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The optimization and flow diagnoses for a transonic fan with stage flow condition

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ABSTRACT

The redesign and optimization of a low-aspect ratio transonic fan is implemented in this study. An advanced 3D aerodynamic optimization design system is adopted, while flow diagnostic methods are employed to discuss the transonic flow in the blade passages. On the basis of maintaining high aerodynamic efficiency, the study seeks to improve the pressure ratio and through-flow capability of the redesigned fan stage. Furthermore, the dynamic principle for the redistribution of passage flow due to geometry change is revealed. In comparison with the prototype, the total pressure ratio of the redesigned fan is increased by 7.54% at the design point, while its mass flow rate and adiabatic efficiency are raised by 6.30% and 1.25%, respectively. Additionally, a wider high-efficiency operation range is also achieved by the optimization. Under stage flow condition, the control of shock wave at the rotor tip and the removal of low momentum fluid in the stator corner are the two keys in improving the aerodynamic performance of the redesigned fan. Moreover, tangential lean of the stator blade has also succeeded in delaying corner flow separations. Further research for these design techniques would give potential to expand the design system for transonic fan/compressor with low-aspect ratios.

1. Introduction

Last few decades have witnessed the vast development of modern aircraft engines, the compression system has much higher pressure ratio and efficiency along with improved stall margin. These achievements should be attributed to the continuous increase in blade loadings. In fact, under given geometric limitation, the thrust-weight ratio of an engine would get higher with the increase of stage loading, thus improving its overall performance. Consequently, it has become inevitable trends that the aspect ratio of fan/compressor gets lower and lower while the wheel speed of the rotor becomes higher [1]. However, problems brought by these trends are also unneglectable: in a low-aspect ratio stage, since the annulus area is smaller and blade is shorter, the endwall boundary layer would take up a much larger portion in the spanwise direction, so it would be quite difficult to ensure the stage efficiency and the stall margin due flow separations and the induced secondary flows. Early in 1979, Urasek et al. [2] tested the performance of a first-stage low-aspect-ratio rotor on a two-stage fan, and the first stage achieved an adiabatic efficiency of 0.870 while the total pressure ratio was 1.655. Law et al. [3,4] implemented the analytical design and experimental test of a low-aspect-ratio transonic compressor stage, results showed that the stage total pressure ratio was 1.93 and the peak stage efficiency was 0.854. They also found that the optimum maximum thickness location for low aspect ratio transonic rotor is at 55 to 60 percent chord length. On the other hand, the increase of rotor wheel speed leads to the increase of relative Mach number in tip area, which is often accompanied by the shock wave. As we know, the compression effect in a transonic blade passage depends on the shock waves in its passage. Meanwhile, shock waves could incur high entropy generation and aerodynamic losses. The complex shock structures and their interaction with the wall boundary layers have greatly increased the design difficulty of transonic stages, and the goal of transonic blade design lies in the control and utilization of these shock structures to obtain the optimum aerodynamic performance. Wennerstrom [5,6] introduced swept blade into the design of a high through-flow transonic fan stage, backward sweep is used at the stator hub to minimize the shock loss and to maximize the incidence range through the control of the secondary flow, while forward sweep is employed at the tip region in order to maintain adequate solidity for the stator. Oyama et al. [7] adopted evolutionary algorithm to optimize the NASA Rotor 67, they proposed that to reduce shock-generated entropy, the shock wave in the passage should be as oblique as possible, and their study also highlighted the influence of blade leading-edge shape on the supersonic bub-

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Nomenclature

Variables

c	Local meridian curve distance
C_m	Total meridian curve distance
h	Local span distance
H	Blade height
m'	Normal coordinate for the streamline
$\dot{m}$	Mass flow rate
M	Mach number
$\bar{n}$	Corrected rotating speed
S	Entropy
u	Non-dimensional coordinate in basic airfoil plane

Greek

α	Absolute flow angle
$\Delta\beta$	Deviation on metal angle
π	Pressure ratio
θ	Circumferential coordinates
$\Delta\theta$	Deviation on tangential lean angle
δ	Deviation angle
η	Efficiency

Subscripts/Superscripts

1	Inlet conditions
2	Outlet conditions
r	Relative conditions
is	Isentropic
$*$	Total condition

Abbreviations

L.E.	Leading edge
T.E.	Trailing edge
PR	Total pressure ratio
SM	Stall margin

ble. Razavi [8] discussed the effects of sweep and lean to a transonic rotor, and found that the main effect lies in the operating range, similar conclusions were also proposed by Denton et al. [9].

