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Airflow hazard prediction for helicopter flight in icing condition

Yihua Cao[1], Guozhi Li[1] and J Sheridan[2]

Abstract

A methodology to predict the airflow hazard of helicopter flight in icing conditions is developed. By incorporating the existent ice accretion codes into an established basic helicopter flight dynamic model and considering airflow disturbance that mainly covers downdraft, head/tail wind, and left/right wind, the hazardous effects on trims, stability, and controllability of UH-60A single rotor helicopter in icing/ice-free conditions and within/without different types of wind field are investigated. The stability and controllability of helicopter that encounters airflow disturbance from wind velocity of 0 to 2.5–5.0 m/s for forward flight are examined. The indications of all the work are summarized at the end of this article. Furthermore, this method can be used to helicopter inflight safety prediction or airflow hazard avoidance analysis in icing conditions. It can also be laid as the foundation of the further research about the more complex airflow hazard prediction in icing conditions for helicopter flight safety.

Keywords

Helicopter, airflow hazard, rotor icing, trims, stability, controllability

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Introduction

For the inflight helicopter, flight disturbance in airflow field that covers downdraft, head/tail wind, left/right wind, and other airflow turbulence from an arbitrary direction may randomly exceed the helicopter performance capability, making flight safety degrade, and become more severe even in icing conditions. According to the American National Transportation Safety Board accident database, airflow-related factors and ice accretion were, respectively, implicated in nearly 10% of the over 21,000 aircraft accidents from 1989 to 1999,[1] and accounted for nearly 803 of civil aviation accidents from 1975 to 1988.[2,3] Even encounters with airflow hazards can be deadly to helicopters because they often have to operate in confined spaces and under operationally stressful conditions, such as emergency search and rescue, or lifesaving and other special operations. Furthermore, the unique ice accretion mainly affects rotor blade aerodynamic characteristics, degrades performance and flying qualities and can also pose a threat to flight safety.[4]

Ice accretion, which mainly affects rotor blade aerodynamic characteristics, degrades flight performance and flying qualities, and even threats helicopter flight safety, is a great hazardous factor. Since the past 30 years, some researchers, having experience with experimental and theoretical studies on airplane and propeller system in icing conditions, investigated the potentially hazardous effects of ice accretion on rotor blades. Korkan et al.[5] and Flemming and Lednicer[6] initially studied helicopter icing problems. Recently, Cao and other researchers[4,7–12] investigated the icing problems that both covers theoretical insight into the mechanism of ice accretion and performance degradation prediction of aerodynamic and flight dynamic characteristics due to ice accretion. Flemming and Luszcz[13] first integrated the rotor ice accretion into a flight simulator. Cao et al.[9,11] presented a detailed theoretical study on flight dynamic characteristics of single/tandem rotor helicopter in different icing conditions.

Airflow-related factors that can be attributed to a series of widely publicized commercial air transportation accidents and incidents close to accident have

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been investigated in the past 40 years.[14–16] Because airflow hazards are hard to detect simply due to the invisibility of air, disturbed airflow is undetectable by pilot unless the air happens to pick up dust, smoke or other aerosols that are visible to the human eyes. Thus, being unable to directly see a factor of potentially great importance to them, pilots can only learn to use their intuition to estimate airflow hazards on helicopter flight. Maybe this is just the main deadly factor that results in airflow-related accidents. Recently, based on the advanced sensor technique that may enable the delivery of airflow data to the helicopter cockpit, NASA Ames Research Center[17,18] began to investigate the airflow hazards on helicopter and developed a prototype flight-deck airflow hazard visualization system that was implemented on a high-fidelity rotorcraft flight dynamics simulator. However, this system may not cover the further detailed airflow hazard prediction of inflight helicopter performance, such as the detailed hazards on trims, stability, controllability, and so on. This study involves attempting to improve the universality of that developed system for studying the detailed theoretical airflow hazard prediction of inflight helicopter performance, by considering ice accretion at the same time.

This study combines a nonlinear helicopter dynamic model, a rotor icing model, and an airflow field model to develop a method to predict the effects of both airflow disturbance and ice accretion on the flight performance of a UH-60A single rotor helicopter. A basic nonlinear helicopter dynamic model is created at first. Considering the effects of a rotor icing encounter, the ice accretion hazards factor is incorporated in this basic helicopter trim model. Then, by continuing to incorporate an airflow field model into the helicopter trim model, the effects of different types of wind field (downdraft, head/tail wind, and left/right wind) on helicopter trims, stability, and controllability with/without icing conditions can be mainly further investigated. At the end of this article, a summary and conclusions are presented.

