Analytical Determination of Propeller Performance Degradation Due to Ice Accretion

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A computer code capable of computing the propeller performance for clean, glaze, or rime ice propeller configurations to determine the performance degradation resulting from a given icing encounter has been developed. The inviscid, incompressible flowfield at each specified propeller radial location is first computed using the Theodorsen method. A droplet trajectory computation then calculates the droplet impingement points and airfoil collection efficiency for each radial location. User-selectable empirical correlations are available for determining the aerodynamic penalties due to ice accretion. Propeller performance is finally computed using strip analysis for either the clean or iced propeller. In the iced mode, the thrust and torque coefficient equations are modified by the drag and lift coefficient increments due to ice to obtain the appropriate iced values. Comparison with available experimental propeller icing data shows generally good agreement. The code's capability of properly predicting the thrust coefficient, power coefficient, and propeller efficiency of an iced propeller is shown to be dependent on the choice of empirical correlation employed as well as on the proper specification of the radial icing extent and propeller blade angle.

Nomenclature

Ac = accumulation parameter, Eq. (3)
BHP = propeller power absorption
c = airfoil section chord, in. (m, ft)
C_d = section drag coefficient
C_ℓ = section lift coefficient
C_P = propeller power coefficient, $= P/\rho n^3 D^5$
C_T = propeller thrust coefficient, $= T/\rho n^2 D^4$
D = propeller diameter, ft
E = total collection efficiency, $= \Delta Y_0/h$, Eq. (2)
h = airfoil projected height, m
I = airfoil drag constant
J = propeller advance ratio, $= V/nD$
K = inertia parameter, $= \sigma\delta^2 V/18c\mu$
k/c = particle roughness diameter-to-chord ratio
K_0 = modified inertia parameter, Eq. (12)
M, M_x = local Mach number
n, N = propeller revolutions per minute
r = leading edge radius of curvature, percent of chord
R_u = droplet Reynolds number
s = airfoil surface arc length, m
t/c = airfoil thickness-to-chord ratio
T_0 = freestream temperature, °F
u = local air velocity, m/s (mph)
V = freestream velocity, ft/s (mps)
w = liquid water content, g/m^3
x = propeller radial location, in fraction of tip radius
Y_0 = initial droplet y coordinate, m
α = airfoil section angle of attack, deg
α_i = induced angle of attack, deg
β = local impingement efficiency, $= dY_0/ds$, Eq. (1); propeller twist angle, deg
β_{max} = maximum local impingement efficiency
ΔC_d = incremental change in drag coefficient due to ice
δ = droplet diameter, μm
η = propeller efficiency, $= J(C_T/C_P)$
μ = absolute air viscosity, kg/m-s
ρ_{ice} = ice density, g/m^3
σ = droplet density, g/m^3
τ = icing time, s
τ_c = corrected icing time, s
ϕ = resultant advance angle, deg

I. Introduction

THE accretion of ice on the lifting or propulsive surfaces of an aircraft is a phenomenon that can have severe consequences if not dealt with properly and in a timely fashion. In many cases, this accretion may produce a serious reduction in lift and increase in drag, requiring more power than is available. Although measures and devices exist which generally prevent this worst-case scenario from happening, ice accretion on airfoils is still a common occurrence in certain atmospheric conditions and as such merits further study because of the significant negative effect it has on airfoil and aircraft performance. It is the objective of this work to provide a single computer program analysis that will accurately predict the degree of performance degradation, primarily with respect to drag increment, resulting from the exposure of an airfoil to some set of atmospheric and flight conditions conducive to ice formation.

Two basic types of ice are found to occur as a result of exposing an airfoil in forward motion to supercooled water droplets in a subfreezing environment. The type of ice that will form may be determined by a variety of factors including the freestream velocity, liquid water content of the cloud, droplet size distribution, and freestream temperature. Based upon an

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investigation of the data currently available, the two latter factors appear to be the most influential in determining the resulting ice type. The first kind of ice, known as rime ice, occurs at relatively low velocities, low liquid water content values (typically 0.5–1.0 g/m^3), and temperatures well below freezing. Due primarily to the very cold temperatures associated with rime ice formation, the droplets tend to freeze on impact to form a fairly smooth addition to the leading edge of the airfoil. At some point with respect to the combination of flight and atmospheric conditions present, there is a transition in ice type from rime to glaze ice. Not only is the crystalline structure of these ice types different, but glaze ice is also produced by higher freestream velocities, higher liquid water content values (on the order of 1.5–3.0 g/m^3), and temperatures near but below freezing. Again, due chiefly to the warmer temperatures involved, the water droplets impacting the surface tend not to freeze on impact but rather to strike the airfoil or existing ice formation and run back in a somewhat chordwise direction before freezing.

Both types of ice cause significant performance degradation of the airfoil. When compared to the aerodynamics of an airfoil in the clean, or noniced, configuration, the iced airfoil will virtually always exhibit a decrease in lift, an increase in drag, and a change in pitching moment that will have a detrimental effect on aircraft stability. Examination of the available icing data base indicates that the degree of performance degradation, specifically with respect to drag increment, is generally more severe for the glaze ice condition. This may be attributed to the more drastic alteration of the leading-edge contour of the airfoil as compared to the typically smoother and less obtrusive rime ice formation.

Both rime and glaze ice negatively influence airfoil performance by physically altering the shape of the airfoil, thereby changing the flowfield around the airfoil. In computing this flowfield for the propeller case, the rotational and induced components of velocity as well as the forward component must be taken into account. The reshaping of the airfoil surface by the ice accretion and the rough peaks and surfaces commonly present in ice accretions, especially in the glaze ice case, serve to induce the premature transition and often separation of the flow around the airfoil, thus spoiling its designed aerodynamic characteristics. For the propeller configuration dealt with in this work, these effects may occur along the entire span of the propeller and have the same effect on propeller aerodynamics as on fixed-wing aircraft. Ice accretion on a propeller may then translate, for example, into an increase in power required to maintain a given flight condition when ice is allowed to form on the propeller blades. Such information provided by this code may be used in establishing propeller ice protection system specifications as well as in future icing certification efforts.

II. Literature Review

Much work has already been done in attempting to better understand ice accretion and its effect on aircraft performance. These efforts have focused primarily on two-dimensional airfoil icing data studies, but the results may in many cases be extended to the rotor or propeller case. Each of these efforts described in the following paragraphs are directly related to the propeller performance code described herein.

Possibly the most complete and informative work relative to ice accretion on propellers was performed and documented by Neel and Bright[1] in 1950. In a flight test program in which efficiency loss was measured during actual natural icing encounters, the authors observed losses of roughly 10% in most cases, with maximum losses on the order of 20%. This data was used for comparison with the analytical predictions generated in this study.

In 1958, Gray undertook an icing study of the NACA 65A004 airfoil[2] and attempted to develop a drag coefficient correlation that would relate ice nature and droplet impingement rates to the associated airfoil aerodynamic penalties. Using experimental icing data, Gray obtained a dimensional correlation that was found to be accurate at angles of attack of less than 4 deg. Gray later published a report[3] in which the available aerodynamic icing data was examined for other airfoils and modified the equation to better fit this data.

Recently Bragg et al.[4] developed a computer program to calculate water droplet trajectories to determine airfoil impingement efficiencies and theoretical rime ice shapes. Along with this droplet trajectory computer analysis, Bragg[4] has also formulated a drag coefficient correlation for the rime ice condition. In this correlation, the change in drag due to ice is given as a function of several variables related to flight and atmospheric conditions, airfoil geometry, and time of ice accretion.

In 1983, Flemming and Lednicer[5] tested a series of scale models of helicopter airfoils to investigate the effects of artificial ice accretion on airfoils at high speeds. The aerodynamic performance degradation of all the airfoils was noted, with the authors citing drag coefficient increases up to approximately 300% in some cases. These data were used to formulate new rime and glaze ice drag coefficient relationships as well as to separate iced lift and moment coefficient relations.

III. Code Operation

Flowfield Calculation

The first step in the process of calculating propeller performance degradation is the computation of the two-dimensional flowfield about the propeller section being investigated. The method used in this code is a Theodorsen technique of conformal mapping, which translates the airfoil coordinates to a circle plane and from that plane determines the velocity distribution about the airfoil. The calculations involved in this method make the assumption of potential flow, which results in little effect on the droplet trajectory for all but the smallest of droplet sizes.

This flowfield calculation technique is limited to incompressible flow, which is acceptable since compressibility effects on droplet trajectory have been found to be negligible up to the airfoil section critical Mach number for all but the smallest of drop sizes. In recent joint studies between NASA and the Royal Aircraft Establishment (RAE),[6] comparisons were made between the impingement efficiency values obtained by the incompressible Theodorsen method at NASA and those calculated using the compressible flowfield code of Garabedian and Korn for supercritical airfoil sections at the RAE. Good agreement was observed between the two methods, thereby validating the use of the incompressible flowfield computation in this analysis.

Droplet Trajectory Calculation

The droplet trajectory code employed in this analysis was developed by Bragg[4] and is used to compute single droplet trajectories and points of impingement on a given airfoil using the previously described flowfield information. From these trajectory calculations, both the total and maximum local collection efficiencies are determined as explained in the following paragraph.

The airfoil local impingement efficiency β is specified as

$$\beta = \frac{\mathrm{d}Y_0}{\mathrm{d}s} \tag{1}$$

where $\mathrm{d}Y_0$ is the vertical distance between adjacent droplet trajectories in the freestream and $\mathrm{d}s$ is the airfoil surface arc length defined by the adjacent trajectories' points of impact. Figure 1 represents a typical variation of β with airfoil surface location for two local blade angles of attack. If Y_0 is plotted vs S, it may be seen that β is simply the slope of the $Y_0 - S$ curve at a given point. The total collection efficiency of an airfoil is defined by

$$E = \frac{\Delta Y_0}{h} \tag{2}$$

The total collection efficiency is then a ratio of the amount of water mass collected by the airfoil to the amount in the freestream sector swept out by the airfoil. Figure 2 exhibits a typical variation of collection efficiencies and accumulation parameter with radial location. The accumulation parameter is a dimensionless icing quantity given by

$$Ac = \frac{uw\tau}{\rho_{\text{ice}} c} \tag{3}$$

The various drag coefficient correlations described in the next section make use of the collection efficiency and accumulation parameter values to compute iced local drag increments.

