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VEHICLE STRUCTURAL FATIGUE ISSUES IN ROTORCRAFT FLYING QUALITIES TESTING

BY

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Abstract

This paper reviews the use and importance of vehicle structural Fatigue and Usage Monitoring (FUM) during flying qualities testing, particularly when using the new rotorcraft handling qualities methodology, ADS-33D (Ref 1). The paper covers the rationale for FUM, FUM instrumentation, the rules used for monitoring on the DRA Aeromechanics Lynx Control and Agility Testbed (ALYCAT), and experience during DRA testing on both ALYCAT and Puma research helicopters. In particular, the paper reviews incidents when conducting both ADS-33 *open and closed loop* testing that highlight the potential to approach and exceed vehicle limits, and accrue longer term usage penalties when using the ADS. The position and importance of FUM, when using the testing techniques outlined in ADS-33, are then reviewed and several questions that come to the fore when FUM problems are experienced are discussed. The paper concludes by considering the role of advanced control concepts to mitigate usage penalties while optimising mission effectiveness.

Introduction

ADS 33

Much has been written in recent years about the revolutionary changes in handling qualities testing associated with the US Army's new rotorcraft handling qualities specification, ADS-33 D (Ref 1), designed to replace MIL-H-8501A (Ref 2). The US Army's Aeroflightdynamics Directorate (AFDD), in association with other research groups, including the DRA in the UK, have spent a considerable amount of time and energy developing the document, establishing requirements for aircraft response characteristic based on mission-oriented tasks for combat rotorcraft. There is little argument about the necessity of the new specification; some aspects of modern sophisticated flight control systems simply cannot be tested with the older document.

In addition, the requirements of the new specification are often stated in terms unfamiliar to traditional flight testers (e.g. terms such as bandwidth and phase delay), and unconventional test and data analysis techniques are also required by much of the new specification criteria.

Although ADS-33 does not explicitly require or recommend Fatigue and Usage Monitoring (FUM) of the vehicle during testing, experience gained during the first few years of testing within the research community on vehicles like the DRA Aeromechanics Lynx Control and Agility Testbed (ALYCAT), has shown that loads monitoring in real time and usage accounting are important in modern handling qualities assessment. As will be shown, this is primarily because the vehicle can be driven to the limits of its performance and to the edges of the standard design mission manoeuvre spectrum during testing against ADS 33. The usage spectrum of the vehicle under test is therefore quite different from the design usage spectrum, if the latter has been established by more conventional methods. This has short and long term implications for the airworthiness of the vehicle and its components, the former because the design limits can be exceeded during testing, and the latter because the actual fatigue damage accumulated during testing may far exceed the actual hours flown.

Testing Outside the UK

DRA Bedford knowledge of the use of FUM and the importance of load monitoring from testing outside the UK is limited. Frequency sweep testing conducted by the US Army on the AH-64A and OH-58D (Ref 3) revealed several potential problems. In particular, a divergent vertical bounce was experienced during longitudinal cyclic hover sweeps in the AH-64A at about 5 Hz. Damaged tail rotor support components were found following yaw sweeps, again on the AH-64A. On the OH-58D, sweep tests excited an oscillation in the mast mounted sight, which was not felt by the crew, but only detected visually by the crew of the chase aircraft and through telemetry at the ground station.

Fatigue Design and Usage Assessment

Introduction

Before we discuss how fatigue is monitored during handling qualities experiments, first it is important to consider some background fatigue design, assessment procedures and considerations.

UK Requirement - Def Stan 970

The requirements for the design of structures for United Kingdom Military aircraft against fatigue are contained in Defence Standard 00-970 (Ref 3). This document consists of a number of mandatory chapters, together with associated advisory leaflets. The fatigue assessment procedures can be considered under three general headings:

- Estimation of the load spectra, and therefore the stress spectra, for the various parts of the aircraft structure.

- Assessment of the fatigue performance of these parts when subjected to the estimated spectra.

- Monitoring the fatigue usage of these parts when subjected to the actual service load spectra and environmental conditions.

Fatigue Loading - General

Fatigue loading on the helicopter and its components originates to a very large extent from the rotors themselves. Certainly the so called "high frequency" loadings (3-4 Hz upwards) correspond to integral multiples of main and tail rotor rotational frequencies. "Low-cycle" fatigue is also present in many components both from aircraft manoeuvring, gust loadings and also rotor stop-start and ground-air-ground cycles.

It is convenient to group components of the helicopter in respect

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of types of fatigue loading, and the following is suggested:

- Rotor system

- Transmission

- Airframe

First, let's consider the rotor system. The components included under this heading comprise the rotor blades, hubs and controls of both the main and tail rotor systems. In translational flight, the airflow through the rotor produces unequal aerodynamic lift distributions on the "advancing" and "retreating " blades. The effect is to generate fluctuating loads on any individual blade dependent upon its azimuth position.

The blade itself is, in effect, a rotating beam subjected to these vibratory load inputs and also the tension due to centrifugal load. The beam has a series of natural modes and frequencies of response in bending both in and out of the plane of the rotor rotation and in torsion.

The blade response is therefore a complex one and, in terms of fatigue, it is clear that all sections of each blade require an in-depth evaluation to determine their criticality.

Furthermore, at the root end attachment of the blades to the hub, residual shears apply vibratory loads to hub, gearbox and the airframe itself. As mentioned previously, part of the blade response is torsional from lag-flap couplings and the centre of pressure fluctuations. This produces a reaction at the blade pitch control horn generating fatigue loads in the control system. Predominant loads are usually at once-per-rev in the rotor control system and "n"-per-rev in the fixed parts of the control system.

Next, let's consider the transmission system. In the "conventional" helicopter, the transmission system consists of a main gearbox with power inputs from one or more engines. Outputs from this gearbox are to the main rotor, tail rotor and, usually, to accessories such as hydraulic and electrical systems. The drive to the main rotor involves a large reduction of rotational speed from the engine inputs and an associated large increase in torque.

The main gearbox usually has to transfer the full lift, shears and bending moments from the main rotor hub to the airframe, in addition to its fundamental purpose of torque transmission. The drive to the tail rotor includes one or two further gearboxes that are required to reverse the direction of the drive, and sometimes speed changes are made at the gearboxes.

The fatigue loadings in the power transmission system can thus come from many sources. Some of these are:

- Pulsed bending of the gear teeth (reversed bending on "idler" gear teeth).

- Aircraft manoeuvre loads and moments on the gear casing.

- Gear tooth frequency loads and moments on the gear casing.

- High frequency rotor loads on the casings.

- Rotating bending and fluctuation torsional loads on the gear shafts.

- Fluctuating torsion on the tail drive transmission shafts and couplings during directional manoeuvres.

- Rolling loads on ball and roller bearings.

In addition, the whole transmission system will respond to vibratory torsional loading of the main and tail rotors dependent on its natural frequencies.

Finally, the major fatigue loadings on the airframe can come from the following sources:

- Manoeuvring and "g" loadings.

- Gust loads on the rotor.

- Fin, tail plane and tail rotor loads.

- Undercarriage loads.

In addition, rotor order loadings from main and tail rotor will be present. The magnitude of these loads is very dependent on the dynamic natural frequencies of the fuselage in bending and torsion.

Terms and Tools

Clearly the complexity of the broad fatigue monitoring problem must influence our approach to fatigue monitoring for handling qualities assessment purposes - *to sort the wheat from the chaff.* It is important to discuss briefly some common terms and tools that are used in fatigue substantiation procedures.

