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HELICOPTER USAGE MONITORING FOR FATIGUE LIFE CALCULATION

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TITLE : Helicopter Usage Monitoring for Fatigue Life Calculation

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The subject of Health Monitoring has been studied greatly by manufacturers and operators of helicopters for some years. Substantially less has been done on Usage Monitoring despite the uncertainties which exist in helicopter usage and the importance of fatigue lives. This paper presents the results of studies carried out at GKN Westland Helicopters into Usage Monitoring for fatigue lifesubstantiation. The paper considers the principal drivers in the fatigue loading of airframe, dynamic component and transmission parts. Compound parameters are derived which show strong correlation with measured loads. These are proposed as effective measures which can be used for efficient post flight damage analyses.

1.0 METHODOLOGY

The fatigue life analysis of fixed wing aircraft is dominated by loading cycles which have a relatively low frequency of occurrence.

Low frequency loading cycles are also present on rotorcraft, where they may be attributable to the rotor start-stop cycle as well as GAG cycles. However, this situation is complicated by high frequency loads, which are associated with multiples of the rotor turning frequency. The relative importance of the two types of loading varies with component, but generally low frequency loading dominates for the airframe structure and drive shafts, whilst high frequency dominates for the rotors.

For the assessment of the most fatigue damaging cycles during this study, load histories were synthesised for a number of mission profiles. The basic form of the profiles are shown by example at Figure 1. Each profile included a number of flight manoeuvres, the occurrence and severity of which were taken from historical data on normal load factor occurrence. Thus the civil profile was the most benign and the military utility, the most severe.

During the study assessments were also made by fatigue life calculations based on usage spectra consistent with the mission profiles. The calculations were performed using the GKN Westland fatigue damage analysis programme, known as DUMBO, which includes algorithms for both high frequency and low frequency fatigue damage.

2.0 AIRFRAME FATIGUE DAMAGE

Detailed analysis of airframe damage rates was made using fatigue strength data derived from full scale fatigue test. Flight loads came from load survey on prototype aircraft.

2.1 Damage Rates for Typical Sortie Profiles

Initially all 32 analysis points on the EH101 main load path were analysed for each mission profile. The most obvious result was the relative damage rates from the different sortie profiles, with the naval spectrum being most benign and the military utility the most severe. Inspection of the data confirmed that this was due to the high GAG rate and the severity of manoeuvres in the military utility spectrum.

During the initial assessment, the sensitivity of the airframe to cg position was also checked. As might be expected, forward cg tends to off-load the rear structure and vice versa. More central areas were less sensitive to cg. It should be recognised that the effects in some areas were significant.

2.2 Damaging Load Cycles

Six fatigue critical areas of the EH101 airframe were selected for more detailed analysis. These were chosen to give a good coverage of the airframe as well as for their individual criticality. See Figure 2.

The results from the fatigue damage analysis programme were reviewed for the six critical locations. In particular, the conditions which were paired in the low cycle analysis were considered. Each cycle was characterised as:

GAG	-	where a flight condition pairs with a ground manoeuvre condition.
FTH	-	where forward flight condition and pairs with a hovering condition.
GRND	-	where the load cycle pairs two ground conditions.
HOVER	-	where the load cycle pairs two hovering conditions.
FLIGHT	-	where the load cycle pairs two forward flight conditions.

The analysis proved the working assumption that the GAG cycles dominate the low cycle fatigue in most cases. However, in the naval (ASW) spectrum, where there are relative few landings, but a large number of transitions to hover, the FTH pairing can be very significant in terms of fatigue damage.

Looking in more detail at the GAG pairings, it was found that the GAG cycle is generally formed by pairing a high speed manoeuvre with a landing, or other ground condition. Nevertheless, one notable exception is found on the shoulder of the airframe at location SB0080B, with load maxima for conditions with high lateral, roll or yaw acceleration such as sideways flight, spot turns and lateral control reversals. This is entirely logical for this point of the structure.

2.3 Phases of Flight

To provide a better understanding of the fatigue damaging cycles which are accrued on the airframe, simulated strain histories were generated. Figure 3 shows the strain profiles for a number of phases of flight, including take off, hover, climb, level flight at a range of speeds, descents, autorotations, transition to hover and landing.

A number of observations can be taken from these strain histories, which are relevant in fatigue usage monitoring.

- The GAG cycle is evident, though its relative magnitude varies greatly; SB0080B shows small variation with flight condition, whereas for SB0238B the variation of load with flight condition is almost as great as the GAG cycle.
- Mean loads often vary significantly through the forward speed range, sometimes increasing and sometimes decreasing.
- Vibratory loads increase with forward speed.
- At some locations, autorotations cause a significant load cycle, which is opposite in direction to the forward speed characteristic.

2.4 Effect of Manoeuvres

Figure 4 extends the strain profile idea to consider manoeuvres about steady state conditions of MPOG, hover IGE & OGE, 0.6Vne, 0.9Vne and 1.0Vne.

The most significant strain cycles tend to be :

- Taxi accelerate / decelerate
- Longitudinal reversals
- Pull-ups
- High g turns

In the fixed-wing part of the aerospace industry, the peak loads assessment is often performed on the basis of normal load factor, Nz. Figure 5 shows that this would be a very inaccurate method for helicopters with almost no correlation between peak load and Nz. Whilst Figure 5 shows the Nz effect in flight, Figure 6 shows that the lack of correlation continues when one considers normal load factors produced on landing. Strain levels at points remote from the landing gear show poor correlation with landing decelerations.

3.0 DYNAMIC COMPONENT FATIGUE DAMAGE

The results presented in this section are based on preliminary fatigue strength data and incomplete loads data. Further no cycle count analyses have been performed. The results in terms of lives are therefore very conservative and not a true reflection of the service life of the production items. Nevertheless, they are suitable for the analysis of trends.

