Performance Degradation of Helicopter Rotor in Forward Flight Due to Ice

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This study addresses the analytical assessment of the degradation in the forward flight performance of the front rotor Boeing Vertol CH47D helicopter in a rime ice natural icing encounter. The front rotor disk was divided into 24 15-deg sections and the local Mach number and angle of attack were evaluated as a function of azimuthal and radial location for a specified flight condition. Profile drag increments were then calculated as a function of azimuthal and radial position for different times of exposure to icing, and the rotor performance was re-evaluated including these drag increments. The results of the analytical prediction method, such as horsepower required to maintain a specific flight condition, as a function of icing time have been generated. The method to illustrate the value of such an approach in assessing performance changes experienced by a helicopter rotor as a result of rime ice accretion is described.

Nomenclature

Ac	= accumulation parameter, $= V(\mathrm{LWC})\Delta t/\rho_{\mathrm{ice}}c$
a_∞	= freestream speed of sound
c	= airfoil chord
E	= collection efficiency
I	= drag constant [Eq. (2)]
k/c	= roughness height [Eq. (2)]
LWC	= liquid water content
M	= Mach number, $= V/a_\infty$
r	= local radial position along rotor blade
R	= radius of rotor
Δt	= icing time
V	= local velocity
U	= freestream velocity
α	= angle of attack
β	= droplet impingement efficiency
$\beta_{\max}$	= maximum droplet impingement efficiency
ρ_{ice}	= ice density
ψ	= blade azimuth angle (measured from downwind position, positive counterclockwise)

Introduction

THEORETICAL and experimental studies related to helicopter icing recently have been emphasized due to the need to define methods leading to the utilization of aircraft with a minimum of weather-associated restrictions. Previous studies have resulted in analytical models which predict the performance degradation of propellers[1] and helicopter rotor blades in hover[2] under the influence of rime ice. Experimental wind tunnel studies have also been carried out with a model helicopter in hover and forward flight[3,4] addressing both clean and simulated iced main rotor blades. Other studies[5] have been performed concerning the actual ice shapes observed on the main rotor of a UH-1H helicopter in hover. In a recent study, Flemming and Lednicer[6] measured aerodynamic performance degradation due to icing of several airfoils during a series of wind tunnel tests in Canada.

As noted, considerable effort has been expended to experimentally quantify the change in the aerodynamic coefficients and, hence, helicopter performance during icing encounters. The methodology established earlier to analyze and provide theoretical values of performance degradation of rotating systems, such as propellers and helicopter rotor blades in hover and axial flight during natural icing conditions, yielded performance levels consistent with those experienced in actual flight. However, the methodology to theoretically analyze helicopter performance in forward flight during icing remains to be fully established and demonstrated. Therefore, the intent of this paper is to address some of the issues involved with the definition of this advanced methodology.

The method of helicopter forward flight analysis (B-65) used to determine the trends presented here is a state-of-the-art computer code including all key aerodynamic and dynamic effects influencing the rotor flow environment as well as the blade motions and elastic deflections. Because the effect of icing presently has been limited to profile drag effects, future work may include other relevant effects such as changes in local maximum lift capability, sectional pitching moment, unsteady effects, blade modal frequencies, mass distributions, etc. However, at present, the most meaningful trends could be drawn by limiting the investigation to the profile drag degradation. To this end, examination of the theoretical model used for the helicopter in hover[2] has provided the basis for the present study.

Method of Analysis

The analytical model described by Korkan et al.[1] and applied to the helicopter hover condition[2] can be meaningfully extended to the helicopter forward flight condition. In summary, the present method employs the basic airfoil icing

