PAPER Nr.: 43

THE PROTECTION OF ROTOR SPEED FOLLOWING POWER FAILURE

By

D. R. HADDON

WESTLAND HELICOPTERS LTD,
YEOVIL, ENGLAND

TWENTIETH EUROPEAN ROTORCRAFT FORUM
OCTOBER 4 - 7, 1994 AMSTERDAM

Printed by the Technical Highschool Haarlem

ABSTRACT

Air Accident Investigation Branch (AAIB) reports into accidents that have occurred to civil helicopters operating in the UK, have highlighted the failure to control rotor rpm following power failure as at least a contributory factor in numerous accidents, some of which have resulted in loss of life.

While helicopter systems, and in particular the engine, have improved in reliability through the years, the design of modern helicopters can make the impact of a total power failure far more severe. Commercial considerations and aircraft performance criteria have tended to influence modern design trends towards low inertia rotor systems which compound the power failure problem by increasing the rotor speed decay rate. This has resulted in a reduction in the time available to the pilot to recover from such a failure.

Any increase in Available Intervention Time, achieved through a fundamental change in rotor inertia, could only be realised at the expense of restricting the performance and operational use of the vehicle. This would be commercially unacceptable to operators. Available Intervention Time could be increased, however, through the use of automatic intervention techniques which are designed to detect and commence the recovery action, following power failure, by reducing the torque demand of the rotor system. The alternative approach, is to improve the Actual Intervention Time which could be achieved through better cues and warnings provided in the cockpit.

In consultation with helicopter pilots and operators, and from the experience of Westland Helicopters Ltd (WHL) and the UK Civil Aviation Authority (CAA), a number of possible solutions have been postulated, including: enhanced visual systems, various auditory warnings and automatic intervention systems, all of which would provide an enhanced rotor speed protection capability. These strategies have undergone an assessment in a recent study at WHL, both analytically in off-line studies (where appropriate) and in a piloted simulation trial. The results of this study are presented in this paper.

1 INTRODUCTION

A recommendation contained within the UK Air Accident Investigation Branch (AAIB) reports following two fatal helicopter accidents (Ref 1&2), called for a review of the airworthiness requirements relating to helicopter main rotor behaviour following total power loss. In particular, the rate of rotor speed decay was highlighted as an area of concern, with the report questioning whether sufficient time was available in which a pilot could be expected to recover from the failure condition.

To address these concerns, the CAA initiated two work programmes. The first, being conducted by the RAF Institute of Aviation Medicine (IAM) at Farnborough, England, is currently in progress and aims to establish a realistic achievable Pilot Response Time, based on a large database of subject pilots exposed to such failures in a simulator. The second study, performed by WHL and which is the subject of this paper, approached the problem from another perspective, aiming to maximize the time available to a pilot in which to respond to the failure condition through the use of enhanced warnings and automatic intervention techniques.

The WHL study comprised the following objectives:

- to assess the extent of the problem,
- to identify rotor speed protection techniques,
- to quantify the benefit of these techniques in off-line analysis,
- to perform a piloted simulation trial,
- to identify the most promising techniques and to recommend the way forward.

2 BACKGROUND

Loss of engine power in any air vehicle has potentially severe consequences. The helicopter, however, has some distinct advantages over fixed wing aircraft, due to its ability to autorotate. Following total power loss, autorotation is possible from virtually anywhere within the flight envelope, provided that the aircraft's height is sufficient and that the pilot acts in a timely manner. Entry into autorotation, however, is not automatic and failure to achieve autorotation, following engine failure, has resulted in many helicopter accidents.

The problem that faces the helicopter pilot is that, in the absence of immediate corrective action, engine failure may lead to a rapid loss of rotor rpm and that, unless the loss is constrained, safe entry into autorotation will not be achieved. Actual Intervention Time and Available Intervention Time (see Fig 1 for definitions), can therefore be crucial to the successful recovery following power loss.

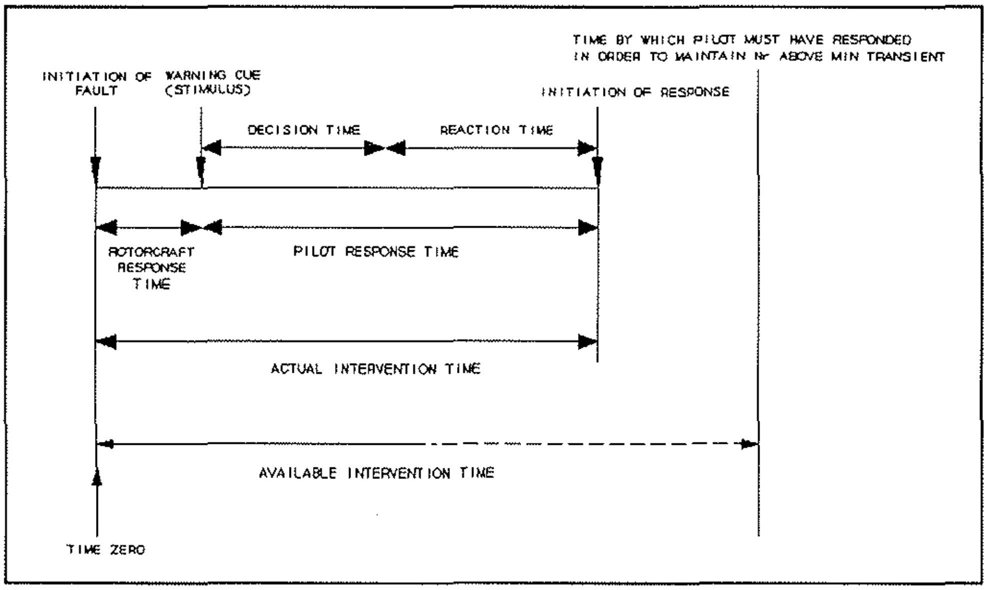


Figure 1: Definition of terms used

Actual Intervention Time can be thought of as comprising two elements, Rotorcraft Response Time and Pilot Response Time. The former represents the time required between the failure occurring and the pilot being alerted to it by a suitable cue. This cue may take the form of an adequate audio or visual warning, or maybe perceived by the pilot as a motion of the vehicle.

