RECENT DEVELOPMENTS IN AIRWORTHINESS ASSURANCE USING UNSUPERVISED DIAGNOSTIC SYSTEMS FOR HELICOPTER MAINTENANCE

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Abstract

Whilst much of helicopter maintenance has been undertaken using carry onboard measuring and processing equipments, the move toward avionic based Integrated Health and Usage Monitoring Systems (IHUMS) is rapidly becoming a reality. In parallel with the associated hardware developments, a number of advances have been made in the handling and processing of data, to aid helicopter maintenance.

This paper presents a number of recent developments in unsupervised diagnostics, ranging from troubleshooting main rotor irregularities, to airframe/component anomalies, to faults which could give rise to catastrophic failure. Once established, the diagnostics are software coded and implemented on a ground station computer, which directly supports IHUMS operations.

Whilst particular emphasis will be placed on full-scale examples, the use of an invaluable mathematical model will also be described. In addition, facilities which have been developed to aid the handling of large volumes of data, including the successful use of machine learning strategies is reported.

Introduction

Integrated Health and Usage Monitoring Systems (IHUMS) will offer a wide range of sensor measurements on a flight by flight basis [1]. These measurements will include airframe mounted accelerometers, main rotor blade positional and velocity measurements along with other parameters such as outside air temperature, pressure altitude etc. Collectively, such a measurement suite offers considerable potential to construct a software based set of unsupervised diagnostics to aid helicopter maintenance.

This paper sets out to report the progress made in unsupervised diagnostics and identifies some of the current developments in this area. Before these matters are presented, however, it would be useful to introduce various abbreviations which will be used in this paper.

For helicopters installed with IHUMS, a complete measurement suite will be available on a flight by flight basis. When referring to these data sets the following abbreviations will be used:

C: Current (latest) measurements
P: Previous measurements
D: (C - P), difference measurements
E: estimated measurements based on the main rotor adjustments
Re: C - (P + E), residue measurements

The difference file, D is determined using vectorial and scalar subtractions for the vibration harmonics and the blade positional data respectively. The calculation of the residue file includes a further calculated file, E, which is derived from a knowledge of the main rotor adjustments performed between P and C and prescribed adjustments sensitivities. The sensitivities represent the affect of a given adjustment on selected measurements at various points in the operating envelope of the helicopter. As an example, figure 1 presents blade track and lag normalised sensitivities for the Aerospatiale Super Puma main rotor track rod adjustment.

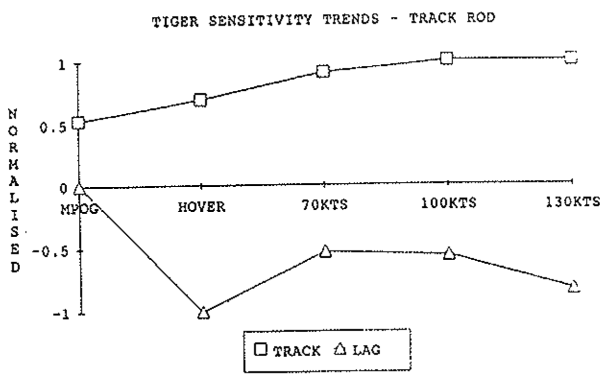

Figure 1: Track rod sensitivities.

When discussing accelerometer signatures both time and frequency domain presentations will be used. External sampling signifies that the analogue accelerometer signature was digitally sampled at a rate which was altered to ensure that the same number of sample points were collected in each rotor revolution. When transforming this timebase signature to the frequency domain using a Fast Fourier Transform, FFT (software algorithm), the spectral lines are exactly related to the rotor frequency, referred to as "R". The transform may be performed on a rev by rev basis or operated on a signal average. In the latter case, n revs of time domain data are overlaid (added) n times. Each sample point amplitude is then divided by n to yield an average signal over one rev. This procedure has the effect of diminishing vibration components which are not an integer multiple of the rotor frequency. Regarding integer multiples, one vibration component which is present in all helicopter airframes is bR, where b is the number of rotor blades.

Both practical and theoretical data will be cited. The latter, based on a computer math model, is introduced in the next section.

Computer math model

The computer math model is based on a suite of software modules which are configured from an editable file, allowing the user to select quick analytical options or more detailed numerical solutions. Based on over 9 years of research and development work [2 & 3], the program combines a representative non-uniform induced velocity wake, detailed non-linear aerodynamic data, a blade elastic response model and a robust trim procedure, combined with several further math models for various fault simulations.

Installed on an IBM PC compatible with a 25 MHz 386 processor and a 387 math co-processor, the run times vary from under 1 second to in excess of 300 seconds. The former time is associated with an analytical approach (linearised model) based on rigid blade and prescribed aerofoil characteristics. The most detailed approach is based on highly non-linear models of the induced wake and aerofoil characteristics combined with full blade flexibility in flap, lag and torsion.

Before presenting the usefulness of the model, however, the challenge of applying unsupervised diagnostics in the "real" world will be discussed, as without a good appreciation of in service difficulties the potential gains of IHUMS will not be fully realised.

In service challenge

Whilst it may be possible to demonstrate that a diagnostic technique is viable in a controlled, scientific environment, this does not guarantee that such a technique will work in service. Experience has shown that a diagnostic assessment must be able to cope with measurement or information corruption. Sources of this corruption are manifold; typical examples range from plausible yet erroneous measurement errors, to incorrectly performed and/or logged maintenance actions.

In essence, a diagnostic approach must encompass sufficient peripheral checking on the measurements and supplied information to ensure integrity.

