ARTIFICIAL ICING FLIGHT TRIALS ON THE EH101

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Abstract

This paper describes the artificial icing trials carried out on the EH101 rotorcraft earlier this year using the US Army Helicopter Icing Spray System (HISS), of which the primary objective was to demonstrate the capability of the rotor ice protection systems at the most severe icing conditions.

An overview of the rotor ice protection system operation and design icing environment is given. A summary of the extensive testing, analytical modelling and natural trials work carried out leads to a discussion of why this evidence was insufficient to offer a complete icing release against the vehicle specification and the requirement for artificial icing trials.

A description of the HISS operation, limitations and test methodology is presented including an explanation of the effective LWC factor, which was derived to account for the width of the rotor disc being larger than the width of the icing cloud.

The results are summarised and a description is given of an analytical extrapolation technique that was developed which uses modelling tools, correlated against test data, to expand the clearance further than the available trials evidence.

The paper concludes by presenting the revised capability of the EH101 rotorcraft for flight into known icing conditions

Units, Symbols & Abbreviations

Units

g	Grams
m	Metres
kn	Knots
°C	Degrees Celsius

Abbreviations

ATTC	Aviation Technical Test Center
APU	Auxiliary Power Unit
ISDS	Ice and Snow Detection System
LWC	Liquid Water Content ($g.m^{-3}$)
MVD	Median Volumetric Diameter (μm)
OAT	Outside Air Temperature
RADS	Rotor Analysis & Diagnostic System
RIPS	Rotor Ice Protection System

Introduction

The AgustaWestland EH101 rotorcraft is a medium lift, multi-role, all-weather capability vehicle that has been designed to allow the aircraft to operate in known icing conditions as defined by UK DEFENCE STANDARD 00-970 (Ref 1).

The trials described in this paper were carried out on a production Search and Rescue variant of the EH101, currently owned and operated by the Canadian Department of National Defence (Fig 1).

Figure 1 – EH101 SAR Variant

Background

Design Icing Environment

The icing conditions in which the system is designed to operate are defined by UK Defence Standard 00-970 (Ref 1). The environment is defined by a maximum LWC that can exist continuously (stratus cloud) and periodically, for short duration (6km in every 100km), rise to a higher maximum LWC (cumuliform cloud). These limits are denoted "Continuous Maximum" and "Periodic Maximum" respectively. The LWC limits vary with temperature and are displayed graphically in Fig 2.

Ref 1 requires the rotorcraft to be capable of continuous operation in the Continuous Maximum condition and requires the rotorcraft specification to specify the duration required for operation in the Periodic Maximum condition, which for the EH101 SAR variant is 15 minutes.
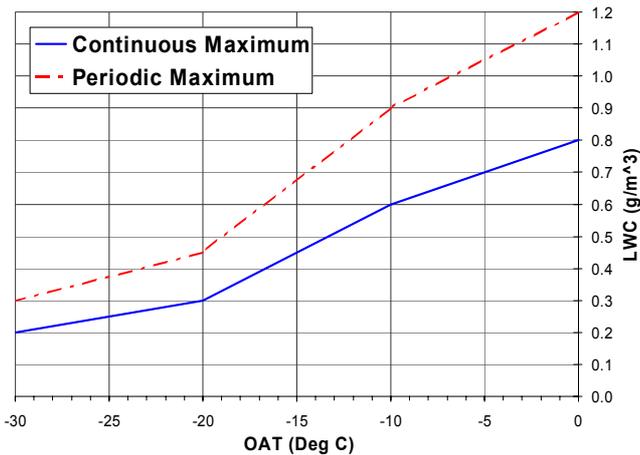
Figure 2 - DEF-STAN 00-970 Icing Environment

Description of RIPS

The Rotor Ice Protection System (RIPS) comprises a single controller that governs the operation of electro-thermal heater elements in both the main and tail rotor blades.

The main rotor ice protection system is a de-icing system with five chordwise heater elements around the leading edge covering approximately 20% chord and separate inboard and outboard zones, changing at approximately 55% rotor radius. The element heating sequence and on-times are dependent on OAT, and off-times between cycles are dependent on LWC.

The tail rotor ice protection system is a running wet anti-icing system comprising a number of heater elements that operate simultaneously at the same power density covering the leading edge of each tail rotor blade. A temperature sensor, embedded in one tail rotor blade, is used to control the temperature of the system and ensure the elements do not overheat the blade structure.

EH101 Experience in Icing Conditions

Throughout development, the EH101 aircraft systems have been tested by various methods to establish their performance during operation in icing conditions.

Ice protection systems have been developed in conjunction with icing windtunnel testing. In particular, the RIPS underwent four phases of icing windtunnel testing with oscillating blade specimens to simulate the cyclic pitch variations.

