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Ongoing Development of a Computer Jobstream to Predict Helicopter Main Rotor Performance in Icing Conditions

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Abstract

Work is currently underway at the NASA Lewis Research Center to develop an analytical method for predicting the performance degradation of a helicopter operating in icing conditions. A brief survey is performed of possibilities available to perform such a calculation along with the reasons for choosing the present approach. A complete description of the proposed jobstream is given as well as a discussion of the present state of the development.

Nomenclature

A	Damping Length Constant
c_{ij}	Interaction Coefficient Matrix
d_i	Local Ice Thickness, m
E_m	Total Collection Efficiency
f	Freezing Fraction
k^+	Dimensionless Sand Grain Roughness
k_s	Equivalent Sand Grain Roughness, m
L	Mixing Length
m_c	Mass Flow Rate Due To Impinging Liquid, kg/sec
m_i	Mass Flow Rate Which Freezes, kg/sec
m_r	Mass Flow Rate Due To Runback, kg/sec
R	Rotor Blade Radius, m
T_s	Static Temperature, °C
u^o	Inviscid Velocity, m/sec
u_e	Tangential Edge Velocity, m/sec
u_p	Total Normal Velocity Component, m/sec
u_T	Total Tangential Velocity Component, m/sec
u_τ	Friction Velocity, m/sec
v_n	Normal Velocity, m/sec (Boundary Layer Calculations)
V	Freestream Velocity, m/sec
V_N	Wake Induced Normal Velocity, m/sec
V_T	Wake Induced Tangential Velocity, m/sec
x	Distance Along Surface, m
y	Distance Normal To Surface, m
y^+	A Reynolds Number, $y\,u_\tau/V$
α	Total Flow Angle, deg.
α_s	Shaft Angle, deg.
β	Local Collection Efficiency
β_f	Flapping Angle, deg.
Δs	Airfoil Segment Length, m
$\Delta\tau$	Icing Time, sec
ρ_i	Ice Density, g/m^3

δ^*	Displacement Thickness, m
δu_e	Perturbation Velocity Due To Viscous Effects, m/sec
Θ	Kinematic Angle of Attack, deg.
κ	Universal Constant, Also Sweep Parameter
ν	Kinematic Viscosity, m^2/sec
ϕ	Aerodynamic Flow Angle, deg.
ψ	Azimuth Angle, deg.
Ω	Angular Velocity, rad/sec

Introduction

Historically, certification/qualification of a helicopter for flight into known icing conditions has been a problem. This is because of the current emphasis on flight testing for verification of system performance. Flight testing in icing conditions is difficult because, in addition to being dangerous and expensive, many times conditions which are sought after cannot be readily found in nature. The problem is compounded for helicopters because of their small range in comparison to many fixed wing aircraft. Thus, helicopters are forced to wait for conditions to occur in a certain region rather than seeking them out. These and other drawbacks to flight testing have prompted extreme interest in developing validated alternatives to flight testing. One such alternative is theoretical prediction.

Any complete analysis of this problem must be able to perform three calculations:

1) Clean performance of helicopter main rotor;
2) Characterization of the effect of icing on performance;
3) Prediction of ice shedding.

The ability to predict the clean performance of a helicopter main rotor has existed for some time. Traditionally lifting line analyses have been the main vehicle for this calculation but recently Navier-Stokes analyses have become a potential option.

The areas of difficulty lie in the last two calculations: prediction of the effect of icing on performance and prediction of ice shedding. Prediction of the effect of icing on rotor performance is possible using empirically based correlation methods. Until recently, this has been the primary means of determining the effect of icing on rotor lift, drag, and moment characteristics. The empirical methods have the advantage of being very simple and yielding acceptable results for their range of applicability. The main drawback of these methods however, is that they are generally limited in terms of the conditions under which they can be properly applied. Thus, a valid analytical method would have a distinct advantage over the correlations. Two possible analytical tools for determining the lift, drag, and moment change due to ice accretion are the Interactive Boundary Layer[1] (IBL) procedure and Navier Stokes[2] analysis. As with any analytical method both of these require characterization of ice shape in order to perform calculations on the effective airfoil shape. While showing a great deal of promise, the Navier Stokes analyses are all still computationally intensive. The IBL procedure seems appropriate for the task because it is not computationally intensive and requires no grid. Thus, it was decided to use the IBL procedure for the current work.

A great deal of research into the ice shedding phenomena is currently underway. It is hoped that eventually the capability will exist to analytically predict the time and location of shedding events on a rotor. Currently however, prediction schemes still rely heavily on correlation methods.