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analysis of Bragg et al.[7,8] in which a Theodorsen transformation is used to calculate the inviscid flowfield around an arbitrary airfoil. The trajectories of the water droplets and the location of impingment on the airfoil surface are calculated by step integration. The local impingment efficiency and accumulation parameter on the airfoil surface are computed and used in the calculation of the drag increment due to ice accretion. The empirical correlation of Bragg and Gregorek[8] is used, i.e.,

$$C_{D_{\text{ice}}} = (1 + \Delta C_D / C_D) C_D \tag{1}$$

where

$$C_D = 0.010[15.798\ell n(k/c) + 28{,}000 AcE + \dot{I}] \tag{2}$$

A new local profile drag value for the airfoil in the icing condition based on the ice-free performance level then can be calculated. As noted in earlier studies,[1,2] for a rotating system such as a propeller or a helicopter rotor, the rotating airfoil sections encounter varying combinations of forward, rotational, and induced velocity components resulting in local Mach number and angle-of-attack excursions which are repeated cyclically as a function of blade radial and azimuthal location. The method described earlier first calculates the impingement efficiency and accumulation parameter as a function of radial and azimuthal location and then the resulting drag increment ratio, $\Delta C_D/C_D$. The drag data used in the rotor performance analysis is then modified by the local drag factor and the performance is recalculated for a fixed icing time.

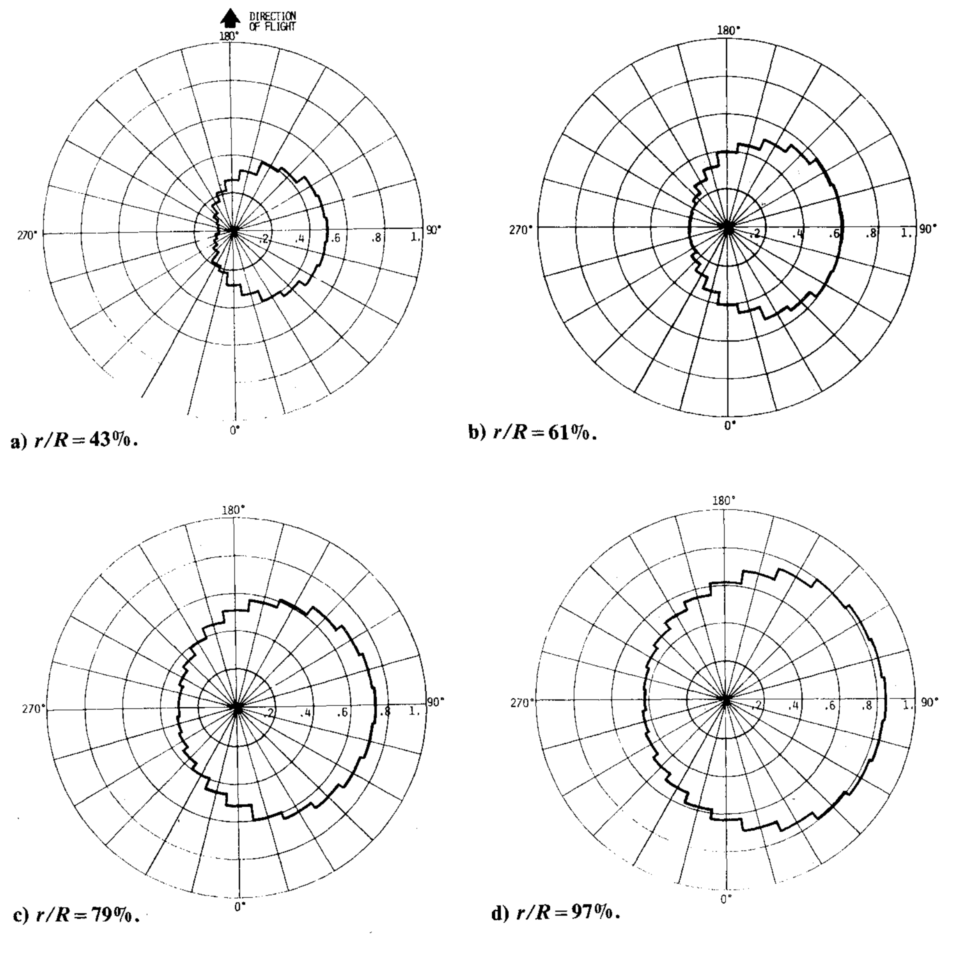
In the present study, the effect of rime ice accretion on the front rotor blades of the CH47D was investigated to determine the horsepower required to maintain a given flight speed as a function of icing exposure time. Basic to the method are the assumptions that the fuselage was not reoriented during the icing period, that no ice was allowed to accumulate on the fuselage, and that only the cyclic pitch was adjusted to maintain the flight condition. The CH47D front rotor consists of three blades with a radius of 30 ft, having a constant chord of 32 in. and rotating at 221 rpm corresponding to a rotor tip speed of 695 fps. The rotor blades utilize the VR-7 and VR-8 airfoils as described by Korkan et al.[2]