3 natural icing trials have been carried out, the first during the development phase of the aircraft and two further trials with the aircraft in a production configuration. The conditions achieved from these trials are displayed graphically in Fig 3.

The rotor ice protection system has been subject to analysis using modelling tools in order to predict the peak blade temperatures during operation of the system. This analysis was validated using data recorded from temperature transducers mounted within the blade during the natural icing trials.

Throughout the natural icing flight trials, the amount of airframe ice accretion was measured with a Vernier Accretion Meter. The maximum cumulative measurement in a single flight was 173mm.
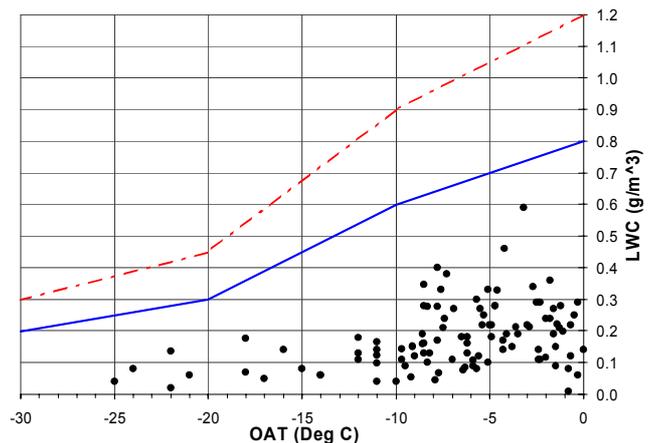
Figure 3 – EH101 Natural Icing Test Points

Further Evidence Required

It is not surprising that the conditions experienced in the natural icing trials did not cover the full envelope as the limits of the design icing environment are based on containing the 99.9[th] percentile of all icing conditions experienced in the data used to compile the requirements. Thus, it follows that there is a 0.1% probability of achieving test points at the limits of the envelope in the natural icing environment.

However, the evidence gained in the activities described in the previous section is sufficient to substantiate safe operation throughout the design icing envelope for most aircraft components. The application of an ice accretion limit and a rate of descent limit is required to mitigate the risk of damage from shed ice.

It was deemed necessary to test the rotor system to the extremes of the envelope. Due to the complex dynamic and aerodynamic behaviour of the rotor system, the windtunnel testing was not sufficient to provide sufficient data on which to base a release to service. While modelling tools exist to predict the performance of the RIPS, these are not yet mature enough to provide sufficient extrapolation data across the entire envelope, as would be required for the EH101. Further flight test data was therefore required to provide substantive data to demonstrate satisfactory performance of the RIPS.

Due to the cost of a further natural icing trial, combined with the unlikely probability of achieving the desired test points, the decision was made to carry out an artificial icing trial with the EH101.

Artificial Icing Conditions

Various facilities exist which are capable of in-flight simulation of an icing condition. All of these create an artificial cloud by atomising water through a matrix of nozzles that is suspended behind a tanker aircraft in forward flight. At ambient temperatures below 0°C the water droplets rapidly become super-cooled and a simulated icing condition is achieved. Most systems currently in use provide a relatively small cloud, as the nozzle matrix is confined to a small area. Additionally most systems are installed on large fixed wing aircraft that fly at high speed relative to rotary wing aircraft. One system exists, however, that uses a large nozzle matrix suspended below a Chinook helicopter, this is called the Helicopter Icing Spray System (HISS).

HISS Trials

Description of HISS equipment

The Helicopter Icing Spray System comprises a modified CH47-D aircraft, owned and operated by the US Army Aviation Technical Test Centre (ATTC).

A large cylindrical aluminium water tank is mounted in the cabin on the reinforced floor. This is pressure filled by an external pump prior to each sortie and a yellow dye is added to make ice accretion on the test aircraft more visible.

Two gas turbine APUs, mounted in the fwd section of the cabin, provide bleed air for two purposes; to prevent the water within the spray boom from freezing and to atomise the water spray at the nozzles.

When deployed, the boom assembly hangs beneath the aircraft supported by a torque tube assembly that passes through the cabin. Two hydraulic actuators rotate the torque tube to raise or lower the boom assembly and mechanical latches hold the boom assembly in either the fully deployed or retracted positions. Water is pumped through the boom to the nozzles via a water pump and flowmeter operated from a control panel in the aft of the cabin. Bleed air pressure is also regulated from this control panel. Thermocouples and pressure transducers in both the boom and the cabin give pressure and temperature feedback to the operator. The water tube is enclosed within an outer tube containing bleed air to prevent the water from freezing in the boom before it reaches the nozzles. The boom has two parallel spray bars 4ft apart, each 32ft long and each containing 50

spray nozzles. The nozzles are spaced evenly with 25 on the upper and 25 on the lower side of each boom. In the distance between the spray nozzle and the test aircraft (120ft) the plume from, each spray nozzle reaches approximately 4ft in diameter, thus the artificial cloud produced measures 36ft by 8ft. Fig 4 shows the HISS rig in flight with the boom deployed and spraying. In the event of an emergency, the pilot may jettison the boom and all the water on board.