Proposed Method of Analysis

As discussed earlier, prediction of the effect of icing on the performance of a helicopter main rotor is a complicated task requiring several steps of calculation. Figure 1 shows a flowchart which outlines the various steps. First, the clean performance of the main rotor must be determined as a baseline. Because other codes which will be used in this analysis are two dimensional, a performance code which makes use of blade element theory allows for easy transfer of information. This type of performance code relies on experimental data tables for two dimensional airfoil lift, drag, and moment values which are integrated to obtain the overall rotor performance. Once the clean performance has been determined, the trimmed values of Mach number and angle of attack can be fed into LEWICE[3], the accretion analysis. LEWICE uses an azimuthal average of these values and calculates the ice shapes at various radial locations along the blade. This averaging technique is discussed in more detail in a later section. The new "effective" airfoil shapes are then passed to the IBL procedure which calculates the new lift, drag, and moment characteristics. A check is then made to determine if any shedding has occurred and if so, where. If shedding has occurred, it is assumed that the radial location of the event is now "clean" and has normal lift, drag, and moment values. It should be noted that the process of ice shedding often leaves residual ice still attached to the surface. Currently, no method exists for predicting how much residual ice will remain after a shedding event. The new characteristics are then used by the performance code instead of the original data tables to calculate the "degraded" performance. Although not included in the present study, future efforts will attempt to predict the effects of various deicing/anti-icing systems using codes now under development.[4] The following sections discuss in more detail the calculation procedure for each step.

Helicopter Performance Prediction

The central part of the proposed jobstream is the performance prediction code. Although other methods exist, it has been decided to use Boeing Helicopters' B65 performance code, which uses lifting line theory in its aerodynamic model. Because the code is proprietary in nature, discussion will be limited to a brief description of lifting line theory in general.

Lifting line theory makes use of blade element theory in which the rotor blade is broken into several discrete radial sections. Characteristics are calculated for each section as a function of radial and azimuth location and then integrated to obtain rotor performance values. Each section acts as a steady 2-D airfoil section with three dimensional, compressibility, and unsteady effects, including dynamic stall, usually included as corrections to the overall behavior. Section characteristics are normally obtained as a function of Mach number and angle of attack by use of an empirical set of data tables.

The crux of a lifting line performance code is the calculation of the flow angle of attack over a 2-D slice of the rotor blade. This flow angle is given by

$$\alpha=\phi+\theta \tag{1}$$

where ϕ arises from the purely aerodynamic behavior and Θ comes from the blade aeroelasticity. The aeroelastic behavior of the rotor is usually significant because the high aspect ratio blades tend to be very flexible and respond to the various airloads. A typical velocity triangle for a rotor section is given in Figure 2. Here the total normal velocity component, u_p, and the tangential component, u_T, are given by

$$\begin{aligned} u_p &= V\cos(\alpha_s)\sin\psi+\frac{d\beta_f}{dt}+V_{N_{ind}} \\ u_T &= \Omega R+V\sin(\alpha_s)\sin\psi+V_{T_{ind}} \end{aligned} \tag{2}$$

In a normal calculation the rotational speed, ΩR, and shaft angle, α_s, are known. Thus, the remaining quantities which need to be calculated are the flapping velocity and the normal and tangential components of the wake induced velocity. The values are obtained through various procedures and iterated upon until the desired trimmed thrust level is achieved. A more complete description of blade element theory can be found in Reference 5 and an in depth discussion of a typical lifting line analysis can be found in Reference 6.

Ice Accretion Prediction

A numerical analysis LEWICE[3] has been developed by the NASA Lewis Research Center which has the ability to predict the analytical ice shape which accretes on a given component exposed to an icing condition for a known period of time. This analysis models four critical steps in the icing process, which are:

(1) Flowfield calculation about the component;
(2) Water droplet impingement characteristics;
(3) Heat transfer processes;

(4) Ice accumulation normal to the surface.
Each of these areas are discussed briefly in the following sections.

Flowfield Calculation

Predicting the flowfield about a body which has an accreted ice shape presents several challenges because of the irregular effective airfoil shape which often occurs. The potential flow program developed by Hess and Smith[7] is incorporated into LEWICE. This method makes use of distributed sources, sinks, and/or vortices to describe the flowfield about a body which has been modeled by a series of line segments. Comparisons of results to experimental clean body data have been favorable for the normal ranges of incompressible flow. A potential problem does exist for applying the assumption of incompressible flow to regions near the tip of a rotor blade. It is felt that the high centrifugal forces in this region will cause shedding to occur, especially for warmer temperatures. Thus, this particular limitation is not seen as causing any significant difficulty.