Figure 1 illustrates a fatigue substantiation methodology. It might suggest that everything is well defined and that a well-established fatigue substantiation methodology for helicopter components exists. This may not exactly be true, as the exercise, initiated by the American Helicopter Society (Ref 5) highlighted in the past.

Life Calculations- Design

The above examples, use terms that might be familiar to the stress community but may not be to the broader helicopter community. Let us expand on some key fatigue monitoring terms.

With reference to Figure 1, fatigue life calculations for helicopter components are based on the Linear Cumulative Damage Hypothesis or Miner's rule. For the application the Miner's rule two sets of data for the section of interest of a component must be available. These are:

- load spectrum

- S-N curves.

The load spectrum gives the number of cycles of various load amplitudes and accompanying mean loads. The load spectrum for the final fatigue damage calculation is derived from the mission profile and measured flight loads. The mission profile may be defined by the procuring agency, airworthiness authorities and/or manufacturers. It contains the percentage of time spent in various flight conditions. Manoeuvres may be given in numbers per hour or percentage of time. However, it is important to note that these profiles are developed from steady manoeuvre cases rather than the transient manoeuvre cases we typically see during flying qualities testing.

Flight loads are measured for the flight conditions and manoeuvres within the mission profile. These loads are reduced to mean loads and the number of cyclic loads and then combined with the mission profile to give the flight load spectrum.

An S-N curve gives the relation between cyclic load and number of cycles until failure for a certain mean load. The endurance limit is defined as the cyclic load level for which the number of cycles to failure approaches infinity. The S-N curve is derived from material/component structural tests.

Life Calculations - Flight Test

The above technique is slightly modified for flight test. Clearly we know the S-N curve (manufacturer) and we know the load spectrum from our strain gauge data capture i.e. Flight test strain gauge data has both mission profile and flight condition load information.

Flight loads vary, not only from one run to another, but also within a run. Clearly for our purposes, a distinction has to be made between steady flight conditions and manoeuvres, since during a manoeuvre cyclical loads and mean loads will vary, Figure 2. Although a number of data analysis techniques exist (uncycle-counted, range pair, rain flow and other cyclic counting methods), it is not the aim of this paper to investigate, or discuss, the merits of these various techniques, since this is not the task of the handling qualities engineer/flight test engineer. However, a few points on the basis for all these analysis techniques are worthy of note:

(i) The simplest counting method is to assume that all cyclic loads have magnitude $(S_{max}-S_{min})/2$ with mean $(S_{max}+S_{min})/2$. S_{max} and S_{min} are the maximum and minimum stress level of the manoeuvre, Figure 3.

(ii) Total fatigue damage is assumed to be equal to the sum of the damages of the individual cycles. The damage of one cycle with amplitude Sa and the mean Sm is equal to 1/Ni, Ni being the number of cycles, with amplitude Sa and mean Sm, at which failure occurs. ni cycles give the damage ni/Ni and the total damage is:

$D = \sum ni/Ni$ (1.1)

(iii) It is assumed that failure of the component occurs when D equals 1.

(iv) If the load spectrum gives the number per hour ni of k different load cycles with amplitude Si, all at mean load Sm, then fatigue life, according to Miner's rule is

$L = 1/\sum k\ ni/Ni$ (1.2)

Current and future substantiation procedures will be discussed later in this paper.

Handling Qualities Assessment - Why FUM?

Introduction

ADS-33 does not call for fatigue and usage monitoring of the vehicle during testing, and as will become clear, there is a considerable burden associated with FUM, so why is it necessary?

Defining Rational for FUM Systems Fits

Both the recent RAE/DRA aeromechanics research vehicles have had FUM systems installed, and this paper will give examples of their value in highlighting potential flight safety hazards during trials, both in real time and in post flight analysis. It is perhaps valuable to review the primary rationale for the FUM fit on these vehicles. The motivator for the FUM system on the Puma aircraft was a high speed flight test programme using a swept tip blade, the forerunner to the so-called BERP tip (Ref 6). The rationale for the ALYCAT FUM system was originally tied to an intended ACT control system programme, since in 1987 there was concern that the flying manoeuvres to be conducted, post an ACT fit, would not necessarily correspond to the assumed manoeuvre spectrum on which Lynx component life was based. Hence, it was planned to instrument the aircraft to monitor the 'actual' fatigue usage on the airframe. Although the programme to fit an active control system to ALYCAT is at a hiatus, due to funding limitations, the monitoring instrumentation was still fitted. There still remained a concern that the projected flying programme manoeuvre spectrum did not conform to the standard operational/training spectrum. In particular, the flying programme for the ALYCAT involved:

- Flight with instrumented blades, where FUM monitoring was required for the airworthiness certification for the aircraft.

- Flight without a collective/tail rotor interlink at high side-slip angles, where the airworthiness certification for the aircraft again called up FUM monitoring.

- System identification and pilot workload research activities. Here, experience on the PUMA aircraft had shown the value of FUM monitoring.

The FUM Task

It is important that the *overhead* associated with FUM should be recognised. Key aspects of this task are:

- Agree trial aircraft instrumentation fit,

- Instrument aircraft and calibrate instrumentation system (including accounting for static droop (blades and tail)),

- Agree FUM analysis technique with manufacturer,

- FUM analysis technique validation,

- Real time trial telemetry monitoring,

- Post flight trial FUM analysis and usage accounting. This might be a multi-level activity i.e. in-house post flight and manufacturers post flight analysis,

- Other tasks (liaison with manufacturer, maintain system).

Instrumentation

Introduction

As will be described later, the manufacturer has a key role defining the instrumentation requirement. This section will describe the instrumentation on the DRA Bedford ALYCAT for FUM. Table 1 details the ALYCAT FUM instrumentation suite.

MODAS and Telemetry

Figure 4 shows a schematic of ALYCAT instrumentation system with main rotor, tail rotor, airframe, body motion and control position data all routing through the Modular Data Acquisition System (MODAS), and/or to a recorder or via the telemetry link to the ground station. The MODAS system has a sampling rate of 256 K samples/sec, which enables the large amount of rotor data, in particular, to be handled.

Role of the Manufacturer/Rules for FUM Monitoring

Introduction

The manufacturer (in particular the stress department) has a key role as advisor to the DRA in establishing, maintaining and reviewing the results from the vehicles FUM system. The manufacturer, as design authority, must have a major role in defining the system, the rules and limits for FUM. The benefits of a good working relationship between the DRA and manufacturer cannot be over emphasised. This section outlines key points from the ALYCAT FUM process that serve to highlight this role and act as a typical system description.

Monitor Limits and Methods of Analysis

For ALYCAT, the manufacturer (Westland Helicopters Ltd (WHL)) produced two documents (Ref 7 and Ref 8). Ref 7 outlines the monitoring limits and methods of analysis for the dynamic components (main rotor system, tail rotor system), and Ref 8 does the same for the vehicle structure. These documents outline the following information:

- Instrumentation.

- Instrumentation location.

- Gauge calibration techniques.

- Defines load limits/never exceed levels/endurance limits.

- Defines monitoring procedures (including real time monitoring requirements).

- Defines post flight analysis procedures.

- Defines substitute gauges (these are alternative gauges that can be used should the primary position gauge fail).

- Defines how to calculate life used and computation of cumulative damage.

Telemetry Monitoring - Load Limits

The manufacturer sets load limits for each component, and it is these limits that are used for real time telemetry monitoring or for post flight analysis. Although the terms used to define these limits vary between manufacturer (Eurocopter France (Alpha and Beta levels) Westland (Level A, B, C)), their definitions remain essentially similar.