Figure 4 – HISS in Operation

Two radar altimeters are mounted on a panel on the rear of the aircraft. These provide an output which operates two sets of "traffic lights" (red, amber, green) mounted on the underside of the aircraft to give the test aircraft a visual cue of the separation distance between the two aircraft.

The HISS also contains an additional temperature probe and a dew point hygrometer to give an accurate reading of the OAT and ambient humidity.

The HISS may be operated in the 1,500-10,000ft altitude band, provided there is a 1500ftAGL band of clear air and at least 3 miles visibility, required for formation flying. Test altitude is chosen to give the required OAT. An OAT as low as -23°C may be achieved, below this temperature there is not enough thermal energy in the bleed air system to prevent the water in the boom from freezing.

Chase aircraft

A chase aircraft was utilised during the trials. This was a Super King Air C-12, equipped with a full suite of icing instrumentation while additionally acting as a platform to record video and photographic evidence of the test aircraft.

Test Aircraft Instrumentation

An instrumentation palette was installed in the test aircraft to record information from the ARINC and 1553B aircraft data buses.

The RADS kit was used to monitor the tail rotor track and balance, and main rotor vibration levels throughout each test point.

Additionally, video camera recordings of the cockpit displays were taken.

The Artificial Icing Cloud

Water is pumped through the nozzles and is atomised using bleed air. Once ejected, the droplets decelerate and very quickly become supercooled to the ambient OAT.

The LWC of the cloud is dependent on the flowrate of the pump and the speed of the aircraft. It is also dependent to some extent on the humidity. HISS tests are done in clear air where the relative humidity is less than 100%. The "dry" air causes evaporation of the liquid water droplets, resulting in a lower LWC. The lower the relative humidity, the faster the rate of evaporation, however this is only a second order effect. The HISS is capable of creating a cloud condition of any LWC greater than 0.25g/m3, however above 1.0g/m3 the volumetric median diameter of the droplets becomes too large to provide a realistic simulation of natural icing conditions.

The droplet diameter is controlled by bleed air pressure, the higher the pressure the better the atomisation of the water in the nozzles. The two APUs provide bleed air sufficient to create droplets approximately 20μm in diameter, although larger droplets exist in the size distribution. The design icing environment specifies a droplet distribution with a maximum droplet size of 44.4μm, however during the trials, droplets of up to 300μm were measured in low concentrations. Fig 5 compares the droplet distribution of the design icing environment with a typical distribution achieved by the HISS.

It can be seen that both curves peak at similar droplet diameters. The primary effect of droplet size on airframe ice accretion is that the larger droplets have higher momentum and therefore less tendency to follow the aerodynamic streamlines around a body. Thus, larger droplets will impinge on the

surface of a body further aft than smaller droplets and the resulting ice accretion will be of greater extent (Fig 6).
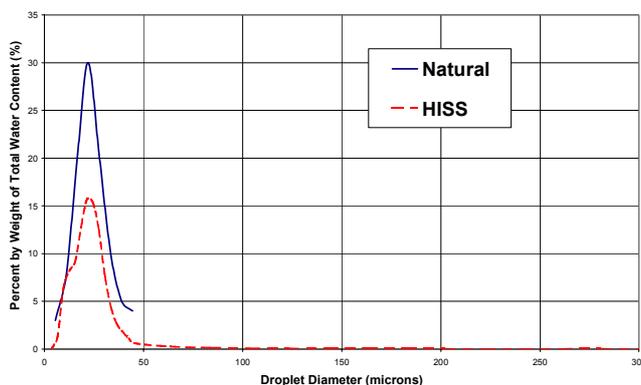
Figure 5 - Droplet Distribution Comparison
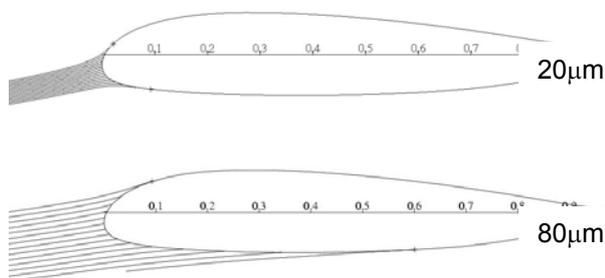
Figure 6 - Effect of Droplet Size on Impingement

The effect of this on the rotor system is that water droplets may impinge and freeze aft of the protected sections. The system is designed to protect the area defined by impingement limits based on a continuous droplet size of 20μm (with a transient size of 40μm), in accordance with Ref 1. Thus the artificial icing condition is considered to be a worse case than the design icing condition.