Impingement Characteristics

Of primary importance in any ice accretion analysis is characterization of the region of impinging water droplets. This characterization consists of the limits of impingement as well as the distribution of the mass of the impinging liquid. This is typically obtained by performing an analysis of droplet trajectories from far upstream. Two important parameters which arise are the total and local collection efficiency. The total collection efficiency is defined as the ratio of the total mass of impinging liquid over the theoretical mass of impinging liquid which would occur if all of the droplet trajectories were straight lines. The local collection efficiency is based on the same definition, except that it pertains to a specific location on the body. A pictorial representation of this is given in Figure 3.

The droplet trajectory analysis used in LEWICE is based on the work of Frost, Chang, Shieh, and Kimble.[8] The method has the ability to calculate trajectories and impingement characteristics of an arbitrarily shaped particle. Although generality has been maintained, for this application it can usually be assumed that the particles are spherical and gravity forces are negligible. This simplifies the calculation somewhat.

Heat Transfer Processes

The freezing process is modeled in LEWICE by performing a mass and energy balance on a control volume located on the surface and extending beyond the boundary layer, as shown in Figure 4. Each segment which describes the surface of the accreting component has a corresponding control volume. The runback model first developed by Messinger[9] is incorporated here. An important quantity in this analysis is the freezing fraction which is the ratio of freezing liquid within a control volume over the total amount of liquid entering. The freezing fraction can be expressed as:

$$f=\frac{m_i}{m_c+m_r} \tag{3}$$

Once the temperature and the freezing fraction are known, the mass balance calculates the mass flow of the liquid runback out of the control volume. Any liquid which leaves the control volume is assumed to leave in the direction away from the stagnation point. Surface roughness strongly influences the local heat transfer processes. The equivalent roughness concept is used here. This concept models the actual surface roughness by using an average value which yields the same heat transfer characteristics. This aspect of the analysis is considered a weak point and much effort is being expended to improve the current heat transfer model in general.[10]

Surface Ice Growth

The ice is assumed to grow normal to the surface. The ice growth rate can be defined using the expression for the freezing fraction and is given as:

$$m_i = f(m_c + m_r) \tag{4}$$

This can be redefined to yield an expression for the ice thickness as:

$$d_i = \frac{m_i \Delta\tau \Delta s}{\rho_i} \tag{5}$$

The iced component is then calculated by adding the corresponding ice thickness normal to each matching segment. This results in a new airfoil surface coinciding with the specified icing time.

Calculation Procedure

Using LEWICE to predict a 2-D ice accretion at a specified radial location on a helicopter rotor is not a straightforward calculation. Thus, a brief discussion of the procedure used in this calculation is warranted. LEWICE is a steady state code designed for use on a fixed wing where the velocity and angle of attack are constant throughout a given time step. However, for application to a helicopter in forward flight where the local angle of attack and Mach number are constantly changing some averaging procedure is necessary. A technique developed in 1983 by Korkan, Dadone, and Shaw[11] dealt with this problem. Here, while attempting to simplify the analysis of a helicopter main rotor in forward flight with a rime ice accretion, several methods of averaging were investigated. It was found that if the local Mach number and angle of attack produced by a helicopter performance code were averaged and input into an icing performance degradation analysis the predicted change only differed by ±2% over that of the traditional method of calculating values at specific azimuth locations around the disk. In view of this, a similar averaging technique is employed in the present study. First, trimmed performance values are calculated using a helicopter performance code. The local flow angle at the desired radial location required for trim is then averaged azimuthally. The local velocity is taken to be the rotational velocity at the specified radial location. This is, in effect, the averaged velocity. These values are then used in LEWICE as the velocity and angle of attack. The calculation procedure from then on is carried out as any normal LEWICE calculation using established guidelines given in the LEWICE User's Manual.[3] As shown in Figures 5 and 6, previous comparisons of results obtained using this procedure to experiment have been very good. More in depth comparisons using this procedure are given in Reference 12.