The Pilot Response Time can be thought of as comprising two distinct elements.

a) Decision Time

This represents the time taken by the pilot to recognise and interpret cues and warnings to identify the problem, as well as the time required to select the appropriate corrective action. The Decision Time will be dependent on the attentiveness of the pilot, the perceived strength of the cue in alerting the pilot to the problem, and the training and experience of the pilot. The Decision Time may be adversely affected by the non-specific nature of available cues, requiring the pilot to perform diagnostic procedures to home-in on the failure condition.

The action to be taken by the pilot following a failure, is not unique and may require the pilot to make a judgment as to the most appropriate control inputs to make, based on his flight speed and height. This may require either the lowering or raising of the collective lever and/or pushing/pulling of the cyclic stick.

b) Reaction Time

Reaction Time is defined as the time taken by the pilot to react to his decision and commence recovery action. Reaction Time will be dependent on whether the pilot is flying 'hands-on' or 'hands-off'.

Increased Available Intervention Time, achieved through fundamental design changes, can only be realised at the expense of restricting the performance and operational use of the vehicle. The rate of rotor rpm decay following total power loss is dependent on the rotor inertia and the in-plane drag forces on the blades, ie the rotor torque requirement. It would therefore be necessary to redesign the rotor to have a high inertia and/or to restrict the torque requirement of the main rotor by limiting the flight envelope and/or all-up-mass (AUM). All of these measures would be commercially unacceptable. There is some scope to increase the Available Intervention Time however, through the use of automatic intervention techniques designed to reduce the rotor speed decay rate.

Considering Actual Intervention Time, the Reaction Time element will generally be fixed for a given pilot involvement level. Factors that may have an influence on Reaction Time are the cockpit ergonomics and the physiological condition of the pilot (age, fitness, health). The effects of these factors are outside the terms of reference for this study, and therefore are not addressed here. The remaining elements, the Rotorcraft Response Time and the Decision Time, are seen as offering scope for improvement through increased state monitoring and through the use of enhanced warning techniques.

As well as the initial action required by the pilot to control rotor speed following power failure, it is also important that the pilot maintains the rotor speed within acceptable limits throughout any subsequent autorotative descent. Failure to constrain rotor speed during autorotative descent may have been the cause of some accidents (eg Ref 1), and is therefore an aspect that needs to be considered here.

To summarise, the areas identified which offer some scope for improvement are as follows:

- reduced Rotorcraft Response Time, through improved state monitoring,
- reduced Decision Time, through the use of improved warnings provided to the pilot,
- increased Available Intervention Time, through the use of intervention techniques designed to automatically detect engine failure/rotor speed loss and take the appropriate action, and
- improved pilot awareness of rotor speed during autorotative flight, through the adoption of an appropriate warning strategy.

3 EXTENT OF THE PROBLEM

A review of the UK CAA's Mandatory Occurrence Reporting System (MORS) database highlighted the extent of the problem. In addition, a subjective interpretation of the accident reports was undertaken with the assistance of a CAA test pilot. This was done to determine the effect that the rotor speed had on the accident and whether the use of some form of additional rotor speed protection system would have helped the pilot in retaining control. Each accident is caused by a unique set of circumstances to which individual pilots will react differently. The action taken by a pilot in this high workload scenario can only be estimated from the limited information available in accident documentation. The data has therefore been broadly classified in three categories:

Highly probable - It is considered highly probable that a rotor rpm intervention strategy, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Probable - It is considered probable that a rotor rpm intervention strategy, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

Improbable - It is considered improbable (or unlikely) that a rotor rpm intervention strategy, in addition to that which may or may not be already configured in the helicopter, would have helped the pilot.

	HIGHLY PROBABLE	PROBABLE	IMPROBABLE	TOTAL	
SINGLES	2 (3%) 2C/0L	63 (80%) 13C/50L	13 (17%) 10C/3L	78 (100%) 25C/53L	90%
TWINS	2 (22%) 2C/0L	4 (45%) 0C/4L	3* (33%) 3C/0L	9 (100%) 5C/4L	10%
TOTAL	4 (5%) 4C/0L	67 (77%) 13C/54L	16 (18%) 13C/3L	87 (100%) 30C/57L	100%

* 1 involving an Nr increase

C = Cruise L = Low level

Table 1: Summary of Reportable Accident Data

	HIGHLY PROBABLE	PROBABLE	IMPROBABLE	TOTAL
SINGLES	2 2C/0L	4 3C/1L	0	6 5C/1L
TWINS	2 2C/0L	1 0C/1L	1 1C/0L	4 3C/1L
TOTAL	4 4C/0L	5 3C/2L	1 1C/0L	10 8C/2L