3.1 Rotorcraft Flight Envelopes

Before one can look in detail at fatigue load trends on dynamic components it is important to understand the construction of the flight envelope. Conventional helicopters are constrained by a combination of three limits.

1) an Equivalent Air Speed (EAS) limit associated with pressure loads on the airframe structure.
2) a retreating blade stall limitation where the local blade velocity is low, combined with a high angle of attack leading to stalling.
3) an advancing blade compressibility limit where local blade velocities approach the speed of sound (this becomes a temperature dependent TAS limit).

The third limit has not been considered in this paper due to lack of cold trial data at the time of the analysis.

It should be noted that the retreating blade stall limit is actually a compound limit providing a minimum margin of 10% on forward speed and a 30° bank angle manoeuvre margin.

3.2 Main Rotor Blade

One section of the EH101 main rotor blade was used for fatigue life analysis against a composite usage spectrum covering most aspects of the mission profiles as shown in Figure 1. The fatigue damaging conditions and rates of fatigue damage are shown in Table 1.

Typical usage spectra for helicopters include an allowance of 0.5% time spent at 1.1Vne and this condition constitutes the bulk of the fatigue damage in this spectrum. The other damaging conditions relate to manoeuvres at high speed and transitions to hover. Closer inspection of the data showed that the high speed conditions were more severe when flown at 3,000 ft HD than at 10,000 ft HD.

An easy mistake to make in recording usage would be to record time spent in altitude and speed bands according to Indicated Air Speed (IAS). However, investigation showed that True Air Speed (TAS) demonstrated better correlation of data from different parts of the flight envelope. The true relationship is in fact based on the advance ratio of the rotor, taking rotor speed also into account. When this load characteristic impinges on the S/N curve the fatigue damage rate is found to rise very rapidly once the speed associated with the endurance limit is exceeded. See Figure 7.

Close inspection of the data shows that blade loads increase with aircraft weight, although the rate of increase is not great. It may be hypothesised that the effect is based on increased rotor thrust. In this case one would expect loads to be a function of aircraft normal load factor, for example in bank turns. Indeed, this was found to be the case, as shown in Figure 8. Damage rates increase with forward speed, and with rotor thrust. Fortunately the combination of high speed and high rotor thrust is infrequently encountered.

3.3 Main Rotor Rotating Controls

Inspection of load survey data showed that main rotor rotating control loads vary even more greatly with weight, speed and altitude than the blade loads. Nevertheless, fatigue damage analysis showed the same high speed conditions to be most damaging, though not the transitions to hover. Referring back to the limiting factors which define the helicopter flight envelope, it was observed that the loads are greatest in proximity to the retreating blade stall limitation. Further, it was found that for level flight conditions the most damaging events were those associated with the 10% speed margin region of the envelope, whereas for the most damaging manoeuvres the most severe events were from the flight envelope region associated with the 30° bank angle manouevre margin. Thus it was shown that the significant feature in terms of speed is the proximity of the condition to the retreating blade stall line, Vrl.

After further experimentation and discussion with aeroelastics specialists at GKN Westland, it was concluded that the data should be normalised according to the rotor disk loading. That is, the measured loads were divided by a factor $WNz / \sigma n^2$.

where
W = aircraft weight
Nz = normal load factor
σ = relative air density
n = rotor speed ratio

The normalised loads were then plotted against the % Vrl for the condition. Figure 9 shows the results, with very great scatter in the raw data collapsing into a single function.

Caution should be exercised when using these results because the evidence shows a reasonably linear function from 70% to 100% Vrl. Beyond this point non-linearities may start to appear. However this may be expected since beyond Vrl the rotor is starting to stall, and stall is not itself a linear phenomenon.

3.4 Tail Rotor Controls

A brief analysis was carried out on tail rotor control component fatigue loads and damage rates. The importance of True Air Speed rather than Indicated was evident again. Like the main rotor blade, the tail rotor did not show a very strong correlation with aircraft weight. The most damaging manoeuvres were those which required pedal inputs at high speeds.

In addition, high tail rotor power conditions such as climb were significant.

4.0 TRANSMISSION COMPONENT FATIGUE DAMAGE

Transmission component fatigue analysis is arguably more simple than for airframe and dynamic components. Essentially, there are two types of loading which are important. Time spent at certain power levels is relevant to gear tooth bending whilst low cycle torque fluctuations and power cycles are important for shafts and couplings.

4.1 Time in Power Bands

The easiest usage recording method appropriate to gear teeth is to record the time spent in pre-defined power bands. In this case, careful consideration needs to be given to the width of and the positioning of bands. This is because the high frequencies associated with gear tooth loading lead to very high fatigue damage rates as soon as the torque rises above the endurance limit. Hence a cut off at the endurance limit and very fine recording bands just above this level are important. In practice, to guard against the effects of in-service arisings leading to reassessment of the endurance limit, fine resolution above and below the expected endurance limit is a wise precaution.

4.2 Low Frequency Loading

The tail rotor drive system is likely to be the most critical for low cycle fatigue. This is because of the number of components, the number of power cycles and the variability of the peak power. Tail drive powers are high in hover conditions, particularly when pedal manoeuvres are made.

Finally, the effect of tail rotor power in different flight regimes should not be ignored in terms of the torque distribution around the transmission system. The tail rotor will consume 10% of total power in hover conditions but only 2 or 3% in cruise conditions.

5.0 USAGE MONITORING

The author proposes that there should be three elements to the implementation of usage monitoring on helicopters.

5.1 Fatigue Spectrum Confirmation

The first element of usage monitoring concerns the general assessment of the usage spectrum. This may be accomplished quite simply by recording the time spent in certain parts of the flight envelope and the number of times that certain manoeuvres occur.