Computational Fluid Dynamics (CFD) nowadays provides researchers with great convenience in blade design and optimization, modern blading is free from the limitation of traditional configuration hence having more potential to suit the real flow condition. However, the key for 3D blade design is the thorough understanding of the flow behaviors in the blade passage and the accurate diagnosis of the specific flow information, which is challenging for the designers. Benini [10] implemented optimization for the NASA Rotor 37, oblique shocks were constructed with changes in both blade profile and radial stacking. Jang et al. [11] employed backward sweep for the same blade and achieved the increase in adiabatic efficiency. More examples of optimization work that reflect diversified design concepts and methods can be easily found in the open literature [12–15].

In order to explore and expand the potentialities of low-aspect ratio, transonic fan under stage flow condition, the redesign and optimization of a fan stage based on flow diagnosis is implemented in this study. The design purpose is to increase the mass flow rate and the pressure ratio of the fan while maintaining its efficiency and stall margin. In this paper, a brief introduction of the prototype fan and optimization method is first provided, then after the validation of the numerical method, the optimization process and the results are presented and discussed in detail. Finally, the correlation between the configuration of the blade passage and the corresponding flows are revealed based on the investigations.

2. Prototype and optimization system

The prototype for the present study is a transonic fan stage with a low-aspect ratio [16]. As shown in Fig. 1, the fan stage consists of two blade rows, both of which would be redesigned and optimized. At the beginning, the redesign of the fan stage is performed based on the prototype. The redesigned fan inherits the meridian flow path as well as the geometric constraints of blade leading and trailing edges in the meridian plane. The number of blades and the rotating speed are also the same for the prototype and the redesigned fan. The profiles of the blade (both for the rotor and stator blade) and the stacking lines (for the stator blade only) are optimized. Design parameters of the redesigned fan are listed in Table 1. Compared with the prototype, the redesigned fan has higher mass flow rate and total pressure ratio, while the stage efficiency is expected to be at least the same as the prototype [16].

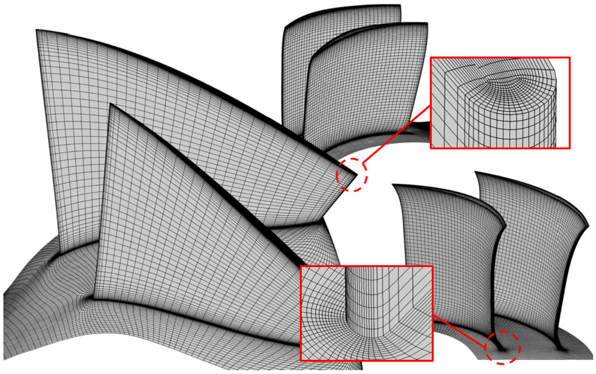

Fig. 1. Geometry and meshes for the prototypical fan stage.

Table 1
Design parameters for the redesigned fan stage.

Parameter	Value
Corrected rotor tip tangent speed (m/s)	411
Corrected design rotating speed (rpm)	28000
Flow coefficient at the rotor tip	0.502
Relative Mach number at L.E. of the rotor tip	1.385
Work coefficient of the rotor tip	0.462
Hub-to-tip ratio at the L.E. of the rotor	0.458
Clearance at rotor tip (mm)	0.5
The number of blades for rotor and stator	13, 36
Design mass flow rate (kg/s)	≥9.35
Design efficiency	≥0.88
Design total pressure ratio	≥2.10

In this work, the optimization system developed by Turner et al. [17] is adopted. With strong 3D modeling capacity, this optimization system combines the optimization codes and the CFD solver skillfully, and has proved its outstanding engineering practicability in a series of realistic works. The operating process is illustrated in Fig. 2. First, input files containing the optimization requirements are given by the users, these commands are then transferred to the optimization program called Dakota [18]. Based on genetic algorithm and the results of the former calculation, Dakota would define the values of optimization parameters and these values are delivered to the optimization module for geometry building and numerical calculation. Finally, after adequate generations, the optimum scheme for the objective function could be obtained. De-