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Computational investigations of water collection efficiency on blades in unsteady vortex flowfield of rotor

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ABSTRACT

To predict ice accretion on the helicopter rotor more accurately, a three-dimensional Eulerian method with a shadow zone dispersion model is developed for calculating the water collection efficiency on blades in the unsteady vortex flowfield of the rotor. Firstly, the unsteady vortex flowfield of the rotor is calculated using a CLORNS code. Secondly, considering the 3-D effect of the rotor deeply, the droplet flowfield on the same embedded grids is solved by the Eulerian method to overcome the defects of traditional 2-D calculation methods for predicting rotor icing. To increase the stability and efficiency of the Eulerian method, the shadow zone dispersion model is presented. Thirdly, the calculated results are respectively validated through the ice amount comparisons with experimental results of UH-1H rotor and SRB rotor. The simulated results show that the blade-tip vortex has a significant effect on the water collection efficiency and causes a drop in the water collection amount along the blade spanwise direction. Finally, the effects of the advance ratio and the forward tilting angle of the rotor shaft on the water collection efficiency are calculated and analyzed, and some new conclusions are obtained. In forward flight, the blade-tip vortex has a more obvious effect on the water collection efficiency in the advancing blade than that in the retreating blade, and this effect decreases with the increase of the advance ratio and the forward tilting angle.

1. Introduction

Ice accretion may occur on rotors during the flight when supercooled droplets within the cloud impinge on the surface of the blade. This phenomenon would be a serious threat to the flight safety of the helicopter [1]. Ice on rotors modifies the designed blade aerodynamic shape and degrades the aerodynamic performance of the rotor [2,3]. As a result, it is meaningful to simulate and analyze ice accretion on rotors. Since the recourse of ice accretion on the aircraft is the supercooled water droplet in the atmosphere [4], the calculation of the water collection efficiency is a key process for the rotor icing analysis.

There are two methods to calculate the water collection efficiency on the aircraft, Lagrangian method and Eulerian method. In the Lagrangian method, the water droplet is treated as the particle moving in the air flowfield [5]. In the Eulerian method, the droplet flowfield is solved like the continuous gas phase flows [6–8]. Generally, the Eulerian method is better suited for complex geometries, and the collection efficiency contours over the whole body can be obtained in one calculation [9]. In addition, the air flowfield of the rotor is characterized by unsteady 3-D flow phenomena [10,11], so it may be easier to obtain the 3-D droplet impingement property by using an Eulerian method [9,12].

At present, some simplified methods are mainly used to predict ice accretion on rotors, especially in the calculation of the water collection efficiency. Cao [13] used a simplified method in the investigation of the flight characteristics of the CH-47B tandem twin rotor helicopter in the icing condition. In his method, representative 2-D airfoil conditions for blade sections at radial and azimuthal locations are extracted, and the water collection efficiency and the ice amount on rotors are predicted. Narducci [14,15] developed a similar simulation method to obtain the ice amount for a helicopter rotor in hover and forward flight, and it is applied to some model rotors for validations. The water collection efficiency and ice amount on rotors can be conveniently achieved by using these simplified methods, but it may be difficult to obtain accurate ice shapes because of a lack of water collection efficiency with 3-D characteristics. Kinzel [12] developed a finite volume method to predict ice accretion on rotors, and the droplet trajectory is determined by using a 3-D Eulerian approach. However, the blade is not rotating in his calculation, and some characteristics of the droplet flowfield due to the rotor rotation may not be found.

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Nomenclature

$\vec{R}$	conservative variable	
$\vec{F}$	convective fluxes	
$\vec{F}_v$	viscous fluxes	
$\vec{R}$	source term	
m	mass in the mass balances	$\mathrm{kg\,s^{-1}}$
q	heat in the thermal balances	$\mathrm{W\,s^{-1}}$
ρ_d	apparent density of the water droplet	$\mathrm{kg\,m^{-3}}$
α	droplet volume fraction	
ρ_w	density of water	$\mathrm{kg\,m^{-3}}$
$\vec{q}_d$	absolute velocity of the water droplet	$\mathrm{m\,s^{-1}}$
$\vec{q}_a$	absolute velocity of the air flow	$\mathrm{m\,s^{-1}}$
$\vec{q}_\omega$	convective velocity	$\mathrm{m\,s^{-1}}$
u	velocity along the X axis	$\mathrm{m\,s^{-1}}$
v	velocity along the Y axis	$\mathrm{m\,s^{-1}}$
w	velocity along the Z axis	$\mathrm{m\,s^{-1}}$
d_d	diameter of the water droplet	m
μ_a	dynamic viscosity of the air	$\mathrm{N\,s\,m^{-2}}$
C_d	drag coefficient of the water droplet in air	