For example, there are 4 different load levels defined for the dynamic components in Ref 7, for the purposes of the trial. These are:

- Level A - It is the 50-hour fatigue life load level, and is used as a guide to determine the necessity, or level, of further investigation.

- Level B - It is the 10-hour fatigue life load level and under normal conditions should not be exceeded. If, however, this limit is exceeded and sustained for more than 10 sec, the manufacturer must be informed for further analysis and, until agreed, flying of similar conditions is to be curtailed.

- Level C and D - These are the 1 hour vibratory and limit load respectively and must not be exceeded. Any exceedence of Level D grounds the aircraft until further investigation by WHL Stress Office has been completed and approval given to resume flying. If level C is exceeded, WHL Stress office must be informed and the condition must not be repeated without WHL approval.

Note:

A. Levels A, B, C are vibratory load limits (0.5* (peak-trough)). Level D is a limit load and is the highest peak or the lowest trough load condition. It should also be noted that level 'C' for structural gauges is the 'never exceed' level.

B. A *1 hour* limit is the most damaging condition since, if continuously subjected to this vibratory load for 1 hour the component would fail. Similarly, a *10 hour* would fail after 10 hours at the lower level.

Monitoring Procedures- Real Time

Again the procedures and rules for monitoring will vary depending on the advice given by the manufacturer. For the ALYCAT, for example, WHL advise that either in-flight monitoring or post-flight monitoring may be performed. However, for post-flight monitoring and subsequent analysis, a number of flights may be combined, provided that the accumulated flight data awaiting analysis does not exceed a total of 4 hours. Monitoring is not required for flights not associated with the trial, i.e. normal operations to the Service release.

The rules for in-flight monitoring are detailed below, and the dependence on the manufacturer throughout the process should be noted:

(i) If, during flight, any gauge exceeds level A, note the flight condition but proceed normally with the trial.

(ii) If level B is exceeded and sustained for more than 10 seconds, then the aircraft is to be called off condition; if less than 10 seconds, treat as a level A exceedence.

(iii) If level C is exceeded, the aircraft is to be called off condition and the condition must not be repeated without WHL approval.

(iv) If, however, level D is exceeded, immediately return, land and ground the aircraft, then report the incident to WHL Stress Office and await instructions.

Clearly the number of channels that can be monitored in real time is limited. The ALYCAT telemetry system is capable of transferring 16 channels of data in real time back to a ground station. As a minimum, 8 channels are normally dedicated to FUM. Again, it is DRA practice to discuss the forthcoming flying programme with the manufacturer before each trial and for the monitoring channels to be agreed.

Analysis Procedures - Post Flight

In addition to the monitoring limits, which are used to signal/highlight flight critical phases during trials, there are also two important post flight analysis tasks. These are:

(i) Data tape replay for visual inspection of data to ensure that no limits were exceeded during the flight and to check those gauges not monitored in real time (if there has been an exceedence, this can be a quantification exercise).

(ii) MODAS data tape replay to calculate life used during the flight.

Although for ALYCAT the algorithms for life calculation were defined in the WHL documents Ref 7 and Ref 8, it was left to the Rotorcraft Group at DRA Bedford to write the analysis software to calculate life used. Essentially the Bedford FUM analysis software FUMAN partitions the signal from each gauge into 0.2 second segments, it checks the segment against the limit load conditions, establishes the vibratory content (0.5 * (peak-trough)) from that segment, calculates the life used in that 0.2 second segment, and totals the life used across the flight. The output from the programme is a list of exceedences, levels and life used for each component. It should be noted that post flight analysis looks at every gauge in the FUM system. It should also be noted that post flight analysis remains a lengthy and time-consuming process since it is dependant on data tape replay. In addition, during analysis, if there has been signal drop out, these will register in the analysis as exceedences and will have all to be checked and filtered. This is a problem that is also shared by WHL, who perform a more complex life cycle counting rainflow analysis for life calculation. Other methods will be discussed in the future work section of this report, as will future proposals for data analysis.

Cumulative Damage Calculation

The life used calculation is essentially based on the Miner rule and was fully defined in the WHL advice to the DRA. It should be noted that currently, if ALYCAT has a level C exceedence, the tapes have to be transferred to WHL, or the design authorities designated contractor, for life used calculation.

FUM in Handling Qualities Assessments Case Histories

Introduction

Having looked at a typical FUM system and the rules for FUM monitoring, it is now important to return to why all this effort is necessary. This section will review some recent case histories that might help to further highlight the importance of FUM in modern handling qualities assessment flying. These case histories are split between ADS-33 *open and closed-loop* flight trials.

ADS-33 Open-Loop Testing

The ADS-33 open-loop tests are conducted to determine the level of compliance with the quality levels of the suite of handling parameters, e.g. agility parameters like quickness and control power and stability parameters like bandwidth and damping. The tests typically require the pilot to apply a pre-defined control input, usually in a single axis, and to allow the aircraft to respond for a sufficiently long period of time to enable the capture of the appropriate characteristic. The control input are therefore untypical of normal pilot control activity and structural loads will develop during both the excitation and recovery portions of the manoeuvre.

DRA (RAE) Bedford PUMA

In Ref 9 Padfield gives the warning that frequency sweeping can damage a helicopter's health, and it is important to take this warning seriously. However, with the right preparations and precautions, the damage can be controlled and quantified. One of these precautions is the use of FUM and this first example highlights experience in 1988 on the DRA (then RAE) Bedford Puma.

The first UK sweep tests were conducted with the Research Puma fitted with a FUM system similar to that described for the ALYCAT above. Relatively high fatigue usage was encountered in pitch axis sweeps in forward flight, and the results are of general significance in understanding the role of load monitoring.

The tests were conducted to derive equivalent low order system models for pitch axis dynamics (reported in Ref 10 and 11), but the test points were essentially the same as for bandwidth measurement. At the time the tests were conducted, the development of criteria for pitch axis handling qualities was being pursued by several agencies. Figure 5 illustrates two longitudinal cyclic frequency sweeps, one with SCAS engaged, the other disengaged, captured at 60 kn airspeed. Additional data are the normal acceleration at the fuselage floor and the stress in the forward gearbox strut, derived from component strain, which transpired to be the most critical for the pitch manoeuvre. The control input is maintained within the recommended range and the control frequency spectrum is primarily below 2 Hz, the required test upper limit. The larger response at the lower frequencies with the SCAS disengaged is noted. Figure 6 shows results at 100 kn, for two cases, one where the frequency range was limited to 2 Hz, the second where it was extended to 4 Hz. In the second case, the crew experienced significant vertical bounce at the higher end of the range. The normal acceleration record shows amplitude excursions of +/- 0.25 g at high frequency. A combination of real time monitoring through telemetry link to a ground station, coupled with post flight fatigue life accumulation analysis, revealed the extent of the damage done during these tests. Figure 7 shows data for one flight (Flt No 728) comprising 9 sweeps over the speed range 60 to 120 kn. The Figure shows the percentage of the never-exceed fatigue load level, the so-called β -level, in the forward gear box strut and the fatigue life used across the speed range, for both SCAS-in and SCAS-out. A striking result is that the SCAS-out manoeuvres were less damaging than the SCAS-in manoeuvres. The SCAS-in sweep at 120 kn resulted in gearbox strut loads within 5% of the β -level. The single triangle point at 100 kn corresponds to the case shown in Figure 6, when the frequency range was extended to 4 Hz, again taking the load close to the limit. At the higher speeds, component life was being fatigued at the rate of more than 40 hours per minute. Following these tests, the calculation of the fatigue life used during flight 728 revealed that more than 11 hours of life had been used in just nine sweeps. Accumulated life over the period of the tests indicated that the gearbox mounts were prematurely approaching their 2000 hour limit. The aircraft was grounded while the gearbox mounts and other related components were replaced.