Checking maintenance integrity

Whilst there are a multiplicity of actions associated with helicopter maintenance, those actions which affect a change in the measurements potentially lend themselves to unsupervised integrity checking. To successfully apply unsupervised techniques, however, all maintenance actions must be stored in a coded form and not reliant upon entered text, which is vulnerable to individual descriptions, spelling/gramatical deficiencies etc.

As an example, take the class of actions which are associated with main rotor adjustments. Such actions include pitch link, tab and mass corrections. By subtracting measurement sets from two consecutive flights, between which main rotor adjustments have been made, maintenance validation may be undertaken. The resulting difference file (current - previous), D, represents the effect of the adjustments. Figure 2 presents a simple example where the track portion of a difference file indicates that the tracking position of the "BLK" blade with respect to its partners has been raised. Such an occurrence is consistent with lengthening the track rod of the "BLK" blade. However, the logged maintenance code indicates that the track rod of the "BLK" blade should have been shortened by -15 clicks. Accordingly a warning message would be presented to draw the attention of this discrepancy to the line engineer.

	BLADE IDENTIFIERS			
Flt state	BLK	BLU	YEL	RED
MPOG	16	-10	-2	-4
Hover	16	-4	-6	-6
70 kts	24	-8	-8	-9
100 kts	27	-8	-10	-9
130 kts	26	-8	-8	-10

Maintenance code: B4217 -15

Figure 2: Track portion of a difference file.

The subtraction process may be taken one step further to produce a residue file:

$$R = C - (P + E) \qquad [1]$$

The derivation of the residue file introduces another possible source of error - the adjustment sensitivities. In theory, the residue file should contain all zeros in that the predicted file, (P + E), should equal the actual measurements, C. In practice the residue file will almost certainly be non-zero, and in addition to incorrectly performed maintenance actions, the residue file will be influenced by measurement error and inaccurate sensitivities. The latter may be identified, however, by looking for consistent non-zero values in the residue file over a number of flights and different aircraft of the same type.

By utilising an approach based on subtracted and residue files maintenance validation strategies may be built, combined with useful measurement and adjustment sensitivity checks.

Checking data integrity

Integrity checks must not only be performed on measurements taken on a flight by flight basis but on data which has been derived from the flight measurements. Whilst the ideal strategy for checking sensor integrity would be generic in form, the range of sensors used by IHUMS may make this difficult. To illustrate the sort of checking procedures that may be applied, examples will be drawn from two types of sensor. First, accelerometer output may be contaminated due to connector or cabling problems, or subsequently distorted through excessive gain ranging prior to analogue to digital conversion. In addition, a loose accelerometer mounting may significantly reduce the validity of the signature. As an example of the latter, figure 3 presents three spectra derived from three airframe mounted accelerometers on a four bladed helicopter. Whilst all the spectra look plausible, a single parameter named SI4B (Structural Index), was calculated to be 84 for one spectrum, whereas a value of less than 10 is typical. The corresponding accelerometer had fallen from its mounting position and was lying on the floor.

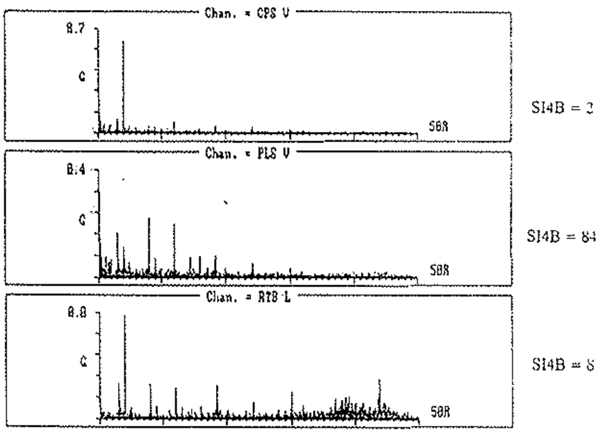

Figure 3: Helicopter airframe vibration spectra.

SI4B is based on the generic quality of all helicopters, in that vibrations with frequencies which are an integer multiple of the blade pass frequency will be present in the airframe unless vibration absorbers or similar are fitted. In particular, the fundamental blade pass frequency of vibration, during a steady helicopter operating state, will generally be stable. Applying external sampling, the phase of this vibration frequency may be accurately determined. SI4B monitors the stability of this phase on a rev by rev basis - the more unstable signatures returning the highest values.

As a second example, a passive optical blade track sensor will be cited. This sensor measures rotor blade displacement (track and lag) and velocities. The following tabulated data in figure 4 depicts actual measurements taken using this device. It has been found that by inspecting the blade velocity magnitudes, the integrity of the other measurements may be assessed. For example if the blade to blade difference in velocities is greater than 1%, the data should be considered suspect. An alternative use of the blade velocity measurement is to assess the test state tagged to the data. Two cases of hover are tabulated in figure 4. The expected blade velocities in the hover would be in the region of 195 m/s, whereas the second set of hover data in the table registered blade velocities of 171 m/s. The most probable cause of this is that the pilot entered the transition before data collection was complete.

Test state: 125 kts (SUSPECT)

Track:	5	-21	-7	23
Lag:	-6	-1	-8	15
Vel:	203	201	200	208

Test state: Hover (GOOD)

Track:	-1	2	4	-6
Lag:	1	1	-1	-1
Vel:	199	199	199	199

Test state: Hover (SUSPECT TEST STATE)

Track:	4	-8	3	0
Lag:	2	-2	0	0
Vel:	172	172	172	171

Figure 4: Blade tracker data.