Re	Reynolds number
$\vec{n}$	normal vector of the wall unit
S	shadow zone variable
η	convergence factor in the shadow zone model
R	radius of the rotor

Subscripts

d	water droplet
a	air flow over the rotor
f	water film
imp	water impinged on the surface
out	water flowing out of the cell
in	water flowing into the cell from adjacent cells
so	water freezing on the surface
evp	water evaporated and sublimated in the cell
Ni	cells close to the current cell
P	current cell
cri	defined value of the shadow zone cell

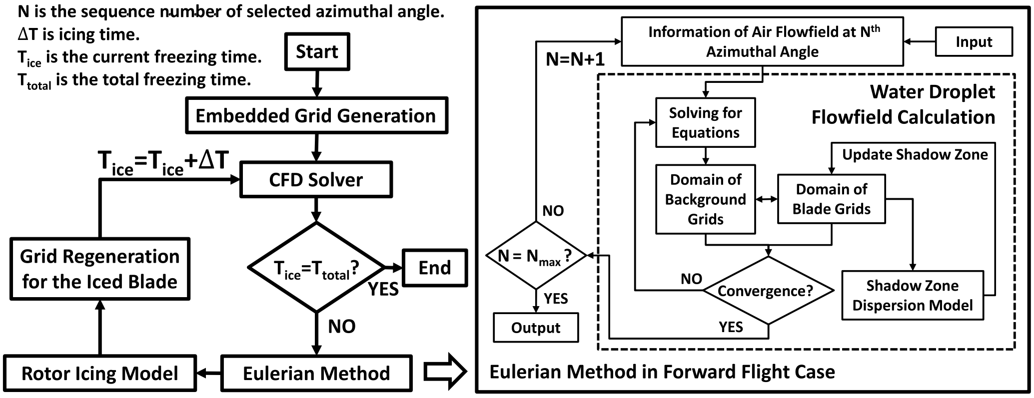

Fig. 1. Flowchart of the numerical method for ice accretion on the rotor.

Compared with the flowfield of fixed-wings, there are many differences in the unsteady vortex flowfield of rotors, such as the rotor wake, the rotor rotation and the blade-vortex interaction [16, 17]. Szilder [18] predicted the ice shape on the helicopter fuselage considering the rotor flow, and he found the alterations in the droplet trajectory due to the rotor wake. Son [19] predicted the ice shape on the helicopter fuselage considering rotor-wake effects, and the droplet collection amount and the total ice amount decrease if the rotor wake is considered. Additionally, the blade-tip vortex may also play an important role in the water collection efficiency and ice amount on rotors. Aliaga [20] developed a new code by coupling the two-phase flow with ice accretion on helicopters and focused on the impingement on the fuselage. In his work, there were some pockets of low apparent density in droplet flowfield of rotors. He thought these dry regions (low water content) is caused by the centrifugal effect of air vortex structures expelling drops from their core.

Based on the above, the objective of the present work is to develop a 3-D Eulerian method for calculating the water collection efficiency and ice accretion on rotors and to analyze the influence of the blade-tip vortex on the water droplet flowfield around rotor. The experimental data of the Helicopter Icing Flight Test (HIFT) program [21] and Spinning Rotor Blade (SRB) developed at Anti-icing Material International Laboratory [22] are used to validate the present numerical method. The influencing mechanism of the blade-tip vortex on the water collection efficiency in these flight conditions is analyzed. Considering the motion complexity of the rotor in forward flight, the effects of the advance ratio and the forward tilting angle of the rotor shaft on the water collection efficiency are analyzed.

2. Numerical methods

The calculation of the water collection efficiency is an important part of the numerical method for predicting ice accretion on rotors. As shown in Fig. 1, the numerical simulation method for ice accretion on rotors consists of several modules, mainly including: (1) CFD solver module for predicting the air flowfield, (2) Eulerian method for predicting the droplet flowfield, (3) 3-D icing model for simulating the ice accretion on rotors, and (4) Grid regeneration for the iced blade. In which, the calculation of the droplet flowfield is based on the converged air flowfield and the same moving-embedded grids system.

2.1. CFD solver and 3-D icing model

The Chinese Laboratory of Rotorcraft Navier–Stokes (CLORNS) code is employed to predict the complex unsteady rotor flowfield [23]. Fig. 2 shows the moving-embedded grid system around the rotor under hovering and forward flight conditions.

The governing equations in integral form for predicting the flowfield of the rotor are described as: