Back to Session Subjects

THE ROLE OF ANALYSIS IN THE DEVELOPMENT OF ROTOR ICE PROTECTION SYSTEMS

J T Cansdale, R W Gent, N P Dart

Mechanical Sciences Sector
DERA, Farnborough, UK

Abstract

Full all weather operational capability continues to be an important priority for both military and civil rotorcraft. To meet this need, icing protection must be provided for the rotor systems. This paper discusses the issues to be addressed in designing rotor de-icing systems and shows how advances in the development of validated computational modelling can contribute to the design and qualification process.

A range of computer codes is described, covering the accretion of ice on the blade, the behaviour of electro-thermal de-icing systems, and the effects of ice on the aerodynamic characteristics of the blade and hence on overall aircraft performance. Example results from each code are presented to illustrate their capabilities and experimental evidence from natural icing trials, particularly recent trials involving the EH101 helicopter, is shown for comparison.

It is concluded that a useful suite of codes for modelling the various aspects of rotor icing and ice protection as well as the behaviour of helicopters in icing is now available in DERA and can play a valuable role in the design and qualification process. In particular, their use during development and in service in addressing various fault or failure conditions of the de-icing system is demonstrated. Limitations are discussed and proposals made for future improvements.

1. Introduction

The capability for operation of rotorcraft in icing conditions remains an important but largely unfulfilled aspiration. As piloting aids, sensors and other systems mature, icing will become an increasingly important issue in the achievement of a true all weather operational capability for rotorcraft. In order to provide a full icing capability, protection must be provided to a number of areas and components including engine intakes, windscreens, aerials, etc, but it is the rotor systems which present the greatest challenges. Electro-thermal de-icing systems have been under development and test for several decades (e.g. Ref 1) but a very small number of helicopter types have achieved full icing qualification to either civil or military certification specifications.

Although a number of alternative systems have been considered for rotor ice protection, the electro-thermal de-icing method remains the favoured solution. Anti-icing, as applied to many fixed wing aircraft wings, might appear more attractive but it is clear that the power required for such protection of a rotor would be prohibitively high.

In designing a rotor de-icing system, a number of issues need to be addressed:

- the chordwise extent of the upper and lower surfaces of the blade which needs to be protected.
- the rate at which ice will accrete on the blades, the form of the ice and hence the degree of aerodynamic degradation.
- the disposition and power density of the heated areas on the blade.
- the control of heating of individual areas of the blade, for instance in duration and sequencing, so as to minimise overall power consumption, maintain rotor balance, and minimise water run-back and refreezing in unheated areas.
- the effect of the heating elements integrated within the blade on structural temperatures and hence structural integrity, paying particular attention to potential fault and failure conditions such as voids within the blade structure and de-icing system control errors.

Although the primary concern is with the main rotor, protection of the tail rotor requires similar considerations.

This paper reviews the range of analytical methods which have been developed and investigated by DERA to address these issues and draws on natural icing flight trials data obtained during winter 99/00 on an EH101 helicopter in Halifax, Nova Scotia. The paper concentrates particularly on the thermal modelling of blade heater mats and its validation against flight test data.

2. Blade Ice Accretion

2.1 General

The modelling of blade ice accretion is done in two stages, addressing firstly the impingement of water on the blade surface and secondly the thermodynamic process of freezing of the water to form ice. Underlying both are aerodynamic calculations to derive data such as the flow field around the blade and the local conditions on the blade such as pressure distribution and heat transfer coefficient.

2.2 Water Impingement

Codes have been developed and validated for calculation of the rate of impingement of cloud water droplets on the blade surface. These are based on the classical 2-D models developed for fixed wing application, using integration of the droplet trajectories adjacent to the aerofoil surface. In the case of the helicopter rotor, 2-D analysis is retained based on mean velocity and angle of attack. A blade element model of the rotor system is used to estimate appropriate local mean aerodynamic angles of attack for the specific flight conditions. The standard tool used by the DERA to calculate the water catch characteristics is the TRAJICE2 (Ref 2) prediction code which provides output data in the form needed for input either to ice accretion calculations or to the blade de-icing code described below. Extreme values of speed and angle of attack may be used to calculate the limits of catch on the blade surface, as guidance in deciding the heated regions for a de-icing system.

2.3 Ice Accretion

Once the aerodynamic and water catch conditions have been determined, a number of codes are available to calculate ice accretion characteristics. These perform a full heat balance and water mass balance calculation sequentially from the stagnation point around the chord of the blade, making appropriate allowance for the compressible flow in the kinetic heating and evaporative cooling terms. Local rates of ice growth and hence accretion rate and shape are derived.

The basic DERA accretion code is TRAJICE2 which uses steady state 2D conditions. Former studies using a DERA code entitled CYBLACC (Ref 3) have shown that the cyclic variation of local velocity (v) and aerodynamic incidence (α) have only minimal net effect on the form of the ice accretion although as noted above, it is important to account for the full variation in v and α from the point of view of determining the catch limits. Another refinement of the analysis which has been assessed is allowance for a fully compressible flow field in determining trajectories. A code named HOVACC (Ref 4) was used but the effects were found to have minimal effect on the water catch distribution and limits. The simpler methods of TRAJICE2, with its lower computing overhead, have thus been found to be suitable for a wider range of conditions than originally expected and this code is therefore used as the standard starting point for rotor icing and de-icing calculations.

2.4 Accretion Results

Fig 1 shows a typical set of calculated trajectory results for an EH101 main rotor blade at 70% rotor radius.

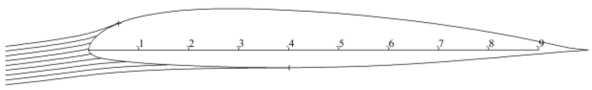

Figure 1. Impinging droplet trajectories on an EH101 rotor blade.

Fig 2 illustrates the different forms that the ice can take, depending on the variables such as velocity, outside air temperature (OAT) and the liquid water content (LWC) of the icing cloud.