ALYCAT LYNX

DRA experience on the Puma helped in the development of an approach to conduct ADS-33 *open-loop* trials for the ALYCAT Lynx flight programme that included frequency sweep testing. During this testing there were several incidences where the ALYCAT FUM system proved essential. An example is detailed below.

Yaw Control Power (Flight 351 Event 39)

Hover spot turns were used to establish the yaw control power criterion (ADS-33D Section 3.3.8 Large-amplitude Heading Changes). The criterion specifies the minimum yaw rates that should be achievable for a number of Mission Task Elements up to ±60°/s for aggressive manoeuvring. In the turns to the left 60°/s was achieved, however high lag strains were noted in the gauge measuring tail rotor blade lag strains at 20.8% span (T203L). Figure 8 , shows the tail rotor lag strain at 20.8% span reaching the Level A limit.

The source of this high lag strains in an effectively steady state test is principally due to a Coriolis coupling of blade flapping motion into lag. Therefore, the unconstrained flapping motion, while large, is still within limits, but is having a severe secondary effect.

Unwitting over stressing of tail rotor blades could lead to severe reduction in tail rotor blade life, and ultimately to increased possibility of blade failure.

It has been postulated that for future tests our approach might be to build from low yaw rates (< 10°/s) until exceedences grow.

ADS 33 - Mission Task Element Testing

General - Fatigue loads in transient manoeuvring/the NOE task

The Lynx has been flown in various flight test campaigns over several years associated with research into handling qualities and agility requirements for the battlefield helicopter role. The battlefield environment places high demand on both pilot workload and vehicle performance; it is characterised by the rapid, transient manoeuvres needed to avoid threats, or to engage other aircraft or ground targets, or in manoeuvring to avoid obstacles or make use of cover in the ground plane. It is also typified by small amplitude closed loop tracking tasks. The pilot will be manoeuvring close to flight envelope limits and the pressures of maintaining flight path accuracy, combined with the need to monitor cockpit gauges, will increase the likelihood of encroaching critical load limits. This proved to be the case in the Lynx flight tests and the three examples presented here, the ADS-33 "Deceleration-to-dash", "Transient turn" and "Rapid slalom" MTEs, illustrate some typical examples.

ADS-33 - Mission Task Elements (MTEs)

The Mission Task Elements (MTEs) are stylised flight test manoeuvres that have been designed to evaluate aircraft response and pilot workload to both single and multi-axis inputs. These are mission oriented manoeuvres, and are intended to cover a full spectrum of anticipated mission profiles for various military rotorcraft, including precision tasks, aggressive tasks, and tasks in a degraded visual environment (DVE).

Deceleration-to-dash (Flight 341)

In this manoeuvre, the pilot is required to execute a rapid deceleration from cruise speed to the speed for minimum power and then to accelerate rapidly back to cruise speed. The main difficulty for the pilot is to coordinate the longitudinal cyclic, collective and rudder pedals control strategy to achieve the deceleration-acceleration, maintain height and heading, while at the same time observing the aircraft's rotor torque limits. In the Lynx tests, the manoeuvre was initiated at a speed of 120kn and height of 100ft, with a minimum speed for the deceleration of 50kn.

The manoeuvre is characterised by the large variation in pitch attitude and power demand needed to achieve the deceleration and acceleration; initially the aircraft is pitched up to around 20-30deg and minimum power selected, followed by a pitch down to 20-30deg combined with maximum power demand. The rapidity of the manoeuvre was set by the time allowed to achieve the required pitch attitude (ADS-33 '...as rapidly as possible') and the time taken to achieve minimum (3s/5s for desired or adequate performance) or maximum (2s/3s for desired or adequate performance) power demand from the initiation of the deceleration or acceleration respectively. It was during the pitch reversal that care was needed to avoid over-torquing and pilots generally applied the power demand in 2-3 discrete steps rather than one continuous pull. In the case illustrated, Figure 9, a single rapid control demand was applied, which resulted in an over-torque to 143% on both engines and subsequent exceedence of the lateral load 'C' limit at the tail cone transport joint. On manufacturer's advice, flying was resumed following the incident when a visual inspection of the tail cone did not reveal any evidence of structural damage (Note: The post flight analysis usage penalty was applied the the airframe). It should be noted that it had been previously demonstrated that the Lynx could achieve the required performance within vehicle limits.

Transient turn (Flight 340)

In the transient turn MTE the objective is to achieve a 180deg change in the flight path direction in the minimum time, starting from an entry speed of 120kn. The manoeuvre is accomplished through application of lateral cyclic and rudder pedals to initiate a rate of turn, while pulling "..a normal load factor of at least the limit of the operational flight envelope" (Ref 1) and reducing power demand to bleed off the speed and maximise the turn rate. For the Lynx tests, maximum angles of bank commensurate with the transient normal acceleration limit of 2.3g were allowed, and again the rapidity of the manoeuvre was set by the target task time (10/15s for desired or adequate performance). In practice, the main difficulty for the pilot was of course the need to observe the normal 'g' limit, and in testing an incremental approach was necessary in order to establish the control strategy needed to achieve the minimum time without exceeding the limit. In the case illustrated, the pilot inadvertently achieved a value of 2.6g, which resulted in high load levels in the rotating components of the flight control system, principally the longitudinal cyclic pitch control link, Figure 10.

Rapid slalom

For the slalom MTE, the objective is to check the ability to manoeuvre aggressively in forward flight with respect to obstacles on the ground. For the tests the aircraft is flown through a course consisting of a sequence of turning gates displaced 15m to the left and to the right of the initial flight path line, while maintaining a target speed of 60kn. In the Lynx tests, the level of task difficulty was regulated by varying the task speed (test cases at 60, 80 and 100kn) and the course aspect ratio (AR), or ratio of lateral (Y) to longitudinal (X) displacement of the turning points. As with the transient turn, the control strategy involves application of lateral cyclic and rudder pedals to initiate and coordinate the turns through the slalom gates, and longitudinal cyclic and collective to maintain speed and height. Different AR's were set by varying X for a constant Y of 30m, therefore as AR increases the turns tighten and require greater angles of bank and normal 'g'. In the Lynx tests a range of AR's between 0.015 to 0.12 were flown with the objective of establishing the limiting case. In the event, a maximum AR of 0.12 was established, where although the pilot could achieve adequate tracking through the gates, the task airspeed could not be maintained. Regarding flight envelope limits and FUMs loads, the normal 'g' limit and tail rotor torque demand gave increasing concern as the AR increased. As the effective turn radius of the course reduced, maximum lateral cyclic was needed, combined with increasing amounts of in-to-turn pedal in order to make the turns, particularly when turning to the left (Ref 12). Tracking errors through the gates tended to build throughout the progression of turns, with the effect of increasing the required turn rates still further. The increase in task demand had the effect of 'driving' the amplitude and rapidity of the pilot's cyclic and pedal demands, ultimately to the point where the normal 'g' limit was reached and the tail rotor torque 'C' limit was encroached, Figure 11. The high 'g' loading, Figure 12, again resulted in high mean pitch control link loads, although, however, the oscillatory load component stayed within bounds. The associated lateral cyclic, pedal displacement and roll attitudes are shown at Figure 13.