Methodology

Basic helicopter trim model

Using helicopter rotor vortex, element, and momentum theories[19] and introducing the methodology for establishing tandem rotor helicopter flight dynamic model,[20] a basic UH-60A single rotor helicopter flight dynamic model that involves no ice accretion and no airflow disturbance can be developed. In this model, the fuselage, horizontal tail plane, and vertical tail plane aerodynamic modeling are mainly based on the tunnel test data from NASA.[21] And the tail rotor aerodynamic modeling is based on the helicopter momentum theory.

In detail, using helicopter momentum theory to establish a uniform rotor-induced velocity distribution model, and combining with helicopter element theory to develop a rotor aerodynamic model, the initial trim calculation can be conducted. Then, incorporating the non-uniform rotor induced velocity distribution model using the helicopter vortex theory into the helicopter dynamic trim process, the final trim calculation can be accomplished.

Incorporation of ice accretion

Previous icing study works on helicopter[11] have mainly involved introducing the icing-related increments of rotor thrust, side force, horizontal force, torque coefficients, and icing-related increment changes in the coning of the rotor flapping and in the first-order longitudinal/lateral flapping coefficients into the uniced flight dynamic model. In this section, using the above basic helicopter trim model, the non-uniform distribution of the angle of attack and Mach number of the rotor disk, based on the helicopter vortex theory, can be calculated. Then introducing them into the existent rotor icing model[9,11] to compute the distribution of the increments of blade airfoil lift/drag coefficients due to icing, those corresponding increment of rotor force/torque coefficients due to icing can be integrated. Finally, the incorporation of ice accretion into the basic helicopter model can be realized.

Incorporation of airflow effects

Typical airflow disturbance discussed in this article mainly includes downdraft, head/tail wind, left/right wind upon the inflight helicopter. In this section, a far uniform airflow field model with airflow disturbance that covers the above five airflow washes is developed and then is incorporated into the helicopter trim model with ice accretion to study the effects of both airflow disturbance and ice accretion on helicopter flight dynamic characteristics.

According to this airflow field model, the wind velocity in the inertial frame ($\vec{V}_{\text{wind}}$) that can just easily describe the above five types of airflow disturbance can be written as

$$\vec{V}_{\text{wind}} = [u_{\text{wind}}, v_{\text{wind}}, w_{\text{wind}}]^{\mathrm{T}} \tag{1}$$

where, u_{wind}, v_{wind}, and w_{wind} are the velocities along with the x-, y-, and z-axes of the inertial frame, respectively.

Considering the effects of wind velocity in the inertial frame and actual flight velocity in the inertial frame ($\vec{V}_{\text{a}}$), simultaneously, resultant flight velocity in the wind frame ($\vec{V}$) is

$$\vec{V} = \vec{V}_{\text{a}} - \vec{V}_{\text{wind}} \tag{2}$$

Then the airflow-related factor can be incorporated into the helicopter trim model. By adopting linear perturbation theory,[22] stability and control derivatives with/without airflow disturbance field can be calculated to allow prediction of airflow hazards on helicopter dynamic characteristics. Figure 1 shows the flow chart describing the calculation of helicopter flight characteristics both considering ice accretion effects and wind field effects.

Results and analyses

Using the helicopter dynamic model described in preceding section, flight characteristics for a UH-60A single rotor helicopter are investigated for forward flight. Present works mainly focus on airflow hazardous effects on the flight characteristics in ice accretion environments encountered in five wind fields (namely downdraft, head/tail wind, and left/right wind), respectively. Icing conditions are selected as the IC② that can be referred in Cao et al.[11]

Airflow hazardous effects on trims

Figures 2 to 4 preliminarily confirm the uniced and iced trim characteristics with no wind environment observed in reference.[11] Present works focus on characteristics due to five wind fields with/without icing environments.

From Figure 2 detailed indications can be drawn as follows:

1. Compared with the longitudinal trim control position in no wind field, left and tail winds (or right and head winds) make the longitudinal control pull (or push) toward the more backward (or forward) position, which shorten the backward pulling (or forward pushing) control range. Downdraft makes the longitudinal control pull on the more backward position at low flight velocity and push on the more forward position at high flight velocity. Furthermore, the more hazardous effect on helicopter is that left wind (or head wind) even makes the backward pulling (or forward pushing) control range shorten more at low (or high) flight velocity with icing encounter. It suggests pilots backward pull longitudinal stick more slowly and gently when encountering left wind at low flight velocity, and forward push the stick more slowly and gently when encountering head wind at high flight velocity, even in icing conditions.