Effective LWC

The Main rotor disc of the EH101 is 61ft in diameter. Clearly this will not fit within the 36ft width of the icing cloud. The LWC is adjusted by a factor to account for this.

The factor is based on the fact that the collection efficiency of the rotor blade varies with the rotor radius and the rotor azimuth position. A section of blade close to the rotor tip has a higher local velocity than a section close to the rotor hub therefore it has a higher collection efficiency. A blade in the advancing side of the rotor disc has a higher local velocity than a blade in the retreating side and also, therefore, a higher collection efficiency.

The rotor section at four radial stations was modelled in a two-dimensional ice accretion prediction code,

TRAJICE2, developed by QinetiQ. For each station the code was run at 30-degree intervals around the azimuth. The WHL R314 rotor performance code was used to assess the local velocity and incidence at each section and azimuth position for input to TRAJICE2.

The collection efficiency at each radial station and azimuthal sector was then multiplied by the local velocity and the resulting values weighted by a factor calculated by dividing the spanwise length of the appropriate radial section by the total spanwise length of the heated section of the rotor blade. Each weighted value was then multiplied by a factor proportional to the LWC of the appropriate azimuthal sector (formed by sweeping the radial section through the 30 degree azimuth). This factor is 1 if the entire sector is immersed in the cloud, 0 if the sector is completely outside the icing cloud and an appropriate value for partial immersion of a sector. Thus, to simulate immersion of the whole rotor disc, the factor for every sector is 1. The resulting values are then summed to give an accumulation parameter for the entire rotor disc if;

i)   the whole rotor disc is in an icing condition

ii)   only the advancing side of the rotor disc is immersed in an icing condition

iii) only the retreating side of the rotor disc is immersed in an icing condition

iv)   the central 36ft wide portion of the rotor disc is immersed in an icing condition

For clarity, a diagram showing the difference between conditions ii and iv is given in Fig 7.

Condition ii   Condition iv
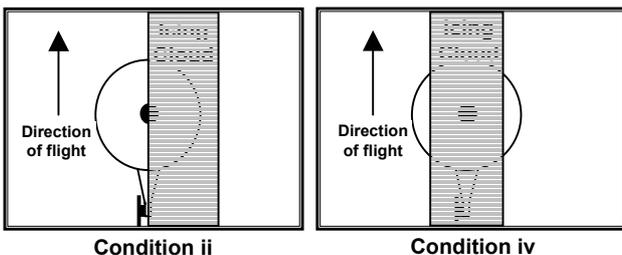
Figure 7 - Effective LWC

The factor between the accumulation parameter assessed for conditions ii, iii, iv and the whole rotor disc (i) was then calculated, concluding that the highest factor is obtained by immersing the advancing side of the rotor disc in the icing cloud (condition ii). This gives a factor of 0.71 (based on a droplet size of 20μm), i.e. the effective LWC seen by the rotor is 71% of the cloud LWC. For a centreline immersion (condition iv) the factor is 0.62.

Therefore during the main rotor test points of the trials, the test aircraft was flown with the advancing

side of the main rotor disc immersed in the artificial cloud. The desired LWC for each main rotor test point was factored by 1/0.71=1.41 and the resultant LWC was the condition requested from the HISS.

In the vertical plane, the 8ft depth of the cloud is sufficient to contain the immersed portion of the main rotor disc, including the effects of disc tilt and coning.

During the trial it was established that the tail rotor could be fully immersed in the cloud by flying along the horizontal centre of the cloud and with the main rotor just below the cloud. It was observed that the main rotor downwash has the effect of stretching the cloud in the vertical plane, increasing the 8ft depth of the cloud to sufficiently cover the 12ft diameter of the tail rotor disc. The width of the cloud was not observed to change significantly. Thus, the effective LWC for the tail rotor is 8/12 of the cloud delivered LWC. The desired LWC for each tail rotor test point was therefore factored by 3/2 = 1.5 and the resulting value was the condition requested from the HISS.

Trial Methodology

Trial Site Location

The Trials were conducted from KI Sawyer Airport, near the town of Marquette, in Michigan, USA on the south-western shore of Lake Superior. The airport has a 12,000 ft runway, with ATC, and regional Airspace control from Detroit. The site has all of the hangars still intact, of which one was adequate to house both the EH101 and CH47. A separate, recently constructed hangar was used for the chase aircraft. The hangars were fully heated and suitable for storage and maintenance of the aircraft. The airport supplied the hangar facilities, with all fuel, tugs and facilities supplied by a local aviation company.