Downstream of the sensor checks, the diagnostic data derived from the flight measurements also needs to be assessed. As an example, adjustment sensitivities are evaluated from a suite of difference files, D = C - P, where ideally between C and P, only a single adjustment has been made. In theory for a given unit adjustment, say one click of a track rod, the same sensitivity in track, lag and 1R vibration would result. In practice discrepancies emerge, and may result from differences in adjustment errors, ambient conditions, helicopter all up weight etc. Figure 5 presents example normalised 1R vibration amplitude sensitivities for a track rod at two helicopter all up weights, namely 16200 lbs and 18960 lbs. Note that an allowance of helicopter weight would be required before the sensitivities may be used to estimate corrective magnitudes.

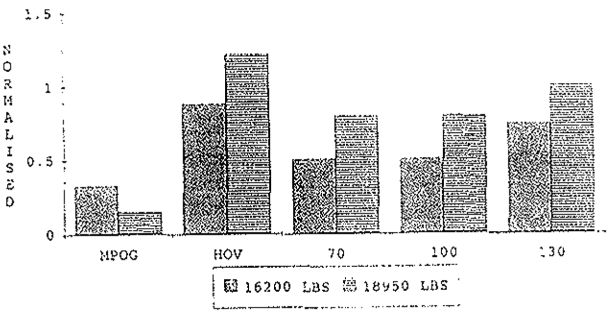

Figure 5: 1R lateral sensitivities - track rod.

Figure 6 presents part of a sensitivities analysis for a track rod adjustment on a S76 helicopter. For each sensitivity, which has been determined from a number of separate flights, the (standard deviation/mean) is calculated and expressed as a percentage. The higher the ratio, the lower is the confidence level that may be attached to the sensitivity. Once established, these confidence levels may be introduced in the computation of the adjustments and is discussed in the next section.

Test state	Track	Lag
MPOG	32	39
Hover	13	11
70kts	22	185
100kts	14	64
120kts	12	26
145kts	28	38
VNE	32	38
Climb	19	24
Descent	12	363
Turn	17	18

Figure 6: S76 sensitivities' analysis.

Rotor adjustment diagnostics

One common source of airframe induced vibration is that which is associated with the fundamental turning frequencies of the rotor systems, typically referred to as 1R and 1T for the main and tail rotors respectively. The range of adjustments available to the line engineer vary greatly between helicopter types and may include track rod, blade tab, spanwise and chordwise mass balance corrections. Often a rotor system has more than one maladjustment at any one time and, accordingly, various methodologies have been developed to address this difficulty. One method is to limit adjustments to one type (i.e. multiple track rod or tab adjustments) per data collection. This has the disadvantage that it may take a number of flights before the problem vibration is resolved. Another method is based on the principle of least squares and can cope with any number of test points in a flight record, and any number of adjustments. Theoretically, if the 1R vibration is caused by maladjustments, a multi-fault, single shot solution is possible. The salient mathematical scaffolding associated with this approach is as follows:

$$S = -\{[W][a]^T[a]\}^{-1}[a]^T[M] \qquad [2]$$

"S" is a column matrix holding the corrective adjustments, "W" is a matrix holding the adjustment weightings (confidence levels), "a" is a matrix holding the adjustment sensitivities and "M" is column matrix holding the measurements. Except for the weighting matrix, all quantities are vectors.

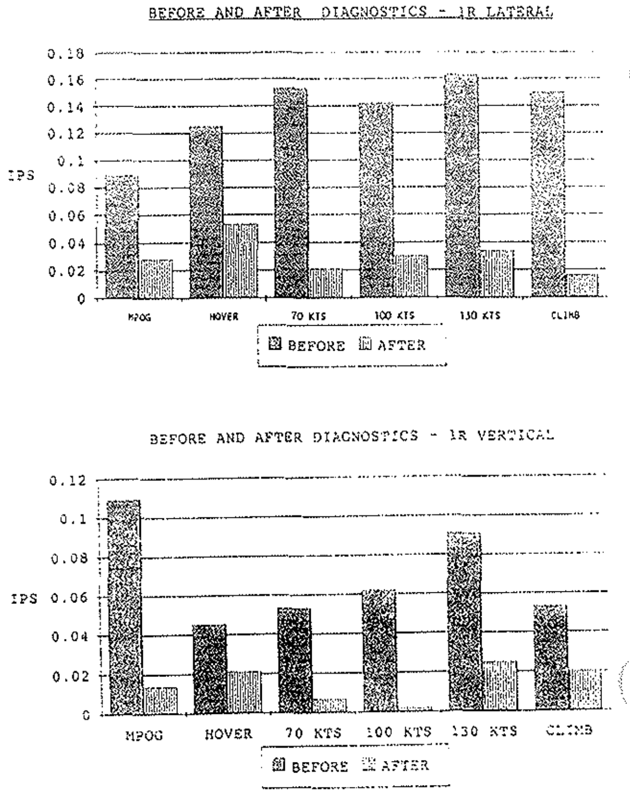

Figure 7: Single shot performance - before and after.

Figure 7 presents the before and after flight vibration measurements using this single shot approach. As can be seen, the vibration levels in two planes have been reduced across the helicopter's operating range. Whilst this approach has proved invaluable on a number of helicopter types covering semi-rigid and articulated rotor heads, configured with either metal or composite blades, it does not directly identify non-adjustable faults. One example of this class of fault is discussed in the following section, namely lag damper irregularities.