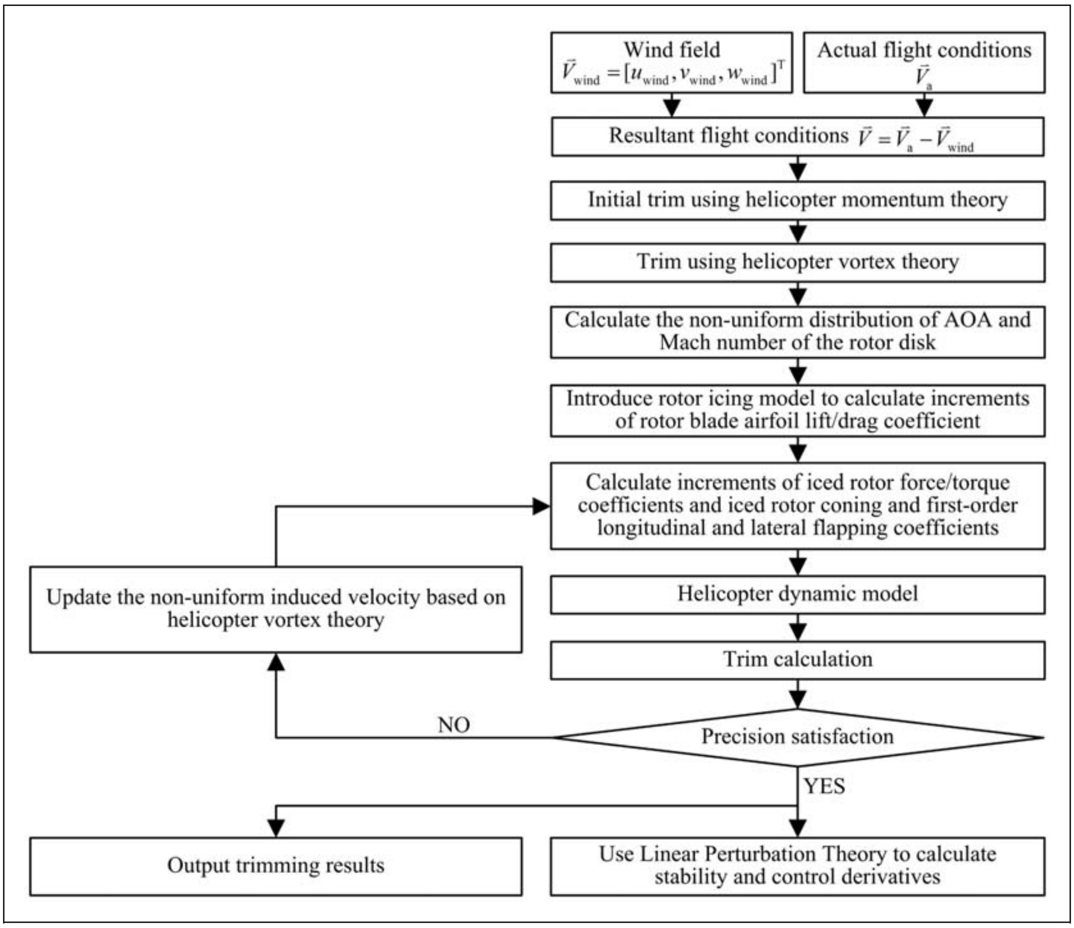

Figure 1. Helicopter flight characteristics calculation.

