Aerospace Science and Technology 77 (2018) 499–509

Contents lists available at ScienceDirect

Aerospace Science and Technology

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Influence of tip leakage flow and ejection on stall mechanism in a transonic tandem rotor

Le Han [a,b,c], Wei Yuan [a,b,c,*], Yanrong Wang [a,c,d]

[a] *School of Energy and Power, Beihang University, Beijing 100191, China*
[b] *National Key Laboratory of Science and Technology on Aero-Engines Aero-thermodynamics, Beijing 100191, China*
[c] *Collaborative Innovation Center for Advanced Aero-Engine, Beijing 100191, China*
[d] *Beijing Key Laboratory of Aero-Engine Structure and Strength, 100191, Beijing, China*

ARTICLE INFO

Article history:
Received 3 March 2017
Received in revised form 26 March 2018
Accepted 3 April 2018
Available online 5 April 2018

Keywords:
Transonic tandem rotor
Stall mechanism
Ejection
Tip leakage flow
Dimensionless mass flow ratio coefficient

ABSTRACT

This paper investigates the stall mechanism of a transonic tandem rotor. The stall mechanism is found to be mainly affected by the tip leakage flow and ejection in the tip area. To quantify the strength of these two factors, ejection coefficient and tip leakage flow coefficient are defined. Basing on the two coefficients, the dimensionless mass flow ratio coefficient (*DMFR*) is further introduced to value the relative strength of the two factors above. If the *DMFR* is large, the tip flow fields of the front blade (FB) passage are dominated by the tip leakage flow, and stall first occurs on the FB. If the *DMFR* is small, the tip flow fields of the FB passage are dominated by ejection, and in this scenario, stall first occurs on the aft blade (AB). The *DMFR* is affected by the tip clearance of the FB and by the axial overlap. A large FB tip clearance and small axial overlap strengthens the tip leakage flow. Consequently, the *DMFR* is large. Conversely, a small FB tip clearance and large axial overlap enhances the ejection. Therefore, the *DMFR* is small. The changing of AB tip clearance has no significant effect on *DMFR*.

1. Introduction

Tandem rotor cascades were introduced several decades ago to increase the loading and reduce the weight of the compressor. Previous research indicates that a fresh boundary layer is recreated on the aft blade (AB) surface which helps reduce the loss and increase the flow turning angle. Therefore, the tandem rotor configuration can achieve higher pressure ratio within a shorter axial length than traditional compressors.

The excellent aerodynamic performance of tandem rotor was first verified in subsonic condition. Bent and Clemmons [1] designed a single-stage compressor with tandem rotor achieving a total pressure ratio of 1.31 and a peak efficiency of 91.8%, confirming that tandem rotors were a promising technology. Bammert et al. [2–4] tested a five stages subsonic compressor, and the middle three rotors were tandem. The results showed that the compressor performed well except a narrow stall margin. McGlumphy et al. [5,6] simulated the 2D and 3D models of different tandem rotors with profile basing on NACA-65 airfoil series at subsonic speed. They concluded that tandem rotors could improve the work output of the core compressor without incurring significantly higher losses. Moreover, the stall margin (S.M.) of the tandem rotor in Ref. [5] reaches nearly 20%.

In transonic conditions, low S.M. has always been problematic in the design process. In 1972, Donald and David [7] described a transonic tandem rotor with a tip speed of 419 m/s and a work coefficient of 0.33. The S.M. was 10%. The transonic tandem rotor of Hasegawa [8], proposed in 2003, achieved a tip speed of 431 m/s and a work coefficient of 0.51 at the design point, but the S.M. remained at approximately 10%. In the same year, Yusuke [9] proposed a transonic tandem rotor with a tip speed of 408 m/s and a work coefficient of 0.54 at the design point, which also yielded an S.M. of 10%. In 2012, Zhao Bin and Liu Bao-jie [10] designed a single-stage transonic tandem rotor with a tip speed of 381 m/s and a work coefficient of 0.55, but the S.M. was only 7.2%. In 2017, Mohsen [11] tactfully split the Rotor 37 into tandem rotor, performing a significant improve of the characteristic, but achieving an S.M. less than 5%. Thus far, to the best knowledge of the authors, the low-margin problem of transonic tandem rotors has not been resolved.

Obviously, it is important to investigate the flow field and stall mechanism to improve the stability at off-design conditions. In tests of a tandem rotor, McGlumphy [6] found that the flow field of the front blade (FB) is similar to that of a traditional single-blade,

* Corresponding author at: School of Energy and Power, Beihang University, Beijing 100191, China.
E-mail address: yuanwei@buaa.edu.cn (W. Yuan).

https://doi.org/10.1016/j.ast.2018.04.007
1270-9638/

Nomenclature

D_{AO}	Axial length of overlap
Df	Diffusion factor
Ec	Ejection coefficient
Ma	Mach number
$\dot{m}$	Mass flow rate
P^*	Absolute total pressure
r	Radius
$S.M.$	Stall margin
Tc	Tip leakage flow coefficient
T^*	Absolute total temperature
V	Absolute velocity
W	Relative velocity
Δx	Axial length from AB leading edge to FB trailing edge
x_T	Axial length from FB leading edge to AB trailing edge

