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Numerical investigation of positive dihedral application conditions in compressor cascades

Detang Zeng*, Meiyuan Li, Yongjun Zhang, Chunqing Tan

Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China

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Abstract This study attempts to make a contribution to the understanding of dihedral application conditions and their aerodynamic mechanisms. The present efforts have finished contrastive investigations on several dihedral blades to their corresponding straight ones with different geometric or aerodynamic conditions including aspect ratio, solidity, aerofoil turning angle, inlet boundary layer configuration and inlet Mach number. A dihedral with the angle between the suction side and the endwall to be obtuse, i.e., positive dihedral, is chosen. The result reveals the dihedral application conditions consist of aerofoil turning angle, inlet boundary layer, inlet Mach number and so on. The further analysis indicates: in a transonic cascade, two considerations are needed on the contrastive relationship between intensities of the two shocks, namely detached shock and passage shock, and the interaction of the shocks with the corner separation.

1. Introduction

Since the idea of using dihedral-twisted blades was proposed by Filippov and Wang [1] in early 60s of the last century, dihedral blade theory research and application have undergone a satisfying development in turbine. However, up to now dihedral blade in compressor was of uncertainty. That means effects of dihedral blade are two-fold in compressor application: benefit and cost in aerodynamic performance.

Variation of flow parameter distribution along radial direction, a recognized effect of dihedral blade on flow field, causes variation of loss and performance along radial direction. Most of reported researches have focused on

*Corresponding author. Tel.: +8610 82543137.

E-mail address: zengdetang@iet.cn (Detang Zeng).

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Nomenclature

Ma	Mach number
AVDR, Φ	axial velocity density ratio
RVDR, Ψ	radial velocity density ratio
Δp	total pressure differential (unit: Pa)
h	blade height (unit: m)
C_p	static pressure coefficient
P.S	pressure surface
S.S	suction surface
HP	high pressure
3D	three dimensional
$\overline{B}$	relative chord length

Greek letters

γ	dihedral angle (unit: °)
γ_{opt}	optimal dihedral angle (unit: °)
$\overline{\overline{\omega}}$	total pressure loss coefficient
$\Delta\overline{\overline{\omega}}$	total loss improvement factor
θ	aerofoil turning angle (unit: °)
ρ	density (unit: kg/m^3); aerofoil curvature
B_s	stagger angle (unit: °)
β_T	geometric angle (unit: °)

Subscripts

MS1	inlet averagequantity
1	inlet
2	outlet
STR	straight blade
DIH	dihedral blade
m	midspan
t	tip

Superscripts

–	surface mass averaged; relative quantity
=	total mass averaged

analyzing the influences of dihedral blade on given cascades performance including secondary flow, separation, stable operation range and overall efficiency. Nevertheless, the factors which affect the effects of dihedral appear not to be fully understood and few of the correlative results are reported.

This study is aimed at searching for some dihedral application conditions, the aerodynamic or geometric factors which decide the beneficial effects of dihedral blade on overall compressor performance, and improving the understanding of the aerodynamic mechanisms of the dihedral application conditions. Based on early studies and experiences [1–16], several aerodynamic and geometric parameters are investigated consisting of inlet boundary layer (IBL), inlet Mach number, incidence, aspect ratio, solidity and aerofoil turning angle in both dihedral and straight compressors by means of CFD method. The numerical method and mesh configuration is shown in the reference [16].

1.1. Definition of dihedral

Blades are said to have dihedral when the blade surfaces are not perpendicular to either of the endwalls in pitch-wise direction [2]. Sasaki et al. [3] had also given a definition of sweep and dihedral. According to them, a lean/dihedral is introduced by moving the gravity centre of the endwall section of a blade in a direction normal to the chordline as shown in Figure 1. Lean/dihedral is ‘positive’ if the suction surface makes an obtuse angle with the endwall and ‘negative’ if it makes an acute angle with the endwall. Classified by shapes, dihedral stacking lines consist of parabola, hyperbola, double arc and multi-curved line (a line consisting of two or more curves). In this study, the multi-curved line is used to produce the positive dihedral stacking line (its detailed configuration will be told in the part Design of stacking line).

1.2. Introduction of dihedral blade in compressor

The part of compression system plays a central role in weight and cost reduction of aero-engines. In order to reduce stage count and improve performance, stage loading must rise and aerofoil boundary layers has to be well controlled as not to separate and to increase losses. The early study about custom-tailored aerofoil, as reported by Hobbs & Weingold [4], mainly focused on the aerofoil boundary layers in order to reduce the profile loss. The first approach to solve flow problems near the endwalls was end bend as given by Behlke [5] and Robinson [6]. The early concept of end bend was based on a two-dimensional way although aiming at a three-dimensional flow problem. The formation of end bend involves a given bend angle and a certain bend depth as to achieve ideal performance. In the 80s of the last century, the technology of end bend was successfully applied into the British engine of RB211-535E4 and the Chinese engine of WP7. Several years later, it was also adopted in the engine of GE-90 [7].

The introduction of dihedral blade provides another approach to change flow behavior in compressor. Actually dihedral is a further evolution of end bend technology. During the past decades, the use of dihedral in compressor has experienced more and more interest. LeJambre [8] demonstrated a 2% rise of polytropic efficiency in a multistage HP-compressor with dihedral stators. Gümme and Wenger [9] verify that dihedral stator could improve radial load contribution and control boundary layer development, furthermore reduce corner stall in hub/endwall