Temperature Profiling

Each morning, just before sunrise, the chase aircraft took off and climbed steadily to an altitude of 10'000ft before steadily descending and landing while recording the OAT throughout the flight. This provided an accurate knowledge of the temperatures available for testing each day.

Test Procedure

The aircrew of all three aircraft were in constant radio contact throughout each flight and a designated member of the ground crew monitored the radio transmissions on a receiver. For ease of identification, each aircraft was given a calling name; CHASE for the chase aircraft, SPRAY for the CH-47 tanker aircraft and TEST for the EH101 test aircraft.

The chase aircraft took off first and identified the best location for testing. The two helicopters took off together, flying in a loose formation with the CH-47 leading. The aircraft climbed to the designated altitude and CHASE joined the formation, also flying aft of SPRAY and always on the opposite side of SPRAY to TEST. While SPRAY started setting up the artificial cloud, TEST broke formation and conducted forward flight performance points measuring power and torque at two different speeds, flying with collective fixed for two minutes.

TEST rejoined formation and when the artificial cloud was established (see next section "Cloud Characterisation") TEST flew beneath the cloud and ascended into the cloud. In order to achieve correct positioning in the cloud, TEST followed cues from the traffic lights on the underside of SPRAY for separation distance and radio communication from CHASE for vertical position and SPRAY for lateral position.

This formation was held for the required time period (30mins for main rotor continuous maximum LWC, 15mins for main rotor periodic maximum LWC and all tail rotor test points). Photographic evidence was recorded from CHASE and SPRAY, with CHASE ensuring positive radio acknowledgement from both SPRAY and TEST before moving to the other side of the formation.

After completion of the test point, TEST broke formation and returned to land, flying two further performance points on the route back to allow comparison of the iced aircraft and the clean aircraft. CHASE re-characterised the cloud (see next section) and then joined TEST for any further photographic evidence as required. SPRAY discontinued creation of the artificial cloud and also returned to base, maintaining a safe distance from TEST and CHASE at all times.

On landing and shut down, photographic evidence was taken of the significant accretions remaining on TEST with some accretions collected and weighed as required. All aircraft were re-fuelled and returned to the hangar. No further flying was carried out until the flight had been collectively de-briefed.

Prior to any testing, a training sortie was carried out to allow the aircrew to practice the formation flying. The workload for TEST aircrew during a test point is similar to that required for in-flight refuelling. An emergency breakaway procedure was rehearsed during the training sortie to allow the formation to be quickly and safely split up at a call from any of the aircraft in the event of any problem.

Cloud Characterisation

The cloud is initially set to the desired LWC using the principal of mass conservation:

$$LWC = \frac{1320.06 \times flowrate}{airspeed \times area}$$

Where: *flowrate* = water flow in gallons per minute (from flowmeter)
airspeed = true airspeed in knots
area = cloud cross sectional area in square feet ($36 \times 8 = 288ft^2$)

Once the cloud was established, the C-12 chase plane sampled the cloud by flying at the same separation as the test aircraft (using the traffic light cues) and immersing, in the centre of the cloud, two instruments located on the starboard wingtip. These are laser probes capable of measuring droplet size and counting number of droplets in a known volume. Each droplet is measured and the appropriate "bin" count for the droplet size is incremented by one. Thus the bin size relates to the resolution of the instrument output. The Forward Scattering Spectrometer Probe (FSSP) is capable of accurately assessing the diameter of smaller droplets up to 46μm with a 3μm bin size and the Optical Array Probe (OAP) is used to measure the larger drops up to 300μm with a 20μm bin size. By combining the size distribution from each probe, a composite distribution is obtained from which the Median Volumetric Diameter (MVD) and LWC are assessed.

It should be noted that in natural icing, hot wire probes and probes based on accretion rate (such as the Ice & Snow Detector System (ISDS) fitted to EH101) give the most accurate measurement of LWC. However when a significant portion of the mass distribution of the cloud is in droplets greater then 50μm diameter, these probes tend to underestimate the LWC. As the laser probes measure the droplet diameter, any error is cubed when calculating the volume of the droplets to obtain the LWC. It is therefore accepted that these instruments are less accurate for measuring LWC in natural conditions, however it is considered to be the most accurate method of calculating the LWC of the HISS cloud due to the larger droplets that are created.

The horizontal distribution of droplet size and LWC is relatively constant except at the edges of the cloud where there is a lesser concentration of smaller droplets (the larger droplets are sprayed further from the nozzles due to their increased momentum). Previous measurements by ATTC have shown that the LWC tapers to zero while the MVD increases at

the edges of the cloud over an approximate transition area of one-quarter width of the cloud (9ft).

