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Tandem Helicopter Trim and Flight Characteristics in the Icing Condition

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This paper describes an established flight dynamic model with two rotor-icing models that are capable of studying CH-47B tandem rotor helicopter trim and flight characteristics in a rime icing condition. First, considering the ice-shedding phenomenon and the local temperature variation on the rotor blade, an engineering rotor-icing model is developed based on the empirical two-dimensional airfoil icing tunnel data. Second, using the principle of computational fluid dynamics, a theoretical rotor-icing model is set up for comparison with the engineering rotor-icing model. As verification, the results of two rotor-icing models are shown to have acceptable agreement. Analysis was made on the effects of icing on trims, stability, and some flying qualities of tandem rotor helicopters in terms of forward velocity, icing time, atmospheric temperature, liquid water content, and median volumetric diameter. The degradation of flying qualities of tandem rotor helicopters in hovering due to icing is studied mainly with respect to the following aspects: attitude quickness, interaxis coupling, and vertical axis control power. Finally, conclusions of all the work are summarized at the end of this paper.

Nomenclature

$\dot{A}$	=	ice accretion rate
A_c	=	accumulation parameter
C'_D, C_D	=	drag coefficient of the iced/uniced rotor-blade airfoil
C'_H	=	iced rotor horizontal force coefficient
C''_H	=	rotor horizontal force coefficient not affected by icing
C'_L, C_L	=	lift coefficient of the iced/uniced rotor-blade airfoil
C_Q	=	uniced rotor torque coefficient
C'_Q	=	iced rotor torque coefficient
C''_Q	=	rotor torque coefficient not affected by icing
C'_T	=	iced rotor thrust coefficient
C''_T	=	rotor thrust coefficient not affected by icing
C'_Y	=	iced rotor side-force coefficient
C''_Y	=	rotor side-force coefficient not affected by icing
D	=	median volumetric diameter
E	=	collection efficiency
F_a	=	adhesion force between ice surface and blade surface
K_{L1}, K_L	=	empirical constants based on the rotor-blade airfoil icing data
K_0	=	modified inertia parameter
k	=	adhesion force coefficient
k_s	=	roughness height-to-chord ratio
L	=	liquid water content
M	=	Mach number of the blade airfoil in each calculating sector
$p_{pk}/\Delta\phi_{pk}$, $\Delta\phi_{min}$	=	indexes of roll attitude quickness
$q_{pk}/\Delta\theta_{pk}$, $\Delta\theta_{min}$	=	indexes of pitch attitude quickness
r, $\bar{r}$	=	local radial position along rotor-blade; nondimensional of r
r_b	=	boundary-layer recovery factor
$r_{pk}/\Delta\psi_{pk}$, $\Delta\psi_{min}$	=	indexes of yaw attitude quickness
S	=	contact area between ice surface and blade surface
T	=	period of oscillatory mode
T_C	=	local temperature on blade surface
T_S	=	atmospheric temperature
t	=	blade airfoil thickness
$\bar{t}$, c	=	blade airfoil thickness-to-chord ratio; airfoil chord
$\bar{u}_P$	=	relative wind velocity from upward flapping at blade section
$\bar{u}_T$	=	relative wind velocity from forward flight at blade section
$w_{1.5}$	=	index of vertical axis control power
$\dot{X}$	=	helicopter forward velocity
α	=	angle of attack of the blade airfoil in each calculating sector
β	=	rotor-blade flapping angle
γ	=	ratio of specific heats
ΔC_D	=	increment of rotor-blade airfoil drag coefficient due to icing
$\Delta C'_H$	=	increment of rotor horizontal force coefficient due to icing
ΔC_L	=	increment of rotor-blade airfoil lift coefficient due to icing
$\Delta C'_Q$	=	increment of rotor torque coefficient due to icing
$\Delta C'_T$	=	increment of rotor thrust coefficient due to icing
$\Delta C'_Y$	=	increment of rotor side-force coefficient due to icing
δ_B, δ_C, δ_S, δ_R	=	longitudinal, collective, lateral, and directional controls in the cockpit
ζ	=	damping ratio of oscillatory mode
θ	=	pitching attitude angle of helicopter fuselage
ρ_I	=	ice density
σ	=	rotor solidity
τ_s, τ, τ_c	=	icing time threshold for ice shedding; icing time; modified icing time
$[\tau/\tau_s]$	=	integer portion of τ/τ_s
ϕ	=	rolling attitude angle of helicopter fuselage
$\lvert\phi_\theta/\Delta\theta_{pk}\rvert$	=	index of roll due to pitch coupling
ψ	=	rotor-blade azimuth angle
Ω	=	rotor rotational speed
ω	=	frequency of oscillatory mode

I. Introduction

HELICOPTER rotor-icing problems have been studied over the last 30 years in order to explore the potentially hazardous

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effects of ice accretion on rotor blades and reduce the aviation accident rate caused by rotor icing. Initial research work was mainly concerned with the rotor-blade airfoil icing, having experience with experimental and theoretical studies on airplane and propeller system in the icing condition [1–4]. Korkan et al. [5–7], Flemming and Lednicer [8], and Flemming et al. [9] initially studied helicopter icing problems, but only rotor-blade aerodynamics characteristics and rotor torque in the icing condition were analyzed in their work, probably due to constraints of the technical level at that time. At present, a few papers have been found on the flight dynamic characteristics of helicopter in rotor-icing conditions. Recently, although helicopter icing problems were summarized in detail in [10], substantial effects of icing on helicopter dynamic characteristics had not been referred to yet.

Indeed, helicopter icing simulation methods can be mainly divided into physics experimental study, theoretical computational fluid dynamics (CFD) simulation, and empirical engineering methodology. Experimental studies on rotor icing, which can be divided into full-scale icing and model-scale icing, usually involve ice wind-tunnel tests and other man-made icing condition tests. The Canada National Research Council (NRC) icing tower, which is perhaps not used anymore, and the U.S. Army helicopter icing spray system are special facilities for helicopter icing research [11]. Since the icing test can obtain exact icing results, which might be used for further investigating the effects of ice accretion on aerodynamic and flight dynamic performance of helicopters [7], these facilities played an important role in the early research, although only two-dimensional (2-D) airfoil icing research was conducted. At present, the model-scale ice accretion tests are mainly conducted. In the past, many ice accretion tests were carried out, such as the model rotorcraft airfoil tests, the OH-58 tail rotor tests, the powered force model tests [9], and so on. Usually, in the tests of model-scale ice accretion, the model rotor was exposed to a range of icing conditions that included variations in atmospheric temperature, liquid water content, and median volumetric diameter. To determine the effects of these parameters on ice accretion, they were operated over ranges of advanced ratio, shaft angle, tip Mach number, and weight coefficient [9]. However, few detailed works on the flight characteristics of full-scale helicopters in icing conditions were conducted due to the high cost, high risk, and long test period of icing test. So those experimental study methods might not be effective, economical, and practical for whole problems of helicopter rotor icing.

Theoretical studies on ice accretion, which might be a compensatory or substitutional method for the experimental study method, mainly involve the numerical simulation using CFD. Many typical tools have been developed successfully, such as LEWICE (developed by NASA Lewis Research Center) [12], ONERA 2-D/three-dimensional (3-D) (developed by ONERA in French) [13], IMPIN3D (developed by Italy) [14], the second-generation 3-D icing simulation system FENSAP-ICE (developed by Numerical Technologies International) [15], etc. Nevertheless, because of the variant airflow speeds and the variant angles of attack on arbitrary radial and azimuthal locations due to rotor rotation, the numerical simulation for rotor icing using a CFD technique is more sophisticated than for wing icing of the airplane, although it can reveal the mechanism of the rotor icing theoretically. Furthermore, study on flight characteristics in icing conditions might be another difficult and fussy work, similarly due to the sophistication of simulation for rotor icing using a CFD technique.