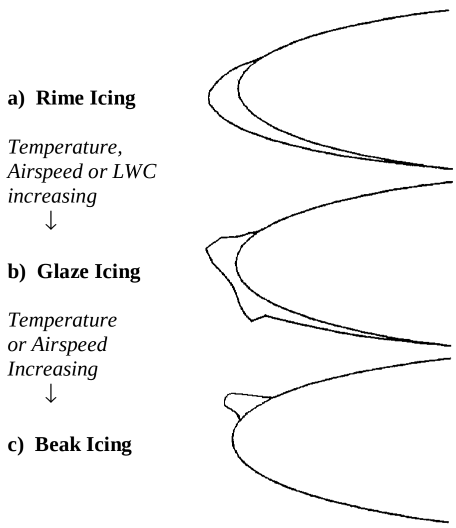

Figure 2. Various categories of ice that may form on helicopter rotor blades.

Fig 3 shows a correlation of the spanwise extent of stagnation line ice as predicted by CYBLACC and as seen during Wessex natural icing trials on the lower surface of the rotor.

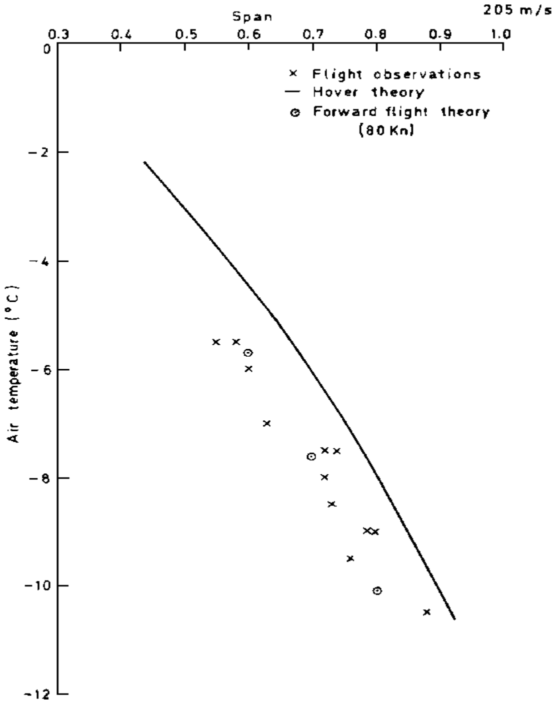

Figure 3. Stagnation line icing threshold as a function of rotor span.

The spanwise extent of ice is a valuable criterion by which to judge the accuracy of the modelling methods. The limit arises from the increase in velocity and hence kinetic heating as a function of span. Whilst the other heat fluxes which contribute to the overall thermodynamic balance will also be dependent on the spanwise variation of conditions, the kinetic term will eventually become dominant to the extent that no freezing of impinging water can occur. This is most obvious along the leading edge of the blade. On the upper surface of the blade aft of the leading edge, the aerodynamic expansion of the air (and water vapour) in the suction region has the effect of reducing kinetic heating and enhancing evaporative cooling, so that ice growth may extend further spanwise in this region, in the form of a ridge or beak of ice (see Fig 2).

Supporting evidence for this has been seen from rotor-head photographs during EH101 icing trials as shown in Figure 4 (published courtesy of Westland Helicopters Ltd). In particular, the beak ice in the suction region can be seen extending along the straight portion of the blade and just on to the 'notch' of the BERP tip.

Figure 4. Ice accretion on an EH101 BERP rotor blade.

In Figure 5 a comparison is shown of the spanwise extent of ice measured post-run on a model rotor (Ref 5) against that predicted by the DERA helicopter performance in icing code HPI (Ref 6, also described in more detail in section 4.2). Two curves are shown for the predicted limit of ice accretion, which refer to the extent at which ice forms at the stagnation line and the extent of beak ice. Since beak ice forms as a result of the aerodynamic characteristics of a rotating blade, it is likely to disappear when the rotor is stopped and the measurements of ice extent are made. Hence, the measured extent of ice should lie somewhere between the two predicted limits, as is the case indicated in fig 5.

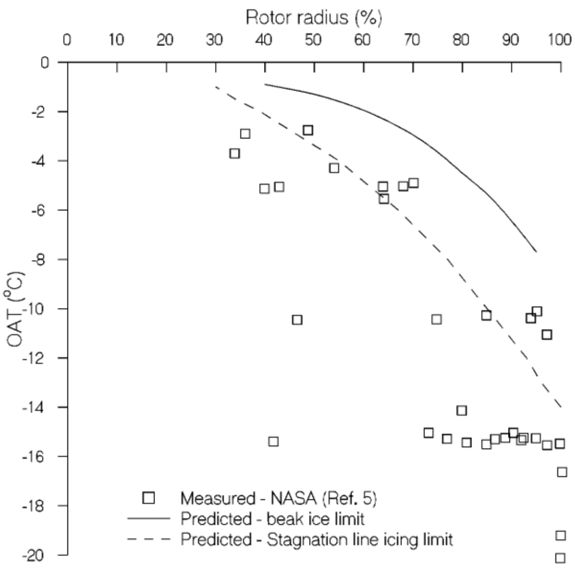

Figure 5. Predicted and measured spanwise extent of ice accretion on a model rotor.

The ability to calculate accurately the extent of ice both spanwise and chordwise, as well as its shape and its rate of growth, is an essential starting point in addressing the design requirements and performance of a rotor de-icing system. Firstly these icing parameters will govern the way in which the performance of the helicopter is degraded by the ice (as discussed in section 4 below) and secondly they must be accounted for in the design of the blade de-icing system and its control.

3. Electro-thermal De-icing Systems

3.1 Rotor de-icing system configuration

Understanding where and at what rate ice will form on the blade, and knowing the effect of that ice on the critical aerodynamic characteristics, is only the starting point for designing and certifying an ice protection system. Though new forms of ice protection continue to be researched experimentally, electro-thermal methods remain the primary option for rotor de-icing.

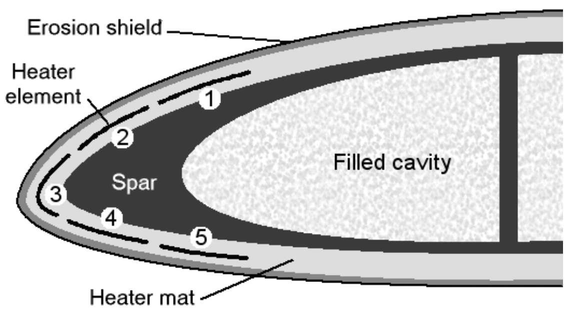

Figure 6. Typical layout of a rotor blade de-icing system (not to scale).

Fig 6 shows the cross-section of a typical electro-thermal installation within a main rotor blade. Three spanwise heater elements are arranged to give primary coverage to the leading edge, with elements further aft around the chord to deal with run-back ice. A major design driver is the need to minimise the electrical power requirement of the overall system and this leads to the sequencing of heater energisation not only around the chord but also between blades or spanwise divisions of blades. On a four bladed rotor, it is conventional to heat two opposite blades and then the other two, so as to maintain balance. On a five bladed rotor, balance is more difficult; one solution is to divide the blade into inboard and outboard spanwise sections and to de-ice these in a sequence. A further complication is the need to protect the tail rotor. This may be by anti-icing (i.e. continuous heating), or by de-icing, with its energisation built into the main rotor sequence. Experience has shown that the overall effectiveness of the system is strongly dependent on sequencing and timing the energisation of individual heater elements as a function of external conditions such as OAT and LWC. Typically, the time of energisation of each individual element (the so-called "on-time") is controlled as a function of OAT, whilst the order in which the elements are heated and the time for which areas of the blade are left unheated are functions of both LWC and OAT. The control is a compromise between de-icing the blades soon enough to avoid undesirable performance degradation but allowing time for a sufficient mass of ice to grow to ensure that aerodynamic and centrifugal loads produce clean shedding. The rearmost elements, numbers 1 and 5 in Fig 6, are used to remove run-back ice, that is ice formed by run-back and refreezing of melt water created during the de-icing of the leading edge. These elements will be heated less frequently.

3.2 System modelling

Modelling of the blade de-icing system requires representation of both the boundary conditions on the outside surface, i.e. the icing heat balance described above, and the thermal characteristics of the blade structure itself. It also requires criteria to be defined for the shedding of the ice as the bond between the ice and the blade is heated. DERA has developed a code named HRB2D (Ref 7) for use in modelling the behaviour of an electro-thermal rotor de-icing system, incorporating these features. The model, based on a finite difference representation of the structure and attached ice layer, includes full representation of the external conditions on the iced surface. A finite difference, rather than finite element, method has been chosen since it is more amenable to inclusion of the non-standard external boundary conditions.

Fig 7 shows the basic physical model used for a typical electro-thermal de-icing system. On the outer surface is the conventional metallic erosion shield - typically made from stainless steel, nickel or titanium. Below this is a layer of adhesive which bonds the erosion shield to the heater mat assembly, the latter consisting of resistive heater elements incorporated within layers of composite material, normally of glass fibre / epoxy. Below the heater mat structure is another adhesive layer which bonds it to the main spar of the rotor. In modern rotors the spar is typically a multi-layered composite construction, using carbon and/or glass fibres in an epoxy matrix.

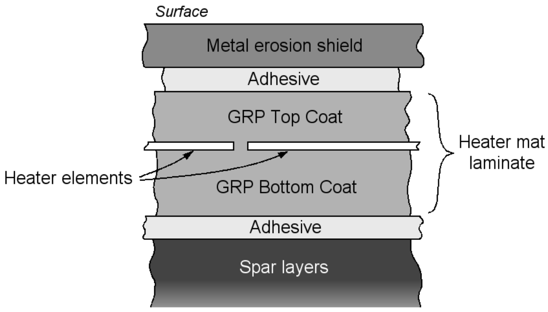

Figure 7. Cross-section showing the layer construction of a typical rotor blade de-icing system.

The aim of the DERA model is to represent the transient flow of heat from the element both to the outer surface of the blade (including an ice layer if appropriate) and to the inner structure and the cavity within the spar which may be hollow or filled with foam. The model also allows for the lateral heat conduction at the edges of each heating element. Heat conduction is therefore modelled in the directions normal and parallel to the heating strips.

As noted above, the external surface is subject to the icing condition, with a resultant complex heat transfer process. The equations for heat transfer under icing conditions as used in TRAJICE2 have been applied, with minor modifications, to the transient heat transfer problem. The equations enable the surface (ice or blade) heat transfer to be characterised into three distinct conditions, namely:

- icing, with surface temperature below 0˚C (rime icing conditions)
- icing, with ice surface temperature at 0˚C (glaze ice conditions)
- non-icing, with blade surface temperature above 0˚C, but with a wetted surface.

In practice, the thickness of the ice layer will vary with both surface position and time.

Another important physical feature of de-icing systems is the ice shedding process. When the blade-ice interface temperature is raised to 0˚C, melting will occur and a water layer will be formed. The degree of melting necessary to achieve ice shedding will depend upon several factors such as the surface width of the melt zone, the thickness and hence the loading (both aerodynamic and centrifugal) on the ice, and the adhesive / cohesive strength of the ice still attached to the blade. It is thus a complex, two-dimensional issue which is difficult to model accurately, particularly when shedding may be assisted by torsional and flapwise bending of the rotor blade during flight as well as by centrifugal loads.