Table 2: Fatal Accidents

Tables 1 and 2 summarise the outcome of the statistical and subjective analysis undertaken using the MORS database and incorporating data from 1976 (the date at which the database began) up to July 1993. The main conclusions are highlighted below.

a) The total number of UK reportable accidents recorded on the MORS database involving 'rotor speed excursions' is 87, of which 10 were fatal.

b) Of these 87 reportable accidents, 78 (90%) involved single-engine machines, of which 6 were fatal.

c) 9 reportable accidents involved twin-engine helicopters, of which 4 were fatal.

d) For single and twin-engine helicopters combined, all of the reportable accidents in the 'Highly Probable' category occurred in cruise flight.

e) For single and twin-engine helicopters combined, the majority of the reportable accidents in the 'Probable' category occurred in low level flight (54/67, 81%).

f) Only 1 reportable accident involved an Nr increase and in this case it is considered that any additional warning and intervention techniques would probably not have helped the pilot retain control.

g) It is considered either 'highly probable' or 'probable' that the fitting of additional warning/intervention systems to aid rotor speed protection would have helped the pilot in 65 reportable accidents (83%) involving single-engine helicopters, and 6 cases (67%) involving twin-engine machines (82% in total).

h) In 9 out of the 10 fatal accidents, it is considered either 'highly probable' or 'probable' that if an additional warning/intervention system designed to protect rotor speed had been fitted, it would have helped the pilot control the aircraft, with the potential of having saved 29 lives.

4 SCOPE OF THE STUDY

The two accidents cited as having initiated this study both occurred to twin-engine helicopters. However, the accident data would indicate that the pilot's failure to protect rotor speed is far more prevalent in single-engine machines. This is not unexpected, since failure in a single-engine helicopter requires the pilot to take immediate corrective action to maintain rotor speed. Furthermore, private pilots who form the majority of the single-engine class, will in general be less well trained than their commercial counterparts and may be inexperienced at dealing with the emergency situation. One of the objectives of the enhanced rotor speed protection system was therefore to ensure that it would be applicable to all classes of helicopter.

Total power loss on a multi-engined helicopter is very rare. Cases which are known to have occurred are mostly successive failures, where a second engine fails some time after the first failure. However, common cause failure modes do exist which can trigger a simultaneous multi-engine failure. Such a failure occurred during the life time of this study to a Super Puma operating in the North Sea. This incident fortunately occurred in the hover at low height and did not result in any serious damage or loss of life. However, it did confirm the need to take a pessimistic standpoint and to design a rotor speed protection system which could cope with a worst failure scenario.

With this in mind, and in light of the accident history, the following points defined the scope of this study and outlined the basic requirements of the enhanced rotor speed protection features.

- All classes of helicopters should be addressed.
- The warning system should be able to cope with a worst case failure scenario.
- The emphasis of the study should be placed on cruise flight as that is where most fatal accidents have occurred.

5 TECHNIQUES SELECTED FOR ASSESSMENT

In consultation with pilots and specialists from within WHL, external organisations and helicopter operators, the following features were identified which offered some potential benefits.

5.1 Prediction Term

The detection of failures at or near the source rather than a symptom such as rotor speed loss, will inevitably reduce the time delay (or Rotorcraft Response Time), between the failure occurring and the pilot being alerted to it. However, the monitoring of engine states to detect engine failure is inherently complex due to the numerous modes of failure which can occur. The number of states that would require monitoring to design a reliable and robust warning system can therefore be considerable. The difficulty of establishing a failure mode is only likely to be met by a fault isolation system. This would compare a 'vector' of actual engine parameters against a model and register a failure only when the vector deviates from some predefined limits. For an automatic intervention strategy which is required to interface with the flight control system, the detection system would undoubtedly require a high level of integrity, and hence inevitably lead to a high cost system. Engine state monitoring has therefore not been addressed in this study.

A far simpler method, and one which still offers significant improvements to current practice, is through the use of a Phase Advance Filter. This technique determines the rate of change of rotor rpm and then, based on this information, assesses when the rotor speed limit is likely to be transgressed. In the embodiment proposed in this study, the Phase Advance Filter was active only for the initial drop in rotor rpm following power failure. Test pilot evaluation during the work-up period demonstrated that continuous functioning of the Phase Advance Filter could lead to pilot disorientation during subsequent recovery and in controlling rotor speed during autorotation due to the system and the pilot's responses becoming out of phase.

5.2 Enhanced Visual Warnings (ENV)

The types of visual warnings that are issued following partial or total power failure vary enormously between helicopter types. In the larger, twin-engined machines, the first visual indication of a failure may be through the illumination of some form of engine failure caption, possibly in conjunction with a visual attention getter in front of the pilots. If rotor speed subsequently falls, this may then be followed in some cases by a further caption indicating low rotor speed. In this case the first warning will ensure that the pilot is attentive and may reduce the Decision Time required by the pilot once the second warning is issued. In small, single-engined helicopters, there may be no indication of engine failure/low rotor speed, resulting in a large Rotorcraft Response Time.

The visual warnings on the more sophisticated helicopters were generally felt by pilots to be adequate, especially if used in conjunction with an auditory warning. An additional visual warning that was considered to offer a possible additional benefit in reducing the time required by the pilot to recognise the fault, was to make the low/high rotor speed indication as obtrusive as possible, eliminating any need for pilot interpretation. The visual enhancement worked in a similar way to a master caution caption but was dedicated to the low/high rotor speed condition. It was installed on the simulator in a prominent location on the instrument panel, in front of the pilot. The low rpm indication was marked with a downwards pointing arrow indicating the low rpm as well as the direction of the collective input required. The high rotor speed indication was marked with an upwards pointing arrow for the converse reason.