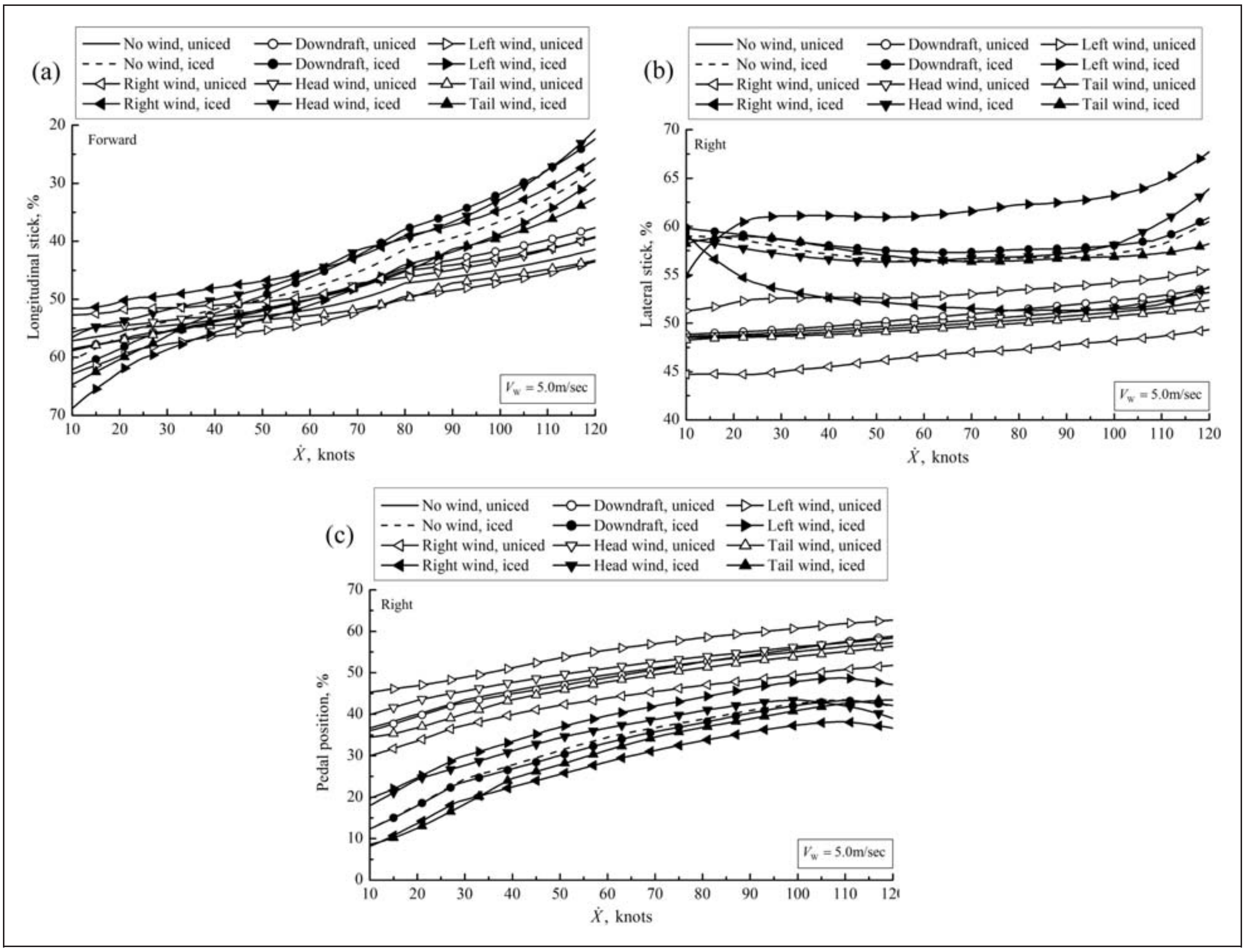

Figure 2. Trim curve of control.

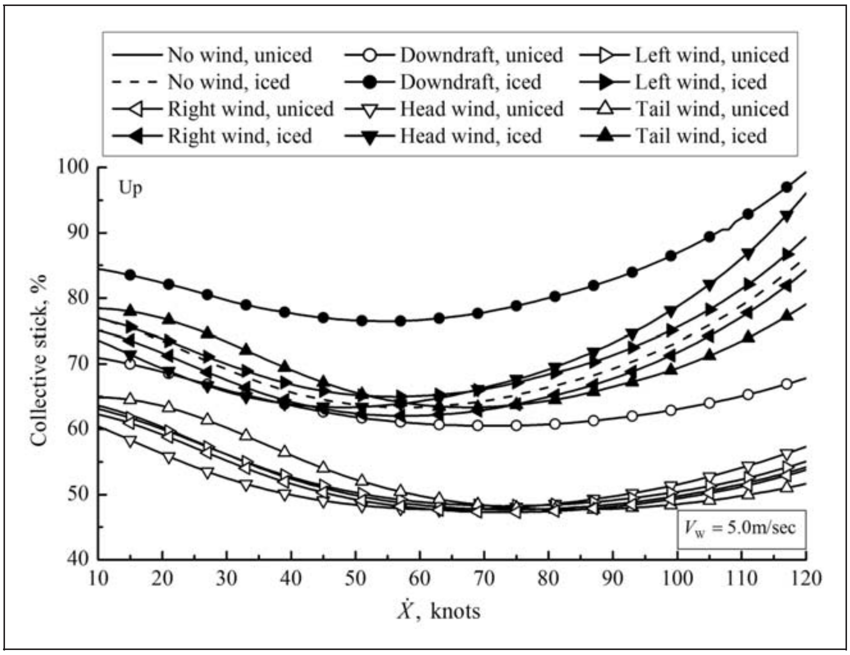

Figure 3. Trim curve of collective control.