All these issues have been addressed in developing the DERA HRB2D code, with use of approximations in some cases in order to avoid over-complexity and hence unacceptable computational burdens. A fundamental approximation is the representation of the blade structure by flat layers. This would appear to be reasonable for calculations at the flank positions which show a resemblance to stacked plates (see Fig 6) but would seem a poor assumption for heat conduction calculations near to the leading edge where there is both variation in the thickness of the composite layers and a high degree of curvature. In practice, however, the relatively poor conductivity of epoxy-based composite materials results in significant temperature transients occurring within a relatively thin layer close to the surface and so limits the inaccuracies resulting from this approximation (Ref 8). This conclusion has now been justified by experimental measurements obtained during EH101 icing trials in Canada in 1999/2000, as described below.

3.3 Correlation of modelling with experiment

The de-iced rotor blades of the EH101 trials aircraft were fitted with internal temperature sensors incorporated within the adhesive layers above and below the heater mat structure, as shown in Fig 8.

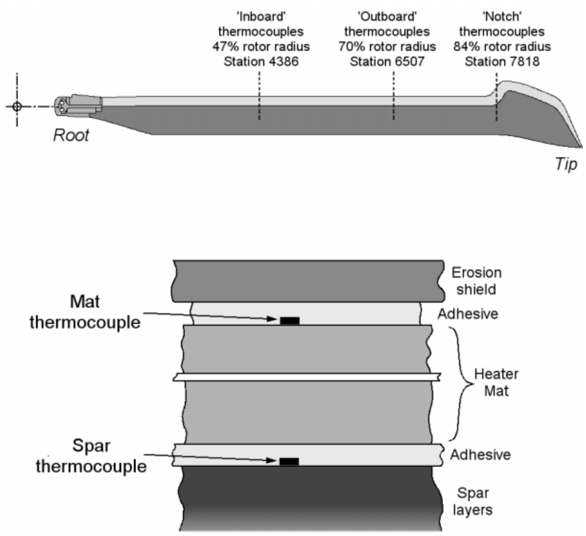

Figure 8. Location of rotor blade thermocouples used during EH101 1999/2000 icing trial.

In setting up the model for comparison with trials data, one of the crucial considerations was the precise position of these temperature sensors. The combination of high heat fluxes and low thermal conductivity through the composite and adhesive materials create steep temperature gradients, sufficient to give a significant difference between a sensor at the inner boundary of the adhesive layer and one at the outer boundary. Inspection of the assembled blade to determine sensor positioning was not feasible. To overcome this problem, an iteration was undertaken in the initial correlation exercise to generate a best fit between prediction and experiment. The sensor locations giving this best fit were then used in all subsequent comparisons and gave sufficiently good correlations to give a high level of confidence in both the derived sensor positions and in the modelling itself.

Measured time histories of blade temperature at station 6507 (refer to Fig 8) during cyclic operation of the heater mats are shown in Fig 9. The corresponding predictions using HRB2D code are also shown. It should be noted that the thermocouple located beneath element 5 was unserviceable at this station. Axis labels have been removed at the request of Westland Helicopters Ltd. As a guide, the y-axis intervals are in 5°C increments.

It can be seen that a very high level of agreement has been achieved, giving considerable confidence in the modelling methods.

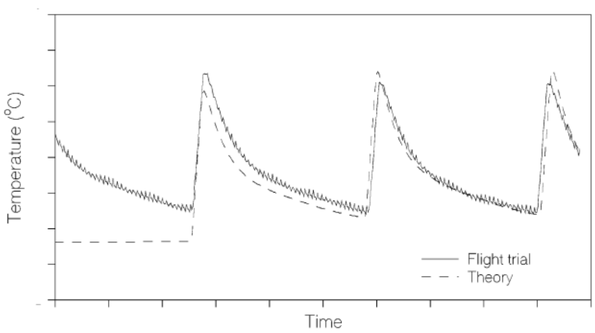

Figure 9(a). Element 1.

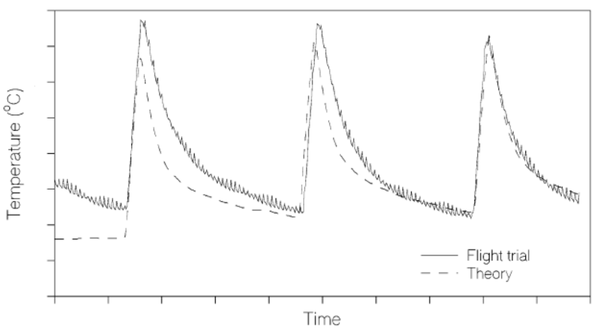

Figure 9(b). Element 2.

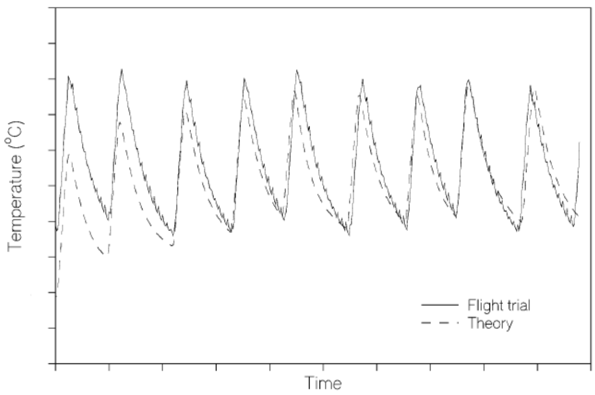

Figure 9(c). Element 3.

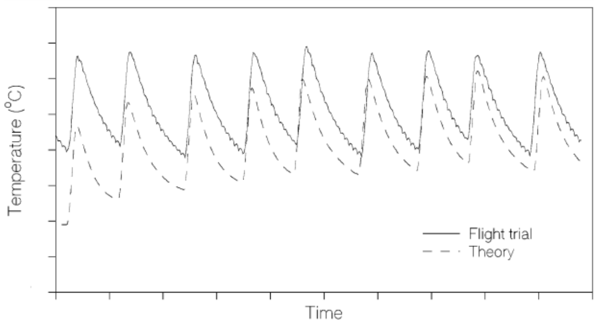

Figure 9(d). Element 4.