Thus occurrence tables for time according to:

- weight v cg distribution
- forward speed v density altitude
- forward speed v bank angle
- rotor speed distribution
- power spectra (main & tail rotor)

Discrete counts tabulated for:

- number of landings by weight v cg
- number of peak Nz occurrences v weight
- number of transitions to hover
- number of autorotations

The recording intervals for each parameter should be based on the assumed fatigue spectrum for the aircraft so that comparisons are readily made.

The purpose of this data is to enable engineers to perform general validity checks on the aircraft usage.

5.2 Flight Envelope Exceedence

Usage data should be recorded, and be readily accessible to identify and quantify exceedences of the flight envelope. Whilst these are unlikely to impact on fatigue lives (assuming they occur infrequently) they may have a bearing on other aspects of structural integrity. Suitable parameters would be:

- Normal load factor
- Rotor speed
- Torque / collective pitch
- Forward speed
- Bank angle

5.3 Fatigue Damage Calculation

a) Airframe Fatigue

The simplest approach to airframe fatigue is to concentrate on the most fatigue significant cycle, the GAG cycle, by counting landings. The analysis showed that this approach could be improved by counting the number of transitions also. The actual damage rate assumed for the GAG cycle could be based on conventional fatigue analysis and the role of the aircraft. Thus the total damage rate for the spectrum would be divided by the number of GAG cycles in the spectrum to produce a GAG damage rate for that type of operation. More severe roles such as the military utility would apply higher damage rates per GAG cycle.

In order to progress beyond this rather crude measure of fatigue damage, two factors become important. Firstly, one needs to develop an algorithm which will accurately predict the strain at a given point in time, and secondly one needs to record the sequence of strain cycles. The analysis of section 2 shows that beyond the basic GAG loading, the factors which define the airframe strain are complex. In particular, one cannot use the fixed-wing industry measure of Nz. Rather, the increase in the number of degrees of freedom for a helicopter leads to a situation where combinations of accelerations (eg normal & roll/pitch) are important. Further, there are strong correlations with power and aircraft speed. The development of algorithms to perform these calculations is beyond the scope of this paper. However it may be anticipated that such algorithms would include factors based on pilot control inputs, and the resultant aircraft motions. An alternative approach, though possibly less accurate, would be to use manoeuvre recognition algorithms in combination with a strain state look-up table holding information from previous load surveys. From a knowledge of the maximum and minimum strain in each flight condition one could reconstitute the significant peak loads in the strain history. This approach would be less accurate because it cannot assess the harshness of a particular manoeuvre, only its type.

Turning to the second point, that strain history is important, one must recognise that a GAG cycle where the aircraft takes off gently to the hover and then lands will be smaller than another GAG cycle which includes an evasive manoeuvre performed at high speed. Equally, two GAG cycles with two evasive manoeuvres will be more damaging if one manoeuvre appears in each GAG cycle than if they both appeared in one cycle. Once the strains can be calculated the strain history can be easily processed through conventional cycle count algorithms, probably loaded to an airborne system.

b) Dynamic Component Fatigue

It has been shown in section 3, that fatigue damage on dynamic components is accrued at the extremes of the flight envelope. Indeed, the importance of True Air Speed and proximity to the rotor stall limits has been highlighted. The high frequency loading associated with dynamic components makes this situation inevitable if reasonable lives are to be obtained.

These characteristics have strong implications for usage monitoring. In particular, the simple approach of recording time in airspeed / altitude bands is unlikely to give the necessary resolution in order to give meaningful results which are not unacceptably conservative. Equally, to substitute % Vne instead of airspeed, will ignore the effect of the different limiting sections of the flight envelope (eg. whether the aircraft is rotor limited or structure limited).

The analysis of section 3 showed that the best way to handle dynamic component fatigue usage is to calculate compound parameters which have a very strong correlation with the component loading. Thus the loads at a given point in time can be assessed more accurately, but they can also be recorded with better resolution.

For the main rotor it would be appropriate to record time against advance ratio, with fine recording intervals at higher values. Similarly, time recording for a matrix of % Vrl and $WNz/\sigma n^2$ would be beneficial for main rotor controls. For the tail rotor, advance ratio combined with a tail rotor servo position term would seem appropriate.

c) Transmission Component Fatigue

As discussed in section 4, gear tooth fatigue is best addressed by recording time in power bands. Fine resolution is important around the power levels associated with the endurance limit, if excessive conservatism is to be avoided.

Since torque can often be measured directly, the best approach for low cycle fatigue is simply to effect an on aircraft cycle count analysis for fatigue damage calculation post flight.

6.0 CONCLUSIONS

It must be recognised that Direct Load Measurement, with strain gauges embedded into components, is the most accurate method of fatigue usage monitoring. Where this is not possible, indirect systems can be employed. This paper has identified ways in which such systems can be made more effective and efficient.

Accurate fatigue damaged algorithms for airframes may be synthesised from motion sensors and pilots control sensors. In the absence of such systems, an acceptable first order approximation of fatigue damage can be obtained from the number of GAG cycles, preferably supplemented with a count of transitions to hover.

For dynamic components it has been shown that fatigue damage is accrued at the extremes of the flight envelope. Further, the rate of fatigue damage is such that any recording system must have fine resolution in these areas in order to identify time which is non-damaging from that which is damaging. The use of compound parameters such as advance ratio, % Vrl and $WNz / \sigma n^2$ will allow this to be achieved.

For transmissions, direct measurement of torque is normally possible. The issues are therefore the torque distribution to main and tail rotors; achieving fine resolution in recording intervals around the endurance limit; and, the inclusion of low frequency cycle counting to address shafts and couplings.

7.0 RECOMMENDATIONS FOR FURTHER WORK

It is recommended that further studies are conducted into the synthesis of airframe loads from aircraft motion and control input data. This may allow improved airframe fatigue usage monitoring.

