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AIRWORTHINESS ASPECTS OF FATIGUE IN HELICOPTERS

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1.0 INTRODUCTION

The extensive and increasing use of helicopters in the commercial transport role, particularly over the North Sea, has led to the helicopter becoming an accepted means of day to day transport for civilians. Currently the United Kingdom has over 525 helicopters on the register of which 140 are twin engined public transport helicopters over 2300 Kg. Utilisation on the North Sea can reach 1800 hours per year. Accompanying this acceptance of the helicopter as a viable and safe means of transport are inevitably a number of concerns in several widely differing fields. One of these fields is fatigue substantiation. This paper sets out to cover some of the important issues in this area (from the viewpoint of a structural specialist within the C.A.A. Airworthiness Division) that have arisen over the last three years. The subject will be discussed under a number of headings : -

- Airworthiness Requirements Background
- Fatigue Substantiation Methods
- Experience with Components in Service
- The Way Ahead

3 AIRWORTHINESS REQUIREMENTS BACKGROUND

The shape and form of the requirements for civil helicopters covering fatigue have changed little over a considerable number of years. The relevant U.K. requirements have been BCAR Section G Chapter 3-1 para 5 with the associated appendices 2 and 3.

As can be seen from Figure 1 where the requirements are reproduced they are broadly expressed and alternative approaches are given; either establishment of a safe life or adoption of a failsafe approach. In this context the failsafe approach is synonymous with the more fashionable, perhaps more explicit, term damage tolerance.

5 FATIGUE STRENGTH

5.1 The strength and fabrication of the rotorcraft shall be such as to ensure that the possibility of disastrous fatigue failure of the Primary Structure and other Class 1 Parts under the action of the repeated loads of variable magnitude expected in service, is Extremely Remote throughout its operational life.

5.2 The method of proving compliance with 5.1 shall be agreed with the Authority.

5.3 Parts of the Primary Structure and other Class 1 Parts, which may be critical from fatigue aspects, shall be subjected to such analysis and substantiating load tests as to demonstrate, either:—

(a) a safe Fatigue Life,† or

(b) that such parts of the Primary Structure exhibit the characteristics of a Fail-Safe Structure.‡

NOTES: (1) Where there are two parts in a rotorcraft, the double failure of which could affect the rotorcraft in the same way as the failure of a Class 1 Part, their Safe Fatigue Lives shall be established as being sufficient to ensure that the possibility of a double failure is acceptably remote. In assessing the possibility of a double failure the ease with which a part can be inspected and the frequency of inspection should be considered.

(2) In demonstrating Safe Fatigue Life the Authority will expect that, at the time of initial certification, the Safe Fatigue Life which can be substantiated will be such as to give reasonable assurance as to the soundness of the structure (see G3—1 App. No. 2, 6.5).

(3) In demonstrating Fail-Safe characteristics, information should be provided in the relevant manual as to the frequency and extent of the repeated inspection of the structure necessary to ensure that any failure will be found within a reasonable period.

(4) In order that vibratory stresses can be kept low, great care should be given to the detailed design of:—
(a) the main and auxiliary rotors including retaining hubs and controls;
(b) the transmission system;
(c) certain parts of the main control system;
particularly with a view to reducing stress concentrations.

FIG. 1 BCAR G3-1

In a similar way the United States requirements of FAR Part 27 and 29 as stated in 27.571 and 29.571 allow the alternative approaches of replacement time evaluation or fail safe evaluation.

In 1983 the FAA issued advanced notice of a Proposed Rule (ref 1) which was stipulating damage tolerance as the prime approach for helicopter fatigue substantiation. This notice evoked a considerable response from Industry and was supported in principle by the European Airworthiness Authorities within JAR.