The flight condition selected for analysis was at an altitude of 6800 ft and a forward velocity of 133 knots with a required thrust of 20,775 lb and a propulsive force of 1460 lb (front rotor only). The rime ice conditions selected for analysis consisted of an average liquid water content (LWC) of 0.44 g/m^3, an average volume median particle diameter of 25 μm, and a free air temperature of 4.30°F.

Theoretical Predictions of Rotor Performance

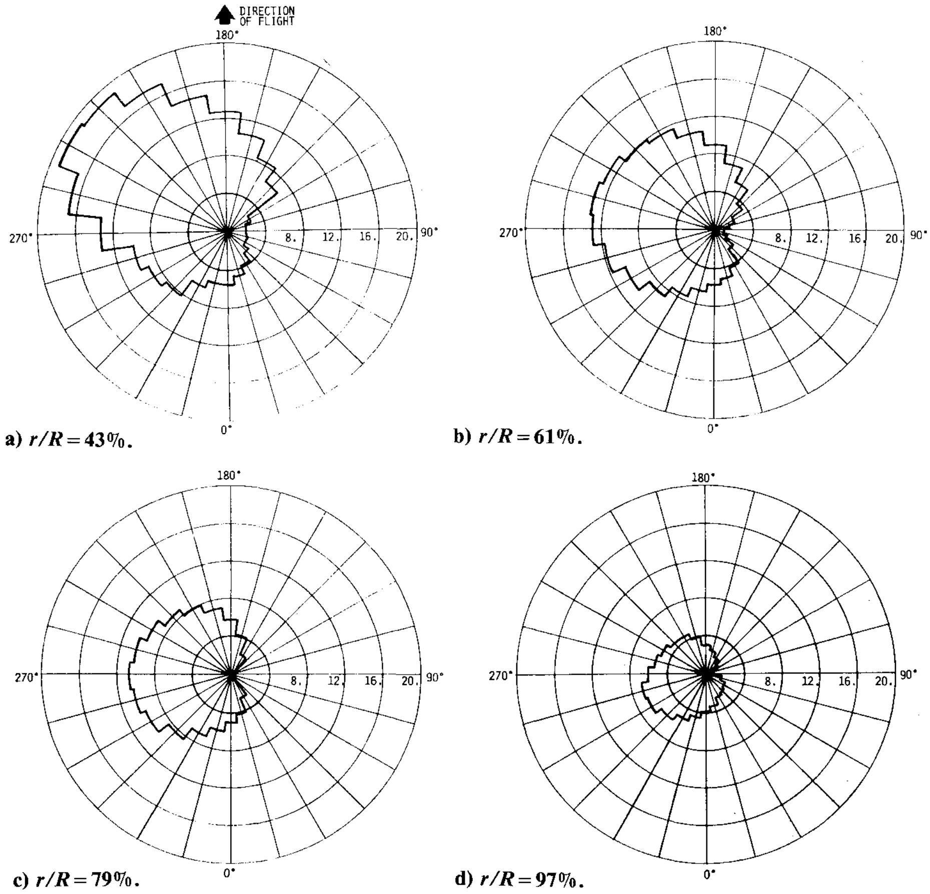
In applying the methodology previously described to a helicopter rotor blade in forward flight, it may be noted as shown in Figs. 1 and 2 that the local Mach number and angle of attack are functions of both radial and azimuthal location on the rotor disk. The numerical procedure has been applied to 13 rotor spanwise stations for each of 24 azimuthal sectors. The azimuthal variations of the total collection efficiency and accumulation parameter were determined as shown in Figs. 3 and 4 for each of the fixed spanwise radial locations. Values of the azimuthal variation of $(1 + \Delta C_D/C_D)$ were calculated using Eq. (2) and are shown in Fig. 5. These drag factors were applied directly to the rotor analysis to determine the performance degradation at each fixed icing time during the assumed natural icing encounter.