Performance Penalty Prediction

Critical to predicting the performance degradation of an icing encounter on an aircraft is the ability to accurately compute the associated changes in sectional lift, drag, and moment characteristics. Navier-Stokes methods have this ability.[2] However, current Navier-Stokes schemes require a significant amount of computer time. A great deal of research is being performed in this area and as mainframe technology advances and the efficiency of the schemes improve it is anticipated that Navier-Stokes methods will eventually be the means for this type of calculation. However, at the present, a simpler short term solution is needed. The Interactive Boundary Layer (IBL) procedure developed by Cebeci[1] has been chosen for its simplicity and apparent success at predicting drag values. The IBL procedure is attractive in that it does not require a computational grid.

The IBL approach consists of solution of inviscid flow and boundary layer equations which are coupled so that one influences the other. The inviscid calculations are derived from the panel method developed by Hess and Smith.[7] This method models the airfoil and ice shape by a series of line segments which contain distributed source and/or vorticity strength. The set of simultaneous linear equations are solved such that the normal velocity boundary condition at the midpoint of the segments is satisfied. The total normal velocity at each segment midpoint is zero for inviscid flow. When modeling the effects of the boundary layer however, the normal velocity, v_n, is given by the derivative along the surface of the product of the displacement thickness and the tangential velocity, expressed as:

$$v_n = \frac{d(u_e \delta^*)}{ds} \tag{6}$$

This surface blowing distribution has the effect of displacing the dividing streamline outward a distance equal to the displacement thickness. Thus, this approach is equivalent to the classic procedure of maintaining the zero normal velocity boundary condition but redefining the aerodynamic surface to include the displacement thickness. While the Kutta condition still must be maintained, researchers have found that better results are obtained if it is applied to the displacement surface rather than the original surface.

The boundary layer equations for steady two-dimensional incompressible flows are solved with the velocity distribution at the edge of the boundary layer coming from inviscid flow theory. The total velocity distribution can be expressed in terms of the inviscid velocity and the perturbation velocity due to viscous effects:

$$u_e(x) = u_e^o(x) + \delta u_e(x) \tag{7}$$

where:

$$\delta u_e(x) = \frac{1}{\pi} \int_{x_a}^{x_b} v_n \frac{d\sigma}{x - \sigma} \tag{8}$$

The range $x_a \le x \le x_b$ is normally taken to be the airfoil plus two chord lengths downstream. Equation 8 provides an outer boundary condition for the viscous flow calculations and represents the interaction between the viscous and inviscid flow. Equation 8 can be generalized to the form:

$$u_e(x) = u_e^{\kappa}(x) + \sum_{j=1}^{n} c_{ij}[(u_e \delta^*)_j - (u_e \delta^*)_j^{\kappa}] \tag{9}$$

where $u_e^{\kappa}(x)$ is the inviscid velocity distribution containing the displacement thickness effect calculated from the previous sweep. The interaction coefficient matrix, c_{ij}, is obtained from a discrete approximation to the Hilbert integral.

The boundary layer solution procedure is derived from Keller's box scheme. The second order finite difference approximations are written in terms of Falkner-Skan variables. Solutions with separation are computed using the inverse form of the equations. The FLARE approximation of Reyhner and Flügge-Lotz[13] is used which sets the convective term, $u(\partial u/\partial x)$, in the recirculation region to zero. This eliminates the numerical instabilities associated with integrating the boundary layer equation against the direction of local flow. The inaccuracies resulting from this approximation are generally considered small because magnitude of the values of u in the reversed flow region are small compared to the external flow velocity. Although methods exist for improving the numerical method if necessary, no attempt was made to do so here. The finite difference approximations yield a nonlinear system of algebraic equations which are linearized by Newton's method and solved by a block elimination procedure. This procedure is described in more detail in Reference 14.

In order to deal with surface roughness associated with ice the mixing length expression of the Cebeci-Smith model[15] has been modified as

$$L = \kappa(y + \Delta y)\{1 - e^{\left[-\frac{(y+\Delta y)}{A}\right]}\} \tag{10}$$

where Δy is a function of the equivalent sand-grain roughness k_s. Δy can be expressed in terms of dimensionless quantities,

$$\begin{aligned} \Delta y^{+} &= 0.9\sqrt{k_s^{+}} - k_s^{+} e^{-\left(\frac{k_s^{+}}{6}\right)} && 5 < k_s^{+} \leq 70 \\ &= 0.7(k_s^{+})^{0.58} && 70 \leq k_s^{+} \leq 2000 \end{aligned} \tag{11}$$

where

$$k_s^{+} = \frac{k_s u_\tau}{\nu} \tag{12}$$

and

$$\Delta y^{+} = \frac{\Delta y u_\tau}{\nu} \tag{13}$$

The roughness is converted into equivalent sand-grain roughness by using the procedure of Smith and Kaups[16] and assuming the ratio of equivalent sand-grain roughness to the roughness of the applied elements to be a function of the concentration and shape of the roughness elements. More detail on this procedure is given in Reference 1.