The CAA has recently completed an overall review of helicopter airworthiness culminating in the publication of a report (ref 2) colloqually known as the HARP report. As an appendix to this report the safety record of helicopters is discussed. Two of the conclusions drawn are that : -

> Helicopter (large twin engine) accident rates, either on a per hour or per flight basis are significantly worse than those for modern jet transports, although comparable to propeller turbine transports.
>
> The percentage of all accidents which is due to airworthiness causes is higher on helicopters than on fixed-wing aeroplanes.

The Report makes a number of recommendations and whole heartedly supports proposals for requirements involving damage tolerance principles to be adopted by helicopters on an international basis. This will be further discussed in a subsequent section.

Whilst discussing requirements it is also relevant to mention some recent collaborative work between FAA and JAR with the Industry. This was to produce the internationally agreed text to an Advisory Circular on composites structures (ref 3). Among other aspects this Circular addresses the issues of fatigue and damage tolerance for composites. Although this work was done in Europe under the banner of JAR Part 25 Requirements applicable to large transport aeroplanes the Advisory Circular is of direct relevance to helicopters which make extensive use of composites in primary components. Indeed in the USA the circular is applicable to both fixed wing aircraft and helicopters.

3.0 FATIGUE SUBSTANTIATION METHODS

Many papers have been written on helicopter fatigue substantiation procedures e.g. ref 4,5 and 6 and it is not proposed to go through them in detail in this paper. Figure 2 summarises these procedures for safe life determination as applied to helicopters.

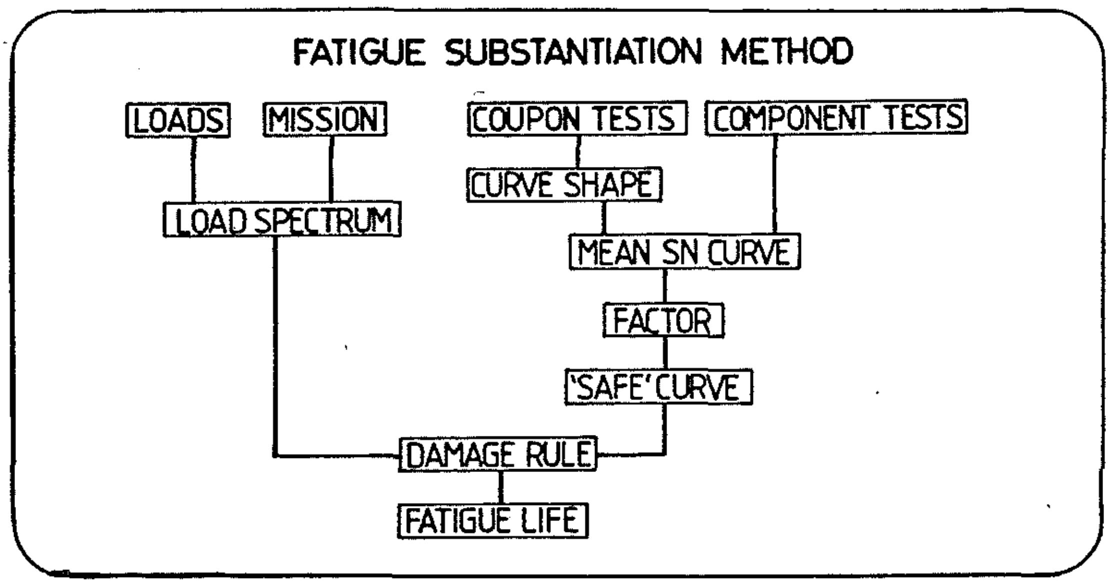

FIG. 2

One of the most widely publicised papers on the subject (ref 7) reported on a comparative exercise in which several manufacturers calculated lives for a given component with a given set of loads information. The predicted lives varied from 58 to over 24,000 hours. The reasons for the differences in the predicted lives was attributed to assumptions made about the SN curve shapes, the reduction factors of scatter and the method of reducing the given loads data. Changes in any one of the boxes in Table 2 can significantly affect the final answer deduced. This paper will focus on two of the areas which the CAA are currently investigating - the SN curve shape and the loads spectrum.