Non-adjustable faults - lag damper irregularities

Devices which suppress blade lead lag motions vary markedly between helicopter types. One factor which dictates the magnitude of damping required is the lag hinge or effective lag hinge offset. Accordingly, the artificial damping requirements for the semi-rigid rotor head of the Lynx helicopter with a large effective hinge offset is small when compared to a fully articulated head of, for example, the Sea King. In addition, damper designs also vary between helicopters. Compare, for example the Sea King damper with the "frequency adaptor" of the Super Puma. In the former case the hydraulic device operates initially as a classical viscous damper until a "blow-off" condition occurs whereupon the damping characteristic is more friction in nature. In contrast the frequency adaptor is based on a visco-elastic material sandwiched between metal plates. Whilst this construction offers inplane damping, it will also contribute to the inplane blade stiffness. Accordingly, in this case individual blade lag positions may be influenced by discrepancies in both frequency adaptor stiffness and/or damping.

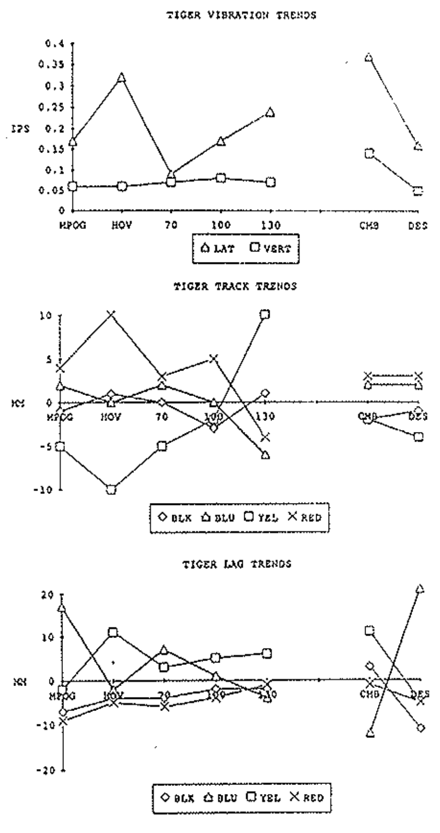

Figure 8: Frequency adaptor mismatch.

Figure 8 presents measurement features associated with a frequency adaptor mismatch. The top graph details the 1R vertical and lateral vibration levels as measured on the bulkhead. The two further graphs contain the track and lag figures respectively. One salient characteristic which highlights the mismatch may be found in the graph displaying the lag trends. Specifically, the lag changes between MPOG (low collective pitch) and hover (high collective pitch) and descent (low collective pitch) and climb (high collective pitch) should be noted, paying particular attention to the "BLU" blade. Whilst the "BLU" blade's track position changes little, between low and high collective pitch settings it moves from a leading to a lagging position. Similar characteristics have been reported for identifying irregularities associated with the elastomeric dampers fitted to the Bell 412 helicopter [4].

In contrast, data acquired on a Sea King helicopter with a deficient lag damper produced a different trend, figure 9. Whilst the corresponding blade was seen to have a marginal lag in the hover, it lead in forward flight. The lag data was recorded at a rotor azimuth of approximately 190-200 degrees. This finding was in conflict with expectation and, accordingly, required further explanation. Figures 10 and 11 presents the predictive behaviour of the defective damper in question based on the math model detailed earlier. In particular, the actual lag position of the blade with the defective damper is seen to be a function of blade azimuth, helicopter airspeed (figure 10) and all up weight (figure 11). Even when given these variables, however, the data in figure 10 compares well with the measured behaviour.

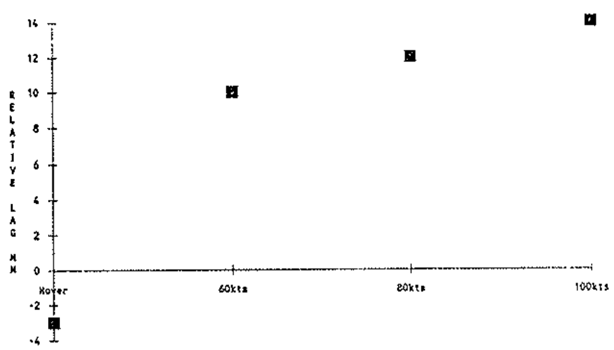

Figure 9: Deficient lag damper - practice.

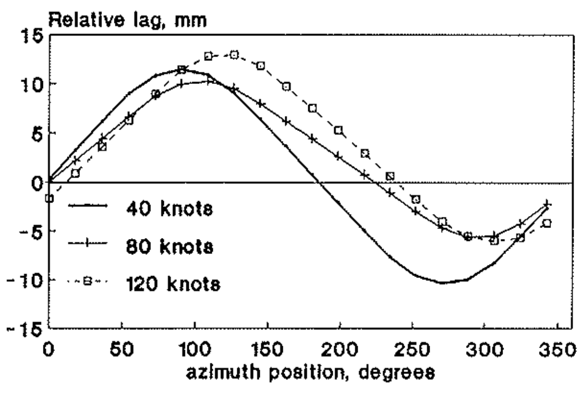

Figure 10: Deficient lag damper - theory.

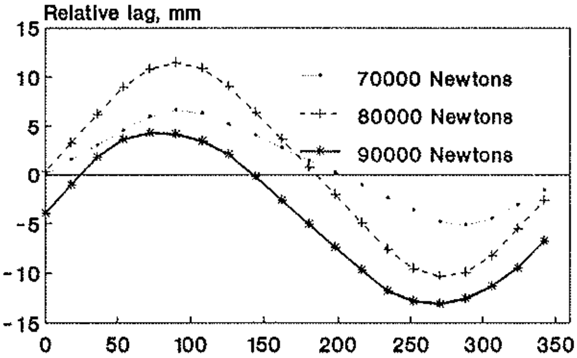

Figure 11: Deficient lag damper, 40kts - theory.