It is also recommended that confirmatory studies using real time data are performed on the dynamic component compound parameters. This will reinforce the results reported here which cover average and peak values from load survey data. Further work should look at free-form flight manoeuvres in addition to the rather prescriptive load survey conditions.

8.0 CAVEATS

This paper would not be complete without considering three important caveats.

a) Components in service may not achieve their fatigue lives.

The commercial benefits from usage monitoring will be attained by extending the lives of components. It should not be forgotten that components are often retired from service before their fatigue life has been reached because of corrosion, wear or accidental damage. In this case there will be no economic benefit. Nevertheless there may still be a safety benefit if the actual usage is more severe than the spectrum assumes.

b) Required Software Integrity

Some of the components monitored by any future airborne system are likely to be VITAL parts. By definition, failure of the parts would be catastrophic. Thus it could be argued that a failure in the airborne software would allow the component life to be compromised, and that this could be considered as potentially catastrophic. The implication from this is that the software would need to be of Level 1 integrity; potentially making it uneconomic to develop. The opinion of the regulatory authorities will need to be sought on this point. However, it may be argued that Level 1 software is not appropriate because a software failure is not immediately catastrophic. Further, one could limit the authority of the system to only extend lives by an agreed amount (e.g. 50%). In this case Level 2 software would suffice.

c) The danger of generalisation

This paper has followed the conventional wisdom that airframe fatigue is driven by low frequency loading and dynamic components by high frequency. This can be an over-simplification. Whilst caution must be exercised in the application of the results of this analysis, the results are robust in that by applying a combination of compound parameters to all components, the contribution from low cycle and high cycle fatigue can be assessed.

Only comprehensive fatigue analysis by conventional methods can provide a sound basis for in service usage monitoring.