3.1 SN Curve Shape

The shape of the mean SN curve is not only important for its own sake but also its shape influences the associated reduction factors needed to produce the safe working curve. Hence it was decided to carry out a study of SN curve shapes in use prior to considering reduction factors.

Figure 3 shows a multiple plot of all the curve shapes of titanium submitted to the CAA in connection with fatigue substantiation of helicopter components over the past few years.

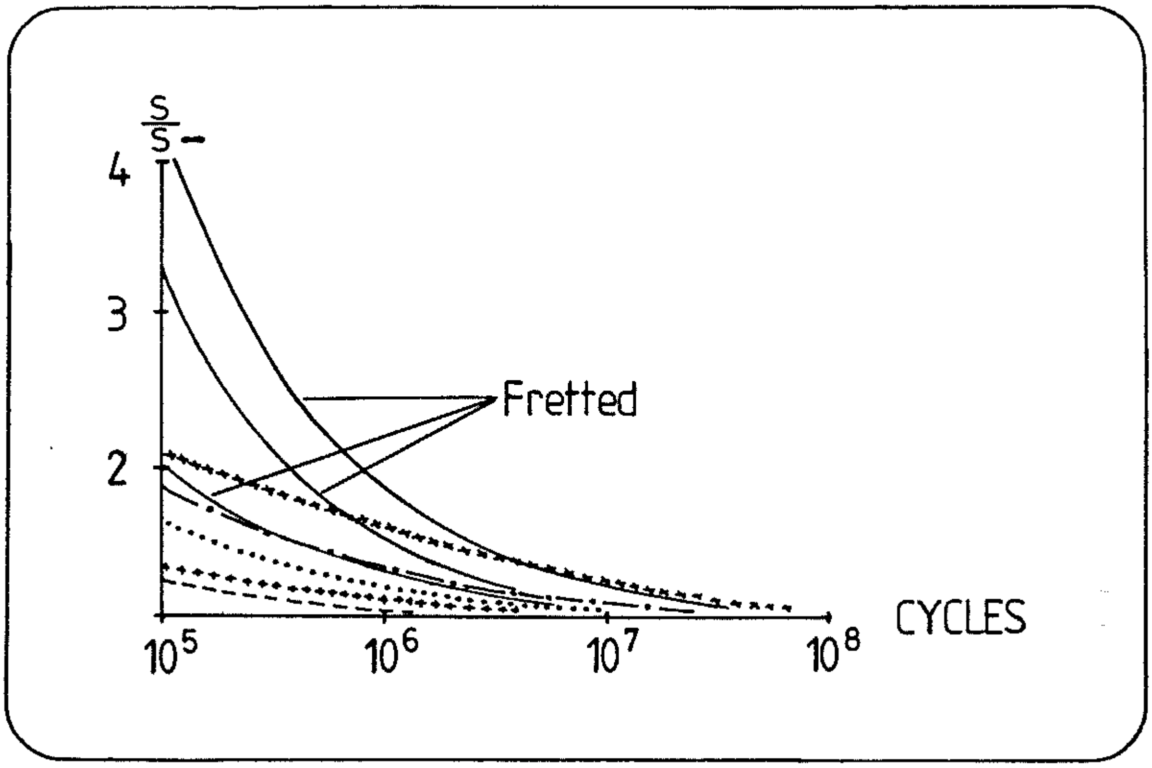

FIG. 3 - SN Curves for Titanium Alloy

The wide range of shapes is disturbing and a similar range is also seen for aluminium and steel. Even with fretting and non-fretting curves separated the disparity is still large. Such disparity is particularly significant when considering the combination of ground air ground cycles of order 10^4 with flight loads of order 10^8 cycles on the SN curve.