5.3 Auditory Warnings

The lack of commonality between manufacturers in this area was again highlighted in this study. The provision of auditory warnings ranges from none through to sophisticated systems which combine warnings with cautionary and advisory messages. In this study, various conflicting views have been aired by the pilots and specialists who have been approached, on the number and type of auditory warnings that should be provided. Patterson (Ref.3) suggests that a balanced set of six immediate-action warnings plus two "attensons"[1] presents no difficulty in being learnt. Chillery (Ref.4) suggested that the time taken to memorise auditory signals increases sharply after the fifth signal.

Comments from pilots would suggest that tones are not explicitly learnt, but that in the most extreme case, they are all used as a general attenson with the decision making process being based on visual diagnostic information. In a high workload/high stress situation, such as in the case of power failure, any effort required by the pilot to identify and interpret warnings will inevitably lead to an increase in the Decision Time.

The type and contents of auditory signals to provide an optimum warning strategy has been the subject of numerous studies. These techniques were reviewed, with the final choice of auditory warnings for assessment in this trial being detailed in the following sections.

---

[1] an "attenson" is an attention getting sound which precedes a voice message. Typically, faults will be assigned one of three priority levels, warning, cautionary or advisory. For an auditory system, individual tones may be assigned to faults in the warning category, whereas attensons would group together messages of lower priority and simply announce the message and the priority level to the crew.

5.3.1 Modulated Tone (Mod)

For the rotor speed protection case considered here, a pure tone warning was considered the most appropriate.

The use of an auditory tone that mimics or enhances the noise of the rotor system was thought to offer great potential in signifying the level of urgency of the rotor speed problem. Being a 'dynamic tone' it was also thought to be easily distinguishable from any other auditory warnings that may be present and that this would lead to a reduction in the Decision Time.

This type of cue is also seen as being particularly beneficial in controlling rotor speed during autorotative descents. It gives a continuous indication of the rate of change as well as actual rotor speed whilst the pilot may be concentrating on other tasks such as attempting to restart an engine or looking outside the cockpit to select an appropriate landing site.

The modulated tones or "trendsons" selected for use in the trial, were based on those developed by Plymouth University under Contract to the Defence Research Agency (DRA) and which had been validated under laboratory conditions. The characteristics of these trendsons change in both pitch and pulse repetition rate in a stepped manner as rotor speed changes. Five levels are used, with each successive level increasing in perceived urgency the further the rotor speed strays from its normal operating condition.

5.3.2 Tones + Messages (T + M)

It was acknowledged that the Modulated Tone warning was at variance to current practice which tends towards a 'tone + message' type warning. In this type of auditory warning, each of the unique tones is followed by a message that confirms the fault. To establish the pilot's preference, this further category of warning was therefore added to the trial.

5.4 Intervention Strategies

The level of authority and the speed of reaction required of a direct intervention system will ultimately determine the integrity, complexity and hence cost of the system. For this reason it was proposed to evaluate the benefits which could be derived by utilising existing flight control systems as well as through new full authority systems. The aim was to determine the performance requirements of a direct intervention technique.

The following strategies were proposed:

a) a series actuator collective pitch reducer, which would rapidly reduce collective pitch by around 10%

b) a series actuator collective pitch reducer coupled with a 10° flare controlled by an ASE pitch attitude hold control system **(Auto 1)**,

c) a slow collective stick lowering system using a conventional parallel actuator, (16 seconds end-to-end),

d) a fast collective stick lowering system using a dedicated fast/full authority actuator (2 seconds end-to-end) **(Auto 2)**,

6 EVALUATION OF ENHANCED FEATURES

The performance of the enhanced features was determined through both off-line quantitative analysis and through quantitative and subjective data obtained in a piloted simulation trial.

Each of the enhanced features was evaluated on a Westland W30 helicopter simulation. This helicopter type was chosen as it was representative of a mid-weight civil helicopter and the simulation was readily available.

The piloted simulation trial was conducted on the Advanced Engineering simulator facility at WHL and shown in Figure 2 & 3. This is a fixed-base simulator that is based around a Westland W30 cockpit mock-up but which incorporates a development instrumentation fit based around CRT displays. This facility is a relatively new addition to WHL's design and development capability and therefore underwent an extensive shake-down period prior to the trial to ensure that the characteristics of the simulator and its computer model were compatible with the objectives of the trial.

Figures 2 & 3: The WHL Advanced Engineering simulator facility

7 OFF-LINE EVALUATION

7.1 The Phase Advance Filter

The Phase Advance Filter was designed to minimize the Rotorcraft Response Time by predicting when the minimum continuous rotor speed limit was likely to be transgressed. The design of the filter being a compromise between predictive capability and noise sensitivity.

Table 3 presents the results of off-line simulations performed using the Phase Advance Filter to minimize Rotorcraft Response Time as a function of torque prior to power failure.