The vertical distribution of droplet size and LWC is not constant for various reasons; the primary one is an effect known as gravitational sorting. A greater mass to drag ratio exists for the larger droplets; thus they will accelerate downwards faster than the smaller droplets. It follows that by the time the droplets ejected from the nozzles reach the test aircraft, there will be a higher concentration of large droplets in the lower portion of the cloud. This causes a peak LWC at the centre of the cloud and a peak MVD at the bottom of the cloud.

Figures 8 and 9, created with data from previous measurements by ATTC, give the typical spatial distribution of LWC and MVD respectively in the vertical plane of the cloud.
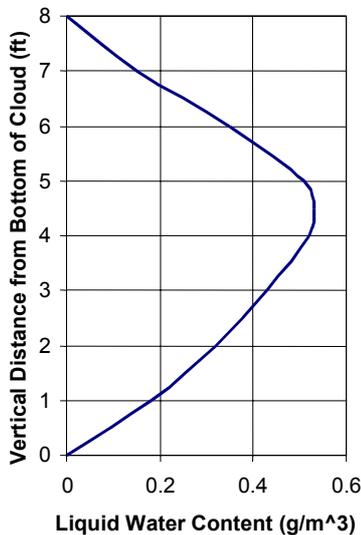
Figure 8 – Typical LWC Variation
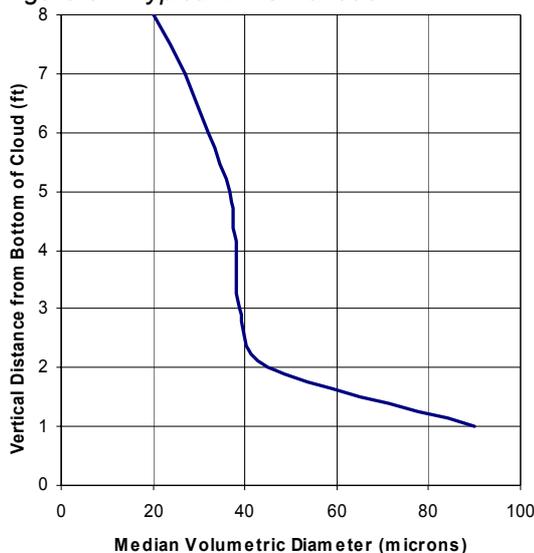
Figure 9 - Typical MVD Distribution

As can be seen from Fig 8, if the chase aircraft probes are positioned in the centre of the cloud, they are likely to measure a higher LWC than that predicted using the principal of mass conservation. There were some problems with the flowmeter encountered during the trial and it became unserviceable after the first two test points. Therefore the flowmeter readings could not be used to calculate the cloud LWC and the measurement probes fitted to the chase aircraft were used instead.

The measurement probes were generally positioned in the vertical centre of the cloud, therefore the measured data is averaged over the peak LWC in the cloud. The EH101 rotor disc, due to coning and forward disc tilt, was observed to occupy most of the cloud height, therefore it would have experienced an LWC averaged over the entire cloud, rather than just the peak area.

The peak value of the LWC in the centre of the cloud has previously been shown by ATTC to be approximately 1.25 times the integrated average of the vertical LWC distribution. Therefore the LWC measured by the probes was factored by $1/1.25 = 0.8$. The factored value was used as the delivered LWC of the cloud for the purpose of analysis.

After the flowmeter became unserviceable, the chase aircraft measured the cloud properties before and after each test point and the average of these two measurements was used for assessment of the LWC and MVD.

Equivalent VAM

The EH101 aircraft is equipped with a Vernier Accretion Meter (VAM) to give the aircrew an accurate measure of how much ice has accreted on the airframe. The VAM is situated just below the pilots window on the port side of the aircraft. During the HISS trial, the VAM was not immersed in the artificial icing cloud. Relating the VAM reading to the HISS test points was necessary as this gives an indication of the amount of ice accreted on the unheated sections of the main and tail rotor blades and hub components. The equivalent VAM was therefore assessed using the TRAJICE2 modelling code, developed by QinetiQ. A two dimensional section of the VAM probe was modelled and the icing conditions of each test flight were input. A datum time (1-minute) was input and the code outputs the size and shape of the ice accretion on the VAM probe. This is used to determine the rate at which ice is accreting and subsequently the equivalent VAM measurement for the HISS test point.