Airframe/component diagnostics

Airframe response to the multi-harmonic force vibrations may be thought of by considering the airframe as a complex mechanical "filter". Ideally the "filter" characteristics would be common across a helicopter type. In practice as a result of wear, helicopter role, fitment and operating conditions, a degree of individual "filter" characteristics will be present. Historically, those vibrations which are not attenuated by the "filter" or, worst still, amplified, and of a frequency sympathetic with a body resonance, have been reported by the pilot. On grounding a helicopter for such a report, the line engineer has been set the arduous task of identifying where in the fuselage the "filter" has broken down. Often this procedure has been based on nothing more than trial and error.

One of the major causes of helicopter unserviceability is where the aircraft has been grounded for high vibration with a frequency equal to the blade pass frequency, bR, - sometimes known as "cobble stone" vibration. As stated previously these frequencies are always present in the airframe. Higher levels than are considered acceptable, however, are not always indicative of a fault.

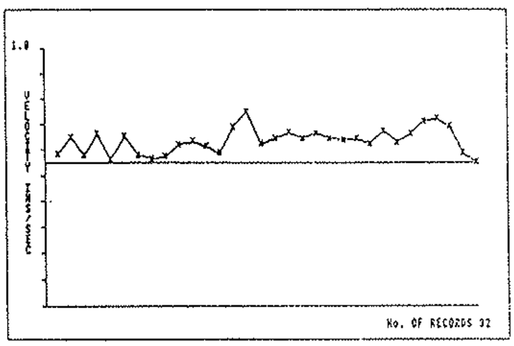

Figure 12: Sea King 5R trends.

Figure 12 details 5R fore and aft vibration levels measured on a Sea King Mk 5 over a year long period, where the prescribed acceptance threshold was exceeded throughout. During this period a variety of maintenance actions were performed along with periods where no actions were taken. It was found that a nil action could have just as significant affect on the 5R vibration amplitude as many of the maintenance activities. Closer examination of the data revealed that the 5R amplitude was influenced by the operating state of the helicopter. In addition to high altitude, warm outside air temperatures and heavy helicopter weights, which tended to have a detrimental affect on the measurements, the pilot set main rotor turning frequency (%NR) was predominant in its effect. The sensitivity of the 5R to %NR is readily explained when considering that the Sea King Mk 5 has a battery mounting which is tuned to be in anti-resonance at 5R with 102.8%NR set. Flight by flight variations in the setting of the %NR was sufficient to degrade the 5R vibration amplitude to the extent that the acceptance threshold could be penetrated. For unsupervised diagnostics to be effective, the 5R values have to be normalised by such variables as helicopter all up weight, density altitude and %NR set, so that the true amplitude of vibration associated with the airframe may be determined.

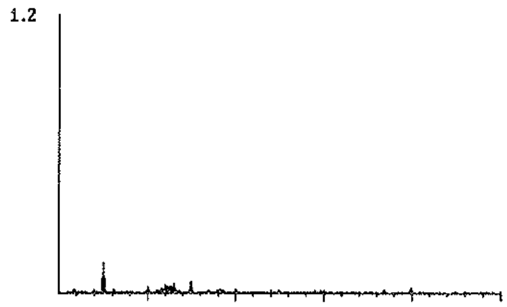

Figure 13: Vibration measurements at the inter-seat console.

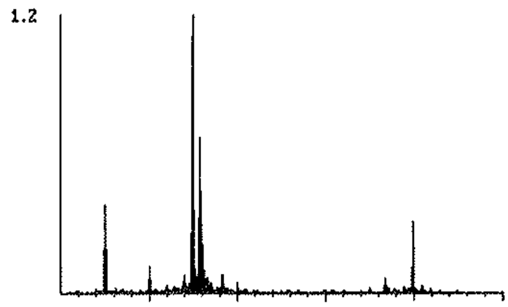

Figure 14: Vibration measurements at station 311.

As previously mentioned, the pilot is/was often instrumental in grounding a helicopter for excessive vibration. Whilst this has often flagged a problem, it is limited for two reasons. First, the pilot's sensitivity to vibration levels is dependent upon his own body resonances and second, not all airframe component defects which produce airframe vibration, whilst excessively high locally, may not be detected in the crew area. As an example of this, figures 13 and 14 present vibration spectra from two physical locations in a Sea King airframe, namely the iner-seat console position (crew area) and station 311. Whereas the symptom of excessive 1S vibration amplitude associated with an impending tail drive shaft disconnect coupling failure was readily apparent at station 311 (the largest peak), nothing significant could be registered in the crew area. Accordingly, unsupervised diagnostics, if to be effective, must have access to vibration signatures from a suite of distributed airframe accelerometers.

In addition to increasing fault visibility throughout the airframe, distributed airframe accelerometers offer the platform on which additional diagnostic techniques may be built. Two such techniques are based upon transfer function and rigid body analyses.

Transfer function analysis

Transfer function analysis may be considered to relate the signals from two airframe locations in terms of their amplitudes and phases. By examining this relationship after signal averaging, the signal to noise is often improved. For certain maintenance actions the airframe transfer function, H, would not be expected to change, whilst for other actions it would. Making the simplification of assuming a single input/output linear system for ease of expression, the following relationships may prove instructive.

To generate the rotor adjustment sensitivities mentioned previously an additive model was assumed:

$$C - P = H.F_m \qquad [3]$$

where F_m refers to the change in forcing attributable to the adjustments.