Figure 9. Comparison of calculated temperatures and those measured at the top of the spar layer during Flight 680 of the 1999/2000 EH101 icing trial. (LWC = 0.4g/m^3, OAT = -10°C).

Comparisons should be focussed on the temperature histories towards the end of the calculation, rather than at the beginning where predictions are expected to be poor. This is because the flight trial data is obtained midway through an icing encounter where conditions have stabilised. However, the initial conditions for the HRB2D calculations have the modelled rotor blade structure set to the ambient temperature. During the first few heating cycles, the spar acts as a heat sink and the mean cyclic temperatures are low. Stable temperature cycling is only obtained towards the end of the calculation when the thermal inertia is overcome.

Figure 9 shows only a small sample of the calculations performed. Similar comparisons between measured data and HRB2D predictions were obtained for other flights, where icing conditions were different. A comparison of predicted and measured peak temperatures at the outboard spar thermocouple locations is summarised in Fig 10.

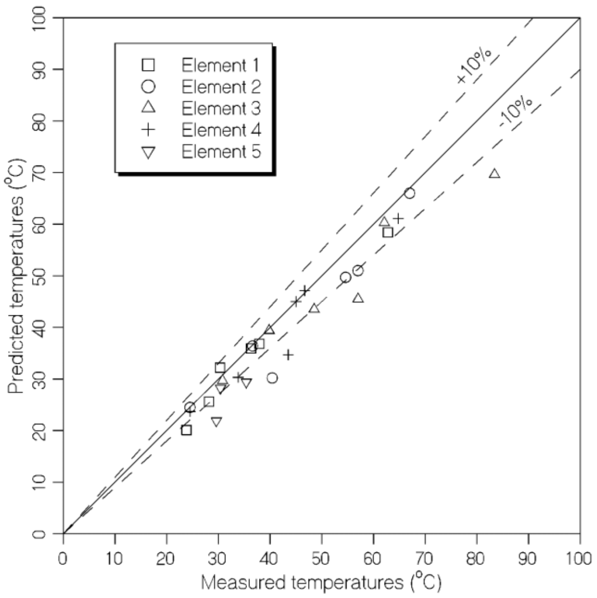

Figure 10. Comparison from six different flight conditions of calculated and measured peak temperatures at the outboard (70% rotor radius) spar location.

The solid line in Fig 10 represents the line of perfect agreement. It can be seen that most of the predicted peak temperatures agree within ±10% the measured flight test data. In assessing the accuracy of the theoretical calculations it is important to consider the following:

- The thermodynamic behaviour during de-icing will be affected by tolerances associated with the manufacture of heater mats, including thermal uniformity, which may be typically as high as 10%. A 10% change in power intensity has been shown to result in an equivalent change in peak temperature attained within the structure (Ref 9). Therefore, peak temperatures may vary by ±10% due to local variations in the heater element manufacture.

- Manufacturing tolerances associated with the rotor blade build, particularly the thickness of the film adhesive layers, will generate a discrepancy between the theoretical model and the actual rotor blade. The adhesive layer will be further distorted by the inclusion of the thermocouples.

Considering these factors that affect the agreement between calculated and measured temperatures, it can be concluded that the accuracy of HRB2D predictions is very good.

3.4 Applications of the modelling methods

The original motivation for development of the HRB2D model was for optimisation of heater mat intensities and understanding of the sensitivity of the de-icing performance to variations in materials and construction of the blade. However it is now apparent that the model has other valuable contributions to make during the design and certification process.

In practice, various faults can arise during the manufacture and service life of a blade and during system operation. These include the following:

- delamination or de-bonding between layers, particularly between the erosion shield and the heater mat. This may result in an increased thermal barrier between the heat source and the outer surface of the blade, with the result that more heat is conducted inwards leading to internal structural temperatures above those expected in normal operation. Depending on the magnitude of this effect and the characteristics of the matrix material this can have structural integrity implications.

- manufacturing variability, for instance in the local electrical resistance characteristics and hence heating power intensity of the heater mats. This can have implications to the effectiveness of the de-icing function, and in extreme cases could result in excessive internal structural temperatures.

- controller errors or faults, leading to conditions such as extended energisation of a particular mat, or failure to heat a mat within a sequence. The former may lead to excessive internal structural temperatures, with structural integrity implications. The latter may degrade the de-icing function over a localised region of one blade, resulting in performance degradation and possible rotor imbalance.

All such imperfections and failures should be assessed within the qualification process, and limits for acceptable build standard and operation established. This is not a problem which may be tackled reasonably by experiment, especially not as a flight test exercise since it will have safety implications. The modelling capabilities of HRB2D are ideally suited to addressing these issues.

Fig 11 shows the predicted effect of a localised air void above a heating element on the temperatures on the outside of the blade and at a point within the internal structure. It will be seen that heating of the outer surface, on which the ice shedding function is dependent, is significantly degraded by the presence of the void. On the other hand, the internal spar temperature is notably higher than normal.