Accreted ice on an airfoil can substantially alter the leading edge geometry in a short period of time which causes rapid variations in flow properties. Thus, some difficulty is met trying to obtain acceptable solutions from the inviscid and viscous flow calculations. Thus, "blanketing" and continuation techniques have been employed to minimize this problem. A detailed description of these techniques is given in References 1 and 16.

Work by Shin, *et al*[17] has shown that the IBL procedure can acceptably predict drag values of iced airfoils. Results from that work are shown in Figures 7, 8, and 9. It was found that the IBL procedure had a tendency to underpredict the experimental drag values. This was due in large part to the fact that the theoretical ice shape from which the IBL procedure made its calculations was much smoother than the experimental shape. In any scheme of this nature the quality of the drag predictions will necessarily depend upon the ice shape prediction and the ability to account for roughness.

Ice Shedding Prediction

An icing analysis of a rotating system differs from that of a fixed system in that ice shedding becomes a predominant factor. The combination of centrifugal force and vibratory airloads makes shedding commonplace for a helicopter main rotor. In a general sense, ice shedding occurs when the centrifugal, bending, vibratory, and aerodynamic forces acting on a mass of ice causes the stress within the ice to exceed a critical value. When this critical value is surpassed, failure occurs within the ice and aerodynamic forces carry it away. Since LEWICE provides the ability to predict the ice shape and approximations exist for calculating the ice density, estimation of the centrifugal force acting on a section of ice is possible. Calculation of the stresses resulting from this force can be carried out with levels of complexity ranging from a simplistic approximation to a complete Finite Element Analysis. Considerations such as CPU time and FORTRAN compatibility have led to the decision to use an approximate model. In the present approach, only centrifugal forces are considered in the stress calculations. The stresses resulting from bending, vibratory, and aerodynamic loads are assumed to be small. Ignoring the bending loads is appropriate for this phase of the study because the initial comparisons will be made to powered force model data taken in the NASA Lewis Research Center Icing Research Tunnel. The blades used for this experiment were extremely stiff and it is anticipated that very little bending of the blades actually occurred. Recent work by Scavuzzo[18] has shown that aerodynamic loading can be significant enough for consideration. Future efforts will attempt to include the aerodynamic forces in the overall calculation of shear and normal stresses. Here, the normal and shear stresses are computed based on the ice shape areas provided by LEWICE. Calculations begin at the tip and progress inward towards the hub. Once the stress levels have exceeded the failure stress, it is assumed that all of the ice from that location to the tip sheds away. The calculation scheme allows ice to begin accreting again in the region after the shed.

Determination of the failure stress of the accreted ice is by far the more difficult task. Scavuzzo, *et al*[9] has attempted to experimentally determine the critical shear and normal stresses of accreted ice for various conditions. These results show a strong dependence on surface temperature (above -11 °C) and surface roughness as well as some dependence on wind velocity and droplet size. Historically, as is the case here, these types of experiments have shown a great deal of scatter in the data. Thus, no method currently exists which will absolutely determine when and where a shedding event will occur. Currently, only probabilities of shedding events can be calculated. For the purposes of this study if the probability of shedding is greater than 50% (based on Scavuzzo's data), then the ice is assumed to have shed.

Summary

A method of computing the effects of an icing encounter on the performance of a helicopter main rotor has been proposed. This method makes use of several codes, each of which play a vital part in the overall calculation. The Boeing Helicopters performance code, B65 is used to make the actual performance calculations. NASA Lewis's ice accretion code, LEWICE is used to calculate the shape of the accreted ice at various radial locations along the rotor. The IBL procedure of Cebeci determines the effect of the ice accretion on the lift, drag, and moment characteristics of two dimensional airfoil slices along the radius. Shedding events are predicted by approximating the stresses in the ice along the blade and comparing to experimental data obtained by Scavuzzo. All of the codes, with the exception of the shedding model, have been independently compared with experiment with generally favorable results. Currently, the performance code has been linked with the ice accretion code. Efforts are now underway to complete the jobstream by linking the IBL procedure and the shedding model to the existing performance/accretion code. Once completed, the results will be compared to experimental data obtained in the NASA Lewis Icing Research Tunnel.

