UK PROGRAMMES TO DEVELOP AN IMPROVED UNDERSTANDING OF HELICOPTER TAIL ROTOR FAILURES AND DEVELOP AIRCREW EMERGENCY ADVICE

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Abstract

This paper reviews recent UK programmes to improve our understanding of helicopter tail rotor failures, and develop the handling advice for aircrew following a tail rotor (TR) malfunction. The paper discusses the original motivation for the work and in particular the research work that has been carried out by the Defence Research Agency (DRA) and Westland Helicopters Ltd (WHL) under UK Ministry of Defence (MOD) funded programmes. This research has included flight trials conducted on the DRA Aeromechanics Lynx Control and Agility Testbed (ALYCAT) to develop Lynx TR control failure handling advice, and simulation trials on the DRA Bedford Advanced Flight Simulator (AFS) to develop Lynx TR drive failure handling advice. The AFS was also used to investigate the influence of helicopter design parameters on a pilot's ability to recover from a TR failure. Also described are off-line simulation and model development activities. The paper concludes with a review of lessons learnt.

Introduction

Motivation & TRAC

A tail rotor failure is arguably the most critical helicopter malfunction. Our individual experience, shocking video footage or a glance down published accident statistics in aviation magazines have perhaps given us all some evidence of the problem and its regularity. It is also clear from feedback and regular articles in Service flight safety magazines, that in operational crew rooms tail rotor failures continue to be a source of great interest and concern. But what are the failure statistics?, what is the nature of these failures?, what can be done to reduce these statistics in new aircraft?, and in particular what is the best advice that can be offered to aircrew in manuals? and can the advice be validated?.

Prompted by many of these issues, in January 1993 the Royal Air Force (RAF) Handling Squadron at Boscombe Down (the group in the UK responsible for publishing aircrew manual and flip-card advice) convened a meeting to discuss the issue of TR failures. This group included representatives from the 3 Services, MOD(Procurement Executive), DRA and the Civil Aviation Authority (CAA). This group was later to be given the title Tail Rotor Action Committee (TRAC). The group's aim was to investigate the problems associated with helicopter tail rotor drive and control failures and to make appropriate recommendations. The group defined four primary tasks:

a. To conduct an analysis of current UK military and civil helicopter safety records to establish the nature and extent of the problem.

b. To review the current advice to aircrew and identify shortcomings.

c. To assess the reliability and failure characteristics of current designs.

d. To make recommendations with respect to handling advice to aircrew, simulation and training, airworthiness requirements and future research.

TRAC Observations

TRAC observations included:

a. Tail rotor drive failures continue to occur at an unacceptably high rate in the UK helicopter fleets. MOD statistics between 1976-1993 show a technical failure rate of 11.2 per million flying hours. The UK design requirement for rotorcraft transmission systems (Ref 1) requires the probability of a transmission/TR drive failure that would prevent a subsequent controlled landing to be very remote ($<1x10^6$).

b. Tail rotor drive failures are more prevalent than control failures (UK military ratio 3:2).

c. Without a normally functioning tail rotor, many helicopter designs lack directional stability and some appear to be uncontrollable.

d. Although the reasons for tail rotor failures are always investigated and if possible remedied, not enough is known about the behaviour of individual helicopter types following tail rotor failure.

e. There are significant differences in the handling characteristics, post tail rotor malfunction, between helicopter types.

f. Improved handling advice for current helicopters is believed to be achievable if the necessary work is put in hand. Better handling advice would enhance survivability in what is always likely to be a difficult malfunction regime.

This paper describes the research activity conducted to support TRAC. The paper describes 3 activities, these are:

a. Flight trials to develop Lynx control failure advice.

b. Activities to develop the DRA HELSIM (Ref 2) simulation model for tail rotor drive failure trials, and the use of non-piloted simulation tools to develop control strategies.

c. AFS trials to develop Lynx drive failure advice.

Advice Validation & Test Facilities

Validation

The requirement set by the Lynx Project Office was to develop and where possible validate the advice given to aircrew in the event of a tail rotor malfunction. During early meetings levels of advice validation were allocated and detailed by WHL (Ref 3). These were:

a. Full/demonstrated in flight (Level 1).

b. Demonstration with best calculation and piloted simulation (Level 2).

c. Engineering Judgements (Level 3).

The tail rotor malfunctions were also placed in two broad categories;

- control failures, where control of tail rotor blade pitch is lost but the rotor continues to rotate and produce aerodynamic forces.

- drive failures where all power is lost to the tail rotor.

After some discussion, it was concluded that the programme would seek to provide level 1 validation of control failure advice, and level 2 validation of drive failure advice. It should be noted that the feasibility of declutching a tail rotor gearbox , in order to conduct level 1 trials, was discussed but it was concluded that:

a. Advanced simulation would be an essential step before in-flight testing.

b. The development of such a system was outside the financial scope of the programme.

It must also be said that there was some scepticism over the safety and wisdom of any such flight trial.

Facilities/Assets

The programme would use two important facilities the DRA Bedford Advanced Flight Simulator and the ALYCAT Lynx aircraft.

Advanced Flight Simulator

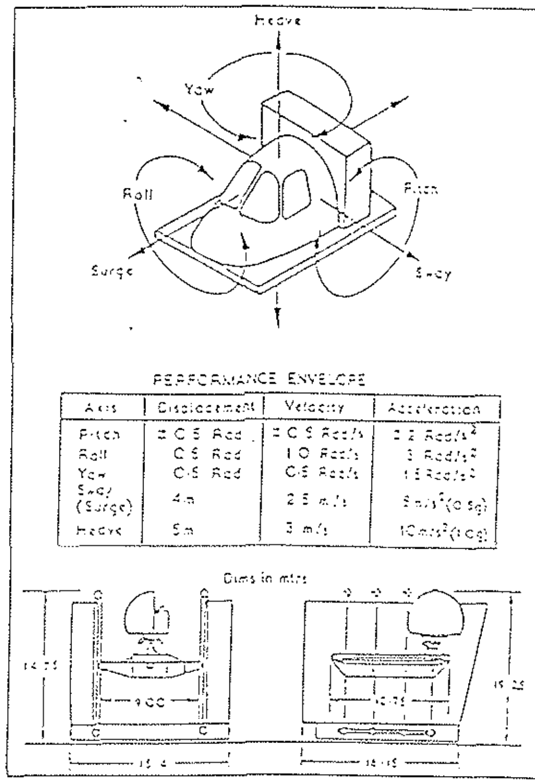
The AFS constitutes the DRA flight simulation facility at the Bedford site. It is a general purpose research tool which retains a high degree of flexibility to enable tailoring for a wide range of fixed and rotary wing applications. The simulation can be configured to meet the needs of a particular task by selecting hardware and software options. Briefly the various elements of the facility are summarised below: a more detailed description can be found in Reference 4.

a. Motion System - Platform motion cues are generated by the 5 degree-of-freedom Large Motion System (LMS). The system provides motion in roll, pitch, yaw and heave axes and, depending on cockpit orientation when mounted on the motion platform, in either sway or surge axes. Figure 1 shows the general arrangement of the motion system together with its performance characteristics. This is one of the highest performance systems in the world and provides excellent stimulation of the pilot's motion sensory mechanisms (Reference 5).

b. Visual System - A photo-textured computer generated image system is employed to provide visual cuing through 5 monitors.

c. Cockpit and controls - The cockpit has a generic layout based on pilot's station of the Lynx helicopter. This gives conventional controls and instrument arrangements. Control feel is provided by an electrically activated digital system. Vibration cues in the vertical axis are applied through an 'active' seat at a simulated 4R frequency and modulated by airspeed and normal acceleration effects.

d. Model - The AFS can be adapted to take any model (fixed, rotary wing etc). The primary model used for this work would be a development of the HELSIM model (Ref 2). Developments are discussed later in this paper.