The approach used in the present study was to average the drag increment due to icing $(1 + \Delta C_D/C_D)$ azimuthally at each radial location for each of the icing times. The results are shown in Fig. 6 as a function of radial extent of icing. As



a) $r/R = 43\%$. b) $r/R = 61\%$. c) $r/R = 79\%$. d) $r/R = 97\%$.

Fig. 1 Azimuthal variation of Mach number (counterclockwise rotation).



a) $r/R = 43\%$. b) $r/R = 61\%$. c) $r/R = 79\%$. d) $r/R = 97\%$.

Fig. 2 Azimuthal variation of angle of attack (counterclockwise rotation).

noted, the drag increment due to icing is linear with time spent during the icing encounter. Also, as the radial extent of icing increases, the drag increase due to icing rises significantly. These values were introduced into the Boeing Vertol B-65 helicopter performance analysis to determine the horsepower required to maintain a propulsive force of 1460 lb and a thrust of 20,750 lb. The results of these calculations are shown in Fig. 7, referenced to the clean front rotor horsepower (HP) of 1990. The variation of the ratio of HP(ice)/HP(ref) with icing time follows the same trend as the drag increments (Fig. 6), i.e., linearly with respect to time. The high sensitivity of the total performance to main rotor tip accretion is also evident. When the results of Fig. 7 are replotted as a function of radial extent of ice for times of 60, 180, and 300 s as given in Fig. 8, the influence of the rotor tip region and icing time on horsepower required to maintain the specified flight speed is emphasized.

Method of Averaging

The numerical procedure previously described involves a matrix of 13 radial locations defined at 24 azimuthal sectors, and requires a considerable amount of time and expense. Therefore, an averaging method was investigated to determine if a more expedient and still acceptable procedure could be established. This investigation was approached using the following three methods.

1) Sum and average the values of $(1+\Delta C_D/C_D)$ calculated for each 15-deg azimuthal sector around the entire rotor disk for each radial location for a specified icing time. For the rotor analysis used in the present investigation, this approach still requires the calculation of the matrix of 13×24 values. However, this method of averaging reduced the required input to the helicopter performance analysis to 13 values.

Table 1 Method of averaging (360-deg average, 15-deg segments/60 s icing time)

r/R	$\overline{1+\dfrac{\Delta C_D}{C_D}}$	$\bar{E}$, $\overline{Ac}$; $1+\dfrac{\Delta C_D}{C_D}$	$\bar{\alpha}$, $\bar{M}$; E, Ac; $1+\dfrac{\Delta C_D}{C_D}$
0.43	2.170	2.114 (2.58%)[a]	2.130 (1.84%)
0.61	2.313	2.277 (1.56%)	2.339 (−1.13%)
0.79	2.474	2.447 (1.09%)	2.489 (−0.61%)
0.97	2.699	2.692 (0.26%)	2.749 (−1.82%)

[a]Percent deviation from $\overline{1+\Delta C_D/C_D}$.

2) Sum and average the total collection efficiency and accumulation parameter for each 15-deg azimuthal sector around the entire rotor disk. Values of $\bar{E}$ and Ac then can be used to calculate an averaged value of $(1+\Delta C_D/C_D)$ for each radial location at a specified icing time. This method eliminates the calculation of drag increments at each of the 24 azimuthal sectors.

3) This method involves the summing and averaging of the local Mach number and angle-of-attack values for each 15-deg azimuthal sector around the entire rotor disk for each radial location, the computation of the total collection efficiency and accumulation parameter from these averaged values of $\bar{M}$ and $\bar{\alpha}$, and the use of the corresponding values of E and Ac to calculate an azimuthally averaged radial variation of $(1+\Delta C_D/C_D)$. This method of averaging requires evaluation of only 13 spanwise values of $\bar{M}$, $\bar{\alpha}$, E, Ac and $(1+\Delta C_D/C_D)$, greatly simplifying the numerical procedure.