Type of Total Power Loss	Engine Torque Before Failure (%)	Time to Minimum continuous rotor RPM Warning (Seconds)	Phase Advanced 'Low Rotor' Warning (Seconds)
Instantaneous	115	0.31	0.08
	100	0.38	0.09
	85	0.48	0.11
	70	0.64	0.13
	55	0.93	0.17
	40	1.47	0.26
Gradual	115	0.83	0.33
	100	0.94	0.37
	85	1.10	0.43
	70	1.30	0.50
	55	1.63	0.61
	40	2.20	0.80

Table 3: Potential reduction in Rotorcraft Response Time through the use of a Phase Advance Filter

Two power loss scenarios, which are applicable to both single and multi-engine helicopters, have been examined in detail. These being:

a) an instantaneous total power loss - this represents the worst case scenario whereby a shaft breaks instantaneously and cuts the engine's ability to supply power to the main rotor,

b) a gradual total power loss - this represents a more probable scenario whereby fuel starvation or internal damage causes the engine(s) to run down gradually. (A time constant of 0.7 seconds is used in the simulations).

The off-line simulation demonstrated that the use of a Phase Advance Filter can reduce the Rotorcraft Response Time by between 60 - 82% depending on the torque level prior to failure and on the failure mode.

7.2 Off-line Evaluation of Intervention Strategies

All intervention strategies attempt either to reduce or eliminate rotor RPM decay below the helicopter's transient minimum rotor speed limit. For the W30, this limit of 76.7% was considered to be sufficiently close to physical limits which, if transgressed, would result in a failure to recover the rotor speed and hence prevent autorotation from being achieved.

The off-line evaluation of the intervention techniques has shown the ability of these systems to increase the time available for the pilot to react following a total power failure. Table 4 compares the performance of the individual systems for the worst case, instantaneous total power loss, and the gradual power loss scenarios in cruise flight condition (120 knots). The use of the standard series actuator with the ASE pitch input to flare the aircraft and the fast acting collective stick lowering system are shown to offer the maximum Available Intervention Time. The other systems show little improvement on the baseline aircraft.

Intervention Strategy	Time to minimum transient rotor speed limit (seconds)	
	Instantaneous Failure	Gradual Failure
None	1.7	2.4
Series actuator collective pitch reducer	2.0	2.85
Series actuator collective pitch reducer and ASE pitch input	4.8	>5
Slow full authority collective pusher	1.8	2.5
Fast full authority collective pusher	>5	>5

Table 4: Time to minimum transient rotor speed limit. (120kts straight and level cruise)

Intervention Strategy	Time to minimum transient rotor speed limit (seconds)	
	Instantaneous Failure	Gradual Failure
None	1.05	1.8
Series actuator collective pitch reducer	1.24	2.15
Series actuator collective pitch reducer and ASE pitch input	1.24	2.15
Slow full authority collective pusher	1.07	1.88
Fast full authority collective pusher	2.00	>5

Table 5: Time to minimum transient rotor speed limit. (Hover)

The flare element introduced into one of the intervention strategies clearly makes an important contribution at high speed. Further analysis using just a flare to control rotor speed (no collective series movement), gives a time to minimum transient rotor rpm for a gradual total engine failure at 120kts of 4.6 seconds. At low speed (Table 5) the advantage of the flare manoeuvre becomes less significant as the magnitude of the up-flow through the rotor diminishes. It may be more advantageous in this condition to initiate a nose down pitching moment through the ASE, provided the aircraft's height is sufficient, to reduce the power requirements of the rotor and prepare the helicopter for entry into a forward flight autorotation.

Following the results of this off-line study only the flare plus series reduction strategy (Auto 1) and the fast acting collective lowering system (Auto 2) progressed into the piloted simulation trial.

8 PILOTED SIMULATION TRIAL

8.1 Experimental Design

Analysis of accident statistics indicates that two areas of flight operations account for the majority of Reportable Accidents where failure to protect rotor speed was at least a contributory factor. These are: the cruise condition, where the pilot may be flying hands-off in a passive mode, and low level flight where the pilot will be fully attentive with his hands on the controls. Both pilot involvement levels were therefore addressed in the trial. In the case of the passive flight condition, this was achieved by setting the pilot a secondary task which took the form of simple word association and numerical sequencing tasks. The subject pilots were instructed to continually perform this task during the sortie.

Each of the enhanced rotor speed protection features were incorporated into an integrated warning system prior to evaluation. This combined dummy warnings, which were similar in construction to the rotor speed warning, for other failure conditions. The integrated warning systems were constructed in such a way that only one parameter varied between each system and the effect of that parameter could therefore be easily identified and quantified (Table 6).

To ensure that no particular strategy had an advantage or that pilots could predict which failure condition would occur, the order in which the strategies were presented and the order in which failures were initiated were randomised.

Thirteen pilots took part in the trial. All held helicopter licences, and the test subjects were drawn from all areas of civil helicopter operations, including: test pilots, commercial pilots, corporate pilots, regulatory pilots and private pilots.