Axis	Displacement	Velocity	Acceleration
Pitch	±0.5 Rad	±0.5 Rad/s	±2 Rad/s²
Roll	0.5 Rad	1.0 Rad/s	3 Rad/s²
Yaw	0.5 Rad	0.5 Rad/s	1.5 Rad/s²
Sway (Surge)	4 m	2.5 m/s	5 m/s² (0.5g)
Heave	5 m	3 m/s	10 m/s² (1.0g)

Fig 1 - AFS Motion System

ALYCAT Lynx

The aircraft used for the trials was the DRA Lynx Mk7 (ZD559) (also known by the acronym ALYCAT for Aeromechanics LYnx Control and Agility Testbed), Figure 2. The ALYCAT is extensively instrumented. Figure 3 shows a schematic of the instrumentation system with main rotor, tail rotor, airframe, body motion and control position data all routing through the Modular Data Acquisition System (MODAS), and/or to a recorder or via the telemetry link to the ground station. The MODAS system has a sampling rate of 256 K samples/sec, which enables the large amount of rotor data, in particular, to be handled during main rotor testing.

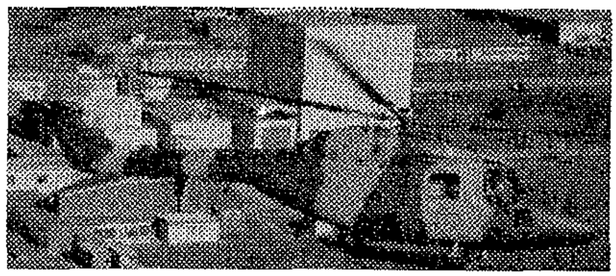


Fig 2 - ALYCAT Lynx over the AFS

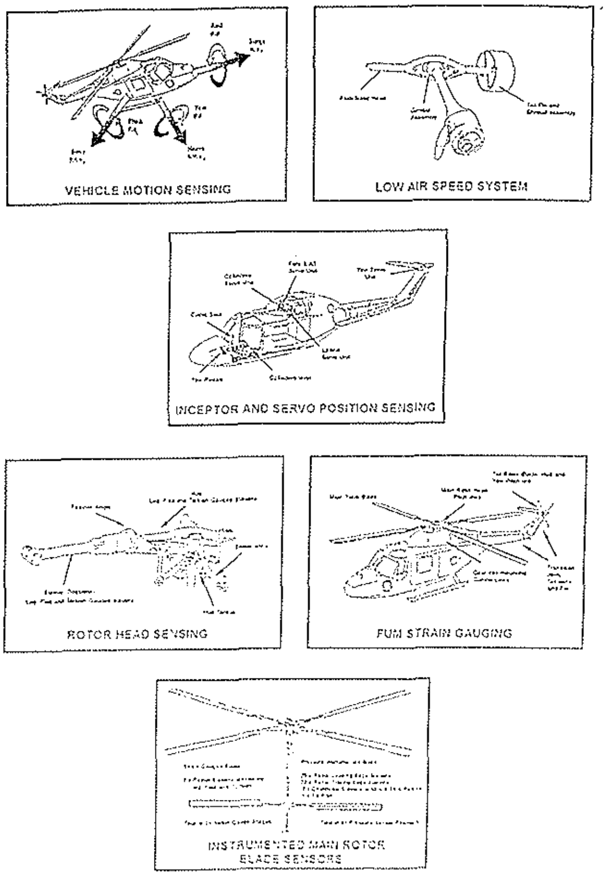


Fig 3- ALYCAT Instrumentation

For the tail rotor failure work the multi-channel telemetry transmitter and FUMS (Fatigue and Usage Monitoring System) were essential to provide real time safety monitoring via telemetry. In addition, test instrumentation gave in-cockpit feedback of precise tail rotor pitch angles and pedal positions. Finally, accurate low airspeed measurement was provided by the Helicopter Air Data System (HADS).

Flight Trials to Develop and Validate Lynx Control Failure Advice

Control Failure - Initial Work

The starting point prior to any flight trial planning was to review the current Lynx control failure advice and the tail rotor control system Failure Modes Effect Criticality Analysis (FMECA) for the Lynx. This work identified the failure modes and defined the flight conditions to be investigated in the flight trial. It also started the process to develop the Lynx advice beyond the often generic broad advice that was found to be prevalent in UK types during the TRAC study.

Control Failure - Aims & Objectives

The aims of the flight trial were to:

a. characterise and investigate handling and controllability of the Lynx post tail rotor control failure from various initial conditions.

b. develop and where possible validate advice to aircrew post a tail rotor control failure.

c. investigate handling and controllability of the Lynx with the tail rotor held at an angle of 3.5° (Note: 3.5° is associated with the Lynx Spring Bias Unit (SBU)).

The objectives of the work were to:

a. increase post-failure survivability.

b. reduce post-failure vehicle attrition/ damage.

c. ensure that the best advice was available to aircrew faced with tail rotor malfunctions.

Control Failure - Current Lynx Advice

A summary of key points from the current Lynx control failure advice are detailed below:

- Establish power and airspeed for level flight.

- Make an engine-off landing into wind or a running landing as appropriate.

Control Failure - Flight Trial Procedure, Special Fit & Conduct

Key points from the DRA Flight Trials Instruction (FTI) (Ref 6) for the work were:

a. The flight programme was divided into two parts, the first being to investigate and develop post control failure recovery techniques, and the second was to gather data to validate the HELISIM simulation model in tail rotor failure recovery flight regimes (i.e. Autorotations).

b. The aircraft used for the flight trials was the DRA ALYCAT Lynx.

c. The, so-called, tail rotor failure phase of the programme was to be flown with the yaw/collective interlink removed.

The in-flight (Level 1) procedure developed to investigate control failures involved the removal of the yaw collective interlink, pedal positions being set and held by the Flight Test Engineer (these equated to the control "failure" positions), and the test pilot flying recoveries using only the available controls i.e. collective, cyclic and engine controls. The removal of the interlink precluded a change in tail rotor pitch with collective.

To enable this procedure, an amendment to the ALYCAT research flight clearance was issued by WHL. This amendment detailed the side slip limits for the flight trial, the requirements for on-line telemetry monitoring and referenced the WHL procedure to remove the yaw collective interlink and fit a pin within the control system.

Prior to the flight trial, work-up flights were conducted. The aim of these flights was to develop the in-flight procedures to establish the "failure" condition. This was achieved by the project pilot establishing the trimmed initial condition (0-120kn), the limiting side slip condition would then be set and the percentage pedal displacement noted from the in-cockpit flight test instrument. It should be noted that during this phase a fatigue limit exceedence on the tail cone lateral bending strain gauge was observed. This led to the 30° side slip limit (120 kn) being reduced to 20°.

Two types of control failure were investigated; control jams and control disconnects. The first three test points flown looked at control jams, the fourth looked at the control disconnect:

a. Recovery from tail rotor control failures in hover.

b. Recovery from tail rotor control failures in straight and level flight (80-120kn) with a resulting high tail rotor pitch setting.

c. Recovery from tail rotor control failures in straight and level flight (80-120kn) with a resulting low tail rotor pitch setting.

d. Handling and control with the tail rotor pitch set to 3.5° pitch (the Lynx SBU setting angle).

During the test flights the percentage pedal displacements recorded at each initial condition during work-up were then used by the Flight Test Engineer to establish the *failure* condition. The project test pilot then recovered the vehicle using the available controls i.e. No pedal.

Control Failure - Failure Classification

A failure resulting in a fixed pitch being applied to the tail rotor can be classified in one of three ways. A failure that predominantly produces left side slip (LSS) (ball out to the left) throughout the speed range, caused by the tail rotor pitch freezing at a setting commensurate with low power operations, Fig 4.

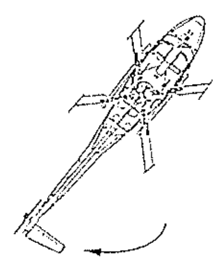


Fig 4 - Low Power Failure

A failure that predominantly produces right side slip (RSS) (ball out to the right) throughout the speed range, caused by the tail rotor pitch freezing at a setting commensurate with high power operations, Fig 5.

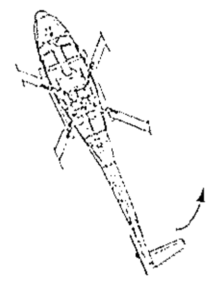


Fig 5 - High Power Failure

Finally, a failure that freezes tail rotor pitch at an intermediate setting allowing the aircraft to be flown throughout the vast majority of its speed range with little or any side slip. A failure that results in operation of the Spring Bias Unit (SBU) can be considered as the last case.

Diagnosing the type of failure present was found to be easier the greater the severity of the problem, and is achieved by reference to the slip ball in straight and level flight. Right ball means right side slip (high power), left ball means left side slip (low power). A failure that is hard to categorise due to only slight ball displacement or changes in direction of the side slip will generally be an intermediate failure.

Simple analysis predicted that an aircraft suffering a high power failure (RSS) would be more controllable at higher collective settings (e.g. low speed, high speed or in the climb). Similarly, a low power failure (LSS) would be more controllable at low collective settings (e.g. operation in the low power region of the power curve or during descent). This conjecture was borne out by flight test, although what was not envisaged beforehand was that the containment and recovery from tail rotor control failure would consist of two very definite and separate phases, the recovery and the approach to land.

a. Recovery Phase - The recovery phase included the recognition and diagnosis of a tail rotor control failure, followed by appropriate actions to bring the aircraft under sufficient control to allow positioning for an approach. The positioning included recovering, climbing and descending.

b. The Approach to Land - The approach to land was generally a short straight-in approach to either a hover or running landing.

Note: In order to protect the skids on the ALYCAT Lynx no running landings were completed during the flight trial, the vehicle was recovered 0-5 ft before touch-down.

By reference to Figures 6 and 7, the general characteristics of a LSS, RSS or intermediate (including Spring Bias Unit) failure can be appreciated.

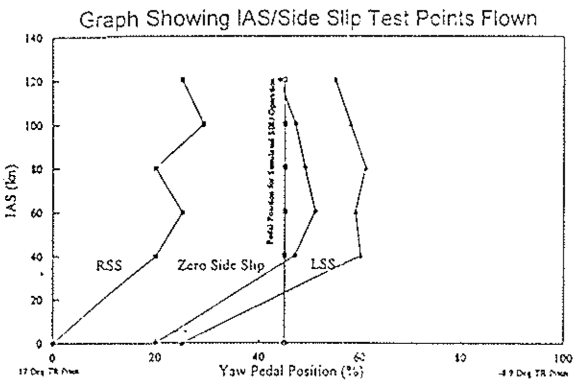


Fig 6 - IFS/Side Slip Test Point Flown

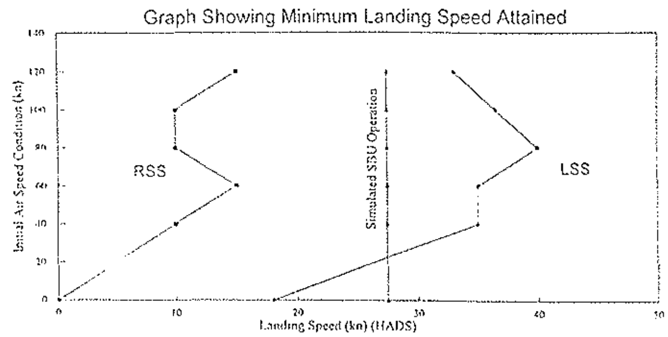


Fig 7 - Landing Speed Attained

These were:

a. LSS failure was characterised by being easy to control in the recovery phase the proximity to the zero side slip yaw control position line, Figure 6) with a high landing speed, Figure 7.

b. RSS failure case was very difficult to control at high speeds but would give a low landing speed.

c. Simulated SBU flying gave flight conditions close to trim for most of the flight envelope with a high landing speed.

The flight techniques developed during the flight trial varied depending upon whether the failure was diagnosed as an intermediate (Spring Bias Unit) failure, a High Power (RSS) or Low Power (LSS) failure.

Control Failure - Simulated SBU Operation

The Lynx tail rotor control loads have been tuned to ensure a steep load pitch gradient, with a zero load condition occurring at approximately 3.5°. However, because the Lynx only has a simplex hydraulic system to the tail servo jack a No 1 hydraulics failure would result in excessive loads at the pilots feet. In order to enable safe manual reversion characteristics a spring bias unit (SBU) has been included in the control circuit close to the jack. On failure of the No 1 hydraulics the SBU becomes active and carries a large proportion of the tail rotor control load, enabling the pilot to operate the tail rotor pitch manually over its full pitch range. In the event of a control circuit disconnect between the jack and the tail rotor, the tail rotor pitch reverts to approximately 3.5°. If a control circuit disconnect occurs between the pedals and the SBU the tail rotor pitch will remain where the jack holds it, within the limits of the AFCS inputs. However, by switching out the No1 hydraulics the SBU becomes active and the combination of SBU forces and tail rotor control loads ensure that the tail rotor pitch once again migrates back to approximately 3.5°. The system used in the Lynx is understood to be a unique safety feature, not currently available on other aircraft.

During the trial the yaw pedals were held in a position to give a tail rotor pitch of 3.5°, and handling was assessed.

Recovery Phase - Recovery flying was easily achieved with the aircraft remaining close to trim in straight and level flight from 30 to 120 kn. Turns, climbing and descending were also carried out with little side slip.

Approach to Land - The minimum air speed achieved for a running landing was 28 kn (HADS). Both the approach to land and landing were easily controllable and safe provided the speed was not reduced below the minimum.

Failure in the Hover - A failure in the hover resulting in the operation of the SBU would result in a rapid yaw to the right. This case was not attempted, since it would have resulted in an exceedance of the spot turn limits detailed in the trial flight clearance. Experience gained during the flight trial would indicate that the onset and stabilised yaw rate would be very rapid and conjecture makes it hard to imagine that anything other than shutting down the engines and cushioning the landing would be possible.

Control Failure - Left Side Slip/Nose Right (Low Power Failure)

In general, this failure case was similar to that detailed above under simulated SBU operation, which is perhaps not surprising if the pedal positions are considered, Figure 6.

Recovery Phase - Recovery flying was easily achieved. Turns, climbing and descending were carried out successfully.

Approach to Land (Considerations) - The following sub-paragraphs detail considerations for the approach to landing.

a. As an LSS failure is associated with trimmed flight in the low power envelope, the high power requirements of a hover landing would clearly be problematic.

b. With fixed yaw pedals, as the collective is raised, the nose yaws from the left to the right.

c. As the undercarriage should be parallel to the flight path of the aircraft for a successful running landing, in still air there is therefore only one collective position for a selected airspeed, rotor RPM and AUW which gives the correct alignment of the undercarriage.

d. If on the final approach the nose is pointing to the left of the flight path, the application of more collective will align the nose and therefore the undercarriage with the flight path.

e. If the nose is to the right of the flight path, the lever must be lowered or the airspeed increased to align the nose.

f. The problem with the approach to landing phase of the LSS failure therefore is that reducing speed too much or easing descent rate with collective will result in the nose stabilising to the right of the aircraft flight path. In addition lowering the collective will result in large rates of descent building up.

Approach to Land (Strategy) - The following sub-paragraphs detail the strategy for recovery:

a. The technique developed during the flight trial to overcome this problem was to fly towards the landing point at an altitude of approximately 100 ft, carrying out a level deceleration until the aircraft nose was coincident with the flight path.

b. At this speed the aircraft is at minimum landing speed (a conservative value since close to the ground, ground effect will reduce power requirements).

c. On approaching the landing point a positive check down on the collective initiated a rate of descent and yawed the nose left of aircraft flight path.

d. The landing was completed by pulling in power to align the nose once again with the flight path.

e. This technique was used to achieve comfortable running landings at air speeds between 18 and 40 kn, Figure 8.

Failure in the Hover - Failures in the hover were tested from the maximum yaw rate condition of 60 °/sec (nose right). It should be noted that it was found to be quite difficult to maintain orientation at this rotational rate. Although it was not tested it was considered doubtful that a conversion to forward flight could be achieved from this initial condition. During the flight trial it was found that by advancing the Speed Select Lever to increase the rotor RPM to maximum, rotational rate slowed dramatically, transition to forward flight could then be achieved and a running landing subsequently carried out.

The reason advancing the rotor RPM reduced the low power failure yaw rate, was because as main rotor RPM was increased, so was the tail rotor RPM, due to the gearing between the two. The increase tail rotor RPM, made the fixed pitch angle more effective, and the rate of rotation was slowed. In addition, as the main rotor RPM was increased, so the main rotor torque was reduced, and the anti-torque required from the tail rotor to balance main rotor torque was reduced. Thus advancing the main rotor RPM had a dual effect of reducing main rotor torque and increasing tail rotor speed to reduce the rate of rotation. The inverse was true in the high power case.

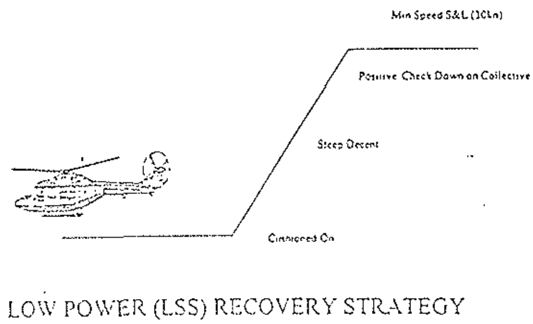


Fig 8 - Low Power (LSS) Recovery Strategy

<u>Control Failure - Right Side Slip/Nose Left (High Power Failure)</u>

In general the high power failure conditions, RSS, was the most difficult to control and, in turn, develop a strategy to enable recovery.

Recovery Phase - The main problem with an RSS failure was how to decelerate through the low power region of the power curve to the low speed, high power region. Initial attempts at relatively gentle decelerations resulted in very marginal levels of control as the aircraft attempted to 'swop ends'. The problem was solved by carrying out an aggressive left hand climbing cyclic turn, Figure 9, with the aim of establishing the aircraft at the top of the climb below 40 kn. At this point the aircraft could be held at low air speed to the final approach position. Care had to be taken, however, to avoid vortex ring.

Approach to Land - Due to the higher power condition of this failure, the landing was less problematic and generally resulted in lower landing speeds. The technique developed was to carry out a slow approach with the nose well to the left of the flight path, as the landing point was reached the nose could be aligned with the flight path by application of collective and a slow running landing carried out.

Failure in the Hover - By retarding the SSL to reduce rotor RPM to the minimum in- flight value, all rotation from a 60 °/sec (nose left) spot turn was arrested and a landing carried out with the failure pedal condition still set on the controls.

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The Lynx tail rotor control loads have been tuned to ensure a steep load pitch gradient, with a zero load condition occurring at approximately $3.5°$. However, because the Lynx only has a simplex hydraulic system to the tail servo jack a No 1 hydraulics failure would result in excessive loads at the pilots feet. In order to enable safe manual reversion characteristics a spring bias unit (SBU) has been included in the control circuit close to the jack. On failure of the No 1 hydraulics the SBU becomes active and carries a large proportion of the tail rotor control load, enabling the pilot to operate the tail rotor pitch manually over its full pitch range. In the event of a control circuit disconnect between the jack and the tail rotor, the tail rotor pitch reverts to approximately $3.5°$. If a control circuit disconnect occurs between the pedals and the SBU the tail rotor pitch will remain where the jack holds it, within the limits of the AFCS inputs. However, by switching out the No1 hydraulics the SBU becomes active and the combination of SBU forces and tail rotor control loads ensure that the tail rotor pitch once again migrates back to approximately $3.5°$. The system used in the Lynx is understood to be a unique safety feature, not currently available on other aircraft.

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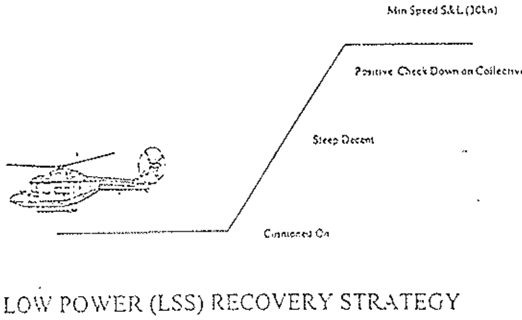

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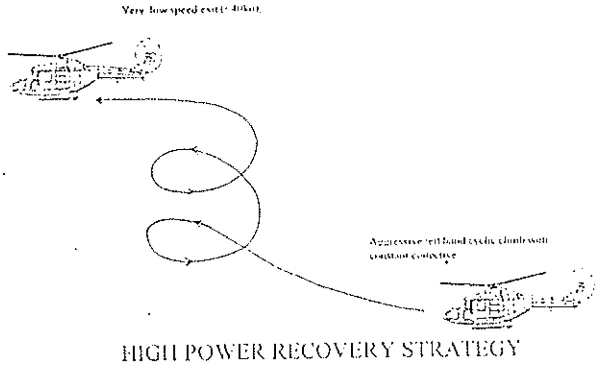

Fig 9 - High Power (RSS) Recovery Strategy

Control Failure - Use of Rotor RPM and the AFCS

A limited evaluation of the benefits of varying the rotor RPM and engaging/disengaging the FCS was carried out throughout the flight trial.

Varying Rotor RPM - As has already been reported, varying RPM had a significant effect in the hover. However, above approximately 20 kn, the benefits were minimal, any changes in RPM having only a transient effect on side slip. Above 40 kn there were no benefits at all.

Use of the AFCS - Should a failure mode allow AFCS inputs to the tail rotor, it was felt that the yaw damping effect in recovery flying should provide some directional stability. However, during the flight trial the reduction of yaw control power that the damping gave in the landing phase was considered detrimental.

Lynx Control Failure - Summary & General Advice

Figure 6 shows that only a small amount of available tail rotor pitch was used during the flight trial. This was due to the side slip restrictions placed on the flight trial. However, it is considered inconceivable that, during normal operational flying the, side slip achieved during the trial would be equalled. Therefore, assuming correct operation of the SBU, the likelihood of a worst case tail rotor control failure might be considered small. (However, it was thought possible that a rotor might 'fly' to an angle post failure and then freeze). Should a failure occur within the envelope tested, the following guidelines should be followed:

a. If flight post failure is uncomfortable due to side slip, bank away from the slip ball and 'drag' the ball into the centre, this will provide time to diagnose and manage the problem.

b. LSS cases will be reasonably comfortable in forward flight but, generally, require fast running landings; RSS cases will be most uncomfortable in forward flight and may require a left cyclic climbing turn.

c. On the approach, the aircraft nose should always be to the left of the flight path to allow collective to be applied to cushion the landing. In the latter stages, should the nose migrate to the right of the flight path OVERSHOOT IMMEDIATELY by lowering the nose, increasing speed then raising the collective.

d. Once on the ground DON'T RELAX, power should be taken from the rotor with great care.

Lynx Simulation Off Line Model and Strategy Development

Introduction

Prior to using the AFS to develop drive failure recovery strategies it was decided to enhance the Lynx simulation fuselage aerodynamics.

Aerodynamic Testing of a Lynx Fuselage

Helicopter computer simulations, whether carried out using a desktop system or through a large motion simulator, rely on a good fuselage aerodynamic data to ensure an accurate representation of the real vehicle. This is particularly important when simulating flight conditions which could quite possibly result in the aircraft operating outside of its normal trimmed flight condition. In order to satisfy this requirement and to achieve the large pitch and yaw angles required, a new small 1/7 scale Lynx model was constructed and tested in Westlands 12ft x 10ft wind tunnel. The model incorporated the main features of a utility Lynx fuselage, tail boom, fin and tailplane. It also included the main and tail rotor hubs but did not include the undercarriage.

Measurements of fuselage forces and moments were achieved in increments of pitch between +90° to -85° and between 0° and +170° of yaw. The forces and moments measured were in tunnel axes and therefore to enable this data to be utilised within the DRA HELISM simulation it had to be converted into the body axes. Because it was not practical, in terms of time and physical constraints of the wind tunnel balance, to measure aerodynamic loads at every possible combination of fuselage pitch and yaw angle, a comprehensive look up table of aerodynamic data could not be generated. Therefore another method of incorporating the new aerodynamic data into the HELISM aircraft model was required. This was accomplished by fitting sets of polynomial equations to the data. Lift, drag, side force and pitching moment were plotted against pitch angle for each of the yaw angles tested and 10th order polynomial equations were fitted to the data. Rolling moment and yawing moments were plotted against yaw angle for each of the pitch angles tested and 6th order polynomial equations were fitted to the data. The polynomial coefficients were then used in new aerodynamic routines written for the simulation and enabled by interpolation, the fuselage steady state aerodynamic forces and moments to be calculated at any desired fuselage incidence and side slip.

Under tail rotor failure conditions fuselage yaw rate terms become important. In order to incorporate these effects into the HELISIM aircraft model, a fuselage strip analysis routine was also developed. This calculated the rate dependent fuselage yawing moments and enhanced the HELSIM yaw rate damping terms.

One remaining area of concern post this work, was the current absence of interactional aerodynamics in the model. Of particular concern in the tail rotor failure problem is the main rotor wake (MRW)/empennage interaction, where the MRW/tail plane interaction can lead to a change in pitching moment as the tail yaws through the wake, post failure. Large changes in pitching moment might have a significant impact on post failure control strategy.

Although the flight test data has yet to be fully analysed, validation flight trials on the ALYCAT showed no apparent tendency for the Lynx to change pitch attitude from a steady heading side slip entry to an autorotation.

Whilst this might be a small effect on the Lynx it is understood to a recognised dominant effect on aircraft with large horizontal tail-planes. This, combined with the influence of fin and tail boom area on the severity of the initial yaw post failure, and later the restoring moment, are examples of why the different aerodynamic characteristics of each type are expected to make type specific handling advice important.

It should be noted that the modelling of these interactional effects is currently the subject of research at DRA Bedford.

Strategy Development - Desktop Computer Simulation

To aid the development of the tail rotor drive failure piloting techniques and to reduce the time required to integrate the new wind tunnel data into HELSIM, a desktop simulation was undertaken at Westlands. The desktop simulation involved incorporating the Westlands HELMSMAN (Ref 7) pilot model with the HELSIM aircraft model. The use of a pilot model has several advantages when developing piloting strategies. It enables the engineer to replicate pilot actions and repeat these in a consistent manner while making parametric changes to the aircraft model. This approach is used frequently at Westlands when developing new piloting techniques. The HELMSMAN model also has the ability to use flight measured data to replay actual pilot control strategies and is an invaluable tool for both engineer and pilot when developing new techniques.

Once the validity of the combined models had been established and the integration of the new aerodynamics routines accomplished, desktop simulation was undertaken to investigate tail rotor drive failures in forward flight and hover. During the desktop simulation study, the pilot model intervened to control the aircraft following the drive failure, once a preset minimum pedal margin had been exceeded. Pilot intervention times were not studied during this phase of the investigation. The outcome from the desktop simulation indicated, as would be expected, that a drive failure in hover resulted in rotation rate building up rapidly. Cutting the engines reduced the rotation rate, but left only inertia in the rotor to cushion the landing. It was evident from the simulation that the landing could only be achieved with the aircraft still rotating. In forward flight, a tail drive failure resulted in the aircraft's sideslip building up. Once the pilot model reacted and removed the main rotor torque, maintaining an aircraft heading still became difficult. This is because, like most current helicopters without large tail fins, the Lynx fuselage without the tail rotor has low weathercock stability (or yaw stiffness) at low pitch attitudes between +/- 25 ° of sideslip, Figure 10.