The three averaging methods have been applied to the case under investigation for an icing time for 60 s with ice accretion allowed to take place along the entire span of the rotor. The

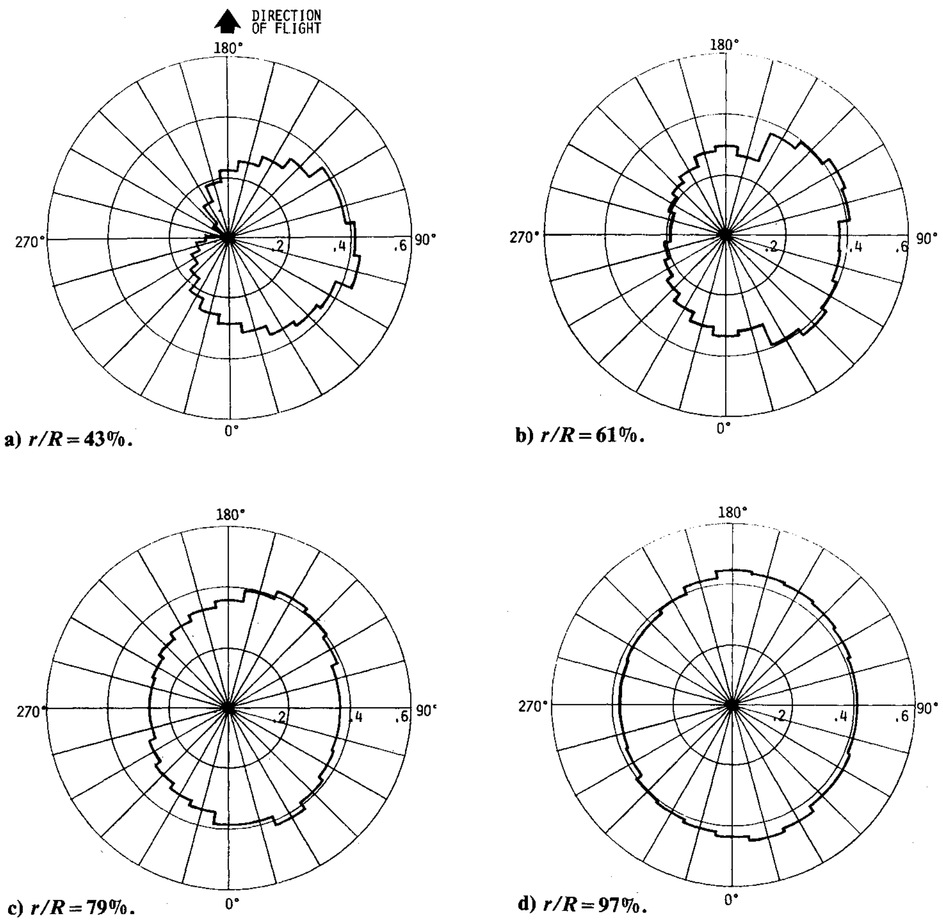


Fig. 3 Azimuthal variation of total collection efficiency (counterclockwise rotation).