Aerodynamic Coefficient Correlations

At present, the only means available for quantitatively determining performance degradation due to the icing of an airfoil in terms of aerodynamic coefficients is through the use of empirical correlations. Incorporated into the present study are the three correlations that are currently used to predicted drag increment.

The first correlation, formulated by Gray,[3] is of the form

$$\begin{aligned} \Delta C_D = {} & \left[8.7\times 10^{-5}\frac{\tau u}{c}\sqrt{w\beta_{\max}}(32-T_0)^{0.3}\right] \\ & \times\left(1+6\left\{\left(1+2.52r^{0.1}\sin^4 12\alpha\right)\right.\right. \\ & \times \sin^2\left[543\sqrt{w}\left(\frac{E}{32-T_0}\right)^{1/3}-81\right. \\ & \left.\left.\left. +65.3\left(\frac{1}{1.35^{\alpha_i}}-\frac{1}{1.35^{\alpha}}\right)\right]-\frac{0.17}{r}\sin^4 11\alpha\right\}\right) \end{aligned} \tag{4}$$

Note that this correlation also has the capability of computing the drag coefficient increment at angles of attack other than that at which the ice was formed through the use of the α and α_i terms. It is also a general correlation, applicable to both rime and glaze ice formations.

When applied to icing data obtained in recent years, the Gray correlation exhibited a trend toward the overprediction of the iced airfoil drag increment,[7] especially for cases with relatively high liquid water content values. Another unpublished study conducted by this author has confirmed this trend using additional icing data, and the overprediction of ΔC_d by several hundred percent was not uncommon.

It may be argued that any such equation should not be expected to perform well outside the ranges of the data from which it was developed. Indeed, many of the points to which the Gray equation was applied in these studies were outside the ranges from which it was developed (these ranges are tabulated for all of the available correlations in Table 1). However, the iced drag even for points within the appropriate ranges was typically overpredicted and seldom predicted accurately.

A correlation has been developed by Bragg[4] for the rime ice condition:

$$\Delta C_d = 0.01[15.8\,\ln(k/c) + 28{,}000\,AcE + I] \tag{5}$$

where I represents a drag constant that varies according to airfoil type. Bragg has recently proposed a modified form of his correlation,[8] applicable when the product $AcE \geq 0.004$, which has also been included in the present study.

Table 1. Ranges of parameters used in correlations development

	Bragg	Gray	Flemming
Temperature (deg.F)			
min	0	0	−4
max	10	25	46
Drop diameter (microns)			
min	7	11.3	11
max	19	19.0	50
Liquid water content (g/m^3)			
min	0.50	0.39	0.24
max	1.86	2.00	3.80
Velocity (mph)			
min	175	125	196
max	275	275	508
Icing time (min.)			
min	1.0	3.0	0.33
max	27.0	17.67	5.0

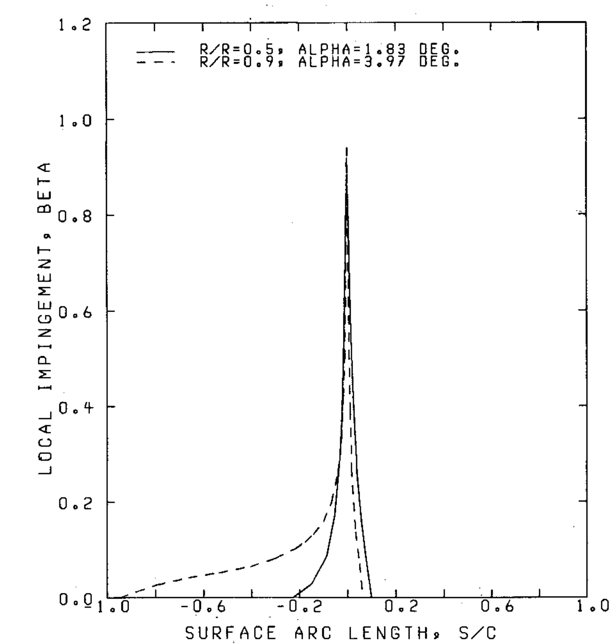

Fig. 1 Variation of local impingement efficiency with surface arc length, Encounter 2, J = 1.18.

$$\Delta C_d = 0.01[15.8\,\ln(k/c) + 1171\sqrt{AcE} + I] \tag{6}$$

In both Bragg equations, ΔC_d is a drag ratio rather than an increment, and it may be used to find the iced airfoil drag coefficient using

$$C_{d_{\text{iced}}} = (1+\Delta C_d)C_{d_{\text{clean}}} \tag{7}$$

Previous studies of these correlations applied to NACA and NASA two-dimensional icing data have indicated a strong tendency to overpredict drag increment.