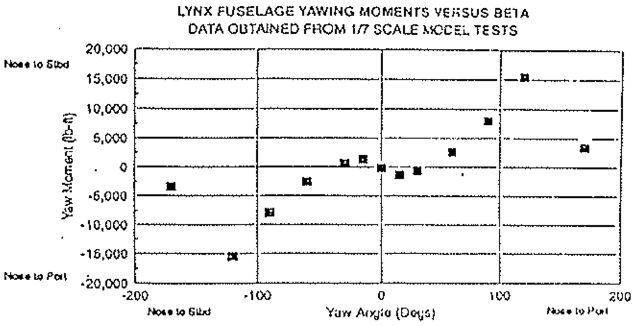

Fig 10 - Lynx Fuselage Yawing Moment versus Yaw Angle

However, as the sideslip builds up the weathercock stability increases and the yawing motion stops. The side force and drag also increase with increased side slip, and this results in a decay of speed. The simulation showed that initially the yaw motion oscillated from nose right to nose left, with the yaw angle increasing on each swing as the speed reduces. This situation would continue, eventually resulting in full rotations of the aircraft. Using the knowledge gained from the desktop simulation, the trials pilot was able to modify the control strategy, by introducing a nose down attitude post failure, to achieve a safe landing in the motion simulator at Bedford. Another advantage of the desktop simulation was that it was used to develop a parachute model that was later successfully tested in the AFS.

AFS Trials to Develop Lynx Drive Failure Advice

Drive Failure - Introduction

A handling assessment of Tail Rotor Drive Failures (TRDF) was carried out in the Large Motion Simulator (LMS), configured as a Lynx AH Mk7 with metal rotor blades. The simulation trial was conducted at DRA Bedford in November 1995. It should be noted that the AFS exhibits some key advantages over a training simulator for this work. These were:

a. The high fidelity motion cueing offered by the LMS.

b. A highly developed Lynx simulation with a known fidelity and validation level.

c. The ability to record data for post simulation trial analysis.

Drive Failure - Aim

The aim of the assessment was to support development of new Flight Reference Card (FRC) Emergency Drills for Lynx users in the event of a TRDF.

Drive Failure - Conditions Relevant

The LMS cockpit was a single-seat cockpit configured as the right hand seat of a Lynx with representative flight instruments N_R and N_F gauges and torque meter. There was a separate slip ball below the main Attitude Indicator. In addition a g-meter was fitted.
Representative Lynx flying controls were fitted, including a functioning four-way cyclic trimmer. For the simulation trial, a button on the collective lever handgrip could be pressed to shut down both engines simultaneously; the FIRE button on the cyclic handgrip could be pressed to deploy a notional drag parachute (modelled in HELSIM) which was intended to increase the model's yaw stiffness in forward flight and yaw rate damping in low speed flight.

The pilots seat was pulsed hydraulically at 4R to provide kinaesthetic cues and there was audio cueing of transmission noise.

The HELSIM model incorporated the WHL supplied aerodynamic routines obtained from wind-tunnel tests of a Lynx fuselage, detailed above. The model replicated a Lynx with AFCS engaged, less the heading hold. The simulation all up mass (AUM) was 10750 lbs and the atmosphere was ISA with nil wind or turbulence. The tail rotor elements of this model could be "failed" and the "run down" time varied.

The assessment test pilot had flown the LMS previously as a fixed base simulator for 8 hours, and with motion for 4 hours. He had flown 550 hrs of test flying in Lynx of all marks, but had no operational experience in Lynx.

Drive Failure - Assessment Criteria

Although Cooper-Harper (Ref 8) was briefly considered as the assessment criteria for the simulation trial it was rejected because it was felt that pilots ratings would fall in the HQR 9/10 bracket. Cooper-Harper simply was not refined enough at the poor end of the ratings scale for this simulation trial. Instead, the success of a control strategy was assessed by noting the vehicle terminal conditions i.e. Maximum Vertical Velocity Touch Down (VVTD), Drift Angle +/- 5° and a Forward Velocity on touch down (UTD).

Clearly, however, there is an absence of criteria for handling characteristics following tail rotor failure. One can now envisage criteria being developed for the two phases of post failure handling (recovery and landing); perhaps the acceptable and desired criteria could be set by the ease with which each of the phases can be achieved, and the terminal conditions of the landing (side slip angle, vertical velocity and landing speed). These criteria currently do not exist.

Drive Failure - Current Advice

Key points from the current advice within the Lynx manual for a drive failure are summarised below:

Drive Failure - Hover Failure

- Reduce collective pitch.
- Cushion touchdown using collective pitch whilst attempting to maintain level attitude using cyclic control.
- Select both engines to off on touchdown.

Drive Failure - Forward Flight Failure

- Reduce collective pitch.
- Establish power and airspeed to minimise yaw.
- Make Engine off landing into wind.

Drive Failure - Structure of Simulation Trial

The simulation trial was divided into four phases. These were:

a. Phase 1 - Handling assessment and subjective comparison of the simulation model with flight tests flown on metal rotor blade Lynx at WHL & Empire Test Pilots School (ETPS) Boscombe Down.

b. Phase 2 - Handling assessment following TRDF's in autorotation.

c. Phase 3 - Strategy development following TRDF's in level forward flight (at two initial heights) throughout the speed range and in the hover, with first a dual engine shut-down using the Engine Shut Down Button (ESDB), then a time delay before using the ESDB to simulate the time taken for a Lynx crew to shut down both engines.

d. Phase 4 - Handling assessment following TRDF's with subsequent use of notional drag parachute.

Drive Failure - Phase 1 - Handling Assessment

The pilots initial assessment of the directional stability and control of the simulation was that he found the model to be more stable than the Lynx. Clearly, for a drive failure simulation trial this is potentially a significant point, since if the basic simulation is more directionally stable, post failure, the response of the vehicle could be more benign than the aircraft. The control strategies developed might then be inappropriate. Despite these comments, it was decided to proceed with the simulation trial since the pilot did not consider the problem was severe enough to negate the worth of the simulation trial.

Other important comments were:

a. Motion system and visual cues both proved particularly beneficial during the simulation. However, the relatively simplistic audio cues in the AFS were thought to be a weakness of the simulation. This point became particularly important in later phases when during high workload element, post failure, the pilot would normally be reliant on audio cues to control N_R.

b. Engine-Off landings (EOL) were flown using a variable flare initiated at 150 ft AGL and 80 kn. These EOLs were considered very realistic and reminiscent of real life EOLs flown in the Lynx. It was also noted that full right pedal was required to hold heading on landing as in the real aircraft. In addition, the LMS heave axis produced "fearsome" vertical g on ground contact which added greatly to the realism.