WARNING STRATEGY		ENGINE FAILURE		FIRE		HYDRAULICS FAULT		PHASE ADVANCE FILTER
		AUDIO	VISUAL	AUDIO	VISUAL	AUDIO	VISUAL	
1	BASELINE	LOW ROTOR RPM TONE ONLY	"ROTOR" CWP CAPTION	-	"FIRE" CWP CAPTION	-	"HYD" CWP CAPTION	NO
2	BASELINE + PREDICTION	LOW ROTOR RPM TONE ONLY	"ROTOR" CWP CAPTION	-	"FIRE" CWP CAPTION	-	"HYD" CWP CAPTION	YES
3	MULTITONES	HI/LO ROTOR RPM TONES	"ROTOR" CWP CAPTION	FIRE TONE	"FIRE" CWP CAPTION	HYD TONE	"HYD" CWP CAPTION	YES
4	ENHANCED VISUAL	HI/LO ROTOR RPM TONES	"ROTOR" CWP CAPTION + DEDICATED ATTENTION GETTERS	FIRE TONE	"FIRE"CWP CAPTION	HYD TONE	"HYD" CWP CAPTION	YES
5	TONES + MESSAGES	HI/LO ROTOR RPM TONES + MESSAGE	"ROTOR" CWP CAPTION	FIRE TONE + MESSAGE	"FIRE" CWP CAPTION	HYD TONE + MESSAGE	"HYD" CWP CAPTION	YES
6	MODULATED TONE	MODULATED ROTOR RPM TONE	"ROTOR" CWP CAPTION	FIRE TONE	"FIRE" CWP CAPTION	HYD TONE	"HYD" CWP CAPTION	YES
7	AUTOMATED INTERVENTION 1	HI/LO ROTOR RPM TONE	"ROTOR" CWP CAPTION	FIRE TONE	"FIRE" CWP CAPTION	HYD TONE	"HYD CWP CAPTION	YES
8	AUTOMATED INTERVENTION 2	HI/LO ROTOR RPM TONE	"ROTOR" CWP CAPTION	FIRE TONE	"FIRE" CWP CAPTION	HYD TONE	"HYD" CWP CAPTION	YES

Table 6: Summary of experimental strategies

8.2 Datum Warning Strategies

To determine the performance of the enhanced warning systems, two datum warning strategies were devised which best represented the types of warnings and cues that are currently used in helicopters to indicate rotor speed excursions.

8.2.1 Baseline (Base)

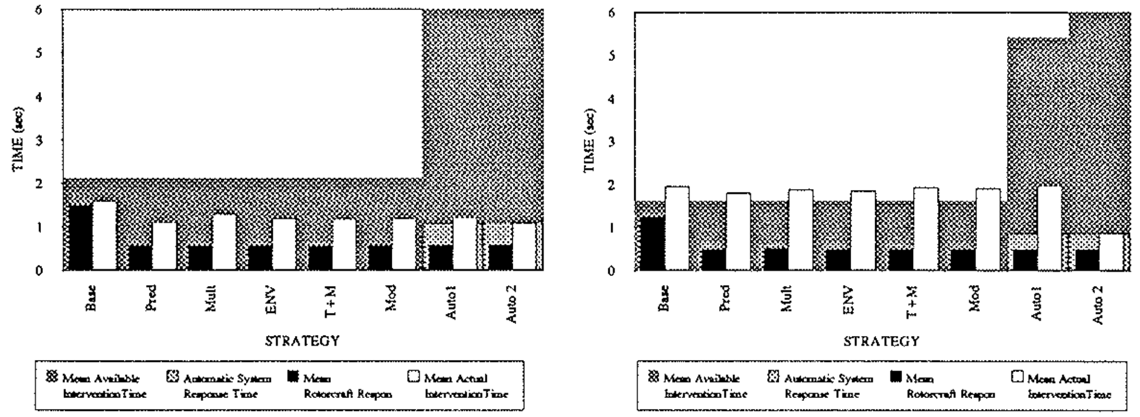
The Baseline configuration was chosen to represent a typical small/light helicopter type. A review of the warning features fitted to various helicopters in this class showed that a representative configuration should consist of a visual indicator to warn of low rotor rpm, with a single auditory tone as an additional low rotor speed warning. This represents the lowest certification standard for rotor speed warnings as outlined in JAR 27.33.

8.2.2 Multitones (Mult)

This strategy included a number of auditory warning tones, and was therefore representative of a growing trend in cockpit warning systems. The auditory warnings developed and validated at DRA(F) for the Merlin EH101 helicopter were used as the basis for auditory warnings used in the trial.

8.3 Results Of The Piloted Simulation Trial

Figure 4 summarises the quantitative results. It shows the mean Rotorcraft Response Time, mean Actual Intervention Time, mean Available Intervention Time and automatic system intervention time for each strategy, under both attentive and passive flight conditions. Also shown, is the mean minimum rotor RPM achieved with each strategy.



a) Mean Times in Attentive Flight

c) Mean Times in Passive Flight

b) Mean Min Nr Reached in Attentive Flight

d) Mean Min Nr Reached in Passive Flight

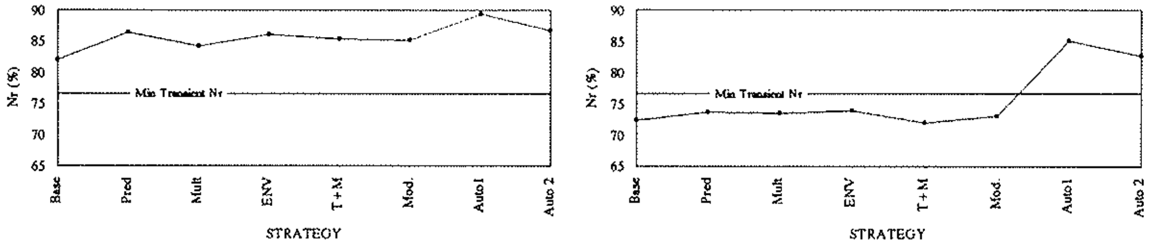


Figure 4: Mean pilot & system response times for each strategy

Statistical analysis of this data showed that there was a very significant effect of attention level on intervention time, signifying Actual Intervention Time was in general slower under passive flight conditions than under attentive flight conditions.

