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New 3-D ice accretion method of hovering rotor including effects of centrifugal force

Zhao Guo-qing, Zhao Qi-jun *, Chen Xi

National Key Laboratory of Science and Technology on Rotorcraft Aeromechanics, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China

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ABSTRACT

A new numerical method for predicting 3-D ice accretion on a helicopter rotor in hover is proposed. The new method creatively takes the centrifugal force into account, and the prediction of ice accretion is fulfilled by loosely coupling the novel 3-D icing model with a CFD method. Considering the complexity of ice shapes on a rotor, orthogonally body-fitted grids around rotor blades are generated and modified by solving Poisson equations, and the CFD method for calculating the rotor flowfield in hover is developed by solving Reynolds-averaged Navier–Stokes (RANS) equations and employing the Spalart–Allmaras (S–A) turbulence model. Based upon an embedded grid system around the rotor, an Eulerian method is presented to obtain the water droplet impingement property, and the multistage Runge–Kutta scheme is adopted for temporal discretization. Subsequently, the new 3-D icing model which considers the effect of centrifugal forces is proposed in the freezing process. In this model, the shear stress, pressure gradient and the centrifugal force drive the water film to move on the blade surface. The ice accretion on a UH-1H helicopter rotor in hover is calculated to verify the accuracy of the new method, and the simulated ice shapes on the rotor blade (especially near the blade tip) correlate better with the experimental data than the numerical results of 2-D icing models. Finally, the influence of the centrifugal force in the icing process is analyzed, and numerical results indicate that the total ice amount would decrease when the centrifugal force is taken into account, which have better agreements with the experimental data.

1. Introduction

Helicopter rotor icing has been studied within the last 30 years. When ice forms on helicopter rotors, there is a large increase in required power and a large decrease of rotor lift [1,2]. Safety concerns regarding rotor icing and the time consuming, high cost of flight tests have created great interest in numerical simulation investigations [3–5].

In recent years, many of the computational methods currently available for ice accretion are mainly applied only to fixed-wing aircraft [6–9]; these include LEWICE [10,11], ONERA [12,13], FENSAP-ICE [14,15], etc. However, the numerical simulation for rotor icing is more difficult than for fixed-wing icing due to the variation of local blade velocities and ram temperature along radial locations of the blade. Nischint [16] and Bain [17] developed numerical methods for ice accretion on helicopter rotors in forward flight. In their investigations, ice accretion calculations on rotors were conducted by dividing the blade into 2-D sections, and a 2-D icing model was used to simulate the ice shape with LEWICE. Helicopter rotors operate in strong non-linear flowfields containing 3-D flow features, unsteady flow and centrifugal forces which are unique for rotors. Compared to fixed-wing aircraft, the radial variation of ram temperature, velocity and pressure on the rotor blades are much larger, so the radial interaction effects on ice accretion should not be ignored. Since it is difficult to solve these problems using 2-D ice accretion analysis, more suitable 3-D ice accretion simulation methods are proposed in this paper.

The centrifugal force from the rotation of the blade influences the ice growth on the blade. In addition, ice shedding occurs when the aerodynamic and centrifugal forces exceed the structural adhesion forces, and this phenomenon is predicted by Bain [18]. Additionally, at moderate temperature, there is a thin film of water flowing over the iced surface which is also affected by the centrifugal force. Therefore, these influences of centrifugal force to the simulation of ice accretion on rotors should be taken into account.

Another challenge of ice accretion on rotors is to obtain accurate droplet impingement. The flowfield is characterized by unsteady phenomena, and local blade velocities are different due to rotor rotation, so it is difficult to get the 3-D droplet impingement property by using a Lagrangian approach. Cao [19] investigated the trim and flight characteristics of the CH-47B tandem

* Corresponding author. Tel.: +86 025 84893753.
E-mail address: zhaoqijun@nuaa.edu.cn (Q.-J. Zhao).

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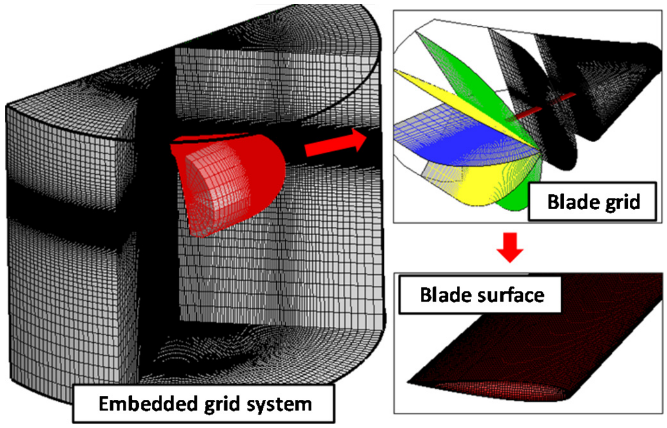

Fig. 1. Embedded grid system around the rotor in hover.

twin rotor helicopter under an icing condition. Narducci [20] developed an analysis method to evaluate the ice accumulation for a helicopter flying through an icing cloud. In their methods, they extracted representative 2-D airfoil conditions for blade sections at radial and azimuthal locations, and predicted collection efficiency and ice buildup on the rotor accounting for the diverse operating environments. However, though ice accretion on rotors could be conveniently achieved by using these simplified methods, it is difficult to obtain accurate collection efficiency with 3-D characteristics. Habashi [21] developed a particular methodology to simulate icing on a jet engine and the 3-D location of the impingement zones was obtained by using an Eulerian approach which accounted for the effects of centrifugal and Coriolis forces. Compared with the traditional Lagrangian approach, the Eulerian approach is more suitable to obtain the 3-D droplet impingement property on the rotor blade.

