Helicopter Rotor Performance Loss Prediction For Ice Accretion

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ABSTRACT

Ice accretion of rotor limits the helicopter use, so it’s significative to study the helicopter rotor performance loss for ice accretion. CFD is a effective method to research the icing progress. Based on the water droplet flow field conception, the Eulerian two-phase flow model for the air flow containing water droplets is employed to calculate the water droplet collection efficiency. Then the iced progress is simulated with the Gresho thermodynamics model. The calculation result is in good agreement with ice wind tunnel experimental data available, indicating that the method is effective. It’s another important research field to cut out the calculation condition, and the continuous and intermittent icing envelope is based on CCAR 29, Appendix C. The helicopter weight, speed and altitude are on consideration. The blade section effective $\alpha$-$Ma$ loops are described by full helicopter trim, and water droplet collection and icing characteristic is simulated using the present method. By CFD the iced airfoil aerodynamics characteristic and iced rotor performance is predicted. The productions of this paper can be used to direct the icing protection area and control rule design.

INTRODUCTION

Liquid water content (LWC) in the helicopter flight field is usually larger enough for ice accretion. Especially, the rotor system icing will decrease the helicopter performance, change the stability, destroy the control character. So it is dangerous to fight in icing condition, and it is important to research the rotor icing and the performance loss.

Usually, there are three ways to research the rotor icing problem: flight test, wind tunnel scaling model test and numerical simulation. Flight test and wind tunnel test is difficult, dangerous and expensive because of providing the icing conditions, and we could not provide all icing environment in full flight Envelope. Compared to the forward two ways, the advantage of numerical simulation is attractive. It is faster, safer, cheaper to study rotor icing by numerical method, and we can gain any icing conditions that we may match in nature flight.

Any complete analysis of ice problem must be able to perform two calculations:
1) Clean performance of helicopter main rotor.
2) Characterization of the effect of icing on performance.

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 and recently Navier-Stokes analyses have become a potential option. The areas of difficulty lie in the second calculation: prediction of the effect of icing on performance. Prediction of the effect of icing on rotor performance is possible using empirically based correlation methods. 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. Navier-Stokes analysis tool is a preferred chosen for determining the lift, drag, and moment change. As with any analytical method both of these require characterization of ice shape in order to perform calculations on the effective airfoil shape, it is necessary to predict the ice shape.

In this paper, we use CAMRAD II code to predict the clean performance of a helicopter main rotor. Than the iced airfoil aerodynamic characteristics were used to instead of the clean airfoil aerodynamic characteristics with C81 format, and the iced rotor performance can be calculated by CAMRAD II. So a complete analysis of rotor icing problem should be able to perform five calculations:

1) Cutting out the calculation condition;
2) Calculation the blade section effective α-Ma loops;
3) Simulation of the airfoil icing progress;
4) Performance prediction of iced airfoil;
5) Prediction of iced rotor performance.

Cutting out the calculation condition

Within the flight envelope, there are so many flight conditions that it is to difficult to calculate the every icing process. It’s most important to cutting out the calculation condition, and in flight envelope four major parameters may be distinguished:

1) Helicopter weight;
2) Flight speed;
3) Flight altitude and environment temperature.

After investigation combinations of these parameters, the maximum weight, normal weight and minimum weight should be considered in hover and forward flight. For the calculation of iced rotor performance it’s necessary to consider hover-flight mode, and for the calculation of the boundary of water droplet impingement and blade ice accretion it’s necessary to consider forward-flight mode. Every helicopter has its own design and use altitude, so it is appropriate to consider which altitude as the calculation point, sea level or altiplano.

Calculation the blade section effective α-Ma loops

It is difficult to calculate the rotor icing progress directly. We should translate the 3D rotor icing problem to 2D airfoil problem. So it is necessary to gain the airfoil’s angle of attack and airflow speed. 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. Section characteristics are normally obtained as a function of Mach number and angle of attack. Examples of the effective α-Ma loops are shown in figure 1 for main rotor and figure 2 for tail rotor.
Simulation of the airfoil icing progress

CFD is an effective method to research the icing progress. Based on the water droplet flow field conception, the Eulerian two-phase flow model for the air flow containing water droplets is employed to calculate the water droplet collection efficiency. Then the iced progress is simulated with the Gresho thermodynamics model. In our icing process simulation method, we defined six postulations as:

- Droplets are carried by the air, but they have their own weight and inertia;
- While the air affects the droplets, the particles are too small and too dispersing to affect the flow;
- The droplets have globular shape, and they never distort and break up in the motion process;
- The droplets never impact each other in the motion process;
- Mass exchange or heat exchange between droplets and air never occur in the motion process;
- The force acting on a droplet are drag, gravity, and buoyancy only.

The droplet flow control functions were defined as:

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}_d) = 0$$  \hspace{1cm} (1)

$$\frac{D(u_d)}{Dt} = \frac{C_p}{24K} (u_d - \mathbf{u}_d) + (1 - \frac{\rho_d}{\rho}) \frac{g}{Fr^2} = 0$$ \hspace{1cm} (2)

Where:

$$Re_d = \frac{\rho_d d u_d}{\mu}$$; \hspace{0.5cm} \(K = \frac{\rho_d d^2}{18 \mu_d}\)

An important parameter that controls accretion on a surface is the local collection efficiency, \(\beta\), defined as:

$$\beta = \frac{\alpha \rho (u_d \cdot n)}{\alpha_{\infty} \rho} \mathbf{u}_{d,\infty}$$ \hspace{1cm} (3)

Where:

- \(\beta\) is water droplet collection efficiency;
- \(\alpha\) is the local droplet volume factor;
- \(\alpha_{\infty}\) is the droplet volume factor in far field;
- \(u_d\) is the local droplet velocity;
- \(n\) is the normal direction of the surface;
- \(u_{d,\infty}\) is the droplet velocity in far field.