The third correlations have been developed by Flemming.[5] Whereas Gray and Bragg dealt strictly with drag coefficient correlations, Flemming has also formulated correlations for lift and moment coefficients for both glaze and rime encounters. For a glaze ice encounter,

$$\begin{aligned} \Delta C_d = {} & KD_1\left[0.00686K_0\left(\frac{t}{c}\right)^{1.5}(\alpha+6) - 0.0313\left(\frac{r}{c}\right)^2\right. \\ & \left. + KD0.006M^{2.4}\right] \times \left[w\left(\frac{c}{0.1524}\right)^{0.2}\gamma_c \Big/ \left(\frac{c}{0.1524}\right)^{1.2}\right] \end{aligned} \tag{8}$$

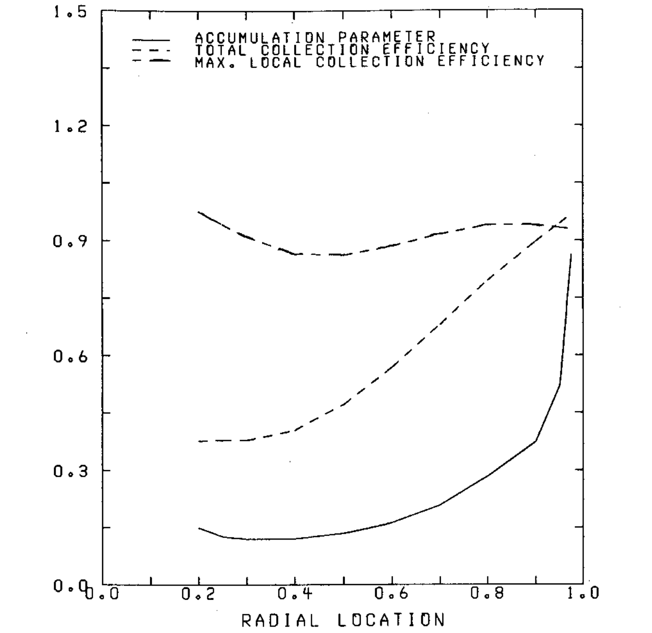

Fig. 2 Radial variation of accumulation parameter, maximum local collection efficiency, and total collection efficiency for Encounter 2, $J = 1.18$.

For a rime ice encounter,

$$\Delta C_d = \left[0.158 \ell n\left(\frac{k}{c}\right) + 175\frac{V}{\rho_{\text{ice}} c} w \tau_c + 1.70\right] \times \left[\frac{\alpha + 6}{10}\right] \times C_{d_{\text{clean}}} \tag{9}$$

and for both glaze and rime encounters,

$$\Delta C_\ell = [-0.01335 K_0 (t/c)(\alpha + 2 + KL_1 (0.00555)(\alpha - 6)^2) KL] \times \left[w\left(\frac{c}{0.1524}\right)^{0.2} \tau_c \Big/ \left(\frac{c}{0.1524}\right)^{1.2}\right] \tag{10}$$

and

$$\Delta C_m = [(0.00179 - 0.0045M)0.000544 K_0 \alpha/(t/c)^{2.7} + 0.00383M(1 - 63.29r/c)] \times \left[w\left(\frac{c}{0.1524}\right)^{0.2} \tau_c \Big/ \left(\frac{c}{0.1524}\right)^{1.2}\right] \tag{11}$$

where K_0 is the modified inertia parameter given by

$$K_0 = K(1 + 0.0967\, R_u^{0.6397}) \tag{12}$$

and KL, KL_1, KD, and KD_1 are functions of temperature and angle of attack and are fully explained in Ref. 5.

Like the Gray and Bragg correlations, the Flemming equations also exhibited deficiencies in application to other two-dimensional icing data. Unlike the other correlations though, the Flemming correlations tended to underpredict the iced drag increment. This general trend was evident even when applied only to points that fell within the correlation development data ranges as presented in Table 1. This separate examination of the various correlations also indicated problems with the ice type calculation feature of the Flemming routine. If the ice type is determined incorrectly in these equations, the incorrect correlation will then be used to calculate the iced drag increment.

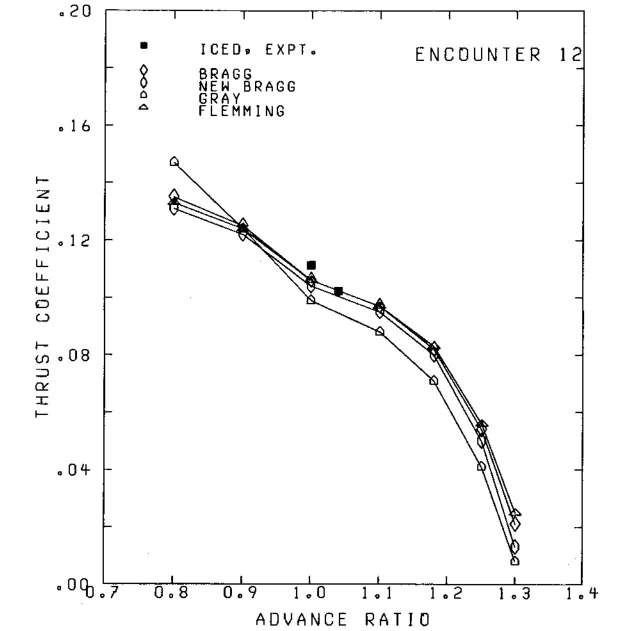

Fig. 3 Variation of thrust coefficient with advance ratio for iced propeller (iced to $r/R = 0.9$). No clean thrust coefficient data available for this encounter.