The empirical engineering method, a practical methodology based on the existent 2-D airfoil icing wind-tunnel data, can obtain the good qualitative results to some extent for engineering application, and it can also avoid the sophistication of the CFD numerical simulation for rotor icing. In this engineering method, the empirical 2-D airfoil icing model and the correlative theories of helicopter flight dynamics and aerodynamics are combined together to establish a rotor-icing model and to further investigate the performance degradation of the helicopter rotor. By combining with the whole helicopter dynamic model, the trim and flight characteristics (the flying qualities can be referred) in the icing condition can also be investigated.

The paper is organized as follows. First, two rotor-icing models (engineering and theoretical models) are proposed. Following this, a tandem rotor helicopter dynamic model in the icing condition is established by combining with the momentum model [16]. Verification of the dynamic model due to icing is accomplished by comparing the trim data calculated by using the two iced helicopter dynamic models based on engineering and theoretical rotor-icing models. In addition, the trim characteristic analysis in uniced/iced conditions is conducted. Second, the stability features of the tandem rotor helicopter in terms of forward velocity, icing time, atmospheric temperature, liquid water content, and median volumetric diameter in the icing condition are calculated and analyzed in detail. To further study the degradation of flying qualities of tandem rotor helicopters due to icing, some assessing indexes according to the requirements of ADS-33E-PRF [17], such as attitude quickness, interaxis coupling, and vertical axis control power, are investigated. Finally, a summary and conclusions are presented at the end of this paper.

II. Rotor-Icing Models

Using the averaging methodology described by Korkan et al. [5], the rotor disk can be divided into $n \times m$ calculating sectors, with n stations along the blade-spanwise direction for each of the m azimuthal sectors. After analyzing the rotor-blade airfoil ice accretion in each calculating sector and synthesizing all of the sectors, the rotor-icing model can be established.

A. Engineering Rotor-Icing Model

The engineering rotor-icing model is mainly based on the high-speed icing tunnel data from the NRC in 1982 [8]. The iced lift/drag coefficient of the rotor-blade airfoil can be written as

$$C_L' = (1 + \Delta C_L/C_L)C_L \tag{1}$$

$$C_D' = (1 + \Delta C_D/C_D)C_D \tag{2}$$

where the empirical correlation of Flemming and Lednicer [18] is used:

$$\Delta C_L = -0.01335 K_0 \bar{t}[\alpha + 2 + K_{L1} 0.00555(\alpha - 6)^2] K_L \times 0.1524(L\tau_c/c) \tag{3}$$

$$\Delta C_D = [0.158 \ln(k_s) + 175 A_c E + 1.7]\left(\frac{\alpha + 6}{10}\right) C_D \tag{4}$$

To improve the calculating accuracy, the present work in this section involves considering both the ice-shedding phenomenon and the local temperature variation on the rotor blade.

First, the ice-shedding phenomenon is considered. Portions of the ice accreted on the rotor-blade surface will be lost due to self shedding if the local centrifugal force generated by the rotating rotor exceeds the adhesion force between the ice surface and the blade surface. This means that ice shedding occurs at high-speed forward flight, and the mass of lost ice due to shedding can be equal to the mass of ice accreted on the blade surface during the time of τ_s.

As indicated in the experiment referred to in [19], the adhesion force between the ice surface and the blade surface can be expressed as

$$F_a = k T_C S \tag{5}$$

Table 1 Rotor-icing conditions

Parameter	Value
T_S, °C	−26.0
L, g/m^3	1.0
D, μm	20.0
τ, s	180.0

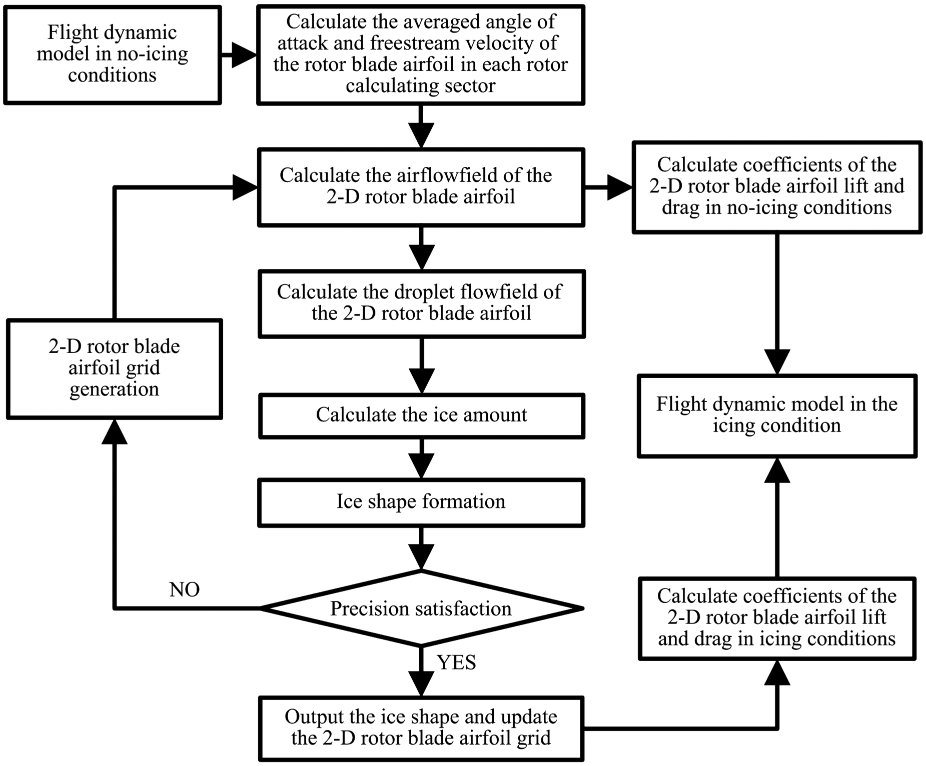


Fig. 1 Numerical simulation of helicopter rotor icing.

Introducing the definition of the ice accretion rate $\dot{A}$ [8], τ_s can be deduced as

$$\tau_s = \frac{kT_C t}{\rho_I \dot{A} \Omega^2 r} \tag{6}$$

The condition of ice shedding on the blade surface is

$$\tau/\tau_s \geq 1 \tag{7}$$

Modifying the icing time of τ,

$$\tau_c = \tau - \tau_s[\tau/\tau_s] \tag{8}$$

Then, τ_c is the modified icing time where the ice shedding is considered. Calculated results indicate that portions of ice shedding begin to occur on the rotor-blade tip at the azimuth angle of 90° for the CH-47B tandem rotor helicopter at a forward velocity of $\dot{X} = 100$ kt in the rime icing conditions of Table 1.

Then, the local temperature variation on the rotor blade is involved. The icing tunnel test [18] indicates that the local temperature on the blade surface is a function of atmospheric temperature, angle of attack, and local Mach number:

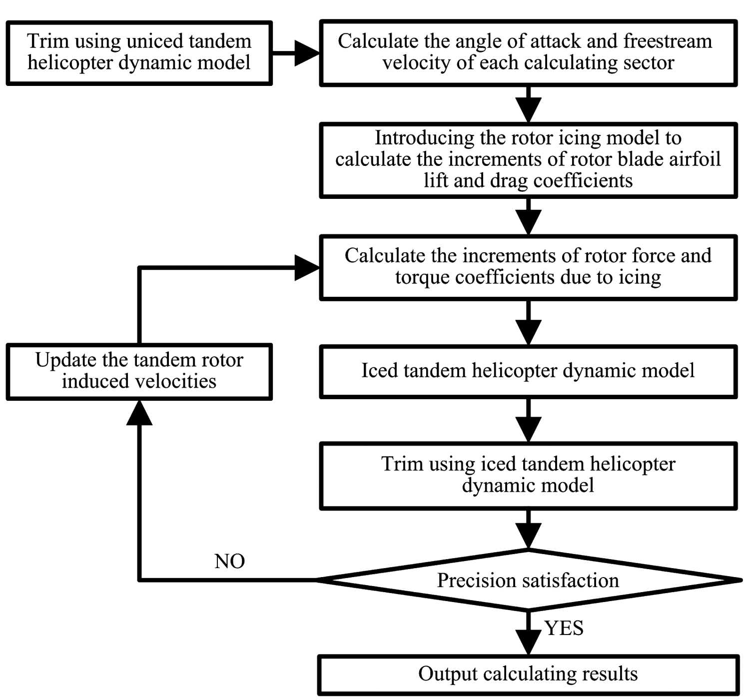


Fig. 2 Flowchart of trimming in icing conditions.