That is an adjustment to the rotor head would be expected to change the induced force from rotor to airframe without changing the characteristics of the load path (transfer function, H) in the airframe.

When troubleshooting defects in the airframe which give rise to excessive bR vibration amplitudes, it is useful to check whether a maintenance rectification has affected the load path. For such an assessment it is more appropriate to use a multiplicative relationship:

$$C / P = H_c / H_p \qquad [4]$$

where H_c and H_p refer to the transfer function associated with measurement sets C and P respectively.

Equation [4] states that if the transfer function of the airframe has been changed as a result of maintenance and is not dependent upon the operating state of the helicopter then the vectorial ratio of the two measurements sets should remain constant. For a practical example, figure 15 tabulates the 4R ratio trends related to C and P, where in between the maintenance action was to re-establish the preload on the top taper roller bearing of the Lynx main rotor gearbox. Clearly a consistent ratio is evident for both lateral and vertical axes of vibration measurement which is constant throughout the speed range.

Test state	Lat	Vrt
100kts	0.69	0.73
120kts	0.66	0.74
140kts	0.66	0.70
150kts	0.67	0.68

Figure 15: Lynx 4R ratios.

The ratio calculation is therefore a useful check to test the effectiveness of certain airframe related maintenance actions. Note also that this approach could be extended to monitor the load paths (transfer functions) between accelerometers in a single flight. By calculating the ratios of all the multiple paths between distributed accelerometers it may be possible to identify the region in the airframe where a change in load path has occurred and hence where the defect component resides.

Rigid body analysis

Given distributed airframe accelerometers, the potential for computing the approximate rigid body response of the airframe to rotor forcing can be realised. How approximate will be dependent in part on the elastic deflections of the airframe. The intention, however, is to define a "normal" pattern of response from which extreme cases (+-2 standard deviations) may impart diagnostic information.

Whilst it may seem possible to deduce the 3 translations and three rotations from the output of two tri-axial accelerometers, this is not possible due to matrix singularities. Three physical airframe locations along with 6 accelerometer measurements are the minimum requirement to compute all the motions. Whilst the rigid body response may be performed for any forcing frequency, the bR frequency response has been studied for two helicopter types, namely the 4 bladed Lynx and the 5 bladed Sea King.

It was a surprising feature of both these aircraft that the calculation of the rigid body response was adequately consistent over a number of aircraft. In particular, both aircraft exhibited a strong roll characteristic. For example, when comparing the phase angles between the roll and pitch rotations for the Sea King helicopter, the mean calculation revealed an angle of -63 degrees with a standard deviation of 26 degrees. The only aircraft in the sample that fell outside 2 standard deviations from the mean, subsequently experienced a tail drive shaft disconnect coupling failure. Given these findings, the characterisation of the helicopter through rigid body response will be pursued with the introduction of IHUMS.

Whilst the previous sections attempted to reduce measured data to patterns associated with the airframe or the response of the complete helicopter, the following section examines patterns in individual accelerometer signatures, to elicit further fault discrimination capabilities.

Advanced signal processing

Much signature analysis work is based on averaging techniques to increase the signal to noise ratio. In the averaging process however, diagnostic information may be lost, including frequency detail which is asynchronous with the averaging period. Accordingly, techniques have been developed which allow the raw time histories to be processed.

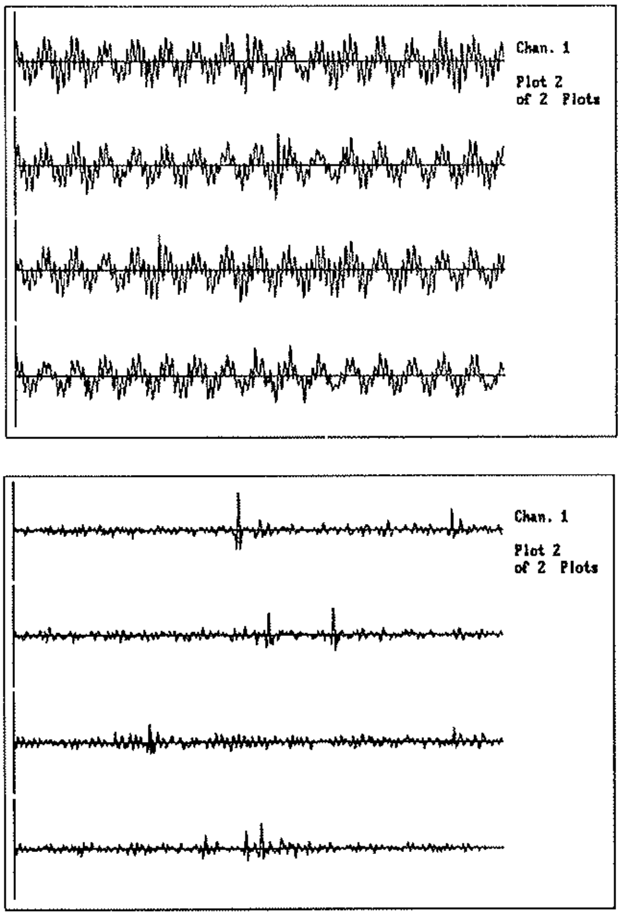

Figure 16: Raw and enhanced vibration signatures.

One parameter, namely structural index SI_1, is derived from a process of signature enhancement. Figure 16 presents vibration data measured on the port control frame of a Lynx helicopter. The top graph in figure 16 represents the raw time based vibration signature, captured over 32 main rotor revolutions. The lower graph is the same signature, post enhancement. The corresponding SI_1 value was in excess of 20. From a serviceability viewpoint, the aircraft was grounded due to a high 4R vibration level. The maintenance action which cured the problem was a main rotor gearbox replacement. SI_1 values returned to typical levels of around 3.