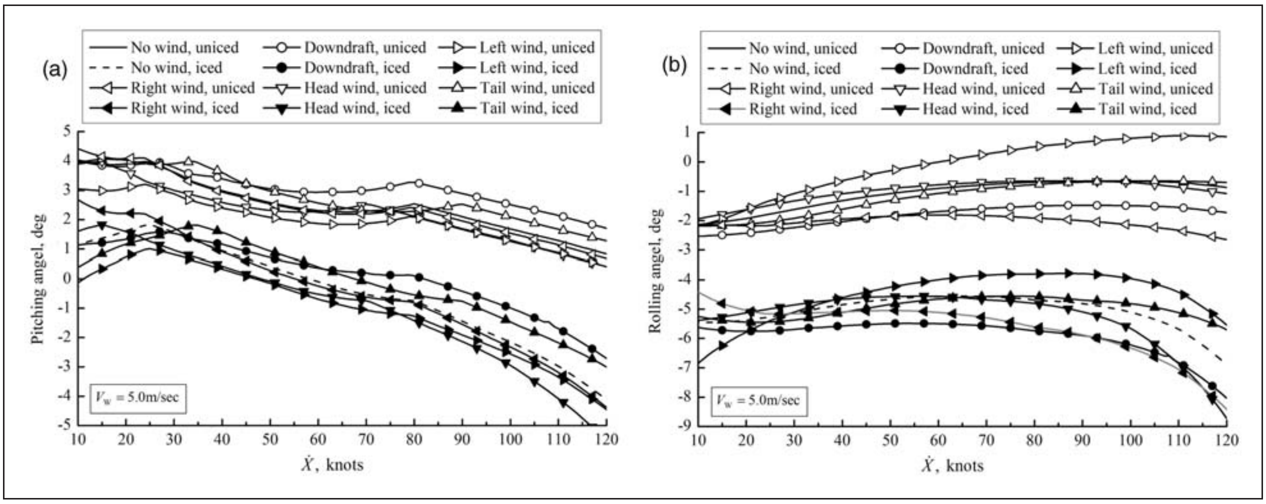

Figure 4. Trim curve of pitching and rolling angles.

2. Compared with the lateral trim control position in no wind field, left wind (or right wind) make the lateral control push toward the more right (or left) position, which shortens the right (or left) pushing control range. Furthermore, the more hazardous effect on helicopter is that left wind even makes the right pushing control range shorten more with icing encounter. But its hazardous effects on lateral control stick are not more critical than the effects on longitudinal control stick. In addition, head wind, tail wind and downdraft have little effect on lateral control.
3. Compared with the pedal trim control position in no wind field, left and head winds (or right and tail winds) make the pedal control move to the more right (or left) position, which shorten the right (or left) pedal control range. Furthermore, the more hazardous effect on helicopter is that right wind even makes the left pedal control range shorten more with icing encounter at low flight velocity. It suggest pilots move the pedal control to left position more slowly and gently when encountering right wind at low flight velocity even in icing conditions.
4. Actually, when encountering with left wind (take the left wind for example), helicopter flight with left sideslip. To keep forward flight along with the initial flight path, just as shown in Figure 2, and compared with the trim control position in no wind field, the lateral control should be pushed toward the more right position, the longitudinal control should be pulled toward the more backward position, and the pedal control should be moved to the more right position. Then helicopter slants to the right, as shown in Figure 4(b), and it flights along with the initial flight path.

Figure 3 shows the trim curve of collective control. It can be seen that downdraft has the largest hazardous effects upon the collective control whether with or without icing encounter, compared with the other types of wind field. It makes the collective control requirement increase evidently and finally makes helicopter flight envelop shrink.

Figure 4 describes the trim curve of pitching and rolling angles. It can be seen that downdraft makes the pitching angle increase, and makes the rolling angle decrease, at the medium and large forward flight velocities, whether with or without icing encounter. Head, left, and right winds make the pitching angle decrease. In addition, downdraft makes the rolling angle decrease whether with or without icing encounter. The changes of attitude angles correlate with those controls.