Firstly, a icing wind tunnel test condition is chosen to simulate. The icing process simulation method is checked up by comparing the calculation result with the experiment data. The test case conditions are documented in table 1.

### Table 1  Conditions for the prediction of ice accumulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Velocity m/s</th>
<th>Attack Angle °</th>
<th>Temperature °C</th>
<th>Altitude m</th>
<th>MV D (\mu m)</th>
<th>LWC g/m³</th>
<th>Total Time s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>120.0</td>
<td>7</td>
<td>-15.0</td>
<td>3000</td>
<td>40.0</td>
<td>0.8</td>
<td>300</td>
</tr>
</tbody>
</table>

Note: MVD is mean volumetric diameter

LWC is liquid water content

Figure 3 shows the LWC distribution and steam line distribution. In the figure, the yellow field marking A is the where the droplet distribution doesn’t interact by airfoil. The blue filed marking B is where the droplet never arrival at, and the red field marking C is were the LWC larger then far filed.

Figure 4 is the water droplet collection efficiency curve, and the highest \(\beta\) appears
at stagnation point near the leading edge of airfoil.

Figure 3  The water droplet stream line

Figure 4  water droplet collection efficiency

Figure 5 is the ice shape from icing wind tunnel experiment, and figure 6 is the ice shape from icing process simulation using present method. The calculation result is in good agreement with ice wind tunnel experimental data by comparing Figure 5 and Figure 6, and it is shown that the method is effective. They so are similar that we can trust the method is accurate enough to obtain the ice shape.

Now, we have a effective ice shape calculation method and the effective $\alpha$-$Ma$ loops of blade sections, so there is no clog on the way to obtain every blade section’s ice shape for every special flight condition by numerical simulation.

Performance prediction of iced airfoil

For iced rotor performance loss prediction, we need the aerodynamic value of the iced airfoils. We also can gain the value by wind tunnel test or CFD method. In the present method, CFD is chosen.

A) grid generation

For accurate performance prediction of the clean airfoil and iced airfoil, the high quality grid is needed. Using structured grid is good for the improving the computation precision. So the structured grids follow a C-topology with sufficient point density to capture flow features resulting from the ice shape on the leading edge. The clean and the iced airfoil’s CFD grids have same point density to establish consistency in the comparison of performance data. The grid point density is sufficient, so the solution is independent on grid. Representative grids around the leading edge are shown in Figure 6.
B) Clean airfoil Performance prediction

Performance degradation due to ice accumulation is quantified by differencing iced and clean performance predictions from Navier-Stokes CFD solvers. The CFD code is a structured finite-volume solver with Spalart-Allmaras model for turbulence. To check the CFD solution, predicted clean airfoil performance is compared with the experiment data from wind tunnel. For lift, the prediction methods give us exact results and agree very well with measurements for conditions before attack angle of stall, and the angle at which stall occurs is well predicted; For drag, calculation results agree well with measurements also before Drag divergence angle, and for moment the CFD solution is accurate on the value and turnover point. So we can thrust in the CFD solution can be used to predict the airfoil performance.

C) Iced airfoil Performance prediction

Performance prediction of iced airfoils is more challenging. In this exercise, the chosen shape is fairly large to be representative of a precarious ice growth, though it is only one of many different shapes that can be encountered. The lift characteristics of the iced airfoil and clean airfoil are shown in Figure 12. Compared to the clean airfoil, there is a noticeable reduction in the lift curve of iced airfoil, and the stall angles at each Ma reduce obviously. The performance degradations also show on
drag increase and moment range of flat curve.

For helicopter airfoil, Lift-Drag Ratio is a key parameter to evaluate the performance. Compared of Figure 11 and Figure 11, it is shown that the airfoil performance is reduced obviously because of ice accumulate. The Maximum Lift-Drag Ratio is larger then 85 for the clean airfoil, but only 15 for the iced one.

**Prediction of iced rotor performance**

Compile the CFD results of the iced airfoil to famous C81format, and instead of the clean airfoil aerodynamic characteristics, iced rotor performance can be gained by CAMRAD II like clean rotor performance.

**Conclusions**

A method of computing the effects of an icing encounter on the performance of a helicopter rotor has been proposed. This method makes use of several codes, each of which play a vital part in the overall calculation.

CAMRAD II code is used to computing the...
rotor performance and the blade section’s effective $\alpha$-Ma loops, and it’s the foundation of ice process simulation. The icing simulation code is used to simulate the icing process. It’s the key part of this paper. The Prediction ice shape is agree well with shape from icing wind tunnel experiment.

An CFD code is used to computing the clean airfoil and iced airfoil performance. The clean airfoil performance is agree well with experiment data, too. CAMRAD II code is also used to computing the iced rotor performance by using the C81 format table of iced airfoil instead of clean airfoil.

REFERENCES