The objective of the present work is to develop a novel 3-D ice accretion model for efficiently and accurately simulating the ice accretion on rotors in hover. The ice is accreted using a loose coupling between the 3-D flowfield solver and the 3-D icing model for rotors. To obtain the droplet impingement property, a 3-D Eulerian approach, which is more suitable for rotors, is proposed. The influence of the centrifugal force is considered in the 3-D icing model, and the effects of spanwise flow are takes into full consideration. The Helicopter Icing Flight Test (HIFT) program [22] is used to validate the present analytical method. Then, particular attention is paid to the influence of the centrifugal force on the ice accretion on rotors compared with the conventional 2-D simplified method. Additionally, the effects of centrifugal force on ice accretion at different temperatures are also analyzed, and some conclusions are obtained.

2. Numerical methods

2.1. Grid generation and CFD solver

Grids around rotor blades are generated by interpolating and folding airfoil section grids constructed by solving Poisson equations. Structured Cartesian grids are used as the background grid system. Fig. 1 shows the embedded grid system of a rotor in hovering flight and the generation procedure of the grid around a blade.

The CFD methods [23] based on the Reynolds-averaged Navier–Stokes equations are employed, and the governing equations in integral form for predicting the flowfield of the rotor in hover are described as

$$\frac{\partial}{\partial t}\iiint\limits_{\Omega}\vec{W}\,d\Omega+\iint\limits_{\partial\Omega}(\vec{F}_c-\vec{F}_v)\bullet\vec{n}ds=\iiint\limits_{\Omega}\vec{R}\,d\Omega \tag{1}$$

where, $\vec{W}$ are conservative variables, $\vec{F}_c$ are convective fluxes, $\vec{F}_v$ are viscous fluxes, and $\vec{R}$ are the source terms introduced by the Coriolis forces. As an improvement of the CFD method of Ref. [23], the implicit LU-SGS scheme is employed in the temporal discretization, and the S–A one equation turbulence model is adopted to calculate turbulence.

2.2. Droplet flowfield solver

There are two primary approaches (Lagrangian and Eulerian [24]) for the prediction of droplet impingement. The Lagrangian approach, developed for fixed-wing aircraft, is suitable for steady fluids. With the Eulerian approach, the mass and momentum conservation of droplets can be simultaneously computed together with the solution of RANS flowfield equations. Considering the general situation that the flowfield of the helicopter rotor is characterized by unsteady phenomena, and the blade is in relative motion, the Eulerian method is more suitable for the simulation of ice accretion on rotors in forward flight. In order to propose a uniform ice accretion method for forward flight and hover, the Eulerian method is used in this paper.

With the Eulerian method, the droplets distributed in the flowfield can be regarded as a kind of pseudo fluid that penetrates the ‘real’ fluid. According to assumptions mentioned in [25], the governing equations for droplets can be simplified and the energy equation needs not to be solved.

The continuity and momentum equations for droplets in 3-D applications on rotors can be simplified as:

$$\frac{\partial}{\partial t}\iiint\limits_{\Omega}\vec{W}_d d\Omega+\iint\limits_{S}\vec{F}_d\cdot\vec{n}ds=\iiint\limits_{\Omega}\vec{R}+\vec{R}_d d\Omega \tag{2}$$

where

$$\vec{W}_d=\begin{Bmatrix}\rho_d\alpha\\ \rho_d\alpha u_d\\ \rho_d\alpha v_d\\ \rho_d\alpha w_d\end{Bmatrix},\qquad \vec{F}_d=\begin{Bmatrix}\rho_d\alpha(\vec{q}_d-\vec{q}_\omega)\\ \rho_d\alpha u_d(\vec{q}_d-\vec{q}_\omega)\\ \rho_d\alpha v_d(\vec{q}_d-\vec{q}_\omega)\\ \rho_d\alpha w_d(\vec{q}_d-\vec{q}_\omega)\end{Bmatrix},$$
$$\vec{R}=\begin{bmatrix}0\\ -\rho_d\alpha w_d\omega\\ 0\\ \rho_d\alpha u_d\omega\end{bmatrix},\qquad \vec{R}_d=\begin{bmatrix}0\\ \rho_d\alpha\frac{C_d\,\mathrm{Re}}{24K}(u_a-u_d)\\ \rho_d\alpha\frac{C_d\,\mathrm{Re}}{24K}(v_a-v_d)+\rho_d\alpha g\\ \rho_d\alpha\frac{C_d\,\mathrm{Re}}{24K}(w_a-w_d)\end{bmatrix} \tag{3}$$

and α is the droplet volume fraction. The subscript d refers to water droplet and the subscript a refers to the flow over the rotor. $\vec{q}_d=(u_d,v_d,w_d)$ is the absolute velocity of the water droplet, $\vec{q}_a=(u_a,v_a,w_a)$ is the absolute velocity of air flow, and $\vec{q}_\omega$ is the convective velocity. Inertial number, K, is given as:

$$K=\frac{\rho_a d_d^2}{18\mu_a} \tag{4}$$

where, μ_a is the dynamic viscosity of the flow, d_d is the diameter of the water droplet which is assumed to be a spherical particle. The expression $C_d\,\mathrm{Re}$ is given by

$$C_d\,\mathrm{Re}=1+0.197\,\mathrm{Re}^{0.63}+0.00026\,\mathrm{Re}^{1.38} \tag{5}$$

The Reynolds number, Re, refers to the water droplet that travels over the blade in air flow with a relative velocity equal to $\vec{q}_a-\vec{q}_d$, which is shown as:

$$\mathrm{Re}=\frac{\rho_a\left|\vec{q}_a-\vec{q}_d\right|d_d}{\mu_a} \tag{6}$$