FUM Monitoring - Thoughts on the Future

Introduction

A major issue associated with FUM monitoring during handling qualities assessment trials has perhaps become clear i.e. the workload associated with establishing a FUM system and in particular, the post-flight analysis of fatigue usage. The ideal system would report usage in real time to the user and present the ground team with a life penalty at the end of each flight. This would reduce the requirement for the telemetry monitoring, with all its expense and limitations, and would also reduce the post flight analysis process that can be long, complex and limited i.e. The manufacturer requires that they calculate the penalty associated with level 'C' exceedences. Recent activity in industry, aimed at the development of a production Health and Usage Monitoring system for in service monitoring, might be able to offer such a system. This section outlines these developments and its prospects.

In-Flight Fatigue Accounting and Progressive Damage Monitoring

The UK Ministry of Defence, Director of Helicopter Project (MOD DHP) is funding studies into parameter based (air speed, bank angle etc) aircraft usage system. The system is based on a neural network. In order to 'train' the neural network proprietary algorithms have been developed, so called Progressive Damage Algorithms (PDA), these collapse strain gauge measurements to instantaneous fatigue damage in real time. Instantaneous fatigue damage could therefore be registered in flight during specific manoeuvres. A development has been proposed to use these PDA's on an IBM PC portable based system that would use a communication link to the MODAS system to enable usage monitoring on board the trials aircraft in real time. A number of potential customers have been identified for such a system. In addition to the aeromechanics research aircraft ALYCAT, there is considered to be a requirement for such a system to support type certification testing at DTEO Boscombe Down. In particular, this is true for vehicles being tested using the ADS-33 methodology.

ADS-33 and FUM

FUM Methods and ADS-33 - A Dichotomy?

There is an apparent dichotomy when the FUM problems associated with testing using the new mission oriented handling methodology are fully considered. This is that ADS-33 is essentially a *mission* oriented methodology. Why therefore should we experience FUM problems when testing using this methodology, if our aircraft has been stressed and lifed for the design *mission* profile?

The answer may lie in the different approaches the Handling Qualities Engineer has taken to break down the mission, compared to the approach of the Stress Engineer. In particular, transient manoeuvre cases might have to be more fully considered by Stress Engineers in usage mission profile definition. A new approach to the usage spectrum might include an improved analysis of the type of flying conducted, that accounts for the impact of transient manoeuvres, that considers and develops aspects of the ADS-33 testing methodology that might be of value.

Another example of this dichotomy is that if during type certification testing the vehicle experiences FUM limit exceedences, or post flight analysis shows high life penalties associated with manoeuvres for that type, several questions come to the fore. These are:

- How should FUM exceedences effect the handling qualities rating? Might we see the rating *Level 1(With FUM Penalty)?*

It is considered that it is better not to mix fatigue with handling qualities ratings. However perhaps we should include a section on structural damage issues in handling qualities reports. It would also be highly desirable to have structural expertise/representation on the test team.

- Might FUM exceedences limit the certification release of the vehicle?

Off Course they already do, however, here it is suggested that the direct link is made between handling qualities testing and this activity i.e. The ADS-33 trials are the acknowledged source of information towards the structural release process.

- Should information on FUM exceedences be passed back to the manufacturer for design review?

We believe so , with the important link being the acknowledgement of handling qualities testing as a part of the structural/vehicle release process.

- Should information on FUM exceedence be used by the logistics authority to help in the definition of Service component lives?

Again, we believe so. Here, the link needs to be made to those conducting the component logistics appraisal for spares and overhaul forecasting.

Clearly, the relationship between testing using ADS-33 and Fatigue Lifing/Logistics techniques needs further consideration and developed.

FUM and Future Control Laws

In addition to considering what the penalty associated with aggressive agile handling or what techniques we might use to record the damage that follows, it is clear we also need be looking to control the situation.

Here carefree handling control laws have a major role to play. Many of the occurrences described above could have been contained with carefree handling features like those proposed at Ref 13. These features would not only protect the transmission system, their current primary focus, but also the aircraft structure. In addition to the vehicle agility and operational benefits associated with these control laws (Ref 13), the life cycle cost benefits also become very clear when considered against the findings of this programme.

The issues associated with the yaw axis in the cases presented above are of particular interest. These are considered to be generic due to the poor cues the pilot has to judge his proximity to yaw axis limits, in particular the limits on yaw performance associated with tail rotor flap. For these reasons Ref 14 highlights the importance of the yaw axis for future carefree handling function development.

Although some of these features might be enabled through limited authority stability and control augmentation systems, others would be dependant on full authority Active Control Technology (ACT). When ACT is considered, the concept of Fatigue Usage Minimising Control Laws (FUMCLAWS) might develop. Here, one might imagine a smoothing control law, which, from the pilots demand offers a response that is designed to minimise the fatigue penalty associated with the demanded manoeuvre.

Taking these issues into consideration redresses some of the criticisms of active control applied to rotorcraft, relating to the potential increased fatigue damage arising from the increased control activity from the ACT system.

Conclusions

This paper has reviewed activities at DRA Bedford relating to the structural fatigue usage during flying qualities testing. Research test aircraft are typically exposed to a different usage spectrum than operational aircraft, and the issues are particularly germane in flying qualities experiments when aircraft can be exposed to greater than 'normal' aggressive manoeuvring. Experience gained in this area has been secondary to the primary research concerns at DRA Bedford, but is considered of potential interest in the continuing development of the flying qualities test methodology. The paper has discussed the approach taken to fatigue accounting, real time monitoring and the intimate relationship needed with the design authority. Examples have been presented of various types of fatigue limit encroachment experienced during open-loop and closed-loop flight test manoeuvres, highlighting the importance of real time monitoring of critical stress levels and post flight accounting.

From the results and associated discussion presented in this paper, the following key points can be noted.

(i) That a FUM system is considered important for flying qualities research test vehicles, where the usage spectrum is consistently different from the design usage spectrum.

(ii) That load monitoring in real time, and usage accounting are highly desirable, if not essential, requirements when testing using the new test methodologies.

(iii) That ADS-33 testing can be carried out without a FUM system if the vehicle type has been cleared for the required ADS-33 test manoeuvres by previous testing using an instrumented vehicle of the same type.

(iv) That there is a significant challenge associated with FUM to any flight test programme, both in terms of definition, installation, calibration, maintenance, trial monitoring and most significantly in post flight analysis.

(v) The manufacturer has a key role as advisor to the authority in establishing, maintaining, advising and reviewing the results from FUM on a research or certification release test vehicle.

(vi) Both real time limit monitoring and post flight usage accounting are required, as are clear rules to enable these to be used effectively during trials.

(vii) Current post flight analysis techniques remain lengthy time-consuming processes. The paper discusses possible development systems to ease this process.

(viii) Several case histories have been presented. Particular areas to be noted are:

- Frequency Sweep Testing.

- Aggressive yaw manoeuvres.

- Recovery strategies post test manoeuvre.

- Slalom, transient turn and the deceleration-to-dash MTE's.

(ix) A FUM system has additional benefits for an aeromechanics research vehicle when testing on tasks other than ADS-33 (e.g. Instrumented blade, tail rotor failure).

(x) The relationship between the FUM exceedences experienced on ALYCAT during research trials has highlighted the importance of In-Service usage monitoring.

(xi) The UK is considering the benefits of a portable PC based on-board system for future research and type certification testing.

(xii) There is an apparent dichotomy between the *mission* based ADS-33 and component design *mission* usage spectra. In particular, why should we experience usage problems when testing using ADS-33 on components designed against a mission usage spectrum.

(xiii) The relationship between handling qualities testing, fatigue lifing/structural release and logistics techniques needs to be developed.