Airflow hazardous effects on stability

The study is now extended to an investigation of helicopter stability due to airflow disturbance (namely wind field) and ice accretion. Figure 5 shows the effects of wind field and ice accretion on helicopter dynamic response as quantified in MIL-F-83300[23] at helicopter forward flight velocity of 40 knots. It can be concluded that the effects of wind field on the Dutch roll mode are more serious than on the phugoid mode, especially the effect of the downdraft. As analyzed in Cao et al.,[11] icing tends to reduce the stability of longitudinal and lateral/directional oscillatory modes with/without airflow disturbance (i.e. wind field).

In addition, different types of wind field and different wind velocity both have different effects on helicopter stability characteristics. As shown in Figure 5(a), left wind, tail wind, and downdraft may make the longitudinal stability decrease. And an increase in airflow wind velocity has more serious effect on stability. In Figure 5(b), left wind, right wind, and downdraft make the lateral/directional stability decrease. An increase in airflow wind velocity also has more serious effect on stability. From Figure 5, it can be indicated that downdraft has the most hazardous

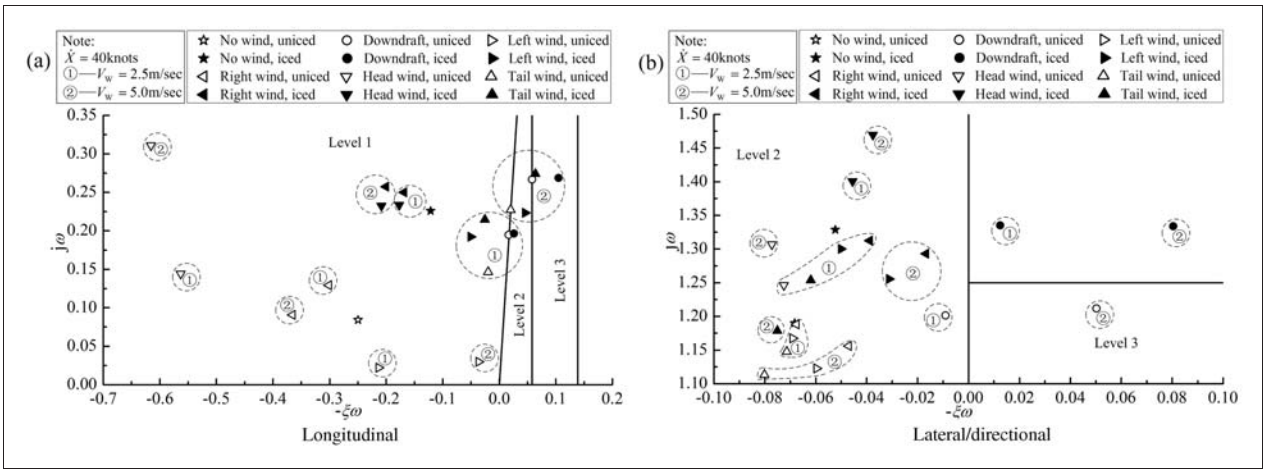

Figure 5. Longitudinal and lateral/directional dynamic responses.