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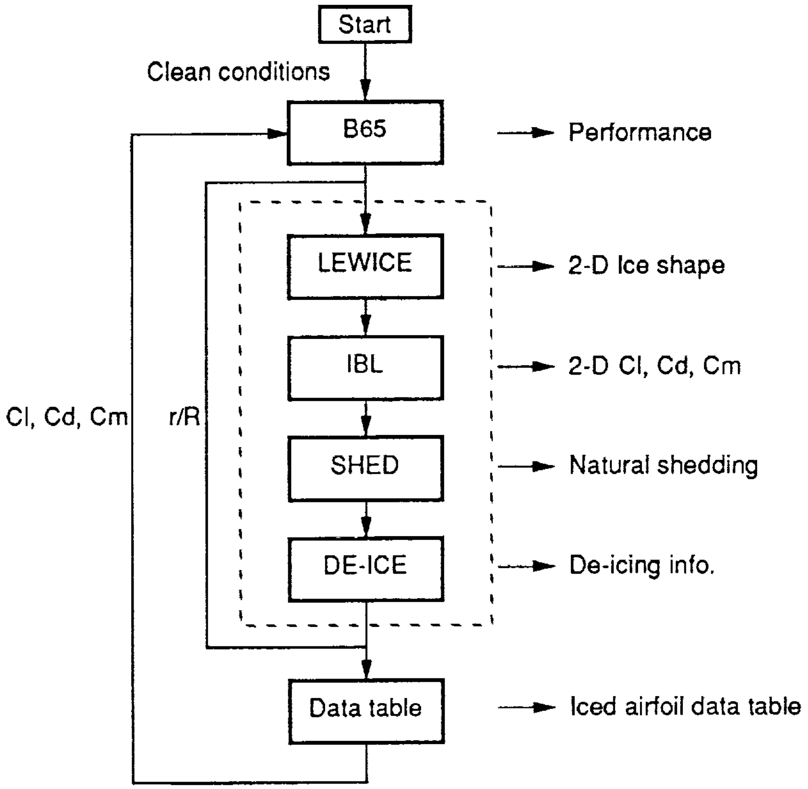


Figure 1.—Helicopter performance in icing prediction jobstream.

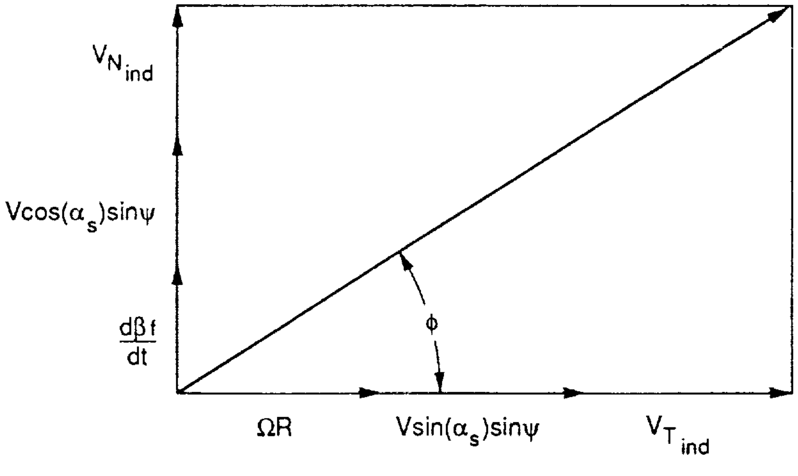
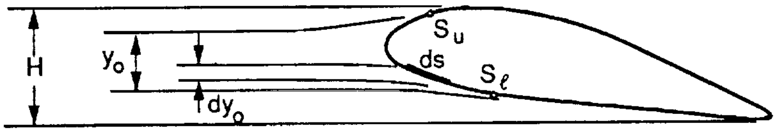


Figure 2.—Blade section velocity triangle.



S_u = Upper - surface impingement limit
S_ℓ = Lower - surface impingement limit
H = Forward projection of the airfoil height

Total collection efficiency

$$E_m = \frac{y_o}{H}$$

$$E_m = \frac{1}{H}\int_{S_\ell}^{S_u} \beta \, ds$$

Total collection efficiency $\beta = \dfrac{dy_o}{ds}$

Figure 3.—Definition of total and local collection efficiency (Ref. 3).