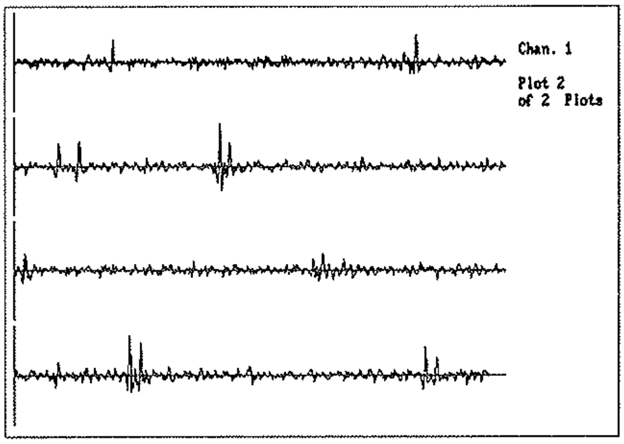

Figure 17: Enhanced vibration signature.

A second example of an enhanced vibration signature, measured on another Lynx aircraft, is presented in figure 17. Again the SI_1 value was in excess of 20. This particular case is of appreciable interest in that the main rotor gearbox was only 15 hours old. Although metal was being produced in the oil, this in itself is not atypical for a new gearbox. On closer inspection it was noted that the preload on the top bearing of the gearbox had increased by 50% from a prescribed figure. The reason for this increase is not known at the time of writing. Post gearbox replacement SI_1 values again returned to around 3.

Whilst the associated gearbox strip reports are awaited, it will be clearly seen that the structural index approach offers considerable promise for unsupervised diagnostics.

Additional structural indices, SI_2 to SI_4 have also been developed to detect structural resonances, repetitive impulsiveness and to test for data integrity. The introduction of IHUMS will offer the required statistical sample of data to prove and develop these techniques for everyday use.

Potentially Catastrophic Faults

Cambell [5] has reported upon a world wide survey of fatal helicopter accidents which involved metal fatigue. In summary, his findings are tabulated in figure 18. It can be clearly seen that catastrophic failures associated with the rotor systems' forms a predominant core to the table. Of further interest was his comment that "the manufacturer is not necessarily at fault in all cases of repeated failure. In many instances the failure area was known and designated for mandatory inspection by the appropriate airworthiness authority at regular intervals. However, the existing fatigue crack was missed during inspection".

Category	Accidents	Fatalities
Tail rotor	29	78
Main rotor	22	111
Engine/Trans	13	34
Flt controls	10	17
Miscellaneous	6	21
Airframe	6	21
TOTALS	90	284

Figure 18: Helicopter accidents [5].

Cambell's findings highlight the need for rotor system diagnostics, which would complement the existing inspection techniques. To obtain a fuller appreciation of the symptomatic behaviour associated with potentially catastrophic faults (PCFs), a world wide survey covering accident investigation reports, technical journals etc, was undertaken [6]. Unfortunately the survey did not isolate many well documented examples which described the PCFs in sufficient detail. However, information from this survey, limited practical examples and extensive use of a rotor math model has identified a suite of approaches for detecting PCFs.

Composite blade crack growth detection

In reference [7] a composite blade was forced to fracture with a representative load spectrum. Implicit in the data presented were two important features:

- The time elapsed from crack initiation at the root to final fracture was in excess of 300 hours.

- Well in advance of blade failure the root stiffness had reduced by 30%.

Given the lead time to failure and the significant change in structural properties, it would seem feasible that this type of PCF could be detected well in advance of failure to provide a meaningful safety benefit.

By considering elementary bending theory and assuming that the out of plane blade deflections may be represented by a series of blade modes, it can be shown that the structural moment is directly proportional to the rate of change of slope contributed by the various modes. On further examination of the blade dynamics using a math model it was found that for a fracture or delamination induced at various points along the blade, only certain modal frequencies where affected. Only when the location of a crack is coincident with a region on the blade where the contribution of a given mode to the net bending moment is high will a change in the frequency of that mode be apparent. Note that other modal frequencies may not be affected at all, even when the crack is well established. Further verification work needs to be undertaken to determine the usefulness of monitoring a matrix of blade modal frequency perturbations during unsteady helicopter operations. It is envisaged that IHUMS will offer such an opportunity.

In addition to the changes in modal frequencies, blade crack development will also affect other IHUMS measurements including blade track and lag positions as well as the induced airframe vibrations. A theoretical study on the measurement changes has been undertaken for over 120 fault cases including blade crack growth, control system irregularities and benign faults such as simple maladjustments [8]. These findings are currently being verified by infield measurements associated with faults which, if they were not detected, could give rise to catastrophic failure. Some infield examples are given in the following sections.

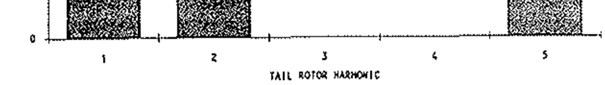

Figure 19: Tail rotor vibration before maintenance.

Brinelled tail rotor flap bearings

Figures 19 and 20 present tail rotor vibration measurements taken during a ground run of a Super Puma, between which the only maintenance action was to replace the tail rotor flap bearings. On examination it was seen that two of the bearings had suffered from brinelling. Clearly this defect not only produced 1T but significantly affected 2T and 5T as well. If harmonic analysis of the fundamental is not performed, the danger is ever present that part of the symptom, namely 1T, could be suppressed by mass balance. Accordingly, even simple rotor balance techniques must be applied with considerable care.

