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Numerical investigation of blade tip grooving effect on performance and dynamics of an axial flow fan

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ABSTRACT

Appropriate changes to the blade tip structure can effectively improve fan performance. The performance of the OB-84 axial fan with different grooved blade tips is simulated using Fluent. The effects of various tip structures on the flow field, losses distribution, and noise characteristics are investigated. Analysis of static structure and vibration characteristics is performed with the Ansys finite element analysis module. Simulated results show that for the grooved blade tips, both the total pressure rise and shaft power of the fan decrease, but the efficiency improves distinctly; the grooved blade tip structure perturbs the flow and vortex fields and impedes the development of the leakage flow; this eventually results in the reduction of mixing losses between the leakage flow and mainstream. Blade tip case 4 produces the maximum efficiency with an increase of 1.07% at design volume flow rate, and case 7 obtains the lowest shaft power compared with the original tip. Grooved blade tips amplify the fan noise, so measures should be taken to control the noise. Analysis of dynamic characteristics reveals that the distortion and fracture failure of the blade as well as resonance of the impeller would not occur by adopting grooved blade tips.

1. Introduction

Maintaining a gap (i.e., tip clearance) between the blade tip and casing wall is necessary to ensure the relative motion between the rotor and stationary casing in an axial flow turbo-machinery. The tip clearance provides a channel for fluid to leak from the pressure surface to the suction surface, which leads to a tip leakage flow. Tip leakage flow results in a passage blockage and a decreased efficiency. Owing to the mixing of the leakage flow and passage flow, a tip leakage vortex is generated at the top of the suction surface corner after the tip leakage flow leaves the suction surface. Thus tip clearance has significant impacts on the performance and stability of an axial flow turbo-machinery.

As an important piece of auxiliary equipment in a power plant, the fan accounts for about 30% of the plant's total electricity consumption. Its operation mode and economy are directly related to the economical operation of the power plant. In China, current design specifications generally require to adopt margins of 20%–30% for flow rate and total pressure rise, which make the actual operation parameters of the fan considerably greater than the required values [1]. This leads to a situation that a high efficiency fan runs inefficiently. The energy-saving potential of the fan is great; therefore, improvements are essential to enhance the efficiency and reduce the power consumption.

Early investigations on the tip clearance mostly focused on the formation mechanism and the development process of the leakage flow, and the effects of different blade tip clearance sizes on the performance and noise of turbo-machinery. In experiments, Storer and Cumpsty [2] measured the linear cascade with the tip clearance taken from numerical solutions to investigate the tip leakage flow and presented a formation mechanism for the leakage flow. They also presented the relation between the leakage flow and the local pressure field. Kameier and Neise [3] experimentally studied the effects of the tip clearance on the aerodynamic and acoustic performance of an axial flow turbo-machinery. Their results showed that noise can be eliminated and the aerodynamic performance can be effectively improved through the insertion of a turbulence generator into the tip clearance. Takahashi et al. [4] conducted a three-dimensional numerical simulation to examine the complex flow fields and vortices in the blade tip and to clarify the behaviour of the blade tip vortices of a wind turbine equipped with a brimmed-diffuser shroud. The simulation results showed that a

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Nomenclature

D:	impeller diameter, mm
f:	the exciting frequency of air flow, Hz
f_n:	the natural frequency of each order, Hz
f_p:	blade passing frequency, $f_p = nz/60$, Hz
H:	blade height, mm
M_f:	the margin of frequency, $M_f = \|f_n - f\|/f$
n:	rotational speed, r/min
n_s:	safety coefficient
p_{ps}:	static pressure on the pressure surface, Pa
p_{ss}:	static pressure on the suction surface, Pa
Δp:	total pressure rise, Pa
Δp_s:	the static pressure difference, $\Delta p_s = p_{ps} - p_{ss}$, Pa
P:	shaft power, kW
q_v:	volume flow rate, m^3/s
q_{vd}:	design volume flow rate, m^3/s
r:	local blade height, mm
r_h:	hub radius, mm
z:	blade number of the impeller
η:	efficiency, %
σ_s:	yield stress limit, MPa
$[\sigma]$:	allowable stress, MPa
τ:	tip clearance, mm

pair of vortices consisting of a blade tip vortex and a counter-rotating vortex can be found; the blade tip vortex is weakened by the counter-rotating vortex. Furthermore, the results showed good agreement with previous wind tunnel experiments. Gao et al. [5] investigated the effects of the tip clearance on three-dimensional viscous flow fields and the performance of a centrifugal compressor using numerical simulation; they examined four different tip clearance sizes under several operating conditions. Their simulation results showed that an optimum tip clearance size to obtain the least flow losses may exist that is not the zero tip clearance. Zhang et al. [6] performed the numerical simulation of a subsonic compressor rotor to distinctly clarify the effect of different tip clearance size on tip flow field. Their results indicated that the increment of tip clearance size has deleterious influence on rotor efficiency and total pressure rise in the whole operating range.