Results

The objectives of the flight trial were to assess the performance of the rotor systems during flight in the most severe icing conditions of the design icing environment. Fig 10 shows the test points achieved during the trial.
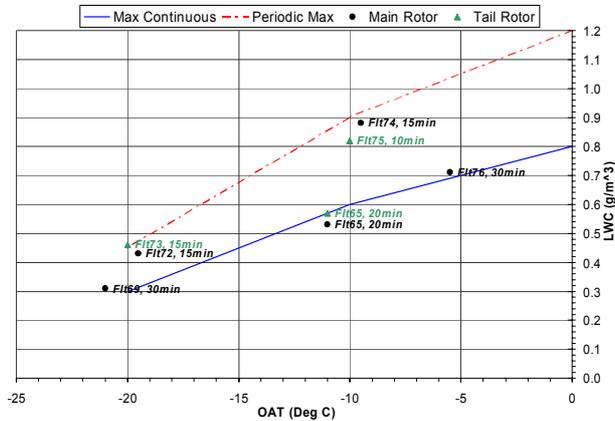
Figure 10 - HISS Test Points

The pre and post-test performance points were used to assess the increase in required torque, including a calculation to allow for the effect of fuel burn. This data was used in conjunction with in-flight photographic evidence and pilots subjective comments on the handling qualities of the aircraft to evaluate the overall effect of the icing condition on the aircraft performance.

In all test points the assessed torque rise was within the acceptable limit for continued safe flight and landing. At no point was there any report of degraded handling qualities from the aircrew. Although specific handling blocks were not performed, the aircrew were manoeuvring the aircraft considerably in order to maintain their position in the cloud and it was considered that any significant change would have been noticeable.

On most flights the photographic evidence showed that the RIPS ensured that the rotor blades remained free of significant ice accretions. However in some cases, all in conditions at or above −10°C, ice accretions did build up aft of the protected area of the main rotor blades. No significant ice accretion was observed in any of the tail rotor test points.

Torque Reconciliation

In order to understand the nature of the torque increases observed and the effect of residual ice on the main rotor blades an analytical assessment was made of the potential contribution to the measured torque rise of the heated and the unheated rotor structures. The test point with the worst case torque rise was chosen.

No ice was observed to accrete on the upper surface of the rotor blade during this flight, however an accumulation was observed on the lower surface, aft of the heater elements (Fig 11).

Figure 11 - Ice accretion on lower surface of MRB

Fig 6 relates to this particular flight and demonstrates the difference in droplet impingement on the aerofoil between the HISS condition and the design icing condition. It is therefore considered that the ice observed on the lower surface was due to direct impingement of larger droplets and not due to run-back ice from the RIPS heater elements. The photographic evidence shows the ice accretion extending outboard to approximately 60%R at which point it sharply tapers off to nothing on the outer section of the blade. This is due to a combination of three effects; change in aerofoil profile, change in aerodynamic incidence and kinetic heating.

Change in aerofoil profile: The main rotor blade on the EH101 has a constant aerofoil profile from 32 to 59%R and a constant profile from 68 to 84%R and the profiles are interpolated between the two sections. The zero lift angle of the inboard section is more than 2° greater than the outboard section and there is a distinct change in the geometric angle of the two sections in order to keep a smooth, linear aerodynamic twist. For a higher geometric angle, there is more of the lower surface exposed to direct impingement. Therefore the inboard section will be more prone to droplet impingement than the outboard section. This may produce a relatively sharp delimitation in the radial extent of accreted ice, as observed in the photographic evidence.

Change in incidence: Aerodynamic incidence varies along the blade due to the twist of the blade, the radial change in local velocity and the downwash through the rotor. Change in aerodynamic incidence has a large effect on impingement limits; the higher the incidence, the further aft the impingement limits will extend on the lower surface. Aerodynamic incidence is relatively constant across the inboard region of the blade, at between 5° and 6°, to around 60%R. Beyond 60%R the aerodynamic incidence steadily decreases to less than 1° at the tip. Therefore the change in incidence matches the limit of ice accretion in the photographic evidence, although, unlike radial transition between aerofoils, the radial reduction in ice accretion would be more gradual if aerodynamic incidence were the only factor.

Kinetic heating: The average advancing side local Mach number for the flight at 32%R was M=0.33 and at 50%R was M=0.45. The corresponding estimated temperature rise at the stagnation point due to kinetic heating is as follows: at M=0.33, 5.9°C and at M=0.45, 11.1°C. Thus there is potentially a 5°C difference between 32 and 50%R. Kinetic heating will have a large effect on the outer regions of the blade. Since kinetic heating is not linear along the blade (it is a function of velocity-squared) the reduction in ice accretion along the blade may not necessarily be gradual. Therefore, from the photographic evidence it is difficult to assess the level of contribution from kinetic heating to the radial limit of ice accretion.