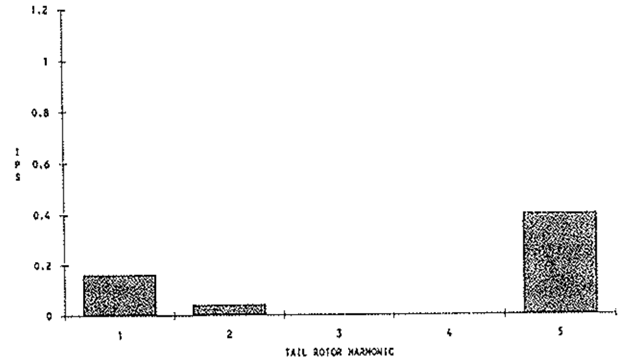

Figure 20: Tail rotor vibration after maintenance.

Tail drive shaft disconnect coupling failure

An accident involving a Sea King helicopter was attributed to failure of a tail drive shaft disconnect coupling. Prior to failure this aircraft was instrumented with accelerometers located at various points in the airframe. Analysis of the accelerometer signatures revealed that, whilst the impending failure was measurable at station 311 in that frequency component, 1S was clearly visible (largest peak in figure 14), at the standard monitoring position in crew area nothing atypical was noticeable (figure 13). Note that the spectrum associated with station 311 also contains 1MDS. Whilst it may be postulated that this arising is an effect and not a cause - associated with a coupling between the two shafts across the main rotor gearbox - the precise mechanism is not fully understood.

This fault clearly demonstrates that if adequate coverage of PCFs is to be realised, distributed transducers around the airframe is essential.

With the introduction of IHUMS many more examples of PCF symptoms will be measured during their early stages of development on a flight by flight basis. Whilst a number of diagnostic strategies will be in place to check for their presence, in the initial stages of IHUMS these techniques will not be exhaustive. Accordingly, automating new diagnostic developments would be highly desirable, particularly given the volume of data IHUMS will produce. The following section describes one area of "unsupervised machine learning" which holds considerable promise.

Handling large volumes of data

For each flight it is expected that an IHUMS will record in excess of 1 Megabyte of data. It will not be feasible to rely on humans to scan through such vast quantities of information. Recent developments at MJAD [9] have concentrated on producing machine learning techniques which use all of the data in a database all of the time, to provide a more effective trigger to critical changes or patterns in the data. The techniques can be driven unsupervised. This simply means that the pattern recognition techniques work in the absence of any background knowledge about the data or its origins.

As an example, a task was set to interpret a database containing 903 oil samples from 62 different gearboxes, over a period in which a number of maintenance actions had taken place. Each oil sample was characterised by spectrometric oil analysis, which quantified in parts per million of lubricating oil the level of 8 separate elements.

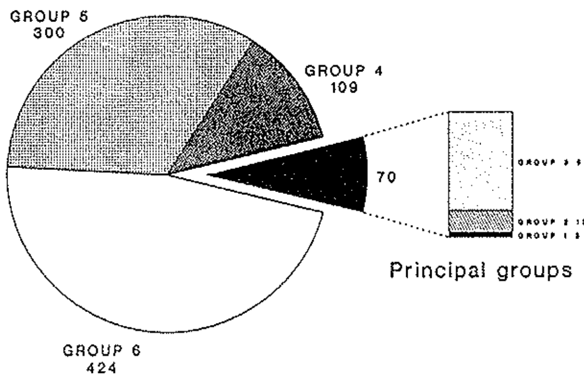

Figure 21: Analysis of 903 gearbox oil samples.

On completion of the task the data had been separated into 6 groups as presented in figure 21. From a diagnostic viewpoint it is appropriate to concentrate on the smaller groups identified as these are the "abnormal" cases. The findings of this analysis were:

- The smallest group, group 1 (3 samples), was composed of consecutive samples taken from one gearbox. Further samples from this gearbox also fell into the next smallest group (12 samples), which contains data from just one other gearbox. Whilst both these gearboxes were removed from the helicopters within 1 month of the last samples, it is worthy to note that the first abnormal sample was identified at approximately 7 months before conventional methods showed that removal was necessary.

- Within the complete database a number of gearboxes had been removed for maintenance. Of these failure cases, 25% were found in group 3, our third smallest group. This is four times more than would be expected on average for a group of this size (55 samples). Again evidence of a considerable period of early warning was noted, with some examples falling into this group 100 days before final failure.

It is important to point out that this analysis was not reliant upon the setting of thresholds or alarm levels that would normally be used in conventional methods. In this approach the system had reacted to changes throughout all the data, and not just the level of a single element. The system therefore succeeded in the objective of achieving true pattern matching.

Conclusions

This paper has detailed a number of developments associated with the formulation of diagnostic and data handling strategies, which will support IHUMS operations. In particular, these developments include:

- A comprehensive math model which has been extensively used to simulate a suite of rotor system irregularities.
- The construction of numerous integrity checks covering sensors, maintenance actions and measurements.
- A robust method for identifying rotor maladjustments, offering a multi-fault, single shot capability.
- An appreciation of non-adjustable faults associated with rotor systems, paying particular attention to the lag damper.
- A suite of techniques targeted at identifying airframe/component anomalies. These techniques encompass transfer function and rigid body analyses, combined with advanced signal processing.
- A study of potentially catastrophic faults with proposed methods of detection.
- An automated "machine learning" facility, capable of true pattern matching combined with the potential for unsupervised development of new diagnostic techniques.

The introduction of IHUMS will offer the required statistical sample of data to prove and develop the above techniques for everyday use.

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