Many paths have been investigated to improve turbo-machinery performance. He et al. [7] explored the impact of the blade installation angle on the performance of a windward axial fan in an air-cooled power generation unit and presented a novel performance by altering the blade installation angle. Recent researches indicated that the geometry of the tip clearance has strong influence on the fan performance. Some significant advances on the tip clearance were developed in the field of an axial flow turbo-machinery, and positive progresses were exhibited. Gao et al. [8] suggested measures to enhance the aero-thermal performance of unshrouded turbines by restraining tip leakage and injection flows. Based on the flat tip, a cavity tip was proposed. Both the effects of the flat and cavity tips on tip leakage flow were investigated on aero-thermal performance of the turbine. Thompson et al. [9] experimentally examined the effect of stepped tip clearances on the performance of a transonic axial flow compressor rotor; their results showed that stepped tip clearances can improve the pressure ratio, efficiency, and flow range under most operating conditions. You et al. [10] analysed the changes in the flow field and pressure distribution of the tip clearance before and after end wall grooving. Saxena et al. [11] presented the effects of various tip sealing geometries on the tip leakage flow and associated heat transfer of a scaled-up HPT turbine blade. Ameri et al. [12] investigated the influence of cavity depth on the GE-E^3 first-stage turbine. Mischo et al. [13] proposed an improved design for the recessed blade tip of an axial turbine rotor blade, and their numerical results showed an increase in the total efficiency of 0.38%. Parkash et al. [14] modified the conventional grooved blade tip and realised a pressure side inclined shelf grooved blade increasing the turbine efficiency by 0.1%–0.2%. Nho et al. [15] verified the impacts of blade tips with a single-sided groove, double-sided groove, and filleting on the impeller performance. De Maesschalck et al. [16] developed an optimization strategy to produce a set of blade tip profiles with enhanced aero-thermal performance for a number of tip clearance flow conditions with numerical simulation. Their results present deeper insights into the physics of tip leakage flows of unshrouded rotors with arbitrary tip shapes, and provide necessary knowledge to guide the design and optimization strategy of a full blade tip surface in a real 3D turbine environment. Park et al. [17] measured the effects of the blade with a squealer rim on heat transfer coefficient and film-cooling effectiveness of a linear cascade gas turbine. Three different types of blade tip surfaces were equipped with a single row of film cooling holes along the camber line, near the pressure and suction-side rim. The results showed that high heat transfer rate and high film cooling effectiveness are observed with the squealer tip. Zhang et al. [18] proposed a new kind of RARS (radial annular rim seal) to minimize the leakage losses and fluid-induced force on the base of traditional turbine tip seals. Their results showed that the flow resistance increases, and the flow-induced force reduces greatly; the leakage flow rate of the RARS is approximately 0.03% lower than that of labyrinth seal. Mohamed and Shaaban [19] suggested optimised airfoil geometries to upgrade the aerodynamic efficiency of turbines by optimizing the blade pitch angle. Gao and Zheng [20] discussed the effects of different blade geometries on the leakage flow and aerodynamic performance of the GE-E^3 first-stage turbine. A blade tip groove decorated with transverse layout ribs can achieve the least amount of leakage flow rate and improve the turbine efficiency by 0.41%. Qi et al. [21] used the numerical simulation to optimize the tip clearance geometry of a turbine blade, and the turbine efficiency is increased by 0.395%. Zhang et al. [22] carried out the numerical investigation of small axial fans with tip flange, and analysed the effects of tip flange shape and number on the structure and characteristics of the blade tip vortex. The results showed that tip flange has effective influence on improving both aerodynamic and noise characteristics of the axial flow fan.

Progress has also been achieved in the research on blade tip winglets. Lee et al. [23] investigated the aerodynamic performance for a turbine cascade with a “pressure side winglet” and “leading edge and pressure side winglet” covering the tip clearance. These winglets are all found to reduce the mass-averaged aerodynamic losses in the tip clearance. Han et al. [24] numerically simulated the effect of suction side winglets with different lengths to examine the influence on the leakage flow in a compressor cascade. Their results showed that the intensity of the leakage vortices is significantly weakened when the winglet has the same length as the blade tip.

The effect of the tip clearance on the noise of an axial flow turbo-machinery also attracts the attention of many studies. Fukano et al. [25,26] investigated the effect of the tip clearance on the noise of axial flow fans and found that appropriately reducing the size of the tip clearance improves the fan performance and effectively reduce

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