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The impact of tandem rotor blades on the performance of transonic axial compressors

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ABSTRACT

A numerical investigation has been undertaken to evaluate the potential of tandem rotor blades in improving the overall performance of transonic compressors. This study aims to address guidelines for the design of tandem rotor blades and to provide insights into the flow field in the transonic regime. A tandem rotor design with same inflow characteristics of the reference transonic rotor 'NASA Rotor 37' is proposed. A parametric study based on two-dimensional numerical simulations is performed at the rotor mid-span section with supersonic inlet Mach number of 1.4 to select the suitable design parameters for the three-dimensional computations. Then the tandem rotor performance at design and off-design conditions is examined. The results are compared with the numerical and experimental results of the reference 'NASA Rotor 37'. The numerical results reveal that large improvements in the flow turning and diffusion are obtained without flow separation. The tandem design has a 17% increase in the total pressure ratio and 2% increase in the rotor adiabatic efficiency relative to the baseline rotor 'NASA Rotor 37'.

1. Introduction

Multi-stage axial flow compressors are the principal type of compressors used in gas turbine engines due to their high efficiency and high flow capacity per unit frontal area. However, the compressor weight is considered the largest among all other components in the gas turbine engine. Manufacturers are always seeking to develop engines with high thrust to weight ratio. This can be accomplished by increasing the single stage total pressure ratio and reducing the number of stages.

To increase the total pressure ratio of a single stage axial flow compressor, there is a challenge of increasing line sweeping and leaning, vortex generators, splitter vanes, slotted blades, tandem blades and counter rotating blades flow turning and diffusion without boundary layer separation. Moreover, in highly loaded transonic axial compressors, the flow diffusion is dependent upon decelerating the flow through a shock system and the flow turning capability is limited by boundary layer separation due to high compressibility effects and the shock-boundary layer interaction.

Several studies are being carried out on the advanced designs of axial flow compressor. Some of them are biased towards the design of advanced blade profile and blade stacking. Other approaches are concentrated on the compressor casing treatment by means of slots and groves, and the tip injection or bleeding [1,2].

One way to overcome the separation problem is replacing single blade with two tandem blades, as shown in Fig. 1, such that a fresh boundary layer is created on the rear blade through the gap flow from the front blade pressure side. The theory of tandem rotors is basically extracted from the flap or slat introduction to a conventional aircraft wing to increase its camber to get higher lift without flow separation. Previous studies [3–10] have shown that tandem blades outperform conventional blades in terms of higher diffusion and turning capabilities with lower losses. However, most of these studies concentrated on subsonic shock-free regime.

Experimental studies on two-dimensional subsonic tandem cascades indicate to the advantages of using tandem cascades in terms of increasing the flow turning with less flow separation [3–5]. A further investigation has been carried out by Bammert and Beelte [6]. The researchers performed a rig test on a five stages subsonic compressor. The first and last rotors are single bladed while the other three rotors are tandem and all stators are single bladed. They concluded that the tandem compressor operation didn't raise any problems except a narrow stability range.

More recently, McGlumphy et al. [7,8] performed 2D and 3D numerical simulations on different tandem cascades with NACA-65 airfoil series at subsonic speed. They found that the tandem design is very sensitive to the relative position between the two airfoils. They concluded that the tandem design has the capability to re-

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Nomenclature

AOR	Axial overlap ratio
CFD	Computational fluid dynamics
C	Absolute velocity
DF	Diffusion factor
EXP	Experimental data
MUSCL	Monotonic Upstream-Centered Scheme for Conservation Laws
P	Pressure
PS	Pressure surface
SS	Suction surface
T	Temperature
TOR	Tangential overlap ratio
W	Relative velocity
y^+	Normalized wall distance
B	Relative flow angle
γ	Gas constant
ξ	Stagger angle
σ	Rotor solidity
π	Total pressure ratio
τ	Total temperature ratio
ω	Pressure loss coefficient

Subscripts

1	Rotor inlet
2	Rotor exit
$t,1$	Total conditions at station 1
$t,4$	Total conditions at station 4
t,rel	Total relative conditions
θ	Tangential component