In the past curve shapes have been typically derived from small coupon data. Currently CAA is gathering data from actual helicopter component tests in an attempt to establish mean curve shapes for realistically tested components rather than coupons. The objective is to establish a set of standardised curve shapes if possible. All the major civil helicopter manufacturers have agreed to supply data for this and to date half of them have responded with that data. Unfortunately the work is therefore not yet completed and will have to be reported at a later time.

3.2 Loads Spectrum

GROUND CONDITIONS	BCAR	% Time for Various Types							
Spin Up	0.5	3/hour	2/hour	0.5	0.5	0.5	0.5	0.5	3.0
Taxying	0.5		1.0	0.5		0.5			3.5
Take-Off % (per hour)	0.5	(3)	(4½)	0.3(4)	0.3(4)	0.5(6)	0.5 (2+)	0.5(2+)	(3)
Shut Down				0.5	0.5		0.5	0.5	
Transition to Forward Flight									4.0
LOW SPEED FLIGHT									
Steady Hover	0.5	13.5	3.6	5.4	2.0	0.5	5.5	4.3	9.0
Lateral Reversal	0.5		0.1	0.01	0.01	0.5		0.4	
Sideways Flight	0.5	1.0	0.66	0.4	0.5	0.5	4.0	4.0	2.0
Longitudinal Reversal	1.0		0.1	0.01	0.01	0.5		0.4	
Backward Flight	0.5	0.5	0.32	0.1	0.25	0.5	2.0	2.0	0.1
Directional Reversal	1.0		0.1	0.01	0.01	0.5		0.4	
Spot Turns		6/hour	1.4	0.3	0.4		0.4	0.4	
Transition to Hover		3/hour	1.5		1.5				0.5
AUTO-ROTATION									
Steady Forward Flight	2.5	2.0	0.3	0.04	1.2	1.0	0.3	0.3	1.4
Right Turns	1.0	0.1		0.003	0.4	0.5	0.4	0.4	
Left Turns	1.0	0.1		0.003	0.4	0.5	0.4	0.38	
Lateral Reversals	0.5				0.02	0.25	0.1	0.1	
Directional Reversals	0.5				0.02	0.25	0.1	0.1	
Longitudinal Reversals	0.5				0.02	0.25	0.1	0.1	
Pull-ups from Level Flight	2.0				0.25	0.5		0.05	
Landings	2.5			0.004		1.5	0.15	0.15	
Recovery							0.5	0.5	

FIG. 4a Helicopter Flight Spectrum Comparison

Figures 4a and 4b of the design flight spectrum for three United States and five European twin engined helicopters. The spectrum given in BCAR G3-1 Appendix.2 for single engined helicopters is included for comparison purposes.

FORWARD FLIGHT	% Time for Various Types								
	BCAR								
Level Flight 20% V_{NE}	5.0	3.0				1.0	5.0	4.0	
Level Flight 40% V_{NE}	10.0	2.0		4.7	14.0	3.0	6.0	5.5	
Level Flight 60% V_{NE}	18.0	10.0	7.4	15.0	16.0	18.0	10.0	10.0	
Level Flight 80% V_{NE}	18.0	15.0	20.0	24.0	22.0	25.0	30.0	30.0	33.0
Maximum Level Flight	10.0	36.0	30.0	30.0	25.0	15.1	10.0	10.0	24.4
V_{NE}	3.0	1.0	15.0	2.90	1.0	3.0			0.2
1.11 V_{NE}	0.5		1.0	0.1		0.5	1.5	1.5	
Right Turns	3.0	2.5	0.66	1.0	0.4	3.0	1.1	1.1	1.8
Left Turns	3.0	2.5	0.66	1.0	0.4	3.0	1.1	1.1	1.8
Climb at M.C.P.	4.0	5.0	6.5	5.0	2.5	4.0	6.0	6.0	1.0
Pull Ups from Level Flight	0.5		0.6	0.2	0.75	0.2	0.45	0.2	
Entry to Autorotation	0.5	1/hr	0.03		0.4	1.5	0.5	0.5	0.01
Partial Power Descent	2.0	3.0	2.86		2.4	2.0	2.0	2.0	
Approach and Landing	3.0	3/hr	0.53	2.6	1.0	4.0	1.7	1.0	4.0
Lateral Reverals at V_{NE}	0.5		0.01	0.05	0.02	0.5			
Longitudinal Reversals V_{NE}	0.5		0.01	0.05	0.02	0.5			
Directional reversals at V_{NE}	0.5		0.01	0.05	0.02	0.5			
Climb at max 1 hour power	2.0			1.2		2.0	2.0	2.0	
Acceleration/deceleration				2.0	2.78				
Forward Flight with sideslip			1.6			0.5			3.2
Moderate Turns			3.4	2.0	4.0		4.0	4.0	6.6
Control reversals at 0.8V_{NE}			0.2				3.0	3.0	
Single engine operation					0.36	2.4		1.7	
Gusts						0.2			
Extreme manoeuvres			0.14				0.2	0.35	0.004
Negative "g" manoeuvres									0.05