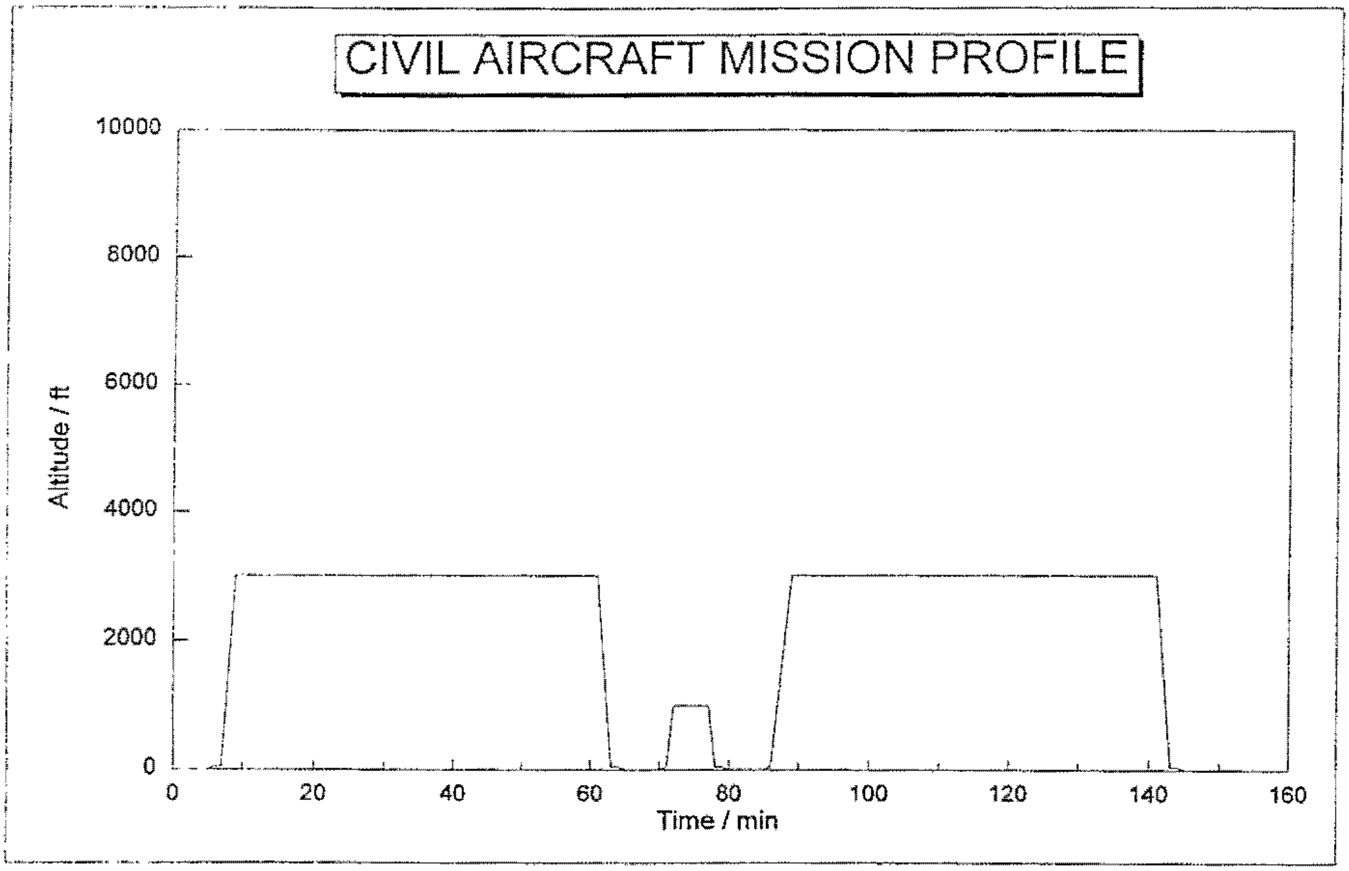

Figure 1. Civil Mission Profile

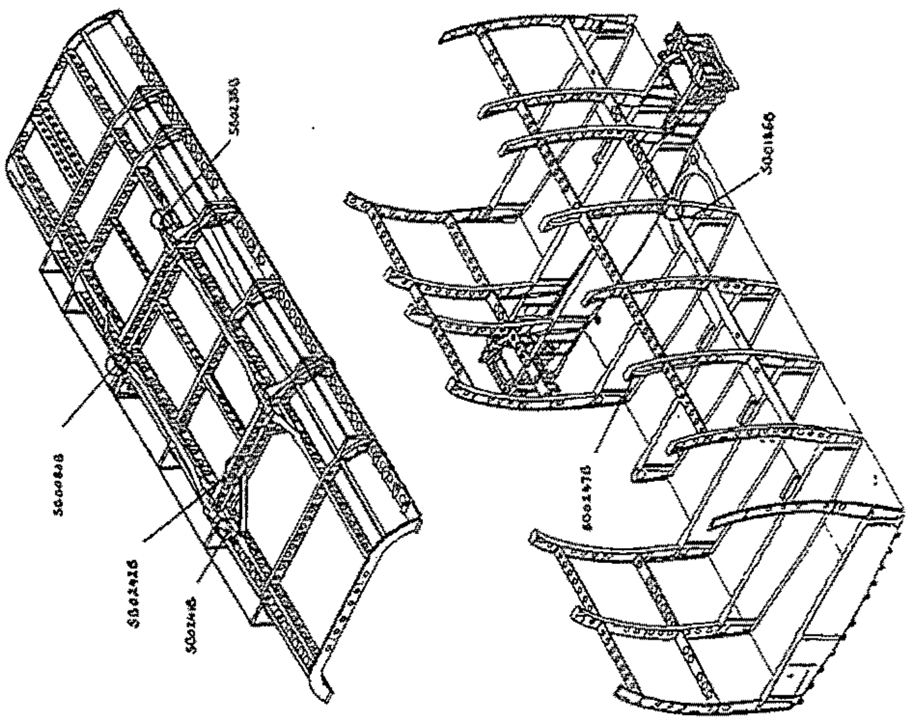

Figure 2. Location of Six Critical Airframe Analysis Points

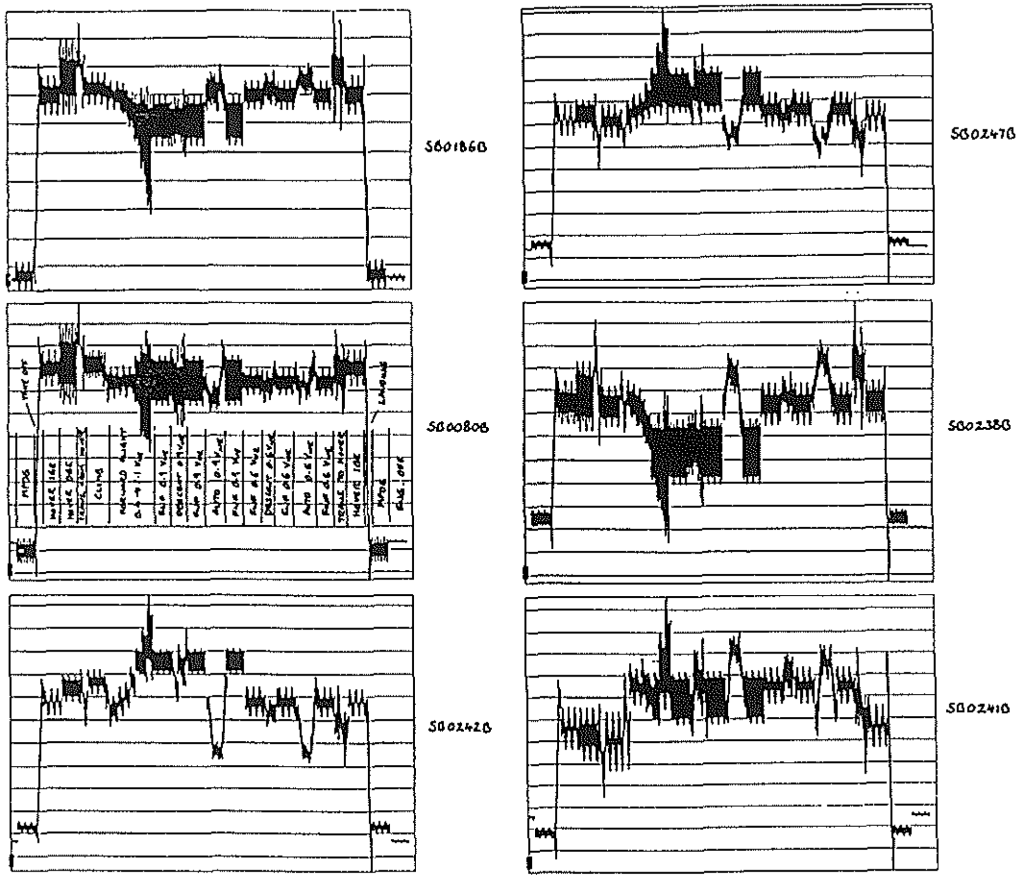

Figure 3. Airframe Strain Profiles - Flight Phases

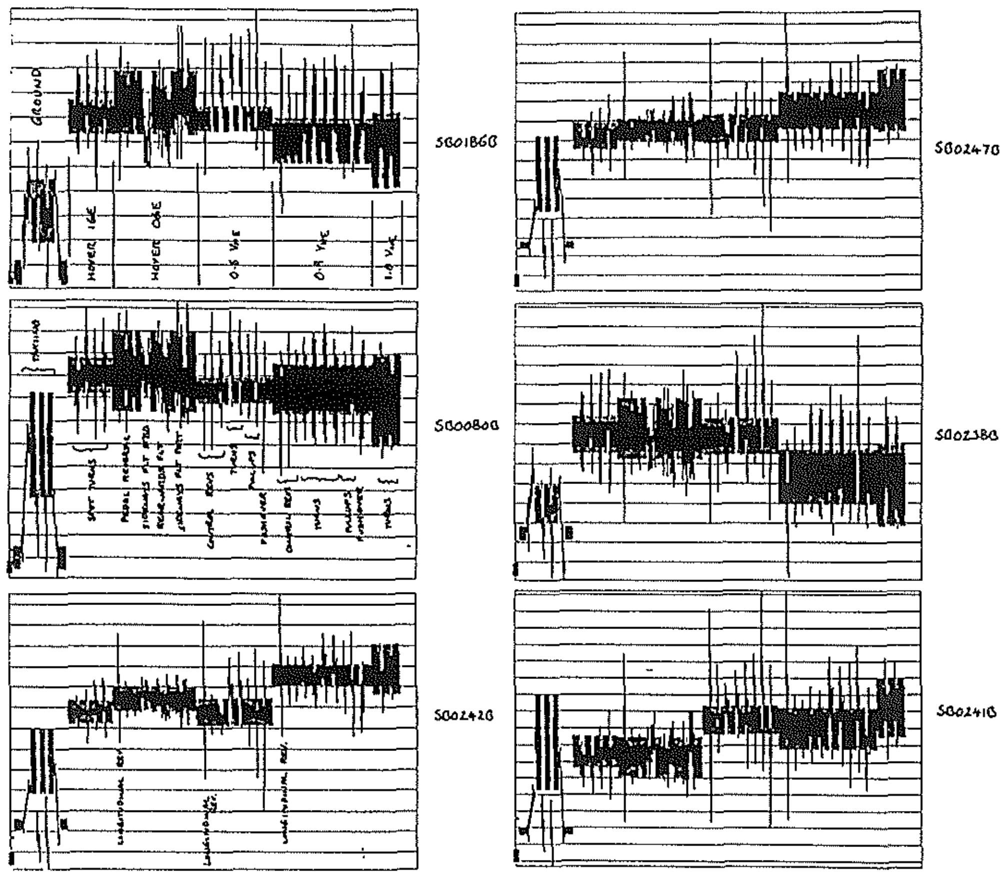