Drive Failure - Phase 2 - Handling assessment following TRDF's in autorotation

Phase 2 was introduced to the simulation trials programme post the difficulties the HELMSMAN pilot model had experienced recovering after failure. Here the pilot established an autorotation before he was given the tail rotor failure. In all cases the pilot was able to recover the vehicle. Note-worthy points were:

a. From the stable autorotation, with a tail rotor failure, the pilot was able to conduct gentle left and right hand turns.

b. From the stable autorotation the pilot was able to conduct EOL. On all occasions touch down velocities were, however, very close to the Lynx undercarriage limits. This was caused by the tendency to keep the speed up, to overcome the nose left yaw (with the rotor) on flare.

Drive Failure - Phase 3 - Strategy development following TRDF's

The procedure adopted for this work was to start with fairly benign initial conditions and gradually present the pilot with more difficult conditions. Therefore, on the first run, the pilot was initiated high and fast (3000 ft, 140 kn); the tail rotor run down time was 30 seconds and the pilot was told of failure immediately. As the pilot developed a strategy to recover the vehicle, these conditions were constrained. In particular the following aspects were addressed:

a. Tail rotor run down time - For the majority of the simulation trial this was set to 2 seconds. It should be noted that an earlier simulation trial (Ref 9) had highlighted the benefits of a slow tail rotor decay time to recovering a vehicle at low altitude.

b. Initial speed - A range of initial speeds was selected (Hover, 50 kn, 80 kn, 140 kn). The aim was to capture data points along the speed axis of the speed/ power curve.

c. Initial height - Two heights were investigated 3000 ft and 500 ft. An additional 50 ft point was investigated for the hover case.

d. Pilot reaction time - In order to maintain consistency in this research simulation trial, the pilot was told that the tail rotor had failed 2 seconds after the failure. Again, an earlier simulation trial (Ref 9) had highlighted the importance of pilot reaction time to success, with a 1 second delay before response to failure considered unrealistically short, and a 4 second delay unrealistically long. 2 seconds, whilst perhaps a little faster than a pilot might be able to react in reality gave the pilot a chance to develop a recovery strategy.

The issue of pilot reaction time is linked to two major problems with simulation of failures. First, the pilot knows the failure is coming, and second, in a simulation trial of this nature, the pilot is asked to recover from so many failures, he becomes trained to the problem. Whilst these are both true the aim of the simulation trial should be recalled - to develop the best possible advice. This is only possible if these inherent problems are withheld.

One additional point from the simulation trial was that, it was decided that the Engine Shut Down Button (ESDB), that was being used by the pilot, was unrepresentative of the Lynx and indeed was having an impact on his control strategy and potential for success. This was proven when, in the later part of the simulation trial a time delay of 10 seconds between calling the dual engine shut down and removing the power was built into the strategy. This 10 second delay was intended to account for the time it would take for a second crew member to react to the call to shut down both engines and carry out the action. (10 seconds was later validated in a Lynx procedural simulator trainer). The recommendations that are going forward for inclusion in the aircrew advice are based on the strategies developed post the inclusion of a 10 second delay.

Drive Failure - Phase 3 TRDF Emergency Drill - Initial Recommendations

Although, at the time of print, the results from the simulation trial are still being reviewed prior to going forward for inclusion within Lynx Aircrew Manual and Flight Reference Cards, the following initial points were noted from the simulation trial:

a. If there is any indication of impending TRDF, such as high 1T to 4T vibration or increasing amount of left pedal being required to hold heading, the pilot should alter pitch attitude to achieve a speed of between 80-100 kn or land the aircraft if in a low hover.

b. When a TRDF occurs in any condition other than a low power descent, the aircraft may yaw violently to the right through up to 270^0 before the pilot has time to lower the collective.

c. On sensing the failure, the pilot should lower the collective lever to reduce the torque to zero. Maintaining the torque below zero is more important than controlling N_R.

d. The yawing motion will increase drag and reduce total airspeed. A rate of descent is required to balance the excess main rotor torque with side slip post failure. (Ref 10)

Note: Up to 1500 to 2000 ft of height may be lost until controlled flight is achieved.

e. Once yawing stops, adjust pitch attitude to achieve 80 kn. 80 kn was found to be the optimum speed for autorotation since it gave a margin above 65 kn. During the trial the Lynx simulation was occasionally found to be unstable in a tail failed autorotation at approximately 65 kn, with the vehicle breaking away from a stable descent. This was particularly true when turns were initiated at this speed. It should be noted that the pilot could consistently decelerate through 65 kn during the variable flare landing without undue difficulty.

f. DO NOT ATTEMPT TO FIND A POWER/SPEED COMBINATION FOR CONTINUED FLIGHT; this will result in a yaw break-away to the right when the torque reaches 5 to 10 %. The aircraft then enters a flat yawing descent at zero IAS which could not be broken out of even with sustained full forward cyclic stick. Attempts to break out of the descent with lateral cyclic may cause the aircraft to invert.

g. Once yawing stops shut down engines whilst in a stable condition. Shutting down engines during the vehicle's initial response to failure had an adverse effect on the pilot's ability to recover the vehicle. After engine shut down, control the N_R with collective lever.

Note: The penalty associated with not shutting down the engines was highlighted when the simulation trials pilot omitted to shut down the engines during the procedure and he lost control of the vehicle for a second time as he tried to control NR, or as he flared for landing.

h. Once in autorotation at 80 kn, gentle left and right turns may be attempted, turns with the rotor (left turns) being more stable.

i. For the landing, a gentle stepped application of collective (variable flare) engine-off landing/ditching should be attempted reducing the speed from the autorotation speed (80kn) to approximately 40 kn. From a stable (engine off) autorotation, the tendency of the vehicle to yaw left (with the rotor) on application of collective was found to be minimal in the simulation. However, this was dependent on maintaining a high (40 kn) run-on landing speed.

j. If a TRDF occurs when the aircraft is in the hover, maintain the aircraft in a level attitude and cushion the touch down with collective lever. If time permits, shut down engines. It should be noted that up to 2000 ft height was found to be required before the vehicle could be 'flown out' of a hover TRDF.

When these points have been reviewed they will go forward to assist with the definition of new advice that will be agreed with RAF Handling Squadron, WHL, DRA and the Service training authorities.

Drive Failure - Phase 3 - Additional Observations

Several other points were noted during the phase 3 Lynx tail rotor drive failure simulation trial. These included:

a. Even from high altitude (3000 ft) initial conditions, and with an 'Apache like' chop collar, landing speed and vertical velocity were always marginal for vehicle/undercarriage survival.

b. Typically, height loss of 1500-2000 ft occurred before the pilot could regain control of the vehicle post failure. The availability of a chop switch had a significant impact on the control strategy; it also saved about 500 ft in recovery.

c. When the initial height was lowered from 3000 ft to 500 ft, the pilot had a major problem recovering the vehicle and failed to complete any landing/ditching within the Lynx undercarriage limits from an initial speed above 60 kts. Landings/ditching were achieved using the standard (collective, engines, attitude, cushion) strategy from initial condition below 60 kts but the pilot observed that, on the best of these, achieving success took all his attention and ability and were only just within the undercarriage design limits.

d. All hover failures at 50 ft resulted in vertical velocities at touch down (VVTD) in excess of 23 ft/s.

e. Two strategies were investigated for a high hover failure. The first was to " fly out" of the problem. Although the pilot attempted to keep the cyclic pointing at one point on the ground, this strategy resulted in a loss of control and inverted crash. The second strategy attempted was to lower the nose and chop engines. The latter was the more successful but still resulted in a landing in excess of the undercarriage limits.