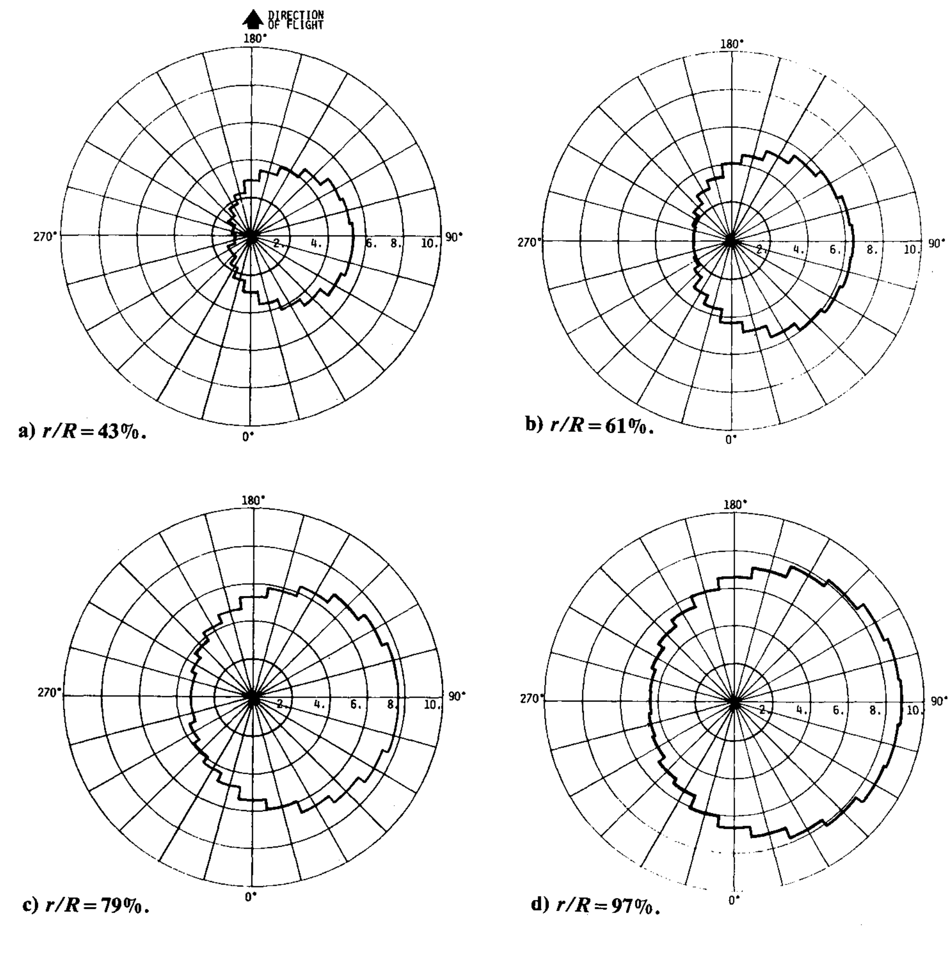


Fig. 4 Azimuthal variation of accumulation parameter ($Ac \times 10^3$) ($\Delta t = 60$ s, counterclockwise rotation).