Figure 4. Airframe Strain Profiles - Effect of Manoeuvres

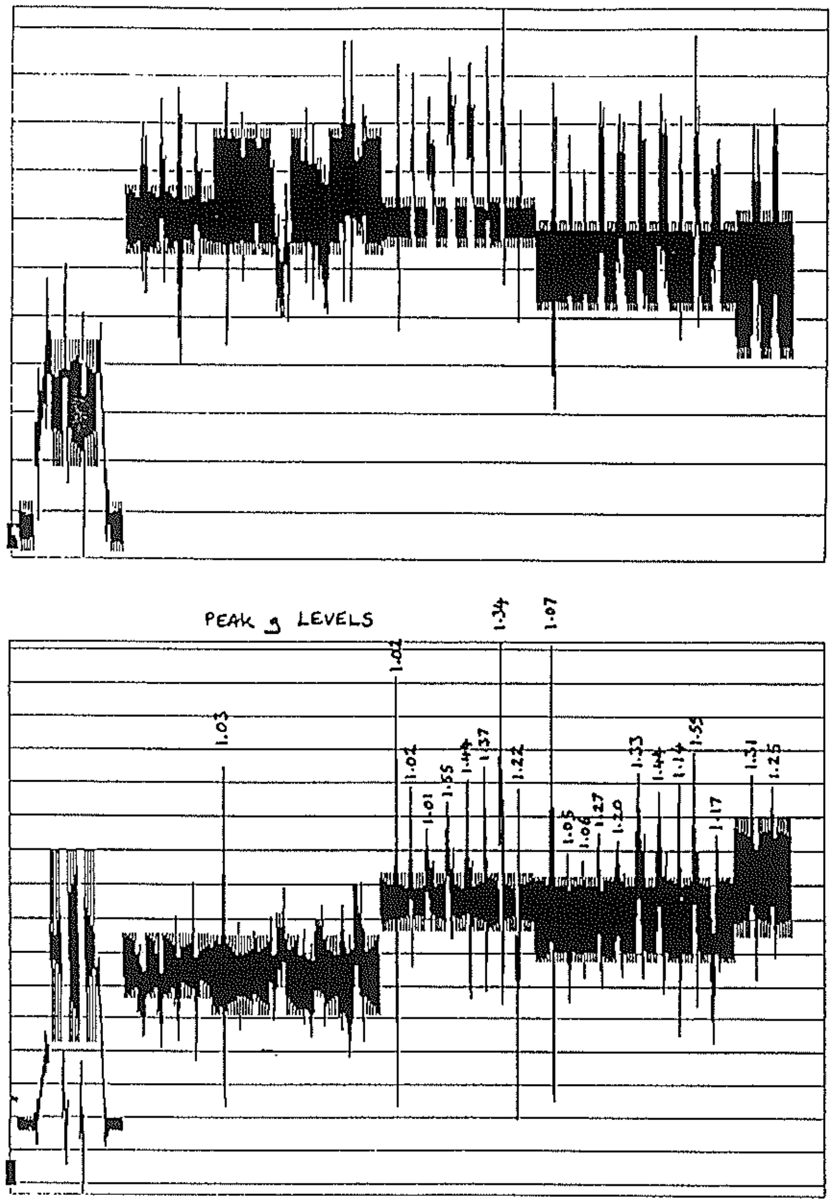

Figure 5. Effect of Normal Load Factor on Airframe Strain

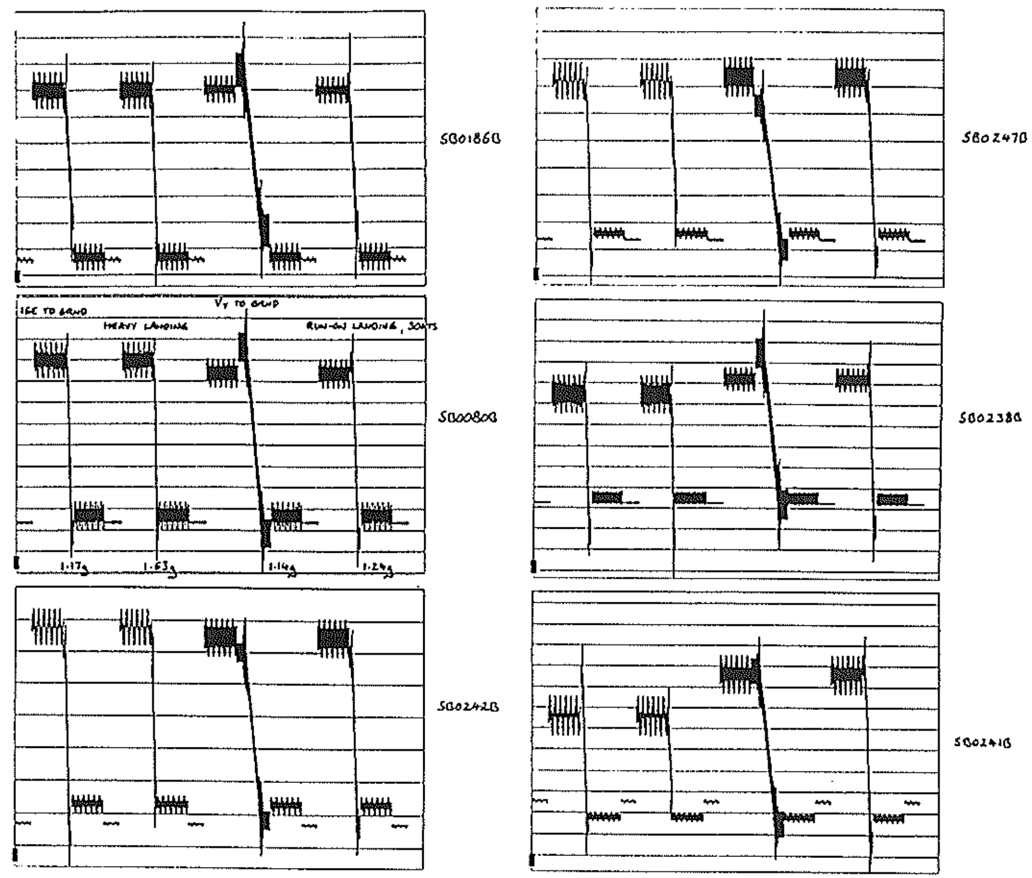

Figure 6. Airframe Strain Profiles on Landing

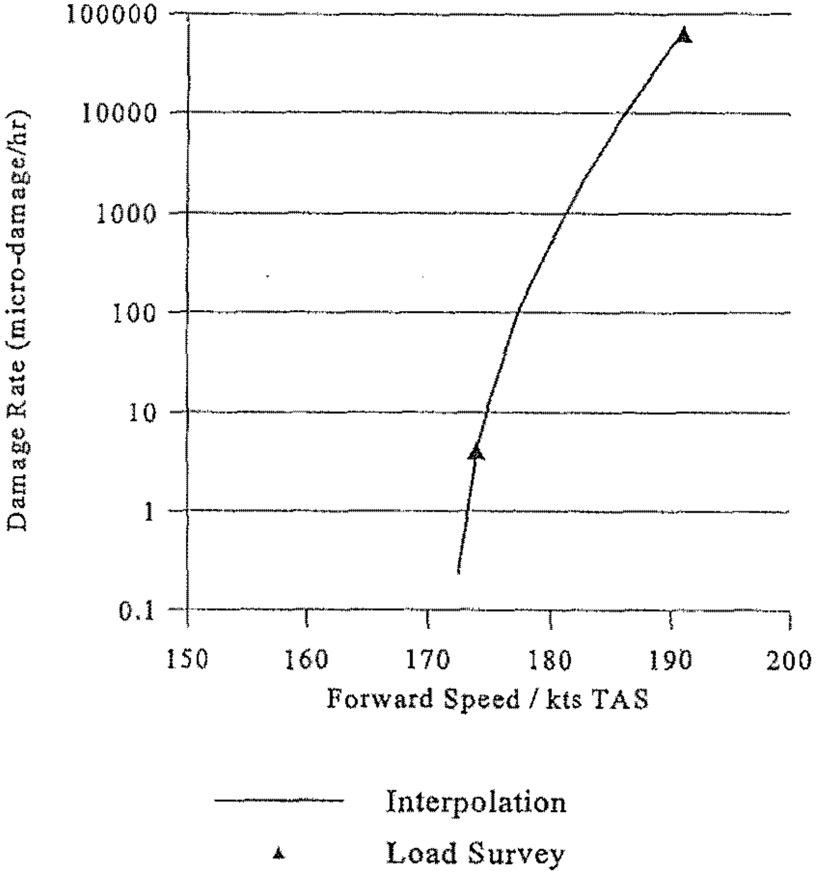

Figure 7. MRB Fatigue Damage v True Air Speed