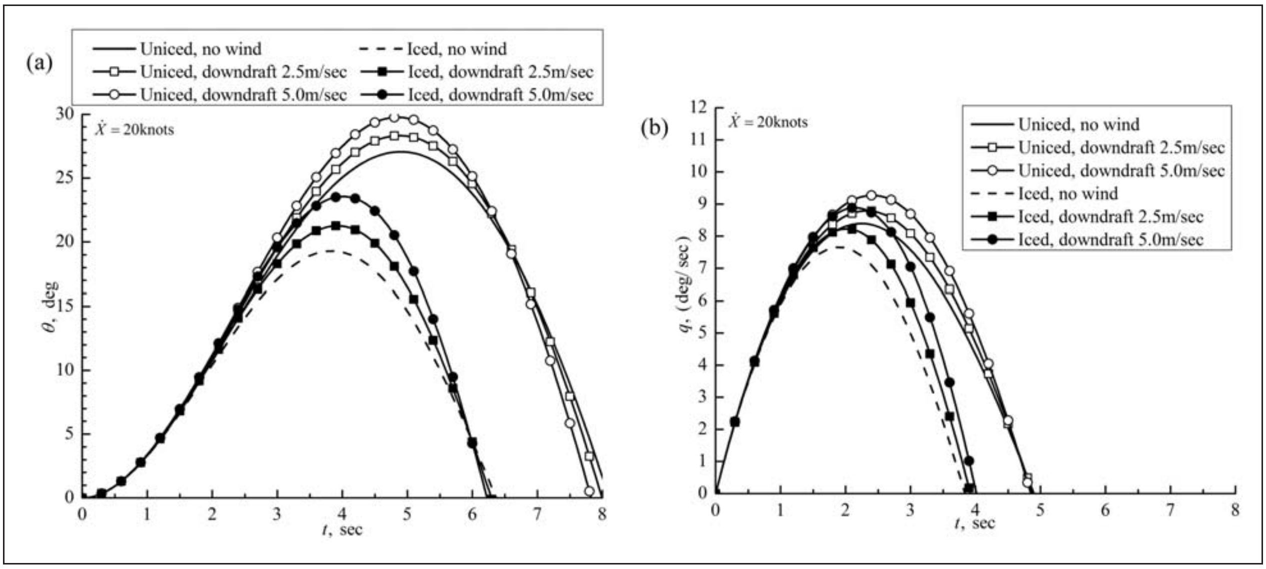

Figure 6. Effect of downdraft on pitch channel responses.

effects on both longitudinal and lateral/directional stability.

Airflow hazardous effects on controllability

Since downdraft has the most evident and serious effects on collective trim characteristics and stability, a 1.0 cm step collective/longitudinal/lateral/directional control input is employed in order to predict the effects of downdraft on helicopter controllability, based on the calculation method depicted by Cao et al.[11] In this section, helicopter controllability from wind velocity of 0 to 2.5–5.0 m/s at the helicopter forward flight velocity of 20 knots is examined.

Figure 6 shows the effects of downdraft and ice accretion on helicopter pitch channel controllability with 1.0 cm step longitudinal control input. Referring to Figure 6, conclusions can be drawn as follows: at the helicopter forward flight velocity of 20 knots, although ice accretion reduces the peak value of pitch-attitude and pitch-rate responses, downdraft airflow makes those responses a little increase. And the pitch increase of attitude response makes the control sensitivity a little increase which finally results in the difficult operation of helicopter and increases the pilot's pitching control load.

The same change trend can be found in Figure 7 that shows the effects of downdraft and ice accretion on helicopter roll channel controllability with 1.0 cm step lateral control input. At the helicopter forward flight velocity of 20 knots, although ice accretion reduces the peak value of roll-attitude and roll-rate responses, downdraft airflow makes those responses a little increase. And the increase of roll attitude response makes the control sensitivity a little increase which finally results in the difficult operation of helicopter and increases the pilot's rolling control load.

Figure 8 indicates the effects of downdraft and ice accretion on helicopter collective channel controllability with 1.0 cm step collective control input.

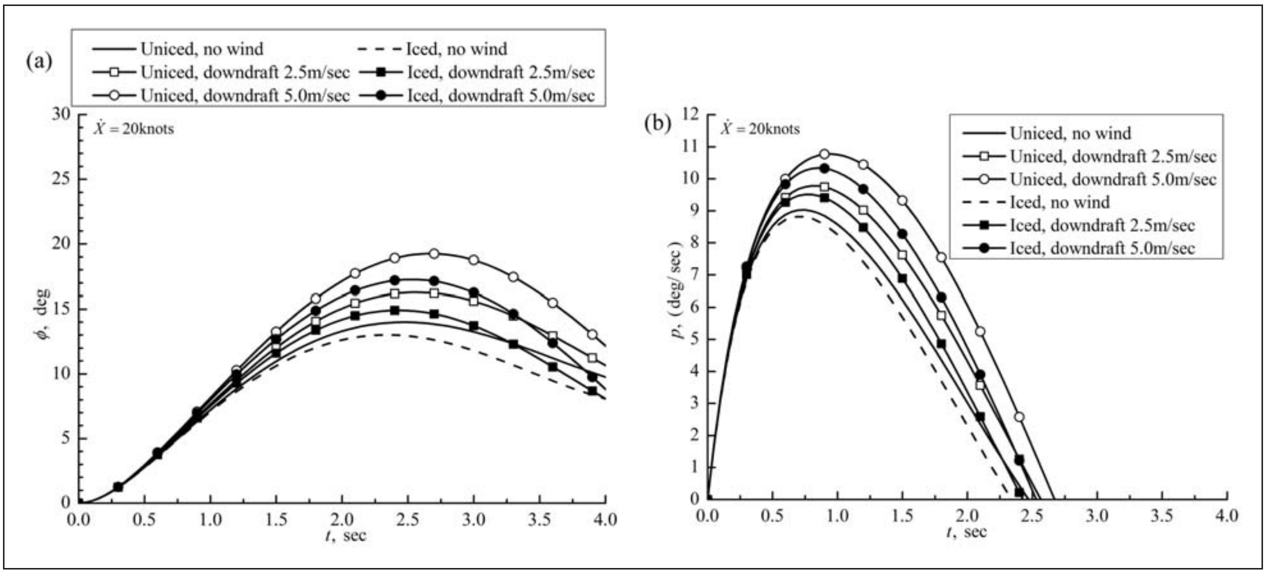

Figure 7. Effect of downdraft on roll channel responses.