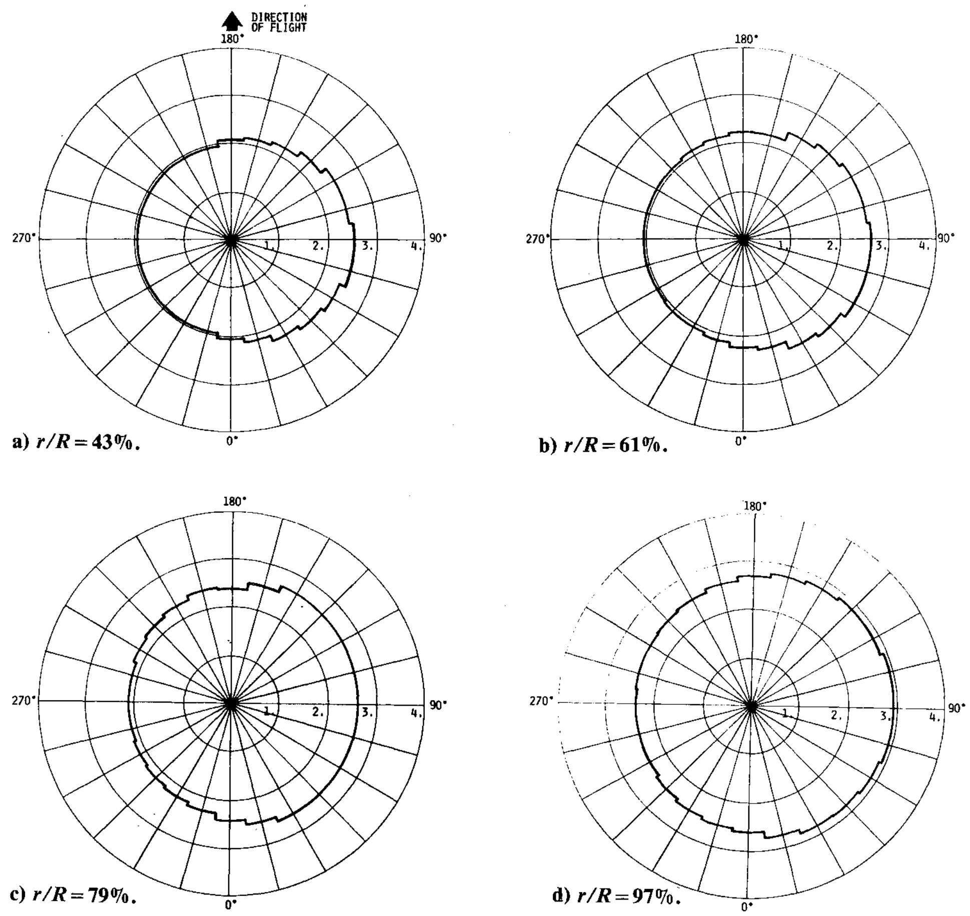


Fig. 5 Azimuthal variation of $(1 + \Delta C_D/C_D)$ ($\Delta t = 60$ s, counterclockwise rotation).

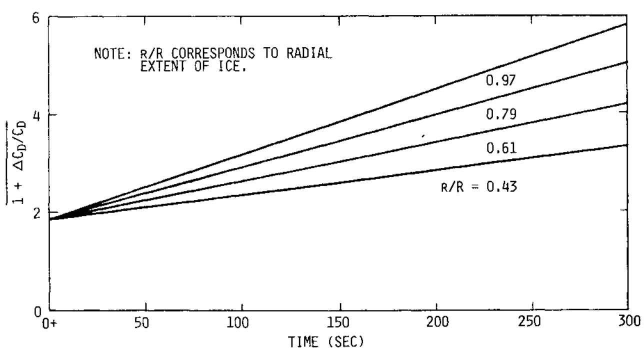


Fig. 6 Variation of drag increment with icing time, fixed radial location (360-deg average, 15-deg segment).

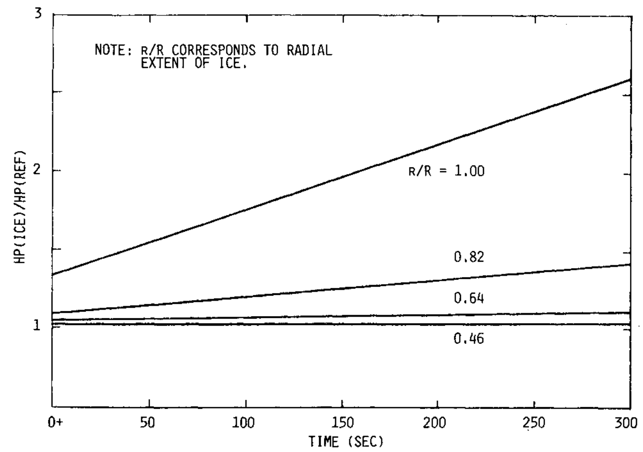


Fig. 7 Horsepower required with rime ice accretion to maintain a propulsive force of 1460 lb, thrust of 20,750 lb [HP(ref) = 1990 (front rotor). (360-deg average, 15-deg segment)].

results are shown in Table 1 for four radial locations along the rotor blade. Using $\overline{1 + \Delta C_D/C_D}$ as a base, it can be seen that averaging E and AC and calculating $(1 + \Delta C_D/C_D)$ results in a 0.26-2.58% variation from the values of $\overline{1 + \Delta C_D/C_D}$. However, if the $\bar{\alpha}$ and $\bar{M}$ averaging procedure is employed, hence, E and AC, the resulting values of $(1 + \Delta C_D/C_D)$ differ only by −1.82-1.84% from the values of $\overline{1 + \Delta C_D/C_D}$ for an icing time of 60 s. This approach (method 3 above) resulted in a required horsepower of 3190 to maintain a propulsive force of 1460 lb for the front rotor thrust of 20,750 lb for ice accretion along the entire span of the blade. In contrast, when unaveraged values were used in the Boeing Vertol B-65 helicopter performance analysis, i.e., when 13 spanwise computational bays were assigned $(1 + \Delta C_D/C_D)$ values for each of the 24 azimuthal sectors for the same icing time, 3364 hp was required to maintain the same flight condition. As can be seen for this flight condition, the horsepower when using values of the detailed 13×24 numerical scheme differs by approximately 5.2% from the most simplified method of averaging. Therefore based upon these results, the method of computing $\bar{\alpha}$ and $\bar{M}$ and, hence, the performance, appears to be acceptable for the conditions under study.