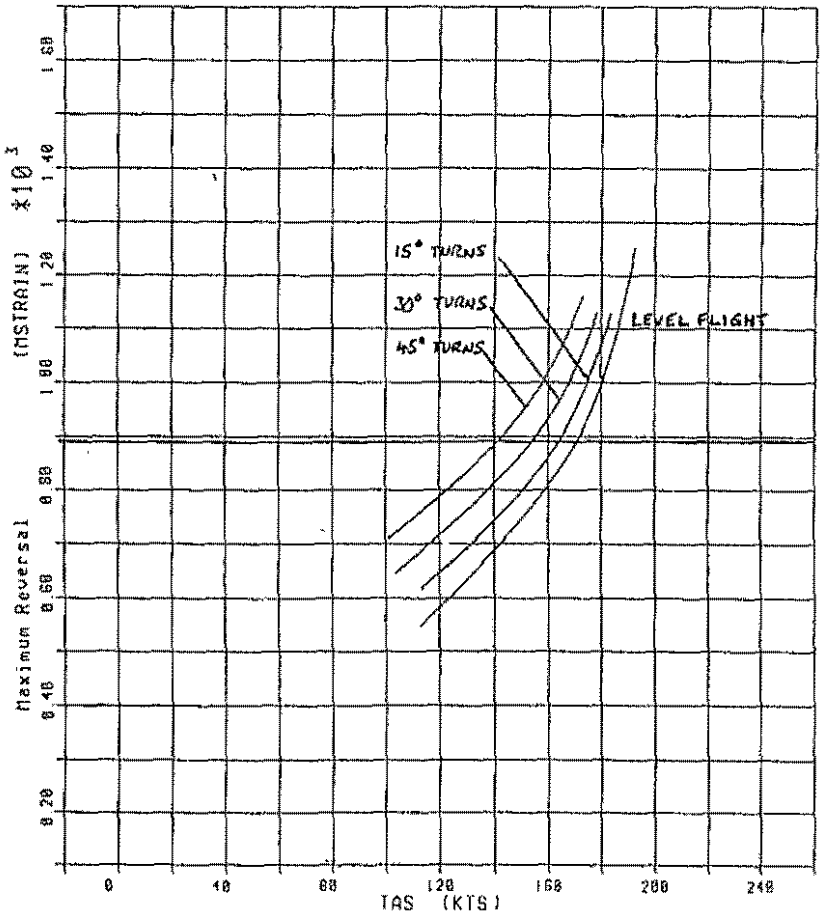

Figure 8. MRB Damage Rates in Turns

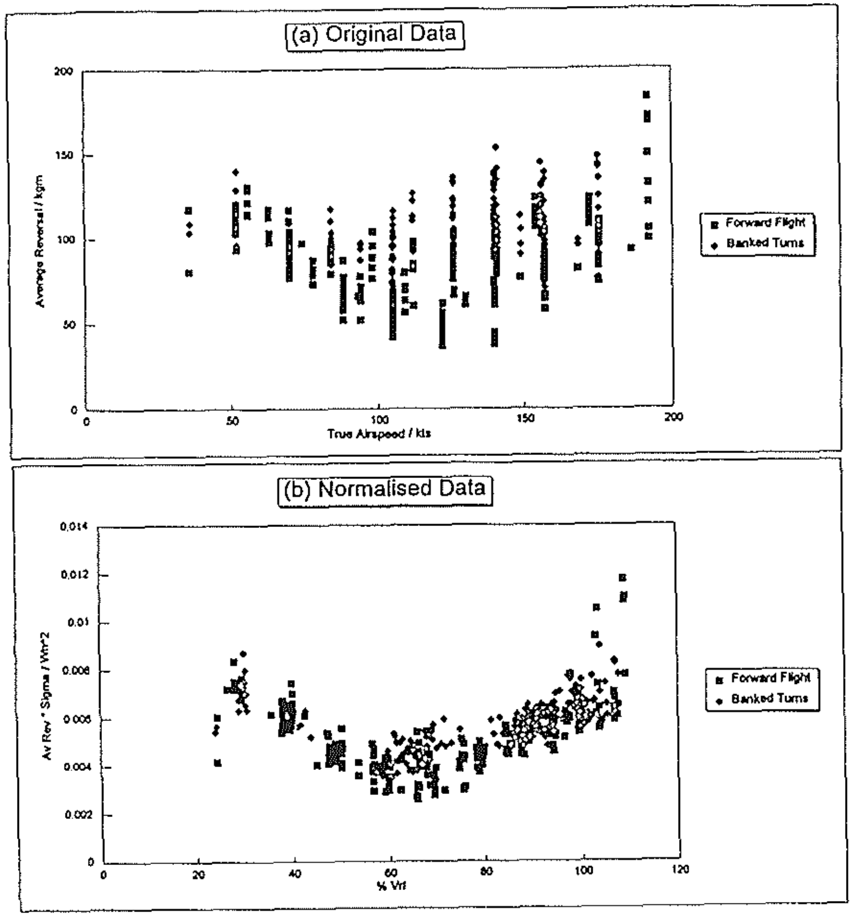

Figure 9. MR Swashplate Load Normalisation

CONDITION	DAMAGE RATE µdamage / hr	% OF TOTAL
Forward Flight 1.1Vne	328.558	95.35 %
1.0Vne 30° Turn Left	3.123	0.91 %
1.0Vne 30° Turn Right	2.515	0.73 %
Transition Vy to HIGE	2.413	0.70 %
Transition Vy to HOGE	1.455	0.42 %
Normal Landing Vy to Grnd	0.917	0.27 %
Forward Flight 1.0Vne	0.653	0.19 %
0.9Vne Longitudinal Reversal	0.630	0.18 %
0.9Vne 1.3g Pull up	0.043	0.01 %
0.9Vne 30° Turn Left	0.023	0.01 %
Total Low Frequency Damage	4.260	1.23 %
Total	344.592	100.00 %

Table 1. MRB Damage Rates for Composite Spectrum