FIG. 4b Helicopter Flight Spectrum Comparison (Continued)

There are a number of observations that can be made from this table.

Each helicopter has a different spectrum of design loads used in substantiation.

Times assumed spent in a given condition vary for example:-

a) the time at maximum level flight speed ranges from 10% to 36% of total time,

b) the time spent in turns is around 6% but maybe divided in to different severities,

c) the time assumed in auto rotation is understandably reduced for twin-engined helicopters as compared with the original suggested single engined spectrum. However the time spent in the condition also varies widely.

d) The assumed time spent in control reversal of all kinds varies widely as does the time in hover.

e) Gust loadings only appear in one spectrum.

The disparities in this table are not as significant as they appear in that different helicopter types may always be operated in different roles and normally only a few phases of flight are damaging. However there must be a good case for rationalisation into a baseline spectrum.

Operational data from the North Sea would indicate some other important variations in load spectra; at least one operator spends 90% of his flight time at maximum level flight speed ($V_{NO} = .9\ V_{NE}$). Another operator having had discussions with the constructor of a rotorcraft on his proposed utilisation settled on 3 landings per hour but subsequently found that the operation was including up to 7 landings per hour.

Such investigations have led to the belief that in-service operational load measurement is necessary before a typical spectrum for twin engined helicopters can be established and agreed on an international basis.

This issue is being approached on two fronts : -

On the requirement front a CAA Airworthiness Notice is being formulated to require U.K. Operators to monitor their operations in terms of speeds, weights, number of take-offs, sector lengths etc and to notify the manufacturers and CAA of any significant changes.

On the research front an extension of the CAA fixed wing data gathering programme to include helicopter operation in the North Sea is underway. The first stage which started in mid 1984 is recording simple performance parameters eg speed, height, engine torque. Later phases will introduce load measurement in certain key components.

4.0 EXPERIENCE WITH COMPONENTS IN SERVICE

Significant events related to fatigue or mechanical failure concerning large transport helicopters since 1981 (ref 1) that have had direct involvement of CAA Airworthiness Division Staff are listed in Figure 5. The importance of each event is indicated qualitativly on the basis of the judgement of the Surveyor concerned. Although this paper is primarily concerned with structural fatigue matters significant failures in the gearbox and transmission are also listed as there are many similarities in the lessons to be learned and the way forward.