The only statistically significant differences found between the strategies were:

- the prediction filter gave reduced Actual Intervention Times in the attentive flight conditions,
- the collective lowering system gave reduced Actual Intervention Times under passive flight conditions,
- under passive flight conditions, only the automatic intervention strategies were able to ensure that all pilots preserved Nr above the minimum transient rotor speed limit,
- the automatic flare system showed a significantly higher mean Nr.

The prediction filter was shown in the off-line studies to reduce the Rotorcraft Response Time and hence enable the various warnings to be triggered that much earlier. In the passive elements of the trial, it would have been expected that a similar result would be attained. However, this was not so, and although there appears to be a small reduction in Actual Intervention Time due to the prediction term, this was not shown to reach significance. This is believed to be due to the influence of the strip gauge instruments used in the cockpit, which were found to be a very powerful cue. Although the subject pilots were fully occupied performing a secondary task in the passive phase of flight, the urgency that was conveyed by the amount of movement on the strip gauge, as perceived by the pilots' peripheral vision, was sufficient to cue them that a failure had occurred.

The Auto 2 (Collective lowering) strategy produced a significant reduction in Actual Intervention Time in the passive flight phase. This was without exception the system, and not the pilot, responding to the failure condition. In attentive flight this did not have the same level of significance, as the system and the pilots' responses tended to coincide.

Pilot subjective views on the warning and intervention strategies are summarised in Figure 5. The subjects were asked to rank the warning strategies in order of preference with 1 being the worst and 8 being the best.

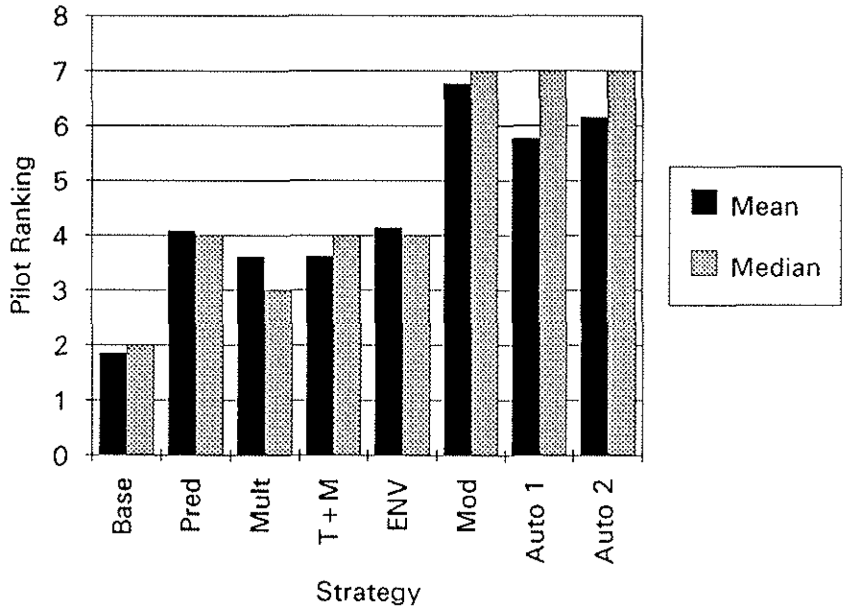


Figure 5:Relative subjective rankings

The results indicate that both of the automatic intervention strategies were well liked by the subject pilots, together with the modulated tone. The baseline system was judged to be the poorest system.

9 GENERAL DISCUSSION OF INDIVIDUAL ENHANCEMENTS

9.1 Phase Advance Filter

This enhancement would be a fairly simple addition to present rotor speed monitoring systems, and would lead to an increased time available for a pilot to react by issuing warnings that much sooner. In the case of a gradual total engine failure the reduction in Rotorcraft Response Time found in the off-line simulation was between 0.5-1.4 seconds depending on the rotor's torque requirement at the time of the failure. In the two scenarios used for the piloted simulation trial, it has been established that the use of a Phase Advance Filter can lead to a trebling in the time available for the pilot to respond to the failure condition.

The implementation of the Phase Advance Filter would be a relatively simple task. It would be applicable to all helicopter types, and could be installed as a retro-fit system to existing vehicles. The only input into the filter is Nr which would be readily available, with the output being made directly to existing warning devices.

9.2 Multitones

The addition of multiple tones into a cockpit environment to warn of failure conditions has not shown any significant change to the average pilot's Response Time. This could be construed as an advantage for this system as it indicates that more information could be made available from audio warnings without affecting the pilot's ability. However, pilot subjective views, and comments from pilots recorded during the study would suggest that the addition of multiple tones is a detrimental step. A number of pilots suggested that an ideal auditory warning system should comprise just two tones; one a dedicated low rotor speed warning and the second an attenson. Voice messages preceded by the attenson could provide additional warning indications, whereas the attenson accompanied by a visual indication would provide cautionary and advisory information.

9.3 Enhanced Visual system

It has not been possible from the results of this study to establish any significant objective benefits for this system. Subjective views tended to be split, with some pilots feeling that it did simplify the diagnostic process or acted as another confirmation of the failure condition, whilst others felt it did not add anything or was more of a distraction. For control of rotor speed during autorotation, pilot opinion was again split but with the majority tending to favour the system. It was acknowledged however, that the nature of the scenarios selected, ie. at dusk, did tend to favour this system.

9.4 Tones + Messages

The Tones + Messages strategy was introduced to ascertain whether the current trend towards this type of warning was as effective at conveying rotor speed information to the pilot as pure auditory tone warnings are. The quantitative results would suggest that there is no significant effect on the performance of Tone + Message warnings relative to the other auditory warning types. However, the Tones + Messages strategy did give the worst failure rate, with all pilots failing with this system in the passive flight scenario.