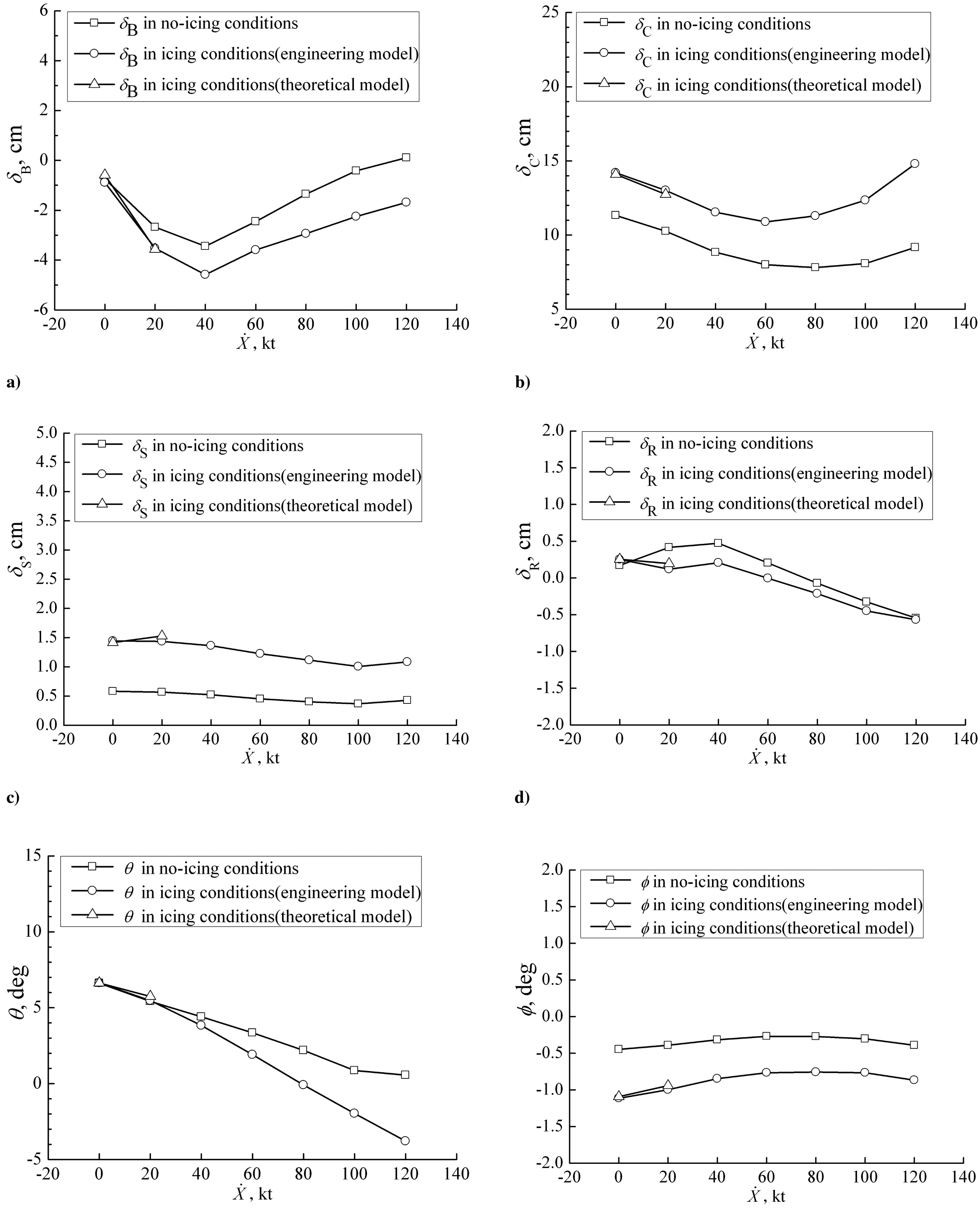


Fig. 3 Trim data of a) longitudinal control stick, b) collective control stick, c) lateral control stick, d) directional control stick, e) pitching attitude angle, and f) rolling attitude angle.

$$T_C = (T_S + 273.15)\left(1 + r_b \frac{\gamma - 1}{2} M^2\right) + 0.33(\alpha - 6) - 273.15 \tag{9}$$

When $T_C < 0°\mathrm{C}$, ice accretion occurs on the rotor blade, and it can be computed by introducing the high-speed icing tunnel data. Nevertheless, when $T_C \geq 0°\mathrm{C}$, icing will not occur. Calculated results also indicate that icing does not occur on the rotor-blade tip at the azimuth angle of 90° for the CH-47B helicopter at a forward velocity of $\dot{X} = 120$ kt in the rime icing conditions of Table 1.

B. Theoretical Rotor-Icing Model

To compare with this engineering rotor-icing methodology, a theoretical rotor-icing model is established. Introducing the numerical simulation method for 2-D airfoil ice accretion based on the principle of CFD [20–23], the theoretical rotor-icing model can be set up. Details about the numerical simulation method for 2-D airfoil ice accretion can be referred to in [22,23], in which the corresponding validation of airfoil lift/drag coefficient and the airfoil ice shape due to icing can be found, respectively. In this section, the theoretical rotor-icing model based on this numerical simulation method is depicted.

When calculating the averaged angle of attack and the freestream velocity of the 2-D rotor-blade airfoil in each calculating sector, based on the tandem rotor helicopter flight dynamic model in no-icing conditions, the airflowfield and droplet flowfield of the 2-D rotor-blade airfoil can be solved. The uniced 2-D airfoil lift/drag coefficient can be computed first, and the collection efficiency can be obtained through solving the droplet governing equations. The ice amount can be determined through the mass balance and energy balance. The process of ice accretion is simulated with the assumption that ice accumulates layer by layer, and the ice shape is predicted with the assumption that ice grows in the direction normal to the airfoil surface. Then, the increments of the iced rotor-blade airfoil lift/drag coefficient can be computed by solving the airflowfield of the iced 2-D rotor-blade airfoil. At last, combining with the uniced flight dynamic model, the tandem helicopter flight dynamics in icing conditions can be further studied. Figure 1 shows the numerical procedure of the tandem helicopter rotor icing. At present, due to not considering ice-shedding phenomenon, this theoretical model can only calculate the rotor-icing problems within the low-speed range of helicopter forward flight.