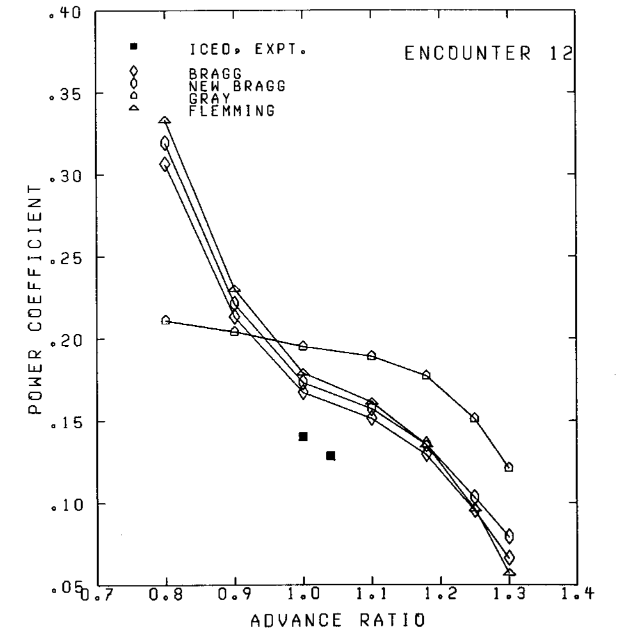

Fig. 4 Variation of power coefficient with advance ratio for iced propeller (iced to $r/R = 0.9$). No clean power coefficient data available for this encounter.

In summary, there are presently three correlations available that are integrated into the computer analysis. As a result, the values of drag, lift, and/or moment coefficient increments for both glaze and rime ice encounters have been quantified. These increments may then be passed to a propeller performance computation to evaluate the propeller performance degradation.

Propeller Performance

The propeller performance calculation integrated into this program is based upon a linearized inflow propeller strip analysis developed by Cooper,[9] in which aerodynamic forces are calculated at selected spanwise blade locations for a given

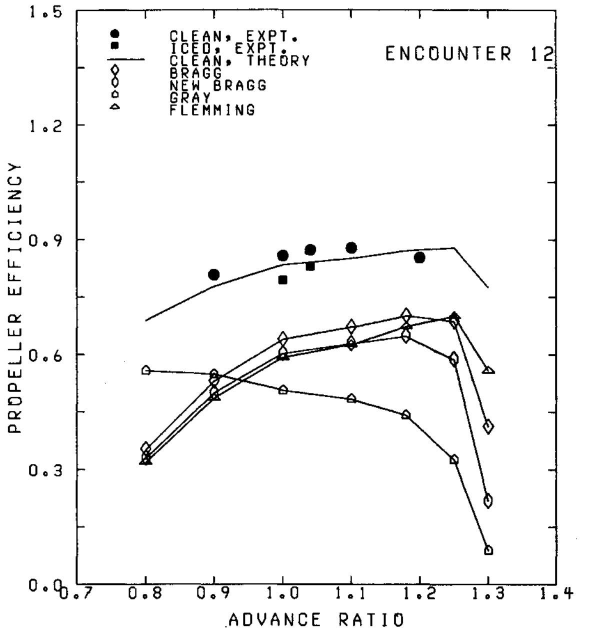

Fig. 5 Variation of propeller efficiency with advance ratio for clean and iced propeller (iced to $r/R = 0.9$).

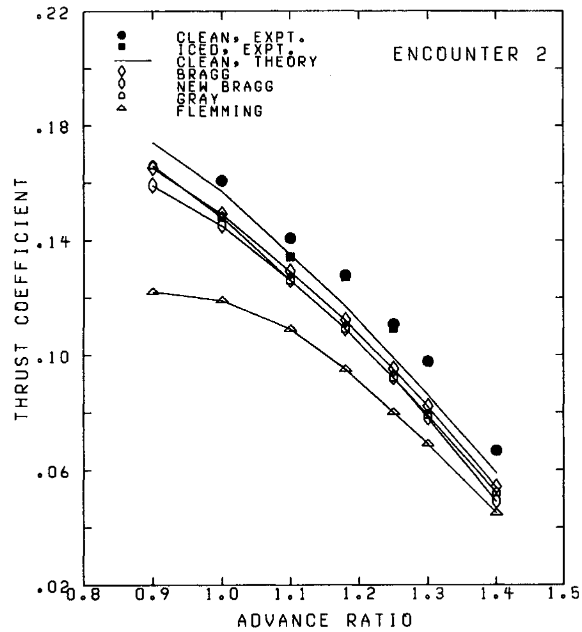

Fig. 6 Variation of thrust coefficient with advance ratio for clean and iced propeller (iced to $r/R = 0.7$).

operating condition and propeller geometry. These differential forces are given in terms of thrust and torque coefficients by

$$\frac{dC_T}{dx} = k\frac{c}{D}M_x{}^2\,(C_\ell \cos\phi - C_d \sin\phi) \tag{13}$$

where

$$k = \frac{900a^2b}{N^2D^2} \tag{14}$$

and

$$\frac{dC_Q}{dx} = \frac{x}{2}\,\frac{dC_T}{dx}\,\frac{C_d \cos\phi + C_\ell \sin\phi}{C_\ell \cos\phi - C_d \sin\phi} \tag{15}$$

Thrust and torque coefficients are obtained by integrating these terms along the blade. The propeller efficiency and power absorbed may then be calculated by

$$\eta = J\frac{C_T}{C_P} = \left(\frac{V}{nD}\right)\frac{C_T}{2\pi C_Q} \tag{16}$$

$$BHP = \frac{C_P \rho n^3 D^5}{550} \tag{17}$$

The iced propeller performance is calculated by modifying the lift and drag values in Eqs. (13) and (15) to add the effect of ice onto these local values.