Subjective comments suggested that although the Tone + Message warnings are generally favoured for other types of failures, in the case of power failure where an urgent pilot response may be required, the message element is often too slow, with the pilot having to respond prior to the message being completed.

9.5 Modulated Tone

Subjectively, the Modulated Tone was given the highest mean rating of all the strategies assessed and was, without exception, deemed to be a beneficial technique by the subject pilots. This was particularly evident in the control of rotor speed during autorotative descent, as the pilots were able to monitor rotor speed without constant reference to head down instrumentation. However, while the Modulated Tone warning was considered to offer real benefits to a warning system, the perceived benefits could not be substantiated in the quantitative results. This may be indicative of the method of implementation of the Modulated Tone, and/or as a result of the less than optimum signal content.

9.6 Automatic flare + series actuator collective pitch reduction

The automatic flare strategy enabled the helicopter to recover from the power failure conditions set in the trial and increased the time available for the pilot to take subsequent recovery action. Further analysis at other flight conditions, showed that the strategy was applicable across the whole speed range, except at the low speed and hover cases, where the benefits of the flare diminish. In these conditions, another form of action would be more appropriate, as would the actions from the automatic system if the failure occurred at low height.

Pilots generally liked this strategy as it not only took the initial action and increased Available Intervention Time, but it also assisted in entry into autorotation by bringing the nose up and bringing the speed back. The automatic flare strategy was felt to be a more practical solution than the collective stick lowering system as it offered increased Available Intervention Time without the full authority control, and the related integrity issues, which go with a collective stick lowering system.

Implementation of the full strategy, requiring both cyclic and collective inputs, would require the helicopter to be fitted with a complex ASE. This would make it only applicable to a few types and totally uneconomic for the smaller, less sophisticated helicopters. However, it has been established that the primary benefit from this system, at least at moderate and high speeds, comes from the flare component. Implementation of just an ASE flare control mode would open up a greater number of potential applications.

9.7 Automatic collective lowering system

The full authority collective lowering system assessed during this study, gave a full speed range low rotor speed protection system that was demonstrated to be able to cope with a worst failure condition (instantaneous total power loss). The only performance limitation on the system, as presently modelled, was the low height limitation.

With an ASE fitted and functioning, there was no need for the pilot to take any immediate action, and often the helicopter would enter a trimmed autorotative descent without exceeding any vehicle limitations. This tended to give a high rotor speed however, with a high rate of descent. To achieve a more desirable autorotative profile, the pilot was required to take command and raise the collective lever.

Pilots felt this system was wholly appropriate and appreciated the improved safety benefits that it could impart. On the negative side, there was also concern shown that such a system would need to have a high integrity and reliability. An additional cue to alert the pilot that the system had operated was felt to be necessary, perhaps in the form of a collective position indicator.

10 CONCLUSIONS

- 82% of all UK Reportable Accidents between 1976 and 1993 where the failure to protect rotor speed was at least a contributory cause of the accident, could have been reduced in severity or possibly prevented, had an enhanced rotor speed warning system been fitted. This includes 9 fatal accidents which resulted in the loss of 29 lives.

- The rotor speed warning systems fitted to current helicopter types are varied with little common ground between manufacturers. No correlation between the accident data and the type of rotor speed warning system fitted to helicopters could be established.

- Rotor speed could be further protected through improvements in the following areas:

  - reduced Rotorcraft Response Time, through improved state monitoring,

  - reduced Decision Time, through the use of improved warnings provided to the pilot,

  - increased Available Intervention Time, through the use of automatic intervention techniques, and

  - improved pilot awareness of rotor speed during autorotation, through the adoption of an appropriate warning strategy.

- The most promising systems which were assessed in this study and offered real potential benefits, included:
    - the Phase Advance Filter,
    - a modulated audio tone,
    - an automatic ASE flare mode which would intervene on detection of a low rotor speed condition, and
    - an automatic collective lowering system.
- The extent to which multiple auditory tones are applied to a helicopter cockpit environment needs to be reviewed. Some subjective evidence was obtained that multiple auditory tone warnings are not being used in the manner in which they were intended; ie, the meanings of specific tone warnings are not retained by pilots. This may lead to the reduced effectiveness of an auditory warning in the urgent power failure case.
- The use of strip gauge instrumentation to present rotor and engine parameters was found to be effective, and following a failure, was a powerful cue to the pilot.

ACKNOWLEDGMENT

The author would like to acknowledge the financial support and guidance given by the UK CAA during this programme, together with the contribution made by UK helicopter operators and by the numerous pilots who took part in the trial.

REFERENCES

1 Report on the accident to Westland Wessex 60 G-AWSI, 12 miles ENE of Bacton, Norfolk on 13 August 1991.
AAIB, Aircraft Accident report No. 4/83.

2 Report on the accident to Twin Squirrel AS355 F1 G-BKIH at Swalcliffe, nr Banbury, Oxfordshire on 8 April 1986.
AAIB, Aircraft Accident report No. 7/87.

3 R Patterson, Guidelines for Auditory Warning Systems on Civil Aircraft
CAA Paper 82017, November 1982.

4 J.A.Chillery, J.Collister, Confusion experiments on auditory warning signals developed for the Sea King Helicopter. Royal Aerospace Establishment Tech Memo FS(F)688, Feb 1988.