III. Flight Dynamic Model in Icing Conditions

As described in the icing tunnel test in [9], the main rotor lift during the icing encounter was controlled in two modes: the constant collective mode and the constant lift mode. Since rotor-icing changes the increments of the blade airfoil lift/drag coefficient, the rotor thrust and torque varies, and the collective control stick would also be changed so as to trim the helicopter in real flight conditions; two control modes are perfect and feasible in the icing tunnel test, undoubtedly, but they might not be used in real helicopter flight conditions. The present work involves improving that shortcoming of the tunnel test in studying the dynamic characteristics in real flight conditions with the natural rime icing encounter by introducing the increments of rotor thrust, side force, horizontal force, and torque coefficients into the uniced helicopter dynamic model, which was mainly based on the helicopter blade-element theory [24]. Those increments of corresponding coefficients are

$$\Delta C'_T = \frac{\sigma}{4\pi}\int_0^{2\pi}\int_0^1 \bar{u}_T^2 \Delta C_L \,\mathrm{d}\bar{r}\,\mathrm{d}\psi \tag{10}$$

$$\Delta C'_Y = -\frac{\sigma}{4\pi}\int_0^{2\pi}\int_0^1 [(\bar{u}_T^2 \Delta C_D - \bar{u}_T\bar{u}_P\Delta C_L)\cos\psi - \bar{u}_T^2\Delta C_L \beta \sin\psi]\,\mathrm{d}\bar{r}\,\mathrm{d}\psi \tag{11}$$

$$\Delta C'_H = \frac{\sigma}{4\pi}\int_0^{2\pi}\int_0^1 [(\bar{u}_T^2 \Delta C_D - \bar{u}_T\bar{u}_P\Delta C_L)\sin\psi - \bar{u}_T^2\Delta C_L \beta \cos\psi]\,\mathrm{d}\bar{r}\,\mathrm{d}\psi \tag{12}$$

$$\Delta C'_Q = \frac{\sigma}{4\pi}\int_0^{2\pi}\int_0^1 (\bar{u}_T^2 \Delta C_D - \bar{u}_T\bar{u}_P\Delta C_L)\bar{r}\,\mathrm{d}\bar{r}\,\mathrm{d}\psi \tag{13}$$

Coefficients of rotor thrust, side force, horizontal force, and torque due to icing can be further deduced as

$$\begin{cases} C'_T = C''_T + \Delta C'_T \\ C'_Y = C''_Y + \Delta C'_Y \\ C'_H = C''_H + \Delta C'_H \\ C'_Q = C''_Q + \Delta C'_Q \end{cases} \tag{14}$$

Using the momentum model described in [16] as an uniced tandem rotor helicopter flight dynamic model, the iced tandem rotor helicopter dynamic model can be established by combining with the rotor-icing model and Eq. (14). Figure 2 shows the flowchart of a tandem helicopter trimming in icing conditions.

IV. Trim Characteristics due to Icing

Using the established tandem rotor helicopter dynamic model in icing conditions based on the two rotor-icing models, a set of trim characteristics for air speeds between 0 and 120 kt in straight forward flight are generated for a CH-47B tandem rotor helicopter.

A. Trim Results and Discussion

The trim data in uniced/iced conditions are shown in Fig. 3. Rotor-icing conditions are described in Table 1. It can be found that the trim data calculated by using the iced tandem helicopter dynamic model based on both the engineering and the theoretical rotor-icing models are in good agreement with each other, which can be clearly seen in Fig. 3. It indicates that both rotor-icing models can be used for analyzing the helicopter flight dynamic characteristics due to icing. However, because of the long solution time and, especially, the huge

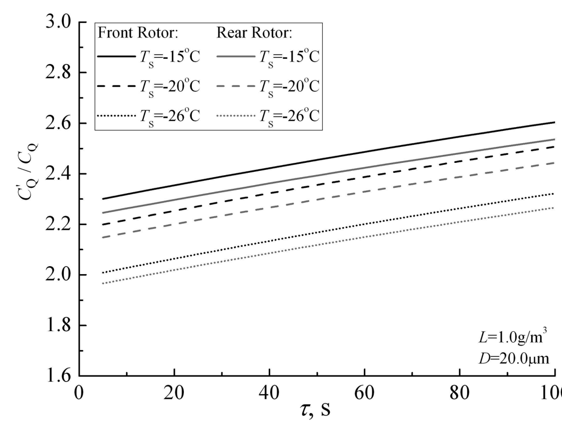


Fig. 4 Effects of icing on C'_Q/C_Q due to τ and T_S.

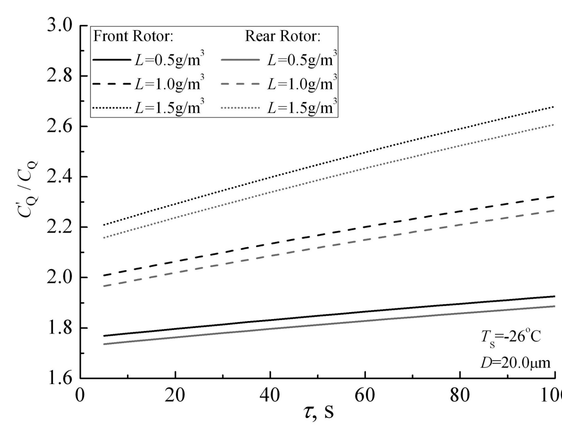


Fig. 5 Effects of icing on C'_Q/C_Q due to τ and L.

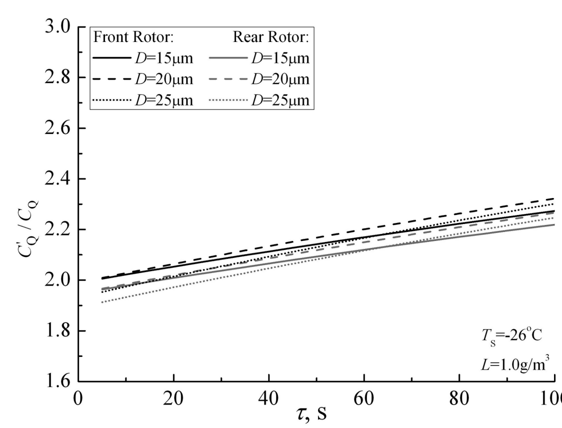


Fig. 6 Effects of icing on C'_Q/C_Q due to τ and D.