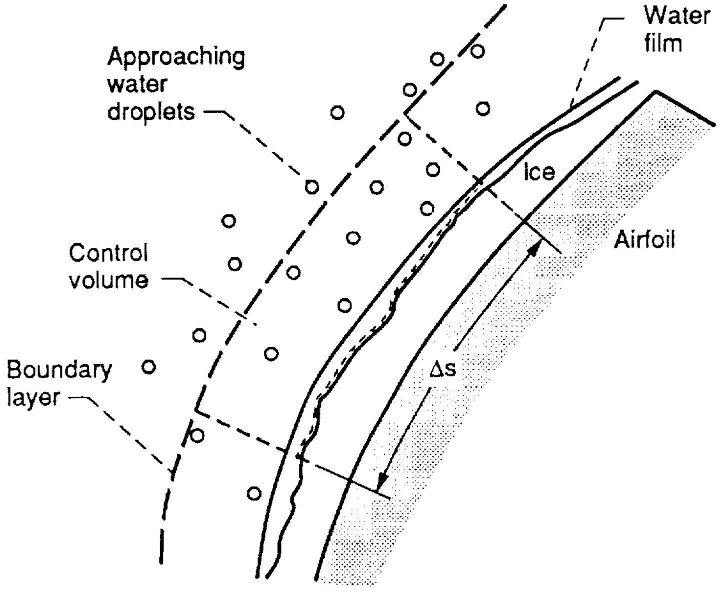


Figure 4.—Control volume on the icing surface (Ref. 3).

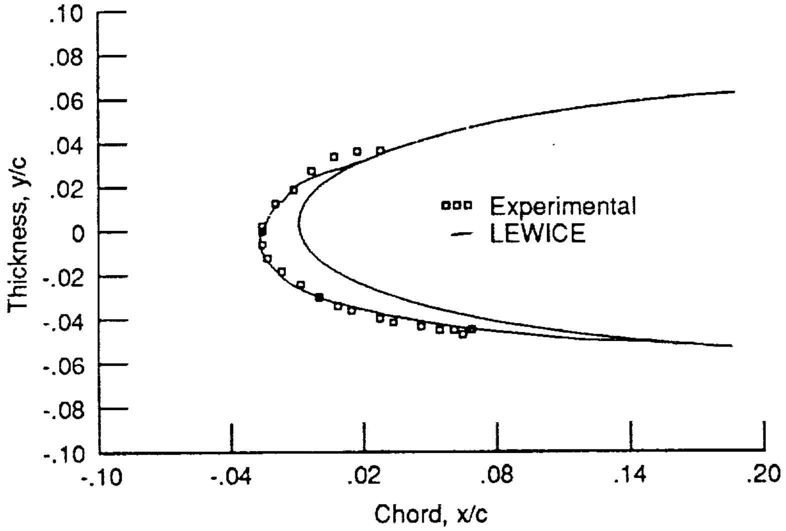


Figure 5.—Comparison between experiment and theoretical prediction of LEWICE. (Ref. 9)

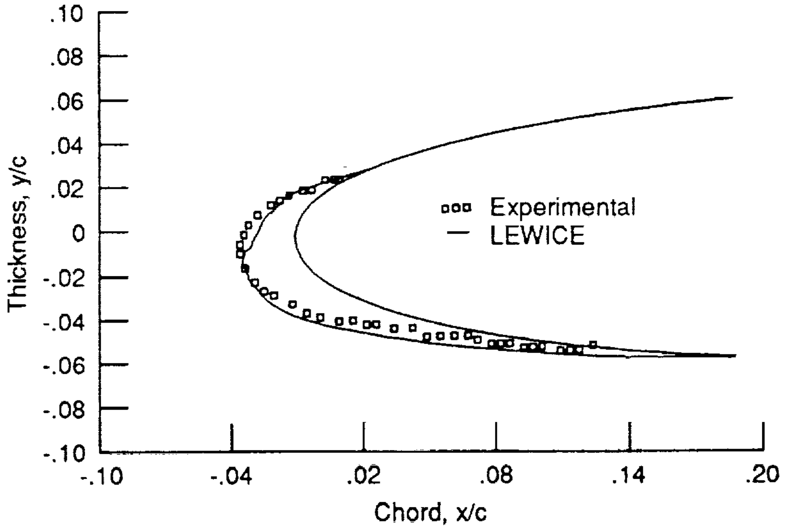


Figure 6.—Comparison between experiment and theoretical prediction of LEWICE. (Ref. 9)