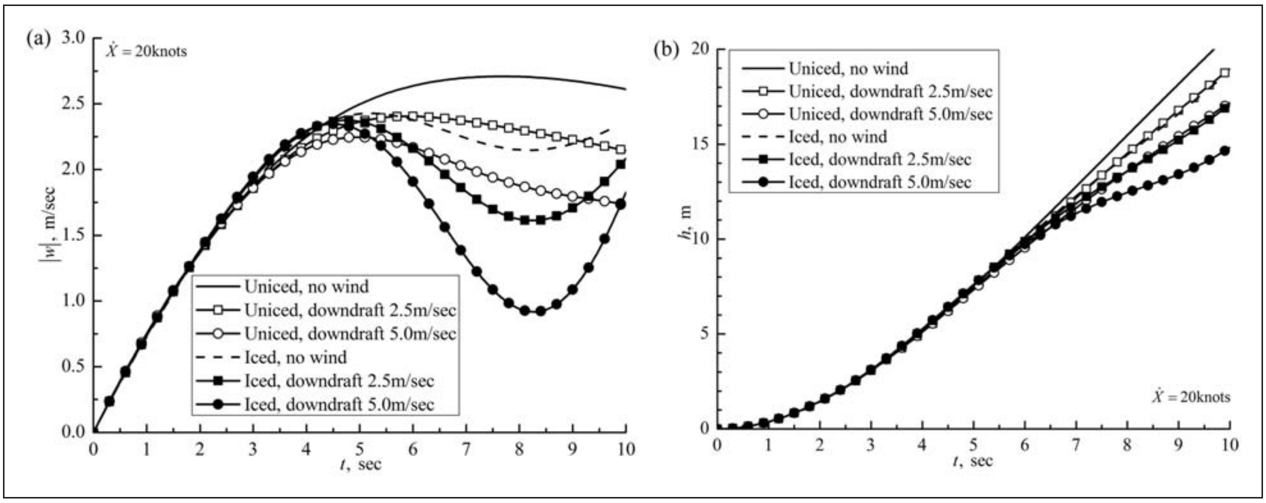

Figure 8. Effect of downdraft on collective channel responses.

According to Figure 8, some indications can be drawn as follows: downdraft airflow makes the helicopter ascending rate decrease after 4.5 s. Furthermore, with the increase of the downdraft wind velocity, the decreasing trend is more and more evident and serious, whether with or without icing encounter. The ascending height of the helicopter has the corresponding change trend, as shown in Figure 8(b).

Conclusions

A nonlinear helicopter flight dynamic model with uniform wind field and icing encounter considered were developed for predicting the airflow hazard on helicopter flight dynamic characteristics in icing conditions. Based on the results presented in this article, it can be concluded that different types of wind field have different hazardous effects on helicopter inflight performance, especially more hazardous in icing conditions. Further conclusions are drawn as follows:

1. Because of wind field, the corresponding control range becomes shrunk. It suggests pilots backward pull longitudinal stick more slowly and gently when encountering left wind at low flight velocity, and forward push the stick more slowly and gently when encountering head wind at high flight velocity, even in icing conditions. And pilots should move the pedal control to left position more slowly and gently when encountering right wind at low flight velocity even in icing conditions. Furthermore, downdraft has the most hazardous effect on collective control, compared with the other types of wind field. It is evident that downdraft makes the pitching angle increase, rolling angle decrease, at the medium and large forward

flight velocities. The changes of attitude angles correlate with those controls.

2. As described in 'Airflow hazardous effects on stability' section, left wind, tail wind, and downdraft make the longitudinal stability decrease. And left wind, right wind, and downdraft make the lateral/directional stability decrease. An increase in airflow wind velocity has more serious effect on stability.
3. As depicted in 'Airflow hazardous effects on controllability' section, at the helicopter forward flight velocity of 20 knots, although ice accretion reduces the peak value of pitching/rolling attitude and pitching/rolling rate responses, downdraft airflow makes those responses a little increase which finally results in the difficult operation of helicopter and increases the pilot's control load. Furthermore, downdraft airflow makes the helicopter ascending rate decrease after 4.5 s. With the increase of the downdraft wind velocity, the decreasing trend of both ascending rate and height is more and more evident, whether with or without icing encounter.

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