(xiv) In the near future, carefree handling may help reduce these usage penalties, and with the development of ACT advanced FUMCLAWS these penalties could be mitigated further to enable enhanced operational mission effectiveness and reduced life cycle costs.

References:

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ALYCAT FUM SUITE	
DYNAMIC SYSTEM MONITORING	STRUCTURAL MONITORING
Main rotor hub flap, lag and torsion (15 gauges)	F/A gearbox beam (forward upper)(port)
Main rotor "dog bones" (15 gauges)	F/A gearbox beam (forward upper)(stbd)
Main rotor blade (FUM) (24 gauges)	Vertical shear load (Frame 420A)(port)
Main rotor "spider arm" bending	Vertical shear load (Frame 420A)(stbd)
Main rotor controls (F/A, lateral and collective)	Tail cone 254mm aft of transport joint (bending)(vertical)
Tail Rotor Blade (8 gauges)	Tail cone 254mm aft of transport joint (bending)(lateral)
Tail rotor controls pitch change lever load	Tail cone/fin intersection (port)
Tail rotor drive shaft torque	Tail fin in-line with strut (port)

Table 1 - ALYCAT FUM Instrumentation

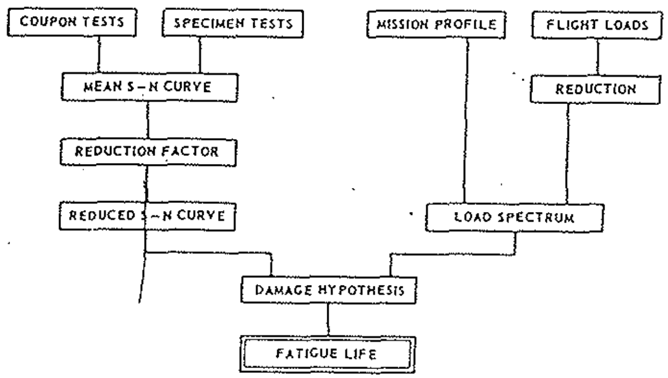

Figure 1 - Fatigue Substantiation Methodology

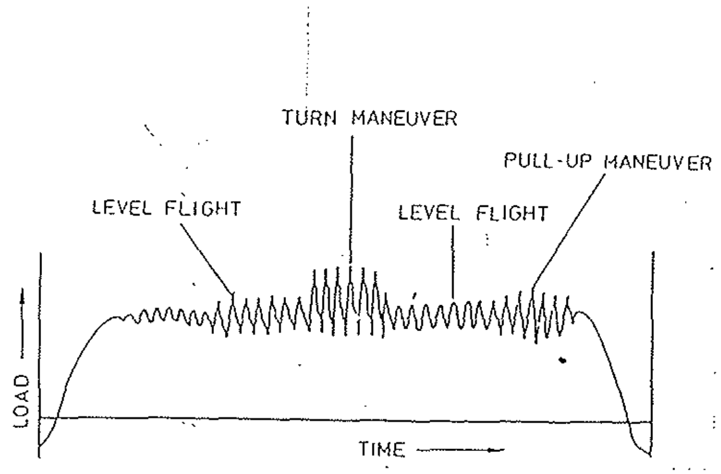

Figure 2 - Manoeuvre and Mean Cyclic Loads

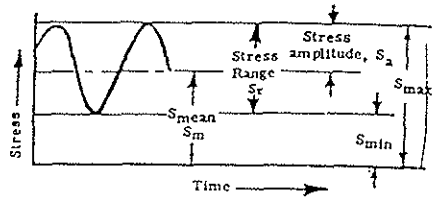

Figure 3 - Definition of Terms for Cycle Counting

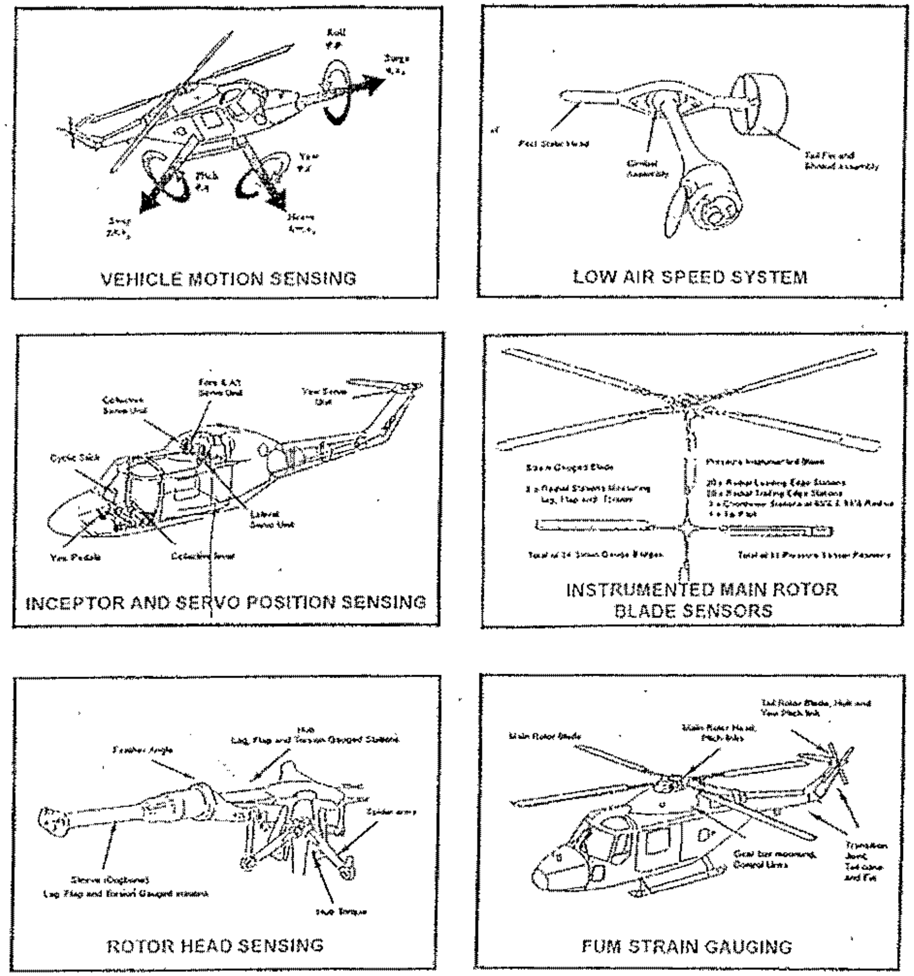

Figure 4 - ALYCAT Lynx Instrumentation Suite

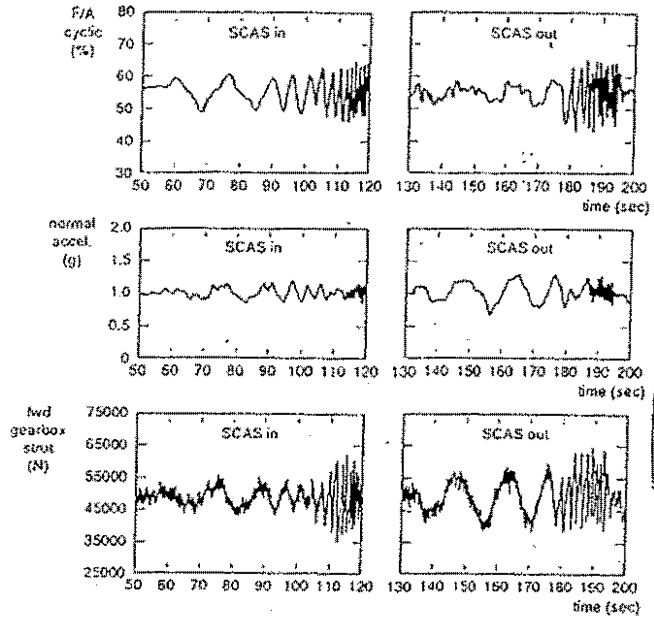

Figure 5 - Frequency Sweep on DRA Research Puma - 60kn SCAS on and off.