Occurrence	Accident	Potential Accident	Serious
Spindle Thread Failed	x		
Head Damper Lugs Failed			x
Spindle Lugs Failed		x	
Hub Spline Cracks		x	
Fuselage Cracks			x
Tail Boom Attachment Cracks			x
Landing Gear Leg Cracked			x
Pitch Shaft Cracked		x	
Rotor Hinge Pin Cracked		x	
Grip Failed		x	
Hub Retention Nut Cracks		x	
Pylon Mounting Cracks			x
Erosion Shield Separation			x
Tail Rotor Control Failed	x		
Tail Rotor Control Fail		x	
Tail Rotor Pitch Horn Failure		x	
Rotor Yoke Crack		x	
Tail Rotor Bush Migration		x	
Rotor Trunion Bolt Failure			x
Damper Attach Bracket Failure			x
Gearbox Failure	x		
Rotor Brake Fire		x	
Gearbox Failure		x	
Oil Cooler Drive Failure			x
Uncontained Gear Failure		x	
Gearbox Failure			

FIG 5 - SIGNIFICANT EVENTS RELATED TO FATIGUE OR MECHANICAL FAILURE

(Large Transport Helicopters - CAA involvement since 1981)

The first observation to be made from this survey of experience is that during the same time period for structural items only three or four events of "serious" classification for fixed wing transport aircraft had to be considered, whereas there are 20 entries for helicopters structures in the table.

Secondly the majority of events did not result in accidents indicating that they were detected before catastrophe which can be taken as a potential capability for damage tolerance in many types of rotorcraft components.

With the benefit of engineering "hindsight" a number of lessons can be learned from the likely causes of each of the failures. Figure 6 (below) indicates for each event the major or important contributory causes as one or more of six categories.

Occurrence	Wear/Corrosion	Loads	Spectrum	Testing/ SN Data	Detail Design	Quality Assurance
Spindle Thread Failed	x	x		x	x	
Head Damper Lugs Failed		x				
Spindle Lugs Failed	x			x		
Hub Spline Cracks	x		x	x		
Fuselage Cracks		x			x	
Tail Boom Attachment Cracks					x	
Landing Gear Leg Cracked			x		x	
Pitch Shaft Cracked		x				
Rotor Hinge Pin Cracked		x				
Grip Failed			x			
Hub Retention Nut Cracks						x
Pylon Mounting Cracks			x			
Erosion Shield Separation						x
Tail Rotor Control Failed	x	x				
Tail Rotor Control Failed		x				
Tail Rotor Pitch Horn Failure					x	
Rotor Yoke Crack				x		
Tail Rotor Bush Migration					x	
Rotor Trunion Bolt Failure	x					
Damper Attach Bracket Failure		x				
Gearbox Failure	x					x
Rotor Brake Fire					x	x
Gearbox Failure	x				x	
Oil Cooler Drive Failure	x					x
Uncontained Gear Failure				x	x	
Gearbox Failure	x					x

FIG. 6 -CONTRIBUTORY CAUSES TO EVENTS (FIG 5)

1. Wear or corrosion in service contributed to nine cases. In three of them the wear or corrosion reduced the fatigue initiation time of the structural component. In the other two cases the effect of wear was to increase loads either by changing the load path or by reducing damping of vibration. It also featured in four of the transmission/gearbox failures.

2. Loads had increased in two of the cases that are mentioned above. Two other cases were a direct error in measurement of the loads and 4 others had unanticipated loads on the components

3. Spectrum assumptions. In 3 cases damage phases (2 of them on-ground) had not been considered in the analysis. In another case interaction of ground and flight cases had not been anticipated but showed up subsequently on test.

4. Testing that was unrepresentative was a contributory cause in four cases and inadequate SN data in another.

5. Detail Design Inadequacies featured in nine of the events.

6. Quality Assurance shortcomings either in manufacture or in operational service contributed to six of the cases.

It therefore follows that improvements in any or all of the above areas should lead to a better fatigue performance. The next section outlines the approach proposed for such improvement.

5.0 THE WAY AHEAD

The proposed CAA approach to fatigue substantiation is in three steps. The first step is already in being within the framework of existing British requirements and is following the guide lines outlined in 5.1. Concurrently work is being undertaken as background to requirements for the short term approach as in 5.2 and the longer term objective stated in 5.3.