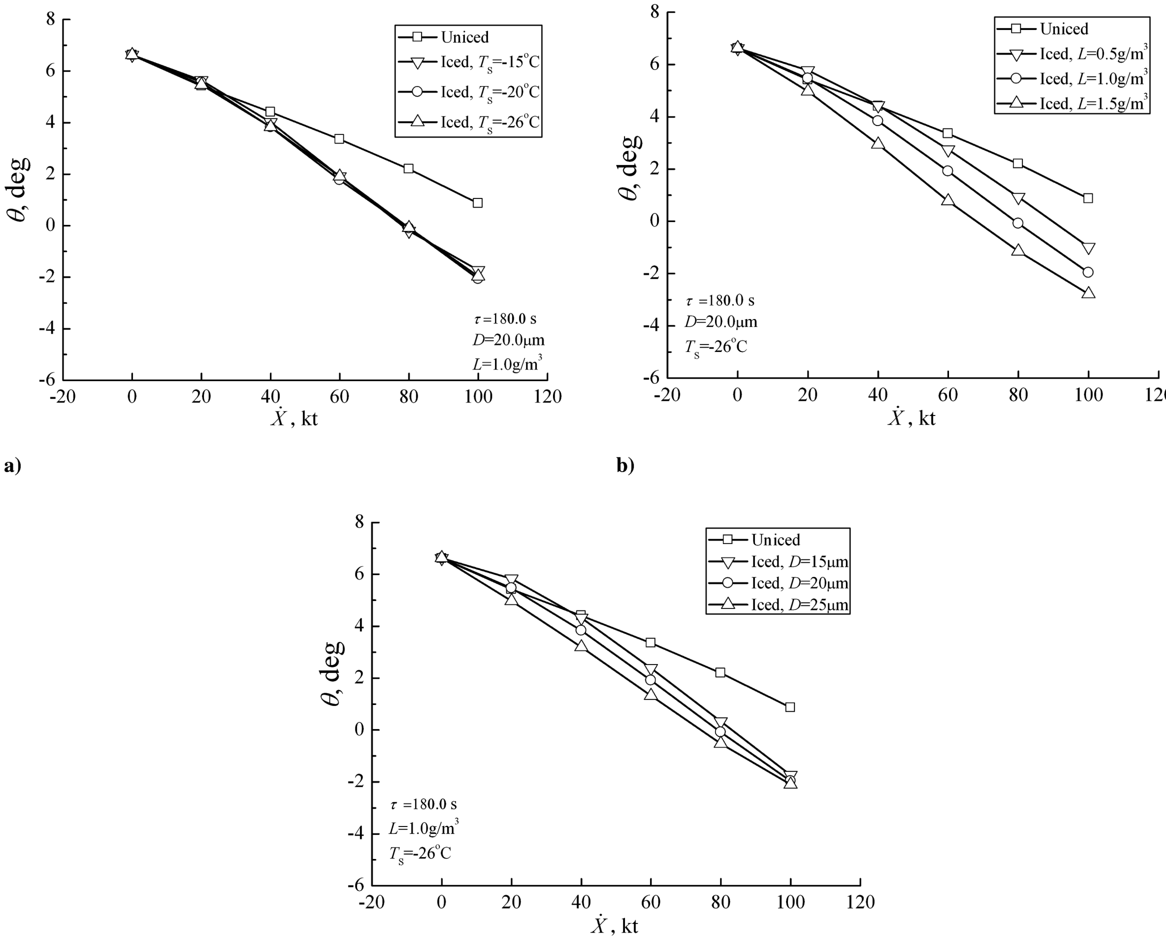


Fig. 7 Effects of icing on instability with speed due to a) T_S, b) L, and c) D.

repetitive manual work for the theoretical model during the numerical process of generating the rotor-blade airfoil grid, computing the airflowfield and the droplet flowfield of the 2-D rotor-blade airfoil in each calculating sector, it may be hardly feasible to use in engineering applications.

Compared with the uniced circumstance, the increase of helicopter forward velocity makes the iced longitudinal and directional control displacements and the iced pitching and rolling attitude angles decrease, but it makes the iced lateral and collective control displacements increase. It is very evident that rotor icing has a more serious hazardous effect on the collective control stick (it makes the collective control range decrease about 4.0 cm) than the other control sticks, which can be seen clearly in Fig. 3. Since the collective control range of CH-47B is $0 \sim 23.16$ cm, it can be predicted that rotor icing finally makes the helicopter flight envelope shrink.

B. Effects of Icing on Rotor Torque

In this section, the effects of icing on the relative rotor torque coefficient (C'_Q/C_Q) of CH-47B at hover due to the variations of icing time, atmospheric temperature, liquid water content, and median volumetric diameter are studied, as shown in Figs. 4–6.

According to these figures, since the relative rotor torque coefficients of CH-47B at hover are approximately linear with the icing time [5,9], the validity and accuracy of this engineering rotor-icing model and the whole computational codes can be further approved. Besides, regarding the effects of icing on rotor torque, some indications can be described as follows.

The effects of icing on front rotor torque are more severe than those on rear rotor torque in the same icing conditions. As approved in the icing tunnel test in [8], the effects on the rotor torque due to icing have a declining trend with the decrease of atmospheric temperature, which can be seen clearly in Fig. 4. In Fig. 5, the effects of icing on

Table 2 Iced/uniced stability roots at hover

Stability roots	Uniced	Iced
Longitudinal	−1.0763	−1.0819
	−0.3055	−0.3040
	0.0967 ± 0.4650i	0.0980 ± 0.4720i
Lateral	−0.9806	−1.0646
	−0.0499	−0.1523
	0.1064 ± 0.5087i	0.1666 ± 0.5720i
	0.0	0.0

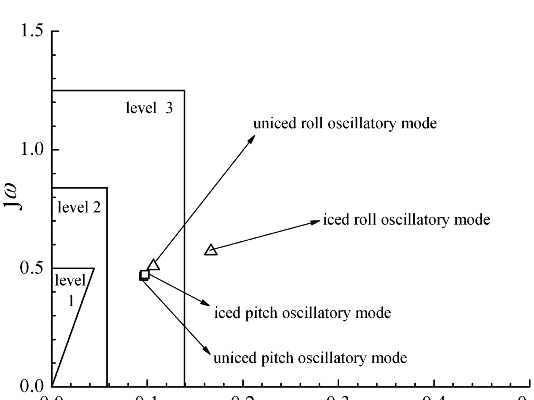


Fig. 8 Effects of icing on dynamic response in hovering.

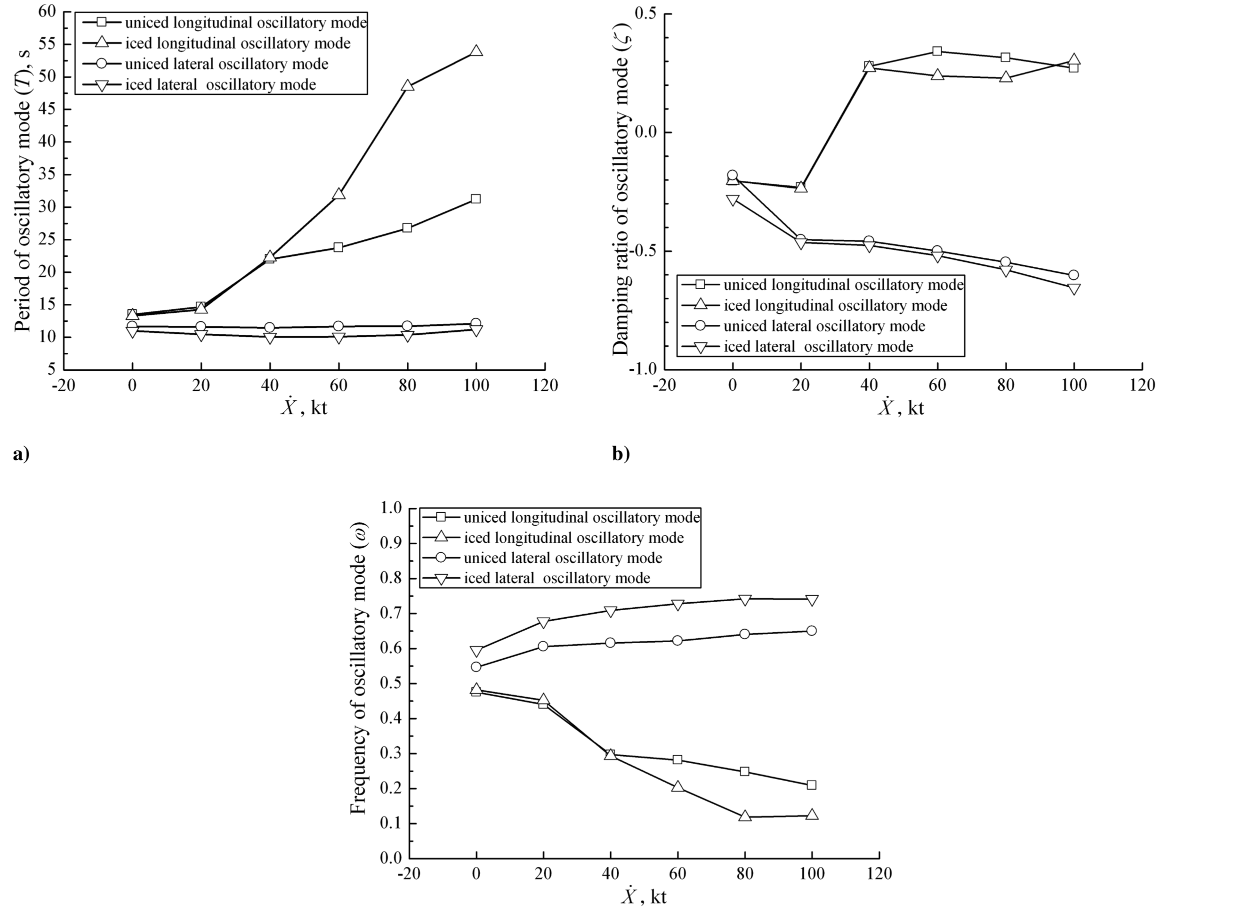


Fig. 9 Effects of icing on a) period of oscillatory mode, b) damping ratio of oscillatory mode, and c) frequency of oscillatory mode.

rotor torque due to liquid water content are also very severe, and once the icing time increases, it would be more severe. Compared with atmospheric temperature and liquid water content, the effects of icing on rotor torque due to the variation of median volumetric diameter become smaller, which can be clearly seen in Figs. 4–6.