Greek

τ	Solidity
φ	Flow coefficient, $\varphi = Vz/V_{tip}$
ψ	Work coefficient, $\psi = Lu/V_{tip}^2$

Subscripts

1	Blade leading edge
2	Blade trailing edge
F	Front blade
in	Inlet of passage
ol	Axial overlap
t	Tangential component
tip	Tip area

but the flow field of the AB heavily relies on the flow structure around the FB. Sumeet Bhaskar [12] and Zhao Bin [13] investigated the relative position of the FB and AB. They found that for constant axial overlap, the total pressure loss coefficient of the tandem rotor reduces with increasing percentage pitch of the AB's leading edge (relative to the spacing). Moreover, the performance was improved by raising the percentage pitch while maintaining near-zero overlap. Hoeger [14] and Mueller [15] pointed out that the overlap of the tandem structure constitutes a form of nozzle. The nozzle could accelerate the nearby flow, which further effects on the stall mechanism. Qian Yu-Ping [16,17] reported that the flow field of FB is significantly influenced by the potential of AB, and when the tip leakage flow (TLF) of the AB mixes with the wake of the FB, the near stall performance of the tandem rotor will be seriously impaired. According to previous studies, the stall mechanism in both of high-load transonic single and tandem rotors depends largely on the TLF. Day [18,19] found that the rotating stall of traditional compressors associates with a short length-scale disturbance known as a 'spike', which relates to the flow condition of TLF. Khaleghi [20] investigated the influence of the tip clearance size and found that the performance of the compressor fades with increasing the tip clearance. The results of Mohsen [11] showed that the stall mechanism of tandem rotor is primarily result from the interaction between the passage shock and TLF, which is influenced by the introducing of the AB. Therefore, the TLF might play an important role in the stall mechanism of the tandem rotor.

Owing to the special structure of the tandem rotor, the flow field inevitably differs from that in a single rotor. Therefore, the stall mechanisms might differ in single and tandem rotors. The authors of the present work also found that the nozzle formed by the overlap significantly affects the flow field of the FB, which is different from the potential effect of the AB. This phenomenon is called the ejection effect in this paper. Ejection influences the tip flow field and enhances the flow ability of the FB passage. Therefore, ejection might also contribute to stall. To solve the abovementioned problem, the present study analyzes the influence of TLF and ejection on the stall mechanism of a transonic tandem rotor with different FB and AB tip clearances and axial overlaps.

2. Methodology and validation

2.1. Numerical method

The flow solver EURANUS in Numeca software is employed for the present work. The steady three-dimensional Reynolds averaged Navier–Stokes equations are computed. The equations are spatially and temporally discretized by a cell-centered control volume method and an explicit four-stage Runge–Kutta method, respectively. A central scheme using Jameson-type dissipation with 2nd and 4th order derivatives of the conservative variables [21] are selected to compute the various fluxes. The one-equation turbulence model of Spalart–Allmaras [22] is utilized for the turbulence calculation, which has shown good results and been widely used in the researches of tandem configurations [11,23,24]. To reduce the computational cost, the discretized equations are solved by local time stepping, implicit residual smoothing, and multi-grid techniques. The numerical convergence and the stop criteria are monitored with the residue decaying or stabilizing at a value lower than 10^{-4}, and the mass flow stabilizing between the inlet and outlet boundaries within a difference less than 0.2%. The total pressure, total temperature and flow direction in absolute frame of reference are applied at the inlet. A static pressure at the mini-span is specified at the outlet, and the static pressure from hub to shroud is obtained by the radial equilibrium equation. No-slip, no-heat transfer boundary conditions are imposed to the solid walls. As the flow is assumed periodic in the pitch-wise direction, a periodic boundary condition is applied between the two pitch-wise-direction boundaries of the single passage. The TLF is also subjected to a periodic boundary condition on both sides of the passage.

2.2. Validation of numerical method

As there is no public geometry and results of transonic tandem rotor to verify the numerical method, Rotor 67 of NASA is selected and simulated here to validate the numerical method using in this paper. The reasons of selecting Rotor 67 are as follows: both of the tandem rotor in this paper and Rotor 67 work in transonic condition and they have almost the same tip inlet Ma (tandem rotor: 1.35 and Rotor 67: 1.37); besides, they also share a similar stagger angle in tip area (tandem rotor: 65° and Rotor 67: 63°). What's more, both of their casings shrink slightly in tip area, which would introduce a similar pressure gradient. The detail parameters and results of Rotor 67 can be found in Ref. [25].

A structured grid system is generated by IGG/Autogrid5 in Numeca software. An H-type grid is generated in the region of main flow and up/downstream of the blades, and an O-type grid is generated in the tip clearance region and around the blades. The minimum grid spacing on the solid wall is 3×10^{-6} m to ensure the y^+ retaining below 3 at the walls. A total number of 0.46 million grids with $57 \times 31 \times 85$ grid points in the spanwise, circumferential and streamwise directions are generated within the blade passage region. The details of multi-blocks structure are shown in Fig. 1.

The characteristics of the simulation are compared with experiment results in Fig. 2. The mass flow rates are normalized by