5.1 Current Guide Lines

a) Manufacturers methods of fatigue substantiation testing and analysis are being re-assessed as the opportunity arises. Existing factors on fatigue strength are not relaxed below current levels e.g. 1.6 for aluminium 1.4 for steel (6 specimens).

b) The factor of 1.2 specified in BCAR G3-1 Appendix 2 Para 4.1.4 to allow for variation in measured flight loads from helicopter to helicopter is retained unless the constructor has sufficient evidence to the contrary.

c) The effects of corrosion, wear and deterioration in service should be monitored by the operator and the manufacturer. Examples of any affected time expired parts should be returned to the manufacturer for repeat fatigue tests.

d) The validity of any declared life should be specified in terms of the flight profile or spectrum, and operators will be required to monitor their fleets accordingly.

e) The flight rules concerning the use of VNO (= .9 V_{NE}) are being retained.Unrestricted use of a higher speed can be permitted only if an additional fatigue substantiation has been conducted.

f) Fatigue damage in level flight at V_{NE} will generally not be accepted.

g) More careful consideration will be given to the substantiation of any change in manufacture of critical parts.

h) Companies are being encouraged to implement effective health monitoring disciplines.

5.2 Short Term Approach

In parallel with activity for the longer term, BCAR requirements are currently being formulated (with the appropriate consultation of the industry) covering the following : -

a) In the absence of fail safe/damage tolerance features, the requirements should provide for substantially higher fatigue strength reduction factors. These are particularly necessary where the design is vulnerable to wear, fretting, corrosion, loss of clamping torque and so on. It is intended that the BCARs should be more detailed, for example

   (i) Reduction factors should be included and broken down to relate the proportions attributable to each part of the substantiation process.

   (ii) S-N curves should be included for use unless it can be shown that more representative shapes are available.

b) Safe fatigue lives should be accepted only on the basis of more representative testing, including : -

   (i) much more accurate and extensive load data gathering, involving wear and service deterioration,

   (ii) a method of testing which ensures that the magnitude of the loads, the stress distribution and the number of cycles are representative of service conditions, and installational effects,

   (iii) testing of worn and service deteriorated parts,

   (iv) more accurate definition of the flight profile/spectrum, which should be monitored in service,

   (v) some spectrum testing in place of single load level testing which should include multi-load levels and sequence of loading representative of operating conditions.

c) Critical parts manufacture should be controlled to ensure that either no process detail is changed without re-qualification, or larger reduction factors are applied. To this end a critical parts plan shall be submitted by the applicant and approved by the CAA.

d) Requirements should be introduced to ensure the design provides for health monitoring, and that the potential benefits are realised in service.

5.3 Longer Term Objective

It is essential that for the longer term requirements must be formulated on an international basis. The CAA will participate in such activity along the lines that mechanical and structural components for helicopters shall be in order of preference : -

(a) damage tolerant by virtue of multiple/alternative load paths, and appropriate means of detection

(b) damage tolerant by virtue of slow crack propagation rates, and appropriate inspection

(c) subject to safe lives in accordance with recommendation in 5.2. This would be acceptable only if damage tolerance is impracticable.

6.0 CONCLUSIONS

In the last four years there has been an increasing awareness within CAA that steps could be taken towards enhancing the safety record of of fatigue related failures in helicopters. In 1980 LeSueur observed "there is need for improvement" reference 8. In 1984 the HARP report endorsed requirements involving damage tolerance principles. This paper has set out to cover some of the steps being taken in that direction. It is strongly felt that the way ahead is the damage tolerance approach supported by a more rigorous safe-life substantiation where damage tolerance has been shown to be impractical.

Acknowledgement

The author would like to gratefully acknowledge the many, various and sometimes protracted discussions on the subject with colleagues in authorities and industry on both sides of the Atlantic that have culminated in the production of this paper.

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