V. Stability due to Icing

To further study the flight characteristics of a tandem rotor helicopter in the icing condition, investigation of stability due to icing was performed. The instability with the speed of a tandem helicopter due to ice and the effects of icing on dynamic response and stability roots were analyzed in detail.

A. Instability with Speed due to Icing

As shown in Fig. 3e, at the same flight conditions, the iced pitching attitude angle becomes smaller and smaller with the increase of the forward flight velocity, which means more instability with the speed of a tandem helicopter in icing conditions. The effects of icing on instability with speed due to atmospheric temperature, liquid water content, and median volumetric diameter were studied in detail, and they are shown in Fig. 7.

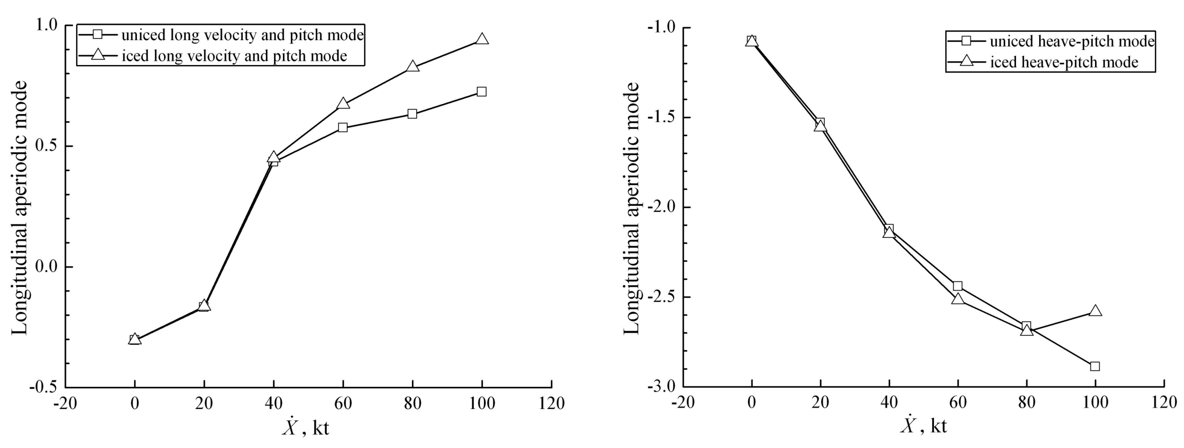


Fig. 10 Effects of icing on longitudinal aperiodic mode.

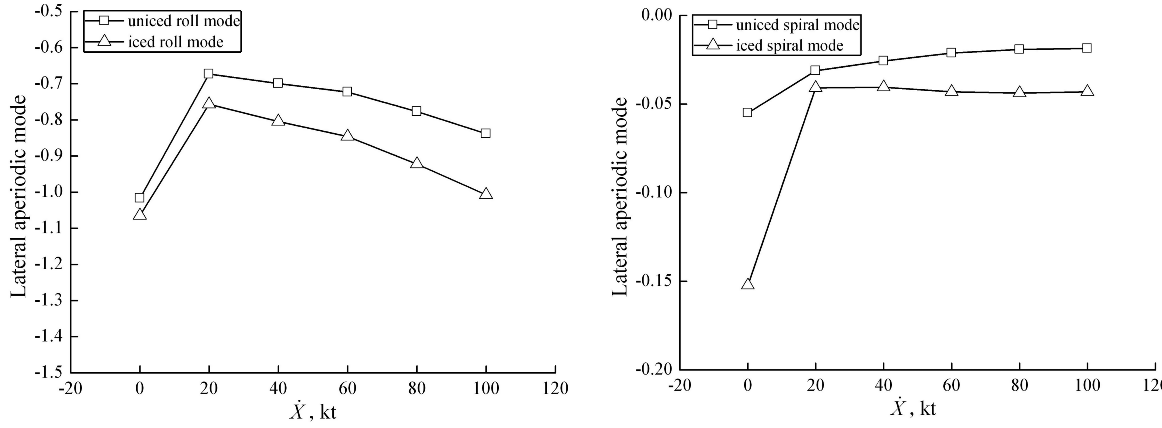


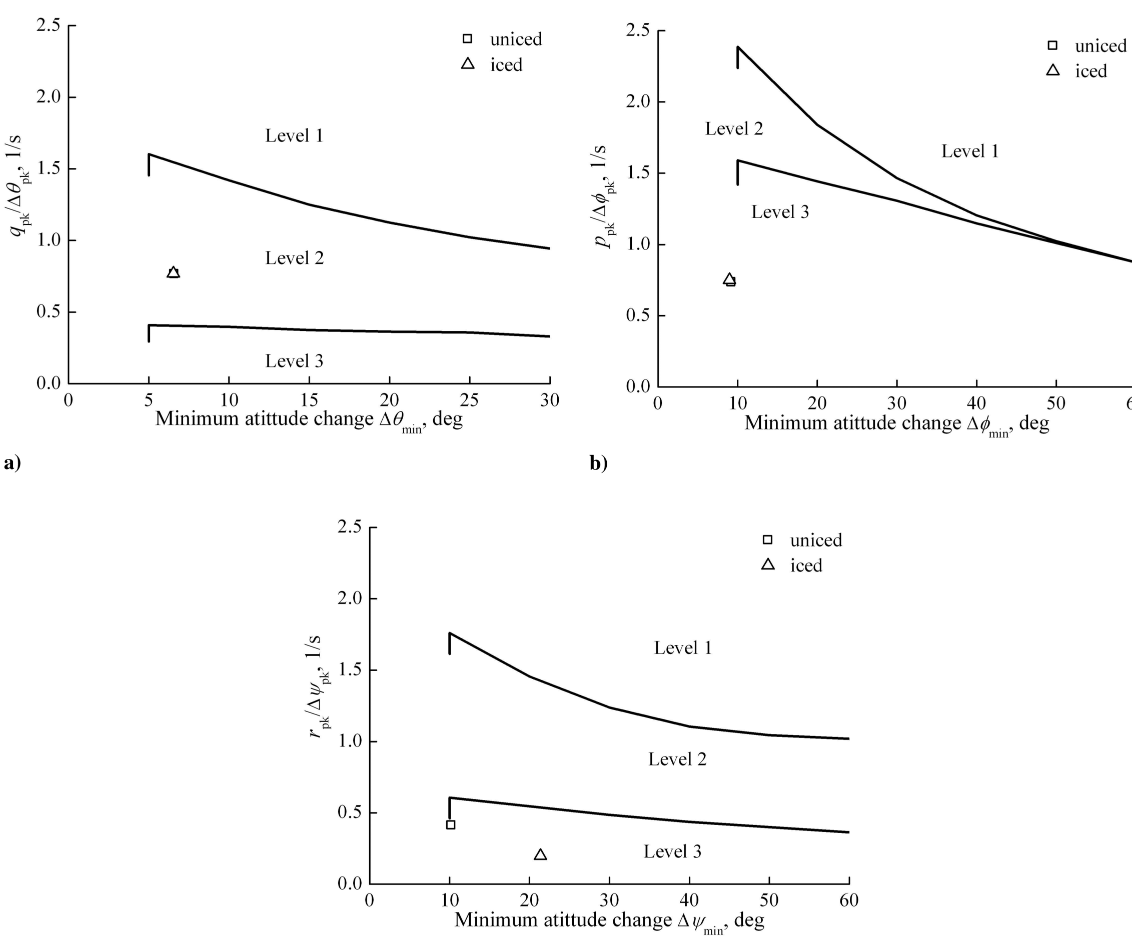
Fig. 11 Effects of icing on a) lateral roll mode and b) lateral spiral mode.