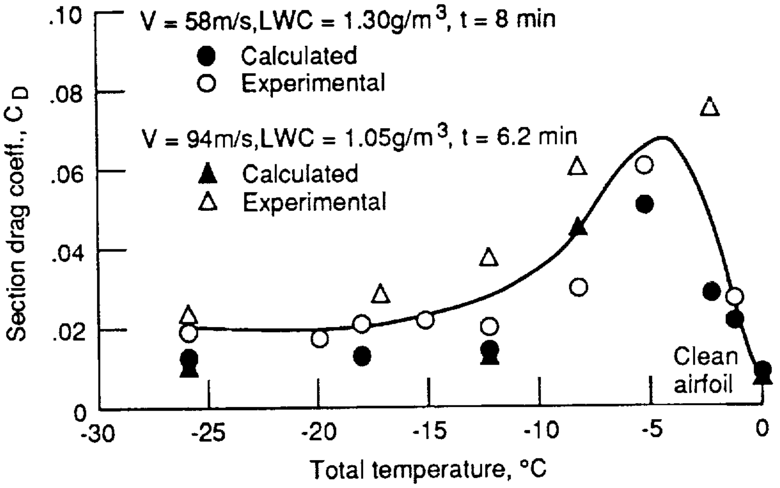


Figure 7.—Comparison between experiment and theoretical prediction of IBL procedure (Ref. 15). (Line is a fit for experimental data).

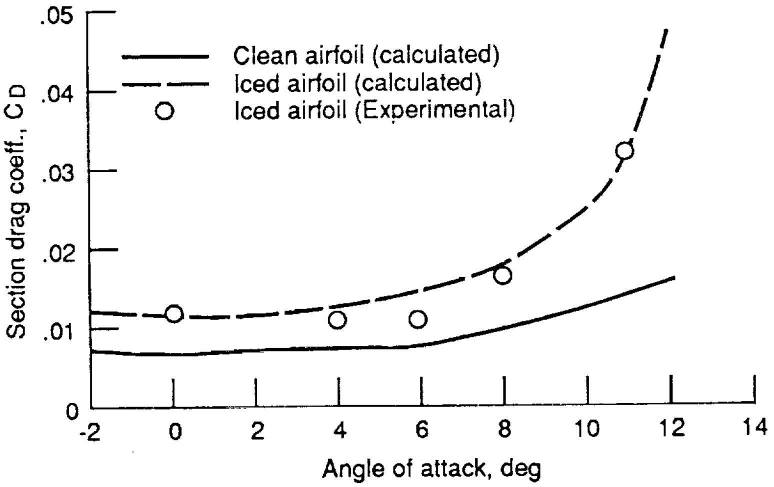


Figure 8.—Comparison between experiment and theoretical prediction of IBL procedure. V = 58 m/sec, T_s = -27.8 °C, LWC = 1.0 g/m3, MVD = 12μm, τ = 5 min) (Ref. 15).

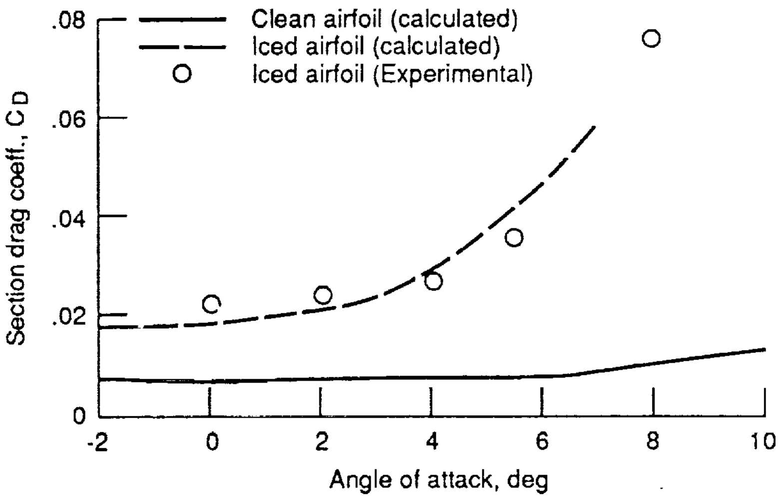


Figure 9.—Comparison between experiment and theoretical prediction of IBL procedure. (V = 58 m/sec, T_s = -9.67 °C, LWC = 1.3 g/m^3, MVD = 20μ m, τ = 5 min.) (Ref. 15)

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16. Abstract

Work is currently underway at the NASA Lewis Research Center to develop an analytical method for predicting the performance degradation of a helicopter operating in icing conditions. A brief survey is performed of possibilities available to perform such a calculation along with the reasons for choosing the present approach. A complete description of the proposed jobstream is given as well as a discussion of the present state of the development.

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