IV. Comparison of Analytical/Experimental Propeller Performance

In the Neel and Bright test, a C-46 twin-engine aircraft was used to quantify propeller efficiency losses as a result of ice formation. Ice was allowed to form on the propeller of the right engine while the left engine propeller was kept clean. Following this procedure, data was recorded for twelve natural icing encounters, and typical efficiency losses of 4–10% were noted. The propellers on the C-46 utilized double-

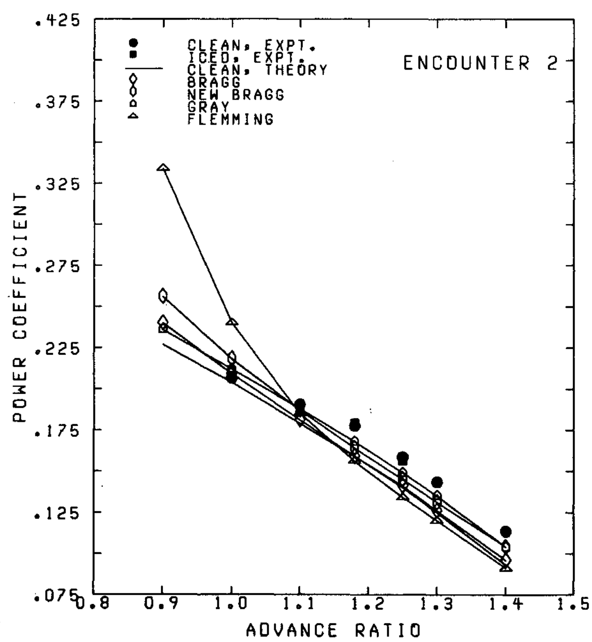

Fig. 7 Variation of power coefficient with advance ratio for clean and iced propeller (iced to $r/R = 0.7$).

cambered Clark-Y airfoil sections.

The Neel and Bright experimental data provided a data base with which to evaluate the iced propeller performance code. For 10 of the 12 encounters documented (Table 2), calculations were performed for the propeller in both clean and iced configurations. The results and the comparison of analytical and experimental performance values are presented here for each of the three correlations employed.

The clean performance predictions were found to agree well with the experimental data for all of the encounters investigated. In all cases, the calculated thrust and power coefficients were found to agree with the corresponding experimental values within an average of 6%. However, since propeller efficiency is essentially a ratio of C_T to C_P, errors of similar magnitude in C_T and C_P may then cancel so that the resulting efficiency values would be much less sensitive to error in performance calculation and would not be as good an indicator

Table 2. Flight and atmospheric parameters for each encounter

Encounter	Propeller RPM	Propeller blade angle at 0.75R (deg)	Pressure altitude (ft)	Icing time (min)	Air temp (F)	Average liquid water content (g/m3)	Average droplet diameter (um)	Radial icing extent (x/c)	Iced propeller efficiency loss %
2	1025	31.8	10000	10	1	0.41	18	.70	1-2
3A	1025	25.8	7000	31	17	0.41	20	.50	4
3B	1025	31.8	7000	31	17	0.41	20	.50	6
4A	1025	25.8	9200	9	3	0.44	25	.40	0
4B	1025	31.8	9200	9	3	0.44	25	.40	8
5	1025	25.8	8200	19	9	0.27	17	.50	4
6	1025	25.8	7500	20	10	0.58	15	.50	4
7	1025	25.8	2000	60	26	0.10	19	.40	1-3
8	1025	25.8	2500	30	20	0.04	9	.50	0
12	1175	28.0	22700	33	−22	0.14	14	.90	5

of analytical prediction accuracy. Therefore, the statements herein relate primarily to thrust and power coefficient calculations rather than to propeller efficiency. Also, the results shown in this work all involved the use of the actual blade angles as measured and reported in the experimental test program. It was found, however, that by increasing the reported blade angle setting by 0.7 deg, much better agreement between theory and experiment could be obtained for all encounters. In addition, the approximate radial icing extent for each encounter was reported by Neel and Bright, and these values were then input for the iced performance calculations. The following discussion details results obtained by each correlation for the several encounters investigated.

Bragg Correlations

Two forms of Bragg's basic rime ice correlation are available in the present computer analysis, as discussed in a previous section of this work. The first of these is a modified form of Bragg's original equation, in which the leading constant was changed from 0.01 to 0.0008, was arrived at by best-fitting the correlation's performance predictions to Encounter 2 data, and was then found to perform acceptably for all other encounters. The second is a more recent correlation proposed by Bragg for conditions in which the product AcE is greater than or equal to 0.004, which includes all of the Neel and Bright propeller data. The original equation has been used herein also, though, for the sake of completeness and comparison with the new correlation's results.