According to Fig. 7, the variation of liquid water content has the largest influential potential when compared with other icing condition parameters. The variation of atmospheric temperature has the least effect on the instability with speed. Besides, with the increase of liquid water content or median volumetric diameter, the instability with speed would become more and more hazardous.

B. Effects of Icing on Stability Roots

The stability roots of the CH-47B tandem rotor helicopter in icing conditions, described in Table 1, were calculated for comparison with the uniced condition. The calculated results in hover are shown in Table 2 based on the established uniced/iced tandem helicopter dynamic model combined with the rotor-icing model. Figure 8 gives the icing effects on the dynamic response at hover, according to the requirements of the visual flight rating referred to in MIL-F-83300 [25].

As shown in Table 2, the topology of tandem helicopter dynamic modes is not changed in the rotor-icing condition described in Table 1, except for some numerical deviation of characteristic roots. The iced pitch oscillatory mode changes little when compared with the uniced, which can be clearly seen in Fig. 8. Nevertheless, the iced roll oscillatory mode has a large change trend with the degradation to the edge of the visual flight rating of level 3. Therefore it can be concluded that the effects of icing on a roll channel are worse than on a pitch channel.



c)

Fig. 12 Effects of icing on a) pitch attitude quickness, b) roll attitude quickness, and c) yaw attitude quickness.

More detailed effects on dynamic modes for air speeds between 0 and 100 kt in straightforward flight for the CH-47B in the icing conditions of Table 1 are analyzed in Figs. 9–11. It can be obviously revealed as follows:

1) In Fig. 9, the period of the longitudinal mode in icing conditions changes little within the low-speed range of forward flight when compared with the uniced period. However, it has a large variation within the high-speed range of helicopter forward flight. Both the iced period and the damping ratio of the lateral oscillatory mode become a little smaller than the uniced, which means that the stability and the dynamic response of the lateral channel are worse than the uniced.

2) The aperiodic modes of tandem rotor helicopter can be divided into the heave–pitch mode, the long velocity and pitch mode, the roll mode, the spiral mode, and the neutral balanced mode [26]. As shown in Fig. 10, rotor icing has little effect on longitudinal aperiodic modes (i.e., heave–pitch mode and long velocity and pitch mode). The heave–pitch mode has a large change at the forward flight velocity of 100 kt, probably because the ice shedding occurred on the rotor-blade tip at the rotor-blade azimuth of 90°, which can be indicated in the calculated results and Fig. 10b.

3) In Fig. 11, rotor icing has little effect on lateral aperiodic modes (i.e., roll mode and spiral mode). In general, the iced lateral dynamic stability becomes bad when compared with the uniced lateral oscillatory mode because of the decreased period and damping ratio and the increased frequency of the lateral oscillatory mode in the range of the forward flight envelope due to icing.

VI. Degradation of Flying Qualities due to Icing

Because the new aeronautical design standard, performance specification, handling qualities requirements for military rotorcraft (ADS-33E-PRF) have more innovation in framework, content, and definition of parameters, etc., more and more research tasks of helicopter flying qualities can be performed and realized. In this section, the flying qualities of the CH-47B tandem rotor helicopter in hover due to icing are studied mainly with respect to three aspects: attitude quickness, interaxis coupling, and vertical axis control power. Effects on those indexes due to icing time, atmospheric temperature, liquid water content, and median volumetric diameter are analyzed in depth.

A. Effects of Icing on Attitude Quickness

Attitude quickness, which can be defined as the ratio of peak pitch (roll or yaw) attitude rate to change in pitch (roll or yaw) attitude angle, is used to display the time transient of the maneuver action and the validity of the maneuver response to control command. According to ADS-33E-PRF, at the same value of the minimum attitude change, the greater the ratio, the better the attitude quickness. In this section, icing effects on pitch (roll or yaw) attitude quickness for target acquisition and tracking were analyzed in detail, as shown in Fig. 12 (rotor-icing conditions are shown in Table 1).

In Fig. 12, icing has little effect on the pitch and roll channels, but it has large effects on the yaw channel. According to the requirements of attitude quickness for target acquisition and tracking in ADS-33E-PRF, the pitch channel is still in level 2 in the neighborhood of the uniced; however, the yaw channel is already in level 3, with some displacement of the uniced.

B. Effects of Icing on Interaxis Coupling

As depicted in the requirements of interaxis coupling in ADS-33E-PRF, control inputs to achieve a response in one axis shall not result in objectionable responses in one or more of the other axes. There are

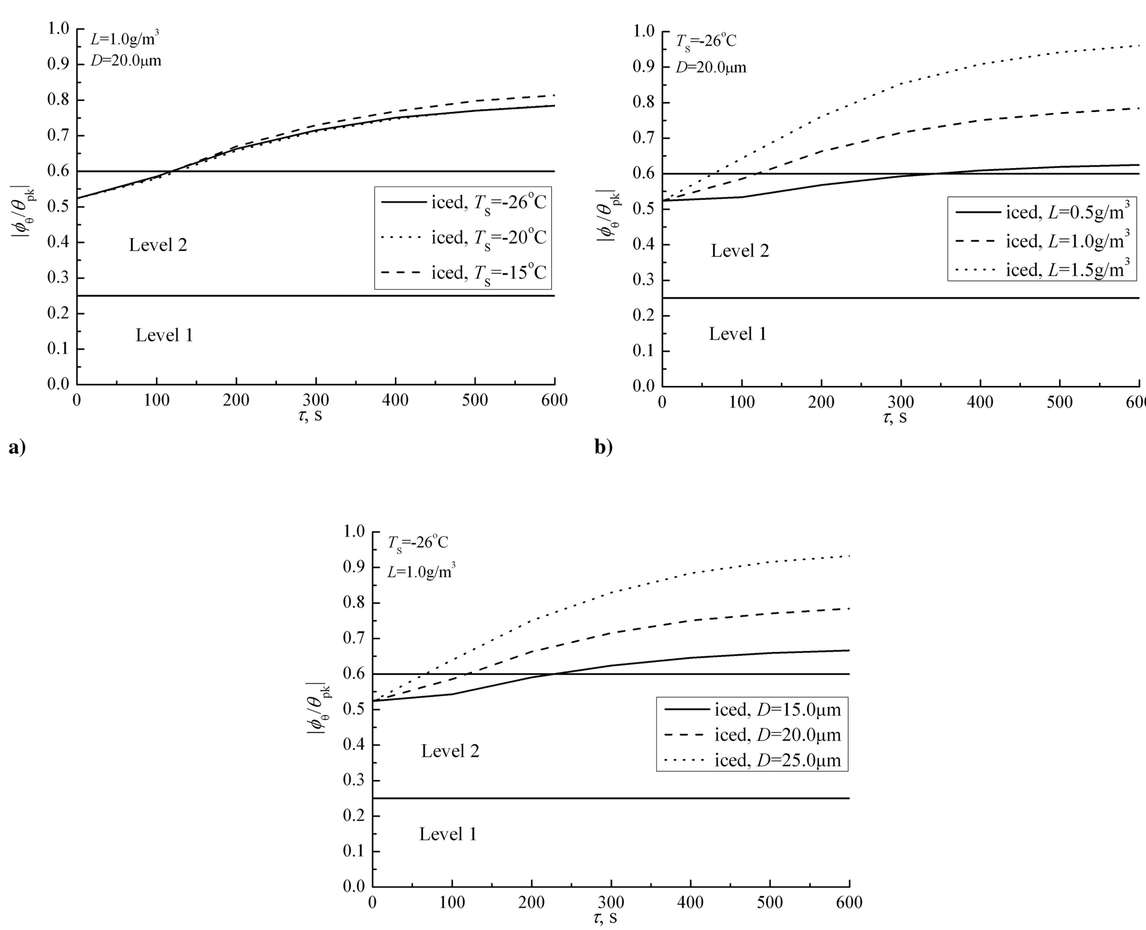


Fig. 13 Effects of icing on roll due to pitch coupling for aggressive agility due to a) T_S, b) L, and c) D.