TRAJICE2 was used to predict the ice shape on the unheated aerofoil. The ice predicted over the heated leading edge of the blade was then removed to leave a residual ice shape that is very similar to the photographic evidence (Fig 12).
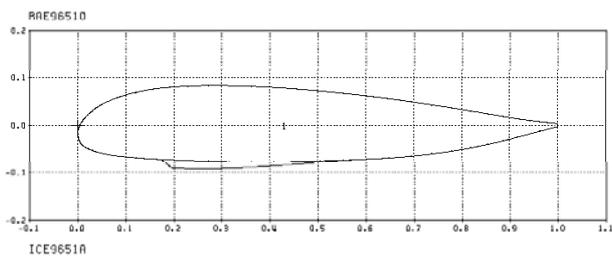
Figure 12 – Predicted ice shape on main rotor blade

The new geometry was then modelled in a structured two-dimensional Navier-Stokes CFD code to obtain the revised aerodynamic properties of the aerofoil. The increase in the aerofoil drag coefficient was assessed and integrated across the radius up to 60%R to give a drag rise for the rotor blade. A simplifying assumption was that the increase in drag is constant to 60%R and there is no increase beyond

60%R. This was one of the contributors to the observed torque rise.

The photographic evidence also shows a significant accretion on the unheated inboard section of the blade and the tension link fairings (Fig 13). The change in drag coefficient over these components was assessed using an empirical model and the contribution to delta torque was calculated.

Figure 13 - Unheated sections of main rotor blade

The remaining contributor to delta torque is the D_{100} increase due to ice on the rotor hub. The increase in D_{100} due to ice accretion was again assessed using an empirical model and the contribution to torque rise was predicted.

The total torque rise from all these contributors was summed and compared with the torque rise measured in the trial. The two values compared well, with the predicted value slightly lower than that measured. Note that a number of assumptions were made in the analytical process and additionally no attempt was made to assess the contribution to torque rise from ice that was observed to accrete on other areas of the airframe. Significant accretions were observed on some topdeck components, the rescue hoist, the fin and the horizontal stabiliser.

<u>Analytical Extrapolation</u>

Fig 10 shows that the HISS trial was not able to simulate the -5°C Periodic Maximum condition as the droplet size from the HISS at this liquid water content would be wholly unrepresentative. Therefore, clearance of this condition has been approached analytically.

During the -5°C Continuous Maximum test point ice was observed to accrete on the main rotor blade, aft of the heated leading edge, on both the upper and lower surfaces. The droplet size was such that impingement limits were within the heated section, therefore the ice observed is considered to be frozen run-back water generated from operation of the heater elements. The photographic evidence from the HISS was compared with photographic evidence from natural icing trials at a similar temperature but with lower LWCs. In both cases run-back ice appeared to accrete aft of the heater elements and to a similar radial extent, again approximately 60%R.

The TRAJICE2 and HRB2D modelling codes, developed by QinetiQ, were used to predict the ice accretion on aerofoil cross-sections for the heated blade under the conditions of the Continuous Maximum test point at -5°C. Based on the ice accretion prediction for several blade sections at different radial stations, the predicted ice shapes on both the lower and upper surfaces compared well with photographic evidence from the test. The same process used for torque reconciliation was then used to predict the torque rise for the test point and again this compared favourably with the measured torque rise in the test point.

The same analysis methods were used to predict ice accretion after 15 minutes for the Periodic Maximum design condition at -5°C. The analysis predicted less ice accretion than for the maximum continuous LWC condition. The reason for this is that at the relatively warm temperature of -5°C the limiting factor is the latent heat energy transfer, thus the freezing fraction is the maximum possible for that temperature, regardless of LWC. Therefore, at the Periodic Maximum condition the runback ice ridges grow in height at the same rate although for only half the time, it follows that the ridges were predicted to be half the height of the ridges predicted for the Continuous Maximum condition. The predicted torque rise for the Periodic Maximum condition is therefore lower than that measured and predicted for the Continuous Maximum condition at the same temperature.

Conclusions

This paper draws the following conclusions:

- The EH101 RIPS has been shown to perform well at the highest LWCs specified by the design icing envelope down to a temperature of –20°C

- The torque rises observed throughout all of the conditions experienced, with LWCs up to Periodic Maximum levels, were less than 10%.

- Due to the large droplets experienced during the trials, especially at the higher LWC values, the HISS icing conditions are considered to be more severe than the equivalent natural icing conditions.

- The HISS was an invaluable tool for demonstrating the performance of the RIPS at the icing envelope corner points

- The test technique of immersing the advancing side of the main rotor into the HISS cloud has been demonstrated to be both practicable and valuable.

References

1   DEFENCE STANDARD 00-970
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