The modified form of Bragg's original correlation was then applied to all of the available Neel and Bright data regardless of assumed rime or glaze ice type, as was Bragg's new form of the correlation. Reasonably good agreement between experiment and theory was obtained using both correlations for all encounters. The newer, unmodified correlation gave results comparable to those of the older form, which was specifically modified to fit the propeller data, indicating that the changes made by Bragg in forming the new correlation improved the quality of the correlation significantly. Thus the drag increments calculated using the more recent equation are generally much less excessive than those obtained with the original equation. In the most severe case (Encounter 12, Figs. 3-5), both correlations seriously overpredict the degree of degradation, especially in terms of C_P, and produce C_P-J curves that inflect upward at the lower advance ratios rather than downward as would be expected.

It should also be noted that Bragg's equations are only for ΔC_d only. The lift coefficient will also generally decrease as a result of ice formation at the leading edge, but this is not accounted for in the Bragg equations. A factor was therefore introduced to provide a simple representation of this phenomenon by assigning the iced section lift coefficient a value equal to 95% of the clean airfoil value. This 5% reduction in lift was arrived at after examining the available iced airfoil data.

Gray Correlation

As was the case with the Bragg correlations, the Gray correlation also provides better performance predictions when the extent of the radial icing is small. It is difficult to make any inference regarding the quality of the correlation under such conditions due to the fact that the propeller is loaded most heavily at the tip and its performance will be most sensitive to geometry changes (i.e., ice accretions) in the tip region. Farther inboard, even quite severe ice growths will have much less effect on the overall performance, and consequently any correlation, regardless of how great the predicted ΔC_d values may be, will appear to work well in low radial icing extent cases. Thus the true measure of the quality of these correlations comes in the more severe icing encounters such as Encounters 2 and 12. In these two encounters, as can be seen in Figs. 3-5 and 6-8, the Gray correlation fails to accurately predict the iced performance, yielding values that overpredict the degree of degradation. The Gray correlation, like those of Bragg, also predicts only the drag coefficient increment, so the same 5% reduction in C_ℓ for the iced configuration was again employed. The Gray correlation itself was unmodified for use in this study, and it is likely that introducing some constant into Gray's equation to affect a constant percentage decrease in its calculated ΔC_d values, as was done with the original Bragg equation, would greatly improve its ability to calculate the iced drag coefficient increment and hence the iced propeller performance.

Flemming Correlations

The Flemming correlations have the ability to calculate ice shedding in addition to ice accretion, so no radial icing extent was input when using these equations. Flemming's correlations may also be used when the radial icing extent is known, and the results obtained using Flemming's correlations with a specified icing extent may be found in a study by Miller.[10] Because the propeller is most heavily loaded at the tip, any changes to the propeller tip geometry such as an ice accretion will have a significant effect on the propeller's performance, as Fig. 9 indicates. It is evident then that any misspecification of the radial icing extent will produce an erroneous iced performance prediction.

Using the Flemming routine to calculate the radial icing extent resulted in an overprediction of this extent for eight of the 10 icing encounters. Also, the equations indicated no icing inboard of the 30% radial location of the propeller for any of the encounters. Because of the overprediction of the icing extent for most of the encounters, the correlations generally yielded an overprediction of the iced performance degradation, as indicated in Figs. 3-8. Yet as Refs. 10 and 11 show, the Flemming correlations in many cases tend to produce drag and lift coefficient increments that are not as severe as those measured experimentally. However, the overprediction of the propeller radial icing extent tends to dominate in this study, resulting in an overprediction of the propeller performance

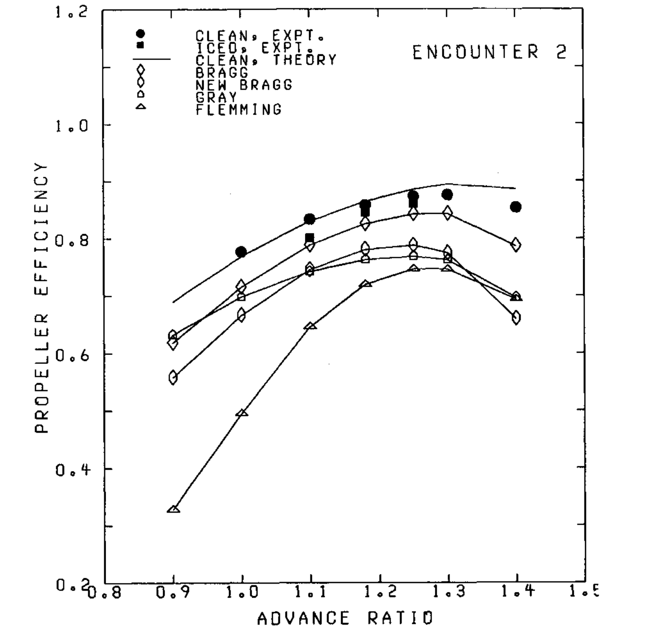

Fig. 8 Variation of propeller coefficiency with advance ratio for clean and iced propeller (iced to $r/R = 0.7$).