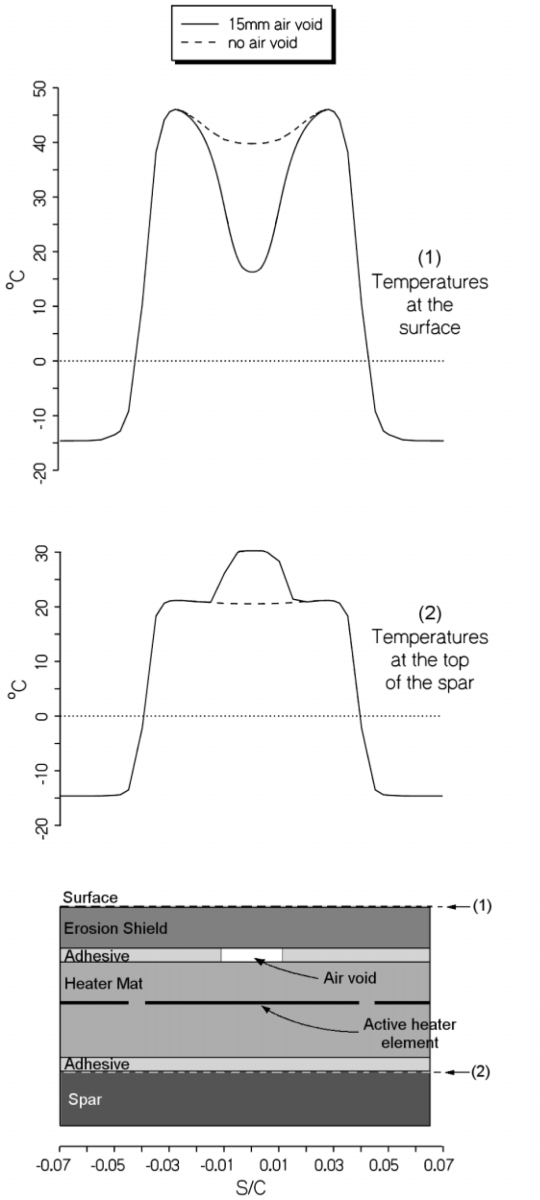

Figure 11. Typical effect of an air void on internal and surface rotor blade temperatures (after 10 seconds of heating).

Calculation of the effect of a controller failure resulting in extended heating of an element is relatively straightforward. Fig 12 shows the effect on internal spar temperature of one heater mat being energised for twice the nominal time. It is seen that significantly higher temperatures are reached than in the normal cycle. Such a condition could cause permanent damage to the blade structure. This analysis capability can have a role in assessing the potential damage to a blade subsequent to a known control failure and may be the basis for a judgement as to whether or not to repair or scrap a blade.

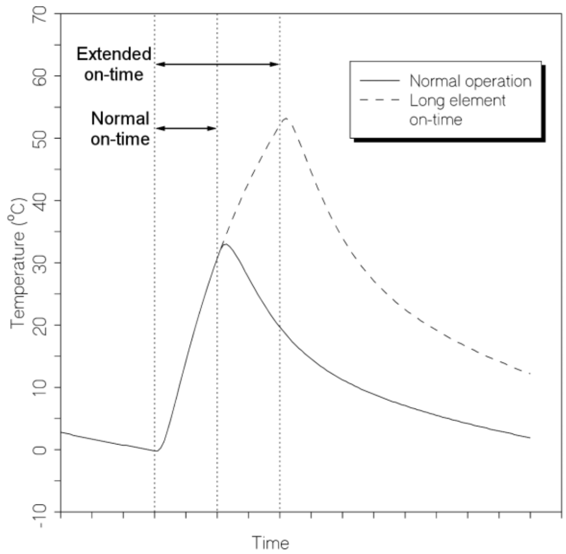

Figure 12. Predicted spar temperatures for a typical controller fault, resulting in an extended heating time.

4. Rotor Performance in Icing

4.1 Aerofoil characteristics

The primary aim of installing a rotor de-icing system is to limit the effects of icing on the rotor aerodynamics and hence on the overall vehicle performance. The features of rotor performance of greatest interest and relevance are increase in torque, loss of lift and control, particularly through premature stall, and increased control system loads resulting from changes in the pitching moment characteristic (also often associated with stall). It has long been known that C_L, C_D and C_M can be degraded by ice but quantification of the effects is more difficult. Tunnel testing has been carried out by several researchers on a range of representative ice shapes in combination with rotor aerofoils (see for instance Refs 10 and 11) and some empirical guidelines have been derived. However tunnel testing is expensive and a potentially more cost effective approach is to use CFD methods. In a previous ERF paper (Ref 12), Dart described the assessment of a range of CFD codes for predicting the performance of an aerofoil deformed by a simplified shape representing a glaze ice accretion, as shown in Fig 13.

Since then, a further unsteady Navier Stokes code, PMB2D (Ref 13), has been tried on the same test case. Results using this, together with results from the Navier-Stokes code evaluated previously are shown in Figs 14 and 15.

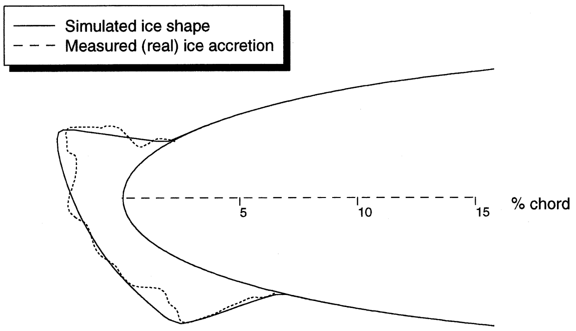

Figure 13. The simulated ice shape selected for this investigation and the measured ice shape on which it was modelled.

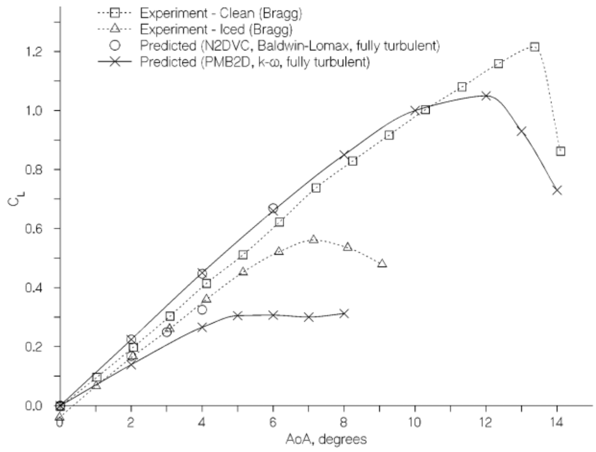

Figure 14. Predicted iced aerofoil lift using two Navier-Stokes CFD codes.

