospace Aerodynamics (CAAA), Yungangxi Rd., Fengtai Dist., Beijing 100074, China*

Received 31 January 2016; revised 2 September 2016; accepted 2 September 2016

KEYWORDS

Database;
Laboratory-scale compressor;
SPIV;
Tip leakage flow;
Tip leakage vortex

Abstract The inner flow environment of turbomachinery presents strong three-dimensional, rotational, and unsteady characteristics. Consequently, a deep understanding of these flow phenomena will be the prerequisite to establish a state-of-the-art design system of turbomachinery. Currently the development of more accurate turbulence models and CFD tools is in urgent need for a high-quality database for validation, especially the advanced CFD tools, such as large eddy simulation (LES). Under this circumstance, this paper presents a detailed experimental investigation on the 3D unsteady flow field inside a laboratory-scale isolated-rotor with multiple advanced measurement techniques, including traditional aerodynamic probes, hotwire probes, unsteady endwall static pressure measurement, and stereo particle image velocimetry (SPIV). The inlet boundary layer profile is measured with both hotwire probe and aerodynamic probe. The steady and unsteady flow fields at the outlet of the rotor are measured with a mini five-hole probe and a single-slanted hotwire probe. The instantaneous flow field in the rotor tip region inside the passage is captured with SPIV, and then a statistical analysis of the spatial distribution of the instantaneous tip leakage vortex/flow is performed to understand its dynamic characteristics. Besides these, the uncertainty analysis of each measurement technique is described. This database is quite sufficient to validate the advanced numerical simulation with LES. The identification process of the tip leakage vortex core in the instantaneous frames obtained from SPIV is performed deliberately. It is concluded that the ensemble-averaged flow field could not represent the tip leakage vortex strength and the trajectory trace. The development of the tip leakage vortex could be clearly cataloged into three phases

* Corresponding author at: Key Laboratory of Science and Technology on Aero-Engine Aero-Thermodynamics, School of Energy and Power Engineering, Beihang University, Beijing 100191, China.
E-mail address: mahw@buaa.edu.cn (H. Ma).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.09.016

Nomenclature

TLF	tip leakage flow
TLV	tip leakage vortex
RMS	root mean square
A	flow area
D_p	dynamic pressure of U_{tip} (Pa)
P_s	static pressure (Pa)
P_t	total pressure (Pa)
C_p	$(P_{s,out} - P_{s,in})/D_p$, static pressure rise coefficient
C_{ps}	$(P_s - P_{s,in})/D_p$, static pressure coefficient
C_{pt}	$(P_t - P_{s,t})/D_p$, total pressure rise coefficient
U_{tip}	tangential velocity of blade tip (m/s)
C_{vz}	$V_{z,\ in}/U_{tip}$, axial velocity coefficient at inlet
C_z	Z-wise velocity coefficient
V	velocity (m/s)
V_{tip}	rotor tip velocity (m/s)
$V_{z,boundary}$	Z-wise velocity on the boundary of the blockage area (m/s)
L	axial chord length in the blade tip
H	span length (mm)
m_t	mass flow rate in one passage
n	rotating speed (r/min)
C	chord length
C_m	blockage coefficient of tip leakage flow
ξ	relative total pressure loss coefficient
λ_2	principle to identify the TLV
Γ	circulation (m^2/s)
ρ	density
β_1	flow angle between the absolute velocity and the tangential direction (°)
β_2	flow angle between the relative velocity and the tangential direction (°)

Subscripts

in	compressor inlet
out	compressor outlet
r	radial direction
θ	circumferential direction
x	perpendicular to spanwise in the measurement slice
y	spanwise in the measurement slice
z	perpendicular to the measurement slice

according to their statistical spatial distribution. The streamwise velocity loss induced by the tip leakage flow increases until the splitting process is weak and the turbulent mixing phase is dominant.

1. Introduction

Nowadays, in the context of turbomachines, flow analysis and design are generally carried out with an averaged approach (RANS: Reynolds-averaged Navier-Stokes), where turbulence is modelled through statistical moments. This approach yields a good overall description of the mean flow, but strong discrepancies arise in separated flow regions, where turbulence is more complex. Such separated flows are found in local regions (e.g. corner separation and tip-clearance) even under design conditions, and over most of the flow passages under some off-design conditions. As known, the modern design system strongly relies on the accurate numerical simulations, and currently the development of more accurate turbulence models and CFD tools is in urgent need for a high-quality database for validation, especially the advanced CFD tools, such as large eddy simulation (LES).

For both the experimental and numerical approach, a large-scale low-speed rig[1] will be a fantastic subject to investigate in the context of turbomachinery. The researchers have performed plenty of investigations using this kind of test rig. For example, the performance of the compressor and loss distribution inside the compressor passage could be studied.[2–5] The flow control techniques are feasible to be applied to such a test rig.[6–8] Almost all kinds of measurement techniques could be applied to the large-scale low-speed test rig for assuring a high level of accuracy.[9–19] Meanwhile, it is quite suitable to apply the LES method in this configuration.

This work is an important part in the Sino-French collaborative project which is named as Advanced Experiments and Simulations of Complex Flows in Turbomachines (AXIOOM). This project is dedicated to pursuing a better understanding of the complex singular flows in turbomachinery with the most advanced experimental and numerical methods contemporarily. As for the content described in this paper, the objectives are (1) to provide a high-quality experimental database dedicated to the validation of LES in a laboratory-scale compressor, and (2) to better understand the complex tip leakage flow structure in this compressor.

In order to fulfill the objectives, the advanced measurement technique stereo particle image velocimetry (SPIV) is adopted together with the traditional measurement method. The particle image velocimetry (PIV) technique has been well-developed recently. Ghanem and Steven[20] performed an investigation on the unsteady leakage flow of a propeller using PIV, and found that some flow variables have to be shifted and scaled to reveal the real unsteady flow features. It is relatively difficult for the conventional experimental measurement techniques, compared with the numerical simulation method, to investigate the evolutionary procedure of the tip flow in the turbomachinery. Fortunately, SPIV technique is improved a lot nowadays, and has been utilized to investigate the tip leakage flow.[12] They