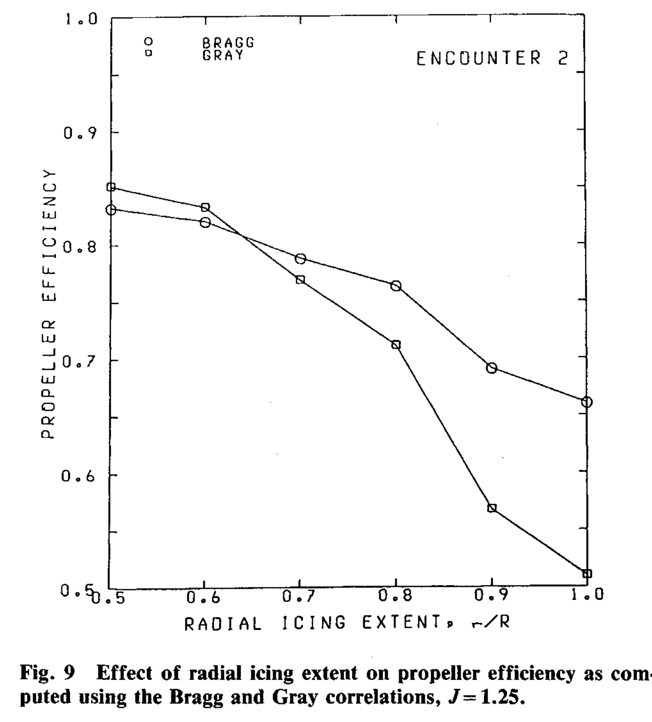

Fig. 9 Effect of radial icing extent on propeller efficiency as computed using the Bragg and Gray correlations, $J = 1.25$.

degradation. Because of the typical underprediction of the drag and lift increment due to icing, it is anticipated that the iced propeller efficiencies calculated using the Flemming correlations would be higher than those measured experimentally when the actual observed icing extent is used, and this indeed has been verified in Ref. 10.

It would appear that the improvement of the shedding equations in the Flemming routine is a necessary next step in improving the predictions generated by the correlations when applied to rotating systems. The results obtained using the present form of the correlations are misleading because of the overprediction of the propeller performance degradation due to icing. It may be assumed that this is due to an overprediction of the drag and lift increments due to icing by the correlations, when in fact the opposite is more common, and the iced propeller performance mismatch generally occurs due to inaccuracy in computing the propeller radial icing extent.

V. Summary and Conclusions

The application of the present computer code to the Neel and Bright experimental data base has provided much insight into the code's performance prediction capability for both clean and iced configurations. The code has been shown to run properly and to produce thrust and power coefficient values accurate within the accuracy limits of the correlations used when the radial icing extent is known and input. Although these correlations computationally represent only a small part of this code, they have a major effect on the output performance predictions.

The results obtained using these empirical lift and drag correlations concurred with the results obtained previously involving these correlations in indicating deficiencies that exist in each correlation. Overall, the Bragg correlations produced the most reasonable drag coefficient increments, but overprediction of iced performance degradation by Bragg's correlations remain a problem, as illustrated in the more severe icing encounters. Ovepredíction also remains a problem with Gray's correlation, whereas Flemming's correlations typically underpredict the aerodynamic coefficient increments[10] but tend to overstate the radial icing extent. Other restrictions and simplifications exist within the code; if they are removed or modified, the code should yield better performance evaluations. The development of a ΔC_ℓ correlation to be used in conjunction with the Bragg or Gray correlations would provide a more precise and complete representation of the effects of ice formation on section aerodynamics. Secondly, the incorporation of some computational mechanism of predicting the transition from rime to glaze ice or vice versa on the blades would enable the code to use the proper correlation at each radial computational station, rather than assuming all rime or all glaze ice in any given encounter. Because of the generally moderate radial icing extent and only slight degree of ensuing degradation, this change will probably have only a very minor effect on the predicted propeller performance. This is in contrast to the helicopter rotor icing situation, in which the radial icing extent and the related performance degradation are typically more severe for a given icing condition.

The present study has also provided insight into the type and accuracy of the experimental data desirable for future test programs. Additional propeller icing data of any type would be useful in further validating and analyzing the code at the present time. Future tests should include, in addition to flight and atmospheric parameters and icing time, the specification of the icing extent as accurately as possible. The values of the radial icing extent presented in this report represent a best estimate of the extent as interpreted from the information in Neel and Bright's report and may possibly vary by 10-20% from the actual extents. Also desirable would be some photographic or other indication of the ice type so that the proper correlation could be applied at each radial location. Finally, the sensitivity of the propeller performance to the blade angle setting has also indicated the need for quite accurate blade angle measurements. Certainly it is desirable to have a high degree of accuracy in the thrust and power measurements as well.

It is evident then that much more two-dimensional validation of the various correlations is necessary before iced propeller performance can be predicted consistently using this method and before the results of this analysis can be fully evaluated. It should be realized that any ultimate analytical treatment of ice accretion on rotating systems will potentially involve much less empiricism than is currently required. The use of these correlations represents an interim approach to the problem, which will continue to be used until more sophisticated analytical procedures such as Navier-Stokes or interactive boundary-layer analyses of iced airfoil flowfields become available.

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