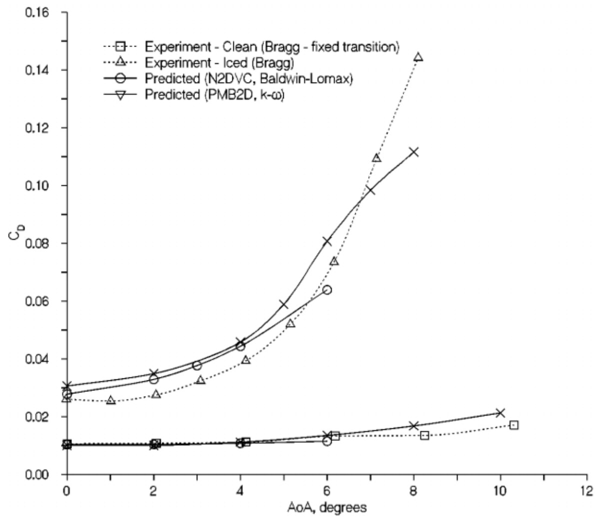

Figure 15. Predicted iced aerofoil drag using two Navier-Stokes CFD codes.

It will be seen that the general characteristics of the degradation are predicted by the CFD codes, although agreement in detail could be better. The loss of aerofoil maximum lift due to ice accretion has been particularly difficult to predict. Even if the immediate difficulties in using CFD modelling on this simplified ice shape are overcome, issues associated with real ice, such as surface roughness and irregularities in shape, will have to be faced. This field of modelling is of interest to both the rotary and fixed wing communities and is being pursued in a collaborative programme under the auspices of GARTEUR.

4.2 Vehicle performance

In parallel with the iced aerofoil characteristics activity, DERA has been pursuing a more pragmatic approach to the prediction of overall air vehicle performance in icing, using empirically based expressions to quantify the aerodynamic degradation. These expressions have been derived from wind tunnel tests such as those described in Refs 10 and 11. A DERA helicopter performance model has then been modified by the addition of two modules. The first calculates the spanwise extent of rime, glaze or beak type ice accretion along with the corresponding ice thickness at given spanwise positions after a given time in icing. Ice thickness values are appropriate to either the stagnation line (for rime and glaze) or to the upper surface (0.01 - 0.07 s/c) close to the leading edge for beak ice. For simplicity, the icing calculations are based on mean conditions, with no allowance for the cyclic variation in parameters which occurs during forward flight. The second module translates the calculated ice form into an increase in profile drag coefficient and a reduction in lift coefficient, by use of the empirically based expressions mentioned above. These data are then used within the vehicle performance model.

Figs 16 and 17 compare measured and predicted stabilised torque values for Puma Mk 1 and EH101 helicopters respectively, during natural icing trials with unprotected main and tail rotors. Results for a range of ambient temperatures are shown.

In general the correlations are encouraging. However a significant difficulty in making this comparison is in the quality of the experimental data. Natural icing clouds are never homogeneous and variations in icing severity with both position and time will occur. Whilst some account can be taken of this if sensitive instrumentation is used to measure the icing parameters of the cloud, in practice considerable uncertainty will remain. Nevertheless the results to date are seen as encouraging in indicating correct trends, for instance with ambient conditions. It is believed that the methods should enable early assessment of the likely sensitivity of helicopter performance, particularly power requirements, to the degrading effects of icing. This understanding can then be used in assessing the required characteristics of rotor de-icing systems, for instance in terms of the time which can be allowed for ice accretion between de-icing cycles.

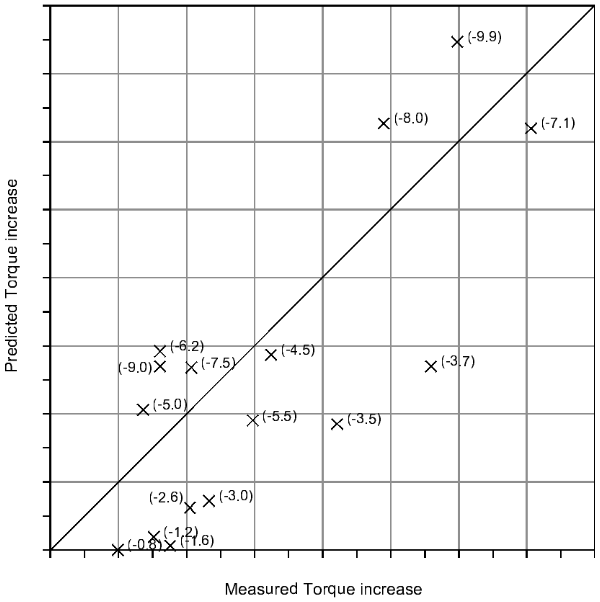

Figure 16. Comparison of stabilised torque increase due to icing against results from flight trials for Puma Mk 1 (OAT values in brackets, °C)

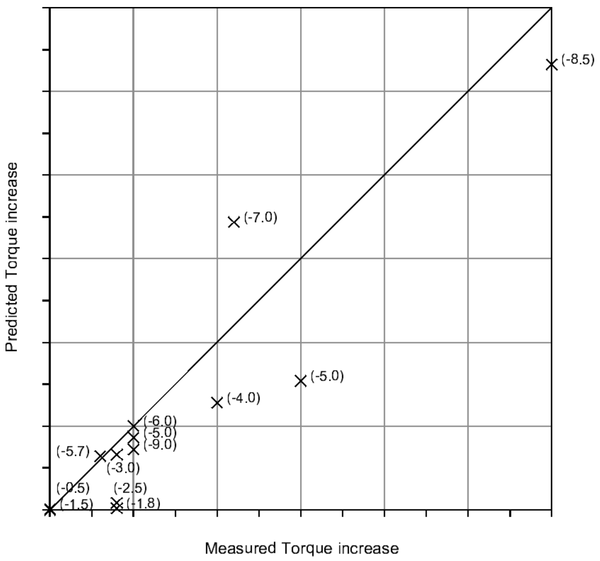

Figure 17. Comparison of stabilised torque increase due to icing against results from flight trials for an EH101 with the ice protection deactivated (OAT values in brackets, °C).