Near- and Far-Term Refinements of Current Methodology

Although the present analytical model does provide reasonable values of performance degradation for the complicated case of the helicopter forward flight condition, the methodology requires refinement and further examination. This future work can be classified into near and far term.

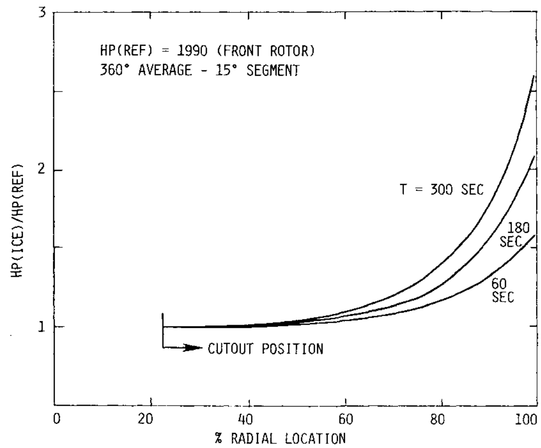


Fig. 8 Horespower required vs radial extent of rime ice accretion to maintain a propulsive force of 1460 lb, thrust of 20,750 lb.

Near Term

1) Quantify cambering/decambering effects due to ice accretion at the leading edge of the airfoil with a resulting shift in the angle of attack for zero lift and, hence, a change in the effective blade twist.

2) Determine the effect of ice accretion on the moment coefficient as well as the lift coefficient.

3) Investigate an appropriate centrifugal/adhesion force model and its relation to the spanwise ice growth along the rotor blade.

4) Assess the influence of kinetic heating on the spanwise ice growth along the rotor blade and its effect on the centrifugal/adhesion force model.

5) Re-examine the drag coefficient correlation for both the rime and glaze ice condition.

Far Term

1) Carry out the present theoretical study for an aircraft configuration with a different airfoil family.

2) Define a standarized helicopter rotor icing model to be used in conjunction with existing rotor analysis codes.

3) Investigate the degradation in the lift and moment stall boundaries due to the ice accretion process.

4) Study the unsteady effects on airfoil performance under the influence of ice accretion.

5) Determine the effect of ice accretion on the mode shapes and modal frequencies of helicopter rotor blades.

6) Establish an airfoil design capability to minimize ice accretion penalties for both helicopter rotor and propeller systems.

Work has started and is continuing in several of these areas. As these new refinements become available, the current methodology will be improved to provide a more complete modeling of the ice accretion process for rotating systems.

Summary

The results of the analytical prediction of performance degradation for a specified CH47D helicopter forward flight condition in the presence of rime ice has been evaluated. The analysis determined the horsepower required to maintain speed and trim as a function of time in an assumed natural icing encounter, and the predicted levels of performance degradation are qualitatively consistent with those experienced in actual flight. The calculations involved 13 rotor spanwise stations, where each computational bay was assigned a drag increment for a given icing time increment for each of 24 azimuthal sectors. The Boeing Vertol B-65 helicopter performance analysis was then used for the front rotor of the CH47D helicopter configuration to assess the additional horsepower required to overcome the increased profile drag. The rotor cyclic controls were changed as necessary to maintain the flight condition. The method of averaging has also been investigated by comparing the $\overline{1+\Delta C_D/C_D}$ for each 15-deg quadrant azimuthally at a fixed radial location to E and Ac hence $(1+\Delta C_D/C_D)$, and $\bar{\alpha}$ and $\bar{M}$ resulting in E, Ac, and, hence, $1+\Delta C_D/C_D$. The procedure of averaging α and M at fixed radial locations to obtain E, Ac, and, hence, $1+\Delta C_D/C_D$ yielded acceptable results within $\pm 1.8\%$ of $\overline{1+\Delta C_D/C_D}$ azimuthally for each 15-deg quadrant at a fixed radial location, thus greatly simplifying the calculation process. Also, the extent of the spanwise icing has been shown to have a significant effect on the horsepower required to maintain the specified flight condition. This stresses the urgency of an investigation of adhesion/centrifugal force models, aerodynamic heating, and ice shedding. Refinements to the present analytical model have been suggested, and a more detailed analysis can be carried out when flight-test data become available.

Acknowledgments

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