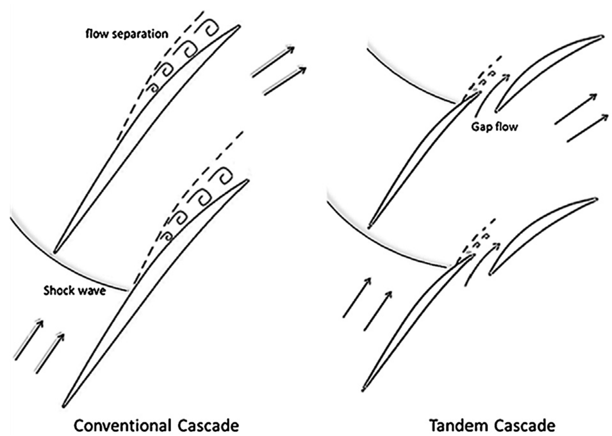

Fig. 1. Layout of conventional and tandem cascades.

place three conventional rotors with two tandem rotors. Hoeger et al. [9,10] conducted 2D experimental and numerical simulations on a developed subsonic tandem cascade at design and off-design conditions. The results of the tandem cascade are compared with those of the conventional cascades of same inlet Mach number and turning. The off-design results showed advantages of the tandem cascade at higher Mach numbers and disadvantages at lower Mach numbers.

In transonic regime, the only work on tandem rotors found in literature was carried out by Hasegawa et al. [11]. They developed a transonic tandem fan for an Air Turbo Ramjet (ATR) engine. The fan testing showed that a pressure ratio of 2.2 could be achieved in a single stage. However, details about the design and analysis of the flow physics at different operating conditions were not presented in details. Other work in transonic regime was performed on stator guide vanes [12,13] with inlet Mach number of 1.06 and 1.25 respectively. This work is focused on the design and performance of stationary tandem blades in which the flow physics is simple compared to rotating blades.

The effect of tandem blades on subsonic compressor performance has been investigated by several researchers. However, the supersonic or transonic flow fields over tandem blades exhibit complicated phenomena such as the shock wave interaction with the gap between the blades. The effect of the shock location on the performance of the tandem blades needs more investigation. Thus, the current study aims at developing an advanced transonic tandem rotor that can benefit from the flow diffusion through a shock system and the large flow turning angle. The simulation of such flow with a shock system requires special treatment of the numerical mesh in order to resolve accurately the flow field near the shock without producing large numerical oscillations. As the flow conditions or the blade shape are being changed during the current study the shock position changes over the blade. Thus, the grids used in the numerical simulations need to be modified carefully.

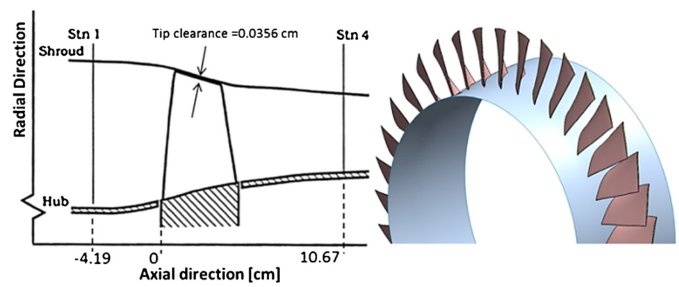

Fig. 2. NASA Rotor 37 geometry.

The inflow characteristics are kept similar to those in the reference rotor NASA Rotor 37 to be able to provide a comparison between their performance at design and off-design conditions. The tandem rotor blades have different spanwise chord, camber, twist angle and inlet Mach number from 1.13 at the hub section to 1.48 at the tip section. 2D and 3D numerical simulations are carried out on the proposed design and the effect of each design parameter is examined. In depth analysis of the flow field is carried out at different operating conditions to explain the physical phenomena and the potential advantages.

2. Validation of the numerical model

Fig. 2 shows the geometry of the reference transonic rotor NASA Rotor 37. The rotor was originally designed and tested by Reid and Moore [14,15] at NASA Glenn research center alongside with three other stages named as stages 35, 36 and 38. The rotor consists of 36 blades with multiple circular arc airfoil sections. Each airfoil section has different chord, camber, thickness and setting angle. The rotor design parameters are summarized in Table 1.

NASA Rotor 37 was tested at Glenn research center by Suder [16] and the experimental results are used for numerical validation of several CFD codes and numerical models. AGARD advisory group conducted intensive numerical study to validate CFD codes and to identify the effect of grid and turbulence models on the solution accuracy [17]. The numerical method adopted in the current work is being motivated by the good results obtained for