5. Discussion / Conclusions

The recommendation for an icing clearance usually requires several winter test campaigns in order to encounter an adequate range of icing conditions to give confidence in the clearance. Such trials are extremely expensive, and because they rely on nature providing the test conditions, will often fail to provide the full coverage needed to generate confidence in system performance throughout the required operational envelope. Although, for the foreseeable future, flight test experience will remain essential in the granting of icing clearances, the use of predictive modelling is now becoming feasible as a means of bringing insight into the sensitivity of the performance of a particular helicopter design to icing conditions and in assessing specific features of the design of ice protection systems. The models may also allow a degree of extrapolation to be undertaken to conditions not found during experimental trials. It is axiomatic that the relatively extreme icing conditions imposed by design specifications will be difficult to find in practice. An example of this extrapolation capability available now from the models is in the assessment of blade structural temperatures resulting from the longer energisation times needed in extreme low temperature conditions; this may be the driver for the system design but will inevitably be difficult to find in the natural environment. In the future, the incorporation of icing into overall vehicle performance codes may allow extrapolation from trials experience to flight and atmospheric conditions beyond those encountered.

Overall it is concluded that the suite of icing codes now available in DERA has reached a sufficient state of maturity and validation that it can be employed usefully within the design and qualification of rotor protection systems.

6. Next Steps

Further refinement of the ice accretion models for helicopter rotors will require test data of a higher quality than that currently available, particularly in terms of the detailed ice profiles. In practice acquisition of such data is difficult since it must rely heavily on in-flight measurements. An alternative is to test a Mach-scaled model rotor in an icing tunnel. This would permit assessment of effects such as the cyclic variations of pitch and speed in forward flight, skewed flow over the front and rear of the disk and centrifugal effects on the flow of water on the blade surface.

A limitation of the current modelling of the rotor de-icing system behaviour is in the prediction of the convective heat transfer coefficient on the blade. The present calculation is based on a rough surface assumption, which is appropriate to an iced surface but may result in excessive values for clean conditions such as those in clear air or in a running-wet state. Over-prediction of external heat loss can result in a consequent underprediction of internal temperature within the blade. The calculation of convective heat transfer coefficient is a key step in both the icing and de-icing modelling and is worthy of further refinement.

Refinement of the prediction of rotor performance in icing will rely on better data for iced aerofoil characteristics. Ideally this should be through improved CFD methods. As noted, this is an area which is of interest to both the fixed wing and the rotary wing aircraft communities and is the subject of active research in several countries. However the difficulty of representing fully the macro and micro features of the ice, both of which are highly relevant to the aerodynamic performance of the aerofoil, should not be underestimated. Validation of the codes will require a higher quality of trials data in terms of both the atmospheric conditions and their effects on the helicopter. For the latter, it is now feasible to compute baseline rotor performance predictions in real time, using measurements of flight state parameters, and hence by comparison with measured values such as rotor torque to compute directly the rotor degradation due to icing. The detailed data which could be obtained in this way would be suitable for correlation with instantaneous measurements of cloud parameters or with the cycling of the rotor de-icing system.

7. Acknowledgement

The research and development of computer codes for the analysis of rotor icing that have been reported in this paper were funded largely from UK MOD Defence Research Package 3d, Tri-Service Helicopters. Additional funding for some of the aerodynamic performance calculations and recent developments of the TRAJICE2 code have benefited from funding by the UK DTI, under the CARAD III programme.

Much of the experimental data shown in this paper and used previously to validate the computer codes was supplied courtesy of Westland Helicopters Ltd.

8. References

1. J T Cansdale — "Helicopter Rotor Ice Accretion and Protection Research." Vertica, Vol 5, pp 357-368, 1981.

2. R W Gent — "TRAJICE2 - A combined water droplet trajectory and ice accretion prediction program for aerofoils." RAE technical report 90054, 1990.

3. R W Gent — "Ice accretion prediction on aerofoils." 1st Bombardier International Workshop, Montreal, Canada, 20-21 September 1993.

4. R W Gent — "HOVACC – An aerofoil ice accretion prediction program for steady, two-dimensional compressible flow conditions". RAE technical report 88052, 1988.

5 R J Flemming, T H Bond, R K Britton — "Results of a sub-scale model rotor icing test." AIAA Paper presented at 29th Aerospace Sciences Meeting, Reno, 1991.

6. — "A review of icing research at the Royal Aerospace Establishment." AGARD conference proceedings 496, published December1991.

7. R W Gent — "HRB2D - A computer program for the detailed design and assessment of electro-thermal rotor ice protection systems." DRA/AS/STD/TR95027/1, 1995.

8. D Guffond, R Henry, J J Reinmann, W Wright, R W Gent — "NASA/ONERA/DRA Collaboration on icing research, Part 3: Electrothermal de-icing system modelling." ONERA technical Report 2/7766 PN, June 1993.

9. N P Dart — Unpublished DERA work.

10. R W Gent, R H Markiewicz, J T Cansdale — "Further Studies of Helicopter Rotor Ice Accretion and Protection." Vertica, Vol 11, pp 473-492, 1987

11. R W Gent, A R Beauchamp — "Measurement of drag increase due to ice accretion on aerofoils of NACA0012 and RAE 9645 section." RAE technical report 87013, 1987.

12 N P Dart, P O'Brien — "Analysis of iced aerofoil performance using CFD codes." Paper presented at 23rd European Rotorcraft Forum, Dresden, Germany, 1997.

13 M R Allan — "Application of PMB2D unsteady Navier Stokes solver for estimation of iced aerofoil performance." DERA/MSS/CR980544, 1998.