three aspects for assessing the interaxis coupling: yaw due to collective for aggressive agility, pitch due to roll (and roll due to pitch) coupling for aggressive agility, and for target acquisition and tracking. In this section, the roll due to pitch coupling for aggressive agility is mainly studied in the rotor uniced/iced conditions, as shown in Fig. 13. The following can be concluded:

1) The change of atmospheric temperature has little effect on roll due to pitch coupling in the icing condition. In Fig. 13a, whatever the atmospheric temperature, the assessing level of roll due to pitch coupling would go out of level 2 only after about 2 min. of icing time.

2) The liquid water content has great effects on the interaxis coupling, which can be seen in Fig. 13b. The more the liquid water content increases, the earlier the assessing level of roll due to pitch coupling goes out of level 2.

3) As shown in Fig. 13c, the median volumetric diameter also has an objectionable effect on roll due to pitch coupling. The assessing level of which would go out of level 2, only needing about 1 min. of icing time, when $D = 25\ \mu$m. Furthermore, the more the median volumetric diameter increases, the earlier the assessing level goes out of level 2.

C. Effects of Icing on Vertical Axis Control Power

In ADS-33E-PRF, the vertical axis control power can be assessed by the vertical rate of 1.5 s after initiation of a rapid displacement of the collective control from trim.

In this section, a 1.0-cm-step collective control input is performed to predict the icing effects on the vertical axis control power. Calculation results are shown in Fig. 14. It can be concluded that the variation of liquid water content and median volumetric diameter have more boring effects on the vertical axis control power than the variation of atmospheric temperature. Furthermore, from Fig. 14b and 14c, it can also be concluded that the control power has a large decline after about 200 s in the icing condition of $L = 1.5\ \mathrm{g/m^3}$ or $D = 25\ \mu$m (the other icing condition parameters are referred to in those figures, respectively).

VII. Conclusions

An engineering rotor-icing model and a theoretical rotor-icing model were developed for predicting the effects of icing on helicopter dynamic characteristics. Validation of the rotor-icing models was conducted by comparison: partly with the experimental data in [9] and mainly with the trim characteristics using the two rotor-icing models for $\dot{X} = 0$ kt and $\dot{X} = 20$ kt, respectively. Detailed analysis of icing effects on trims, stability, and degradation of flying qualities of the CH-47B tandem helicopter were performed using the iced tandem helicopter dynamic model combined with the engineering rotor-icing model.

Based on the results presented in this paper, the conclusions are drawn as follows:

1) Both the engineering methodology and the theoretical CFD technique can be used to study the rotor-icing problems. Combined with the helicopter dynamic model, the effects of rotor icing on the trim and flight characteristics of a tandem rotor helicopter can be reasonably investigated. The calculated results indicate that ice shedding would occur on the rotor blade within the high-speed range of helicopter forward flight.

2) According to the results of the trim characteristics of a tandem rotor helicopter in the rotor-icing condition, some important indications can be summarized that rotor icing appears to have a more evident and serious hazardous effect on the collective control stick, which might make the helicopter flight envelope shrink because of the increase of the required rotor collective control and the torque due to icing, as analyzed in sec. IV.

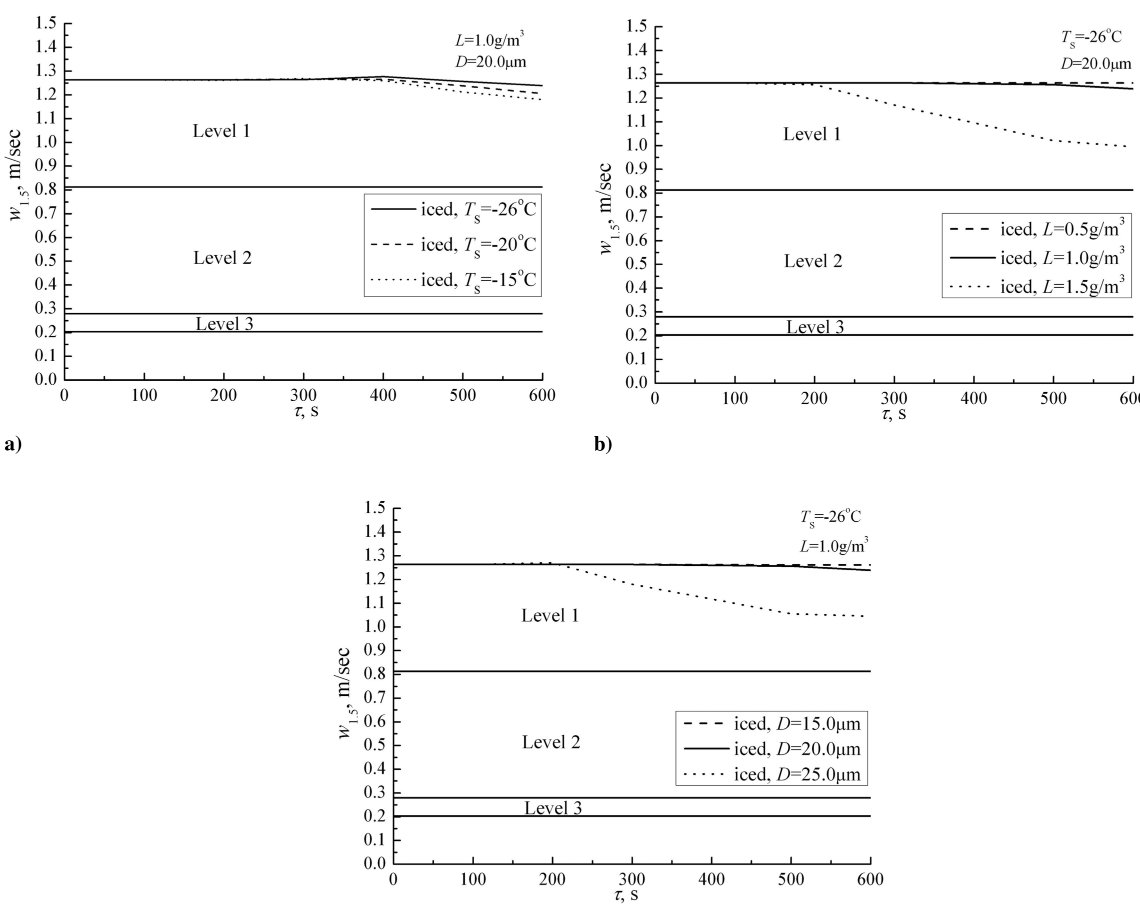


Fig. 14 Effects of icing on vertical axis control power due to a) T_S, (b) L, and (c) D.

3) Calculation results indicate that the severity of ice accretions on helicopter rotor blades is highly dependent on helicopter forward velocity, icing time, atmospheric temperature, liquid water content, and median volumetric diameter. Furthermore, atmospheric temperature has fewer effects than other factors once the rotor-blade icing occurs.

4) Rotor icing has more hazardous effects on the lateral oscillatory mode, as discussed in sec. V. Furthermore, rotor icing has little effect on attitude quickness, but it has worse effects on the interaxis coupling, according to the requirements of ADS-33E-PRF. Besides, the liquid water content and median volumetric diameter have large hazardous effects on vertical control power.

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