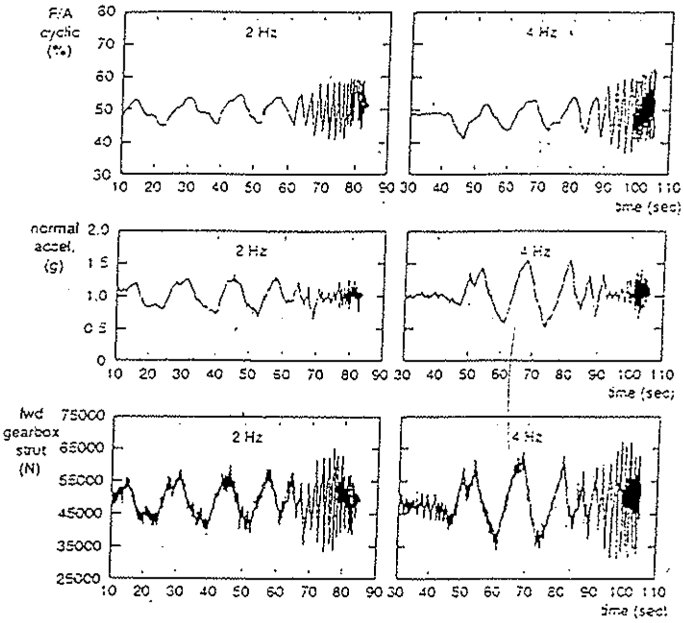

Figure 6 - Frequency Sweep on DRA Research Puma - 100kn, 2 Hz and 4 Hz

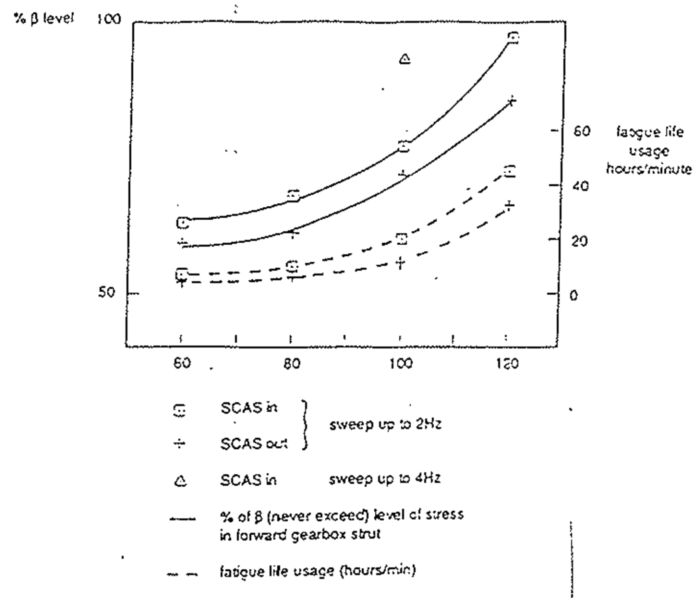

Figure 7 - Fatigue Life Usage on DRA Research Puma due to Longitudinal Cyclic Frequency Sweeps