Drive Failure - Phase 4 - Emergency Systems

The final phase of the simulation trial looked at the use of an emergency drag parachute. In an earlier simulation trial the benefits of a larger fin (Ref 9) had been noted and it had been postulated that a deployable fin might assist recovery. For this simulation trial a parachute was modelled and tested off-line using the HELMSMAN/HELISIM combination. Again it was tested from various initial conditions (height, speed) being "deployed" by the pilot from a switch on the cyclic.

This parachute had a significant impact on the pilot's success, in particular:

a. The chute allowed the pilot to recover the vehicle within undercarriage limits on all occasions, the only exception being the hover failure cases.

b. The chute allowed the vehicle to be recovered consistently within limits from below 500ft.

c. The chute allowed the pilot to handle the aircraft more freely in turns and in particular, allowed the pilot to fly the vehicle on, post failure.

The emergency chute system is thought to merit further consideration, despite the immediate problems associated with such a system of weight and uncommanded deployment.

Tail Rotor Failure Future Requirements and Designs

Based on results from Lynx TR trials, when future requirements, design standards and designs are considered, several points come to the fore;

a. There is an absence of criteria for handling characteristics following tail rotor failures. Since these criteria might be the basis for any future military design it is recommended that this should be one of the focus areas for development to ensure future types have more benign handling qualities post failure.

b. Procurement agencies should always be made aware of the impact on post failure handling of reducing fuselage/fin directional stability to achieve large low speed wind envelopes.

c. The advantages of a suitably protected power chop device operated from a control on the collective should be considered.

d. As was highlighted in an earlier study (Ref 9), pilot reaction time is a key to survival. Pilot reaction time is also increasingly important as aircraft height is reduced. The introduction of a tail rotor drive failure warning "caption" in cockpits, might reduce initial reaction times (even the smallest reduction would be important), and remove uncertainty e.g. a caption combined with the often quoted "bang from the rear of the aircraft" might allow the pilot to make the correct first action more promptly. It might also allow the pilot to make the sometimes important distinction between a control failure and a drive failure. With the introduction of HUM systems, this is perhaps now more readily technically achievable and economically justifiable.

e. Particular consideration should be given to enhancing current designs which have weak fuselage/fin directional stability with:

(1) Health and Usage Monitoring Systems (HUMS) for at least the TR drive train.

(2) Emergency devices deployable to improve post failure recovery.

f. The control failure work highlighted the importance of a Spring Bias Unit (SBU) or similar device in the TR controls.

g. That undercarriage design limits are currently marginal, if not too low, to withstand post tail rotor failure landing conditions.

h. Further in the future the use of Active Control Technology (ACT) systems and perhaps cyclic control of tail rotor pitch might allow the available energy on failure to be harnessed and maintained by autorotating the tail rotor.

Conclusions & Recommendations

A research activity has been conducted by the DRA and WHL for the UK MOD Lynx Project Office, to improve the understanding of helicopter tail rotor failures, and develop handling advice for aircrew following a Lynx tail rotor (TR) malfunction.

Conclusions from the work include:

a. Tail rotor drive failures continue to occur at an unacceptably high rate (can be as high as 12 times UK requirement) in the UK MOD helicopter fleets.

b. The tail rotor malfunction can be separated in two broad categories;

- control failures, where control of tail rotor blade pitch is lost but the rotor continues to rotate and produce aerodynamic forces.

- drive failures where all power is lost to the tail rotor.

c. Tail rotor drive failures are more prevalent than control failures (UK military ratio 3:2).

d. Without a normally functioning tail rotor, many helicopter designs exhibit low directional stability.

e. Although the reasons for tail rotor failures are always investigated and if possible remedied, not enough is known about the behaviour of individual helicopter types following tail rotor failure. As a result, existing handling advice is inadequate and largely unsubstantiated.

f. Improved handling advice for current helicopters is believed to be achievable if the necessary work is put in hand. Better handling advice would enhance survivability in what is always likely to be a difficult malfunction regime.

g. Tail rotor failure aircrew emergency drill advice can often be weak and based on generic previous advice.

h. The programme used three important facilities the DRA Bedford Advanced Flight Simulator, the ALYCAT Lynx aircraft and the WHL HELMSMAN pilot model.

i. A useful procedure to develop and validate control failure advice is to remove the yaw collective interlink and fly recoveries, from various initial conditions, with the tail rotor pitch fixed from the co-pilots seat.

j. This (in-flight) control failure advice validation technique requires that:

(1) The design authority define the flight test envelop for the trials and any requirement for test instrumentation. e.g. Multi-channel telemetry transmitter and FUMS (Fatigue and Usage Monitoring System). The design authority must also define the stress/strain limits for in-flight telemetry monitoring.

(2) The design authority must give permission to fly without the interlink and define the method for its removal and gagging.

k. Tail rotor control failure flight trials have been conducted and recommendations for amendments to Lynx aircrew failure emergency drills have been developed.

l. The DRA HELSIM Lynx simulation was developed, by included new aerodynamic fuselage data at high angles of attack and high yaw angles, for the AFS trials.

m. The different dynamic characteristics (aerodynamic, transmission, dynamic response) of helicopter types are expected to make type specific handling advice important in this key area.

n. Future work to develop interactional effects (MRW/ empennage) is required to improve confidence when using simulation to define post failure handling advice.

o. Tail rotor drive failure simulation trials have been conducted on the DRA AFS and recommendations for amendments to Lynx aircrew failure emergency drills have been developed.

It is recommended that:

a. Procurement agencies should be reminded of the penalty to post failure survivability of reduced fuselage/fin directional stability to achieve large low speed wind enevelopes.

b. Consideration should be given to the provision of a suitable protected power chop device operated from a control on the collective.

c. Particular consideration should be given to enhancing current designs which have weak fuselage/fin directional stability with HUMS.

d. The advantages of post failure emergency devices (parachutes, deployable fins) might outweigh the penalty and risk of their installation.

e. All future designs should include, and all current designs should be modified to include, an SBU (or similar device) in the TR controls.

f. Where possible, type-specific tail rotor failure advice should always be developed.

g. The use of a tail rotor drive failure cockpit warning "captions" should be considered for future designs.

h. In the absence of criteria, post failure handling characteristics are likely to remain poor. In particular, standards like ADS-33 (Ref 11), should be developed to provide criteria for post failure handling characteristics.

Figures

Fig 1 AFS Motion System

Fig 2 ALYCAT Over the AFS

Fig 3 ALYCAT Instrumentation

Fig 4 Low Power Freeze

Fig 5 High Power Freeze

Fig 6 Graph Showing IFS/Side Slip Test Points Flown

Fig 7 Graph Showing Landing Speed Attained.

Fig 8 Low Power (LSS) Recovery Strategy.

Fig 9 High Power (RSS) Recovery Strategy.

Fig 10 Lynx Fuselage Yawing Moments versus Yaw Angle.

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