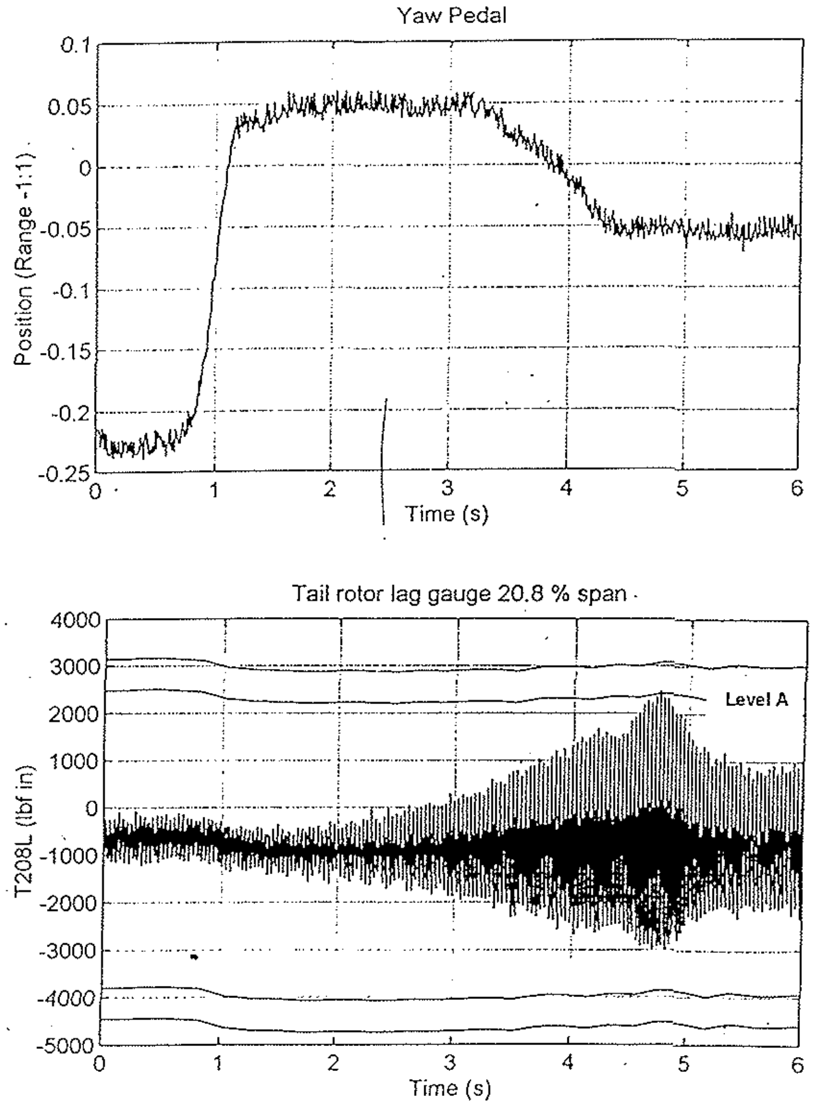

Figure 8 - Yaw Control Power - Tail Rotor Lag 20.8% Span

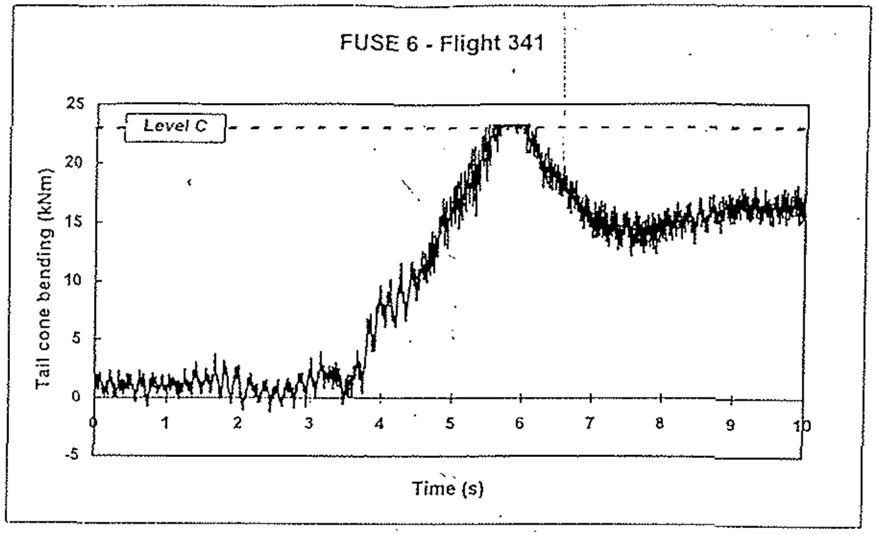

Figure 9 - Deceleration to Dash MTE Tail Cone Bending Level 'C' Exceedence

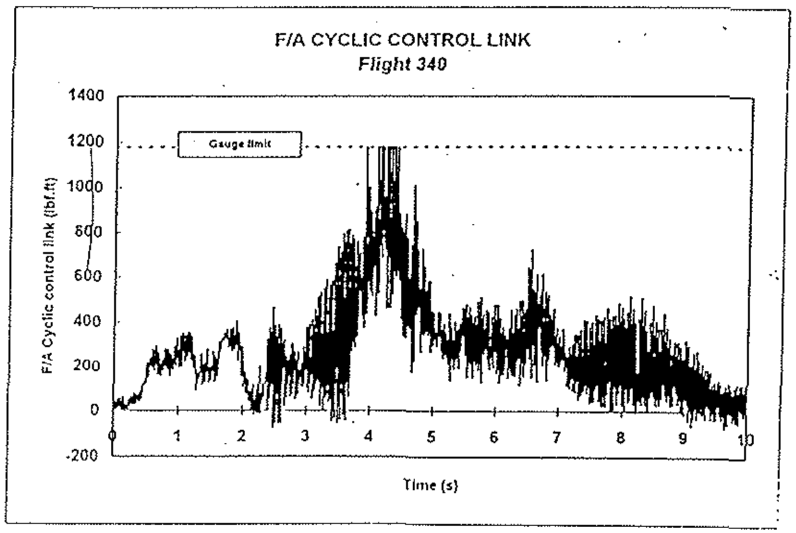

Figure 10 - Transient Turn F/A Cyclic Control Link Level 'C' Exceedence

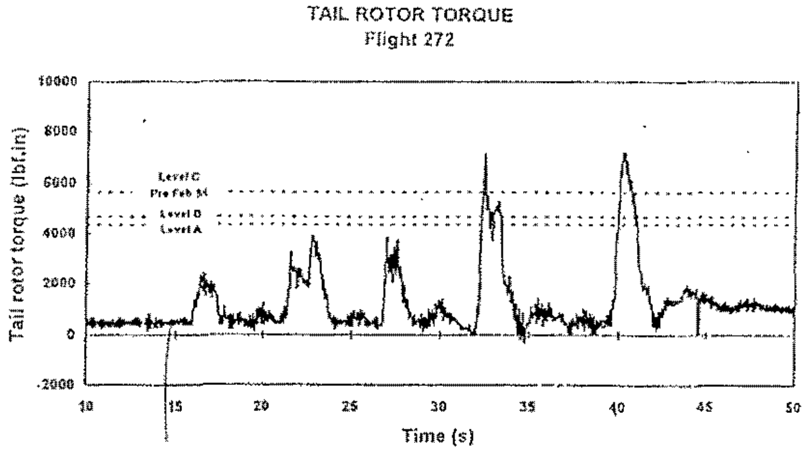

Figure 11 - Slalom MTE Tail Rotor Gearbox Over Torque Level 'C' Exceedence

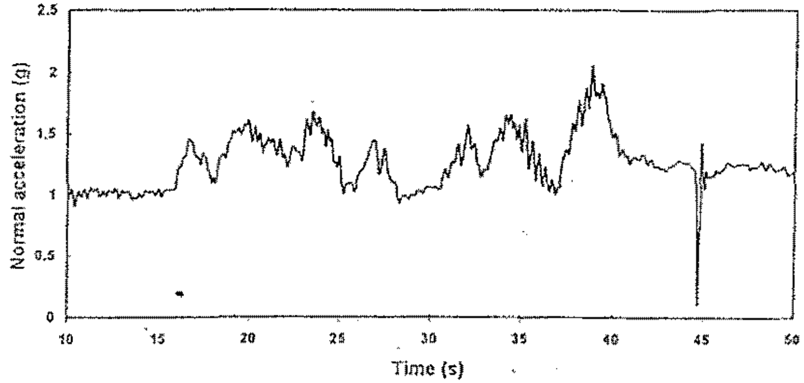

Figure 12 - Slalom MTE Associated Normal Acceleration

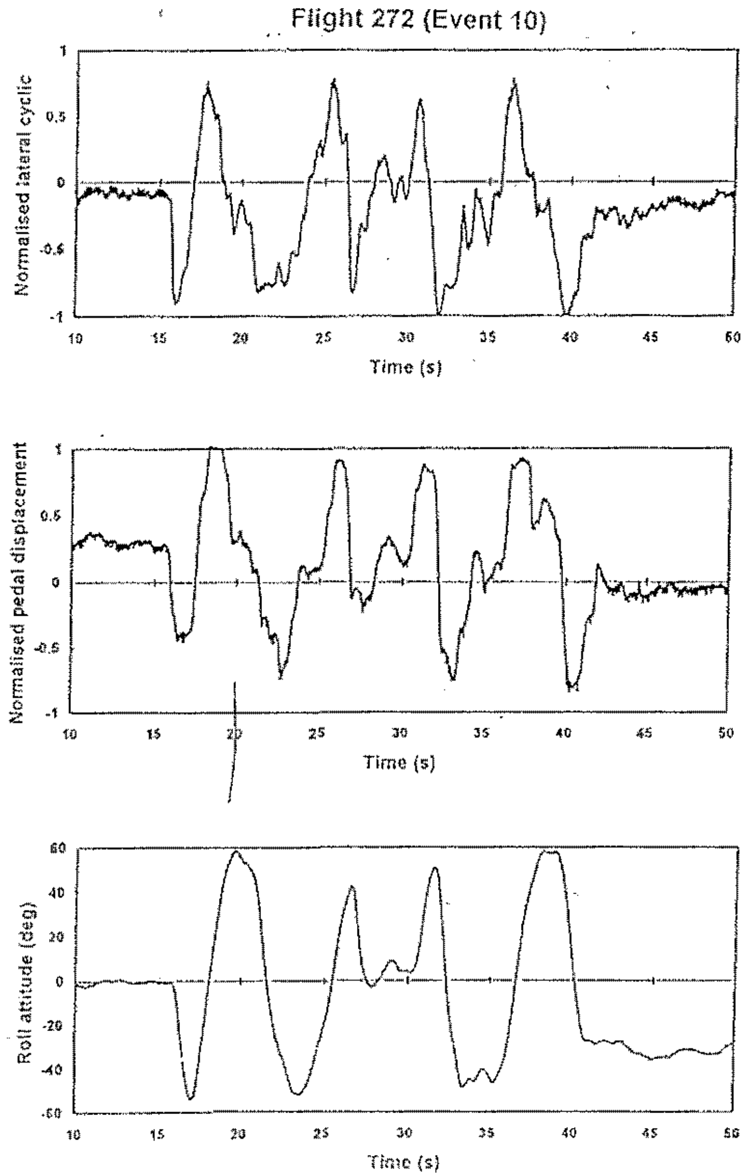

Figure 13 - Slalom MTE Associated Lateral Cyclic, Pedal Displacement and Roll Attitudes