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THE DIAGNOSIS OF HELICOPTER MAIN ROTOR FAULTS

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ABSTRACT

Excessive vibration caused by helicopter main rotor faults such as track rod maladjustments, errors in blade trim tab settings, blade mass imbalance (both spanwise and chordwise) and lag damper defects present a major helicopter serviceability problem.

This paper describes the approach taken at Stewart Hughes Limited, to address the problems of helicopter main rotor diagnosis including a simplified example of the usage of mathematical models, enhanced diagnostic procedures ultilising non-steady rotor analysis, the development of an advanced, multifunction, portable diagnostic analyser and the application of Expert Computing.

Examples of non-steady blade track and lag behaviour of a full-scale, ground running Westland Lynx helicopter are also presented.

1.0 INTRODUCTION

The faults common to most helicopter rotor systems are errors in blade track, blade tab setting, mass imbalance of the blades (both spanwise and chordwise) and defective lag dampers. Methods of diagnosing these faults unambiguously and specifying their rectification would cover more than 60% of the rotor maintenance activites currently undertaken on a rotor system.

Some success has been achieved in diagnosing these faults using vibration monitoring equipment together with devices which give information on the blade motions. The interpretation of such information requires considerable skill for the following reasons.

First, the measurements are always made in a fuselage based frame of reference but the conclusions relate to the rotating frame of reference of the rotor. This leads to loss of information due to addition and cancellation of components which cannot be resolved in the fixed frame. A result is that different faults can produce what appears to be the same signature in the fixed frame of reference.

Second is the power of the analysis equipment which has been available to process the information obtained from the tests. Vibration information can be analysed in both the time and space domains. This analysis needs to be correlated with the detailed motions of the blade in order to provide a number of diagnostic tests for an individual fault and remove the possible ambiguity in the signatures mentioned above. This means that the maintainer is faced with information on which to make a diagnosis which, in itself, could be a drawback.

Stewart Hughes Ltd at the Chilworth Centre for Advanced Technology, Southampton, England have addressed the above problems as follows:

First, the rotor has been mathematically modelled to allow imperfections rather than ideal rotor conditions. This permits the understanding of signatures which previously were confused.

Second, the tests have been extended by taking advantage of the information generated during non steady rotor rotational speed running.

Third, the development of an advanced, multifunction, portable diagnostic analyser (the Mechanical Systems Diagnostic Analyser - MSDA for short) has made possible a much greater range of data gathering and processing than was previously possible.

Fourth, the use of Expert Computing to provide a mechanism for defining a structure in which the considerable expertise of design and maintainence specialists may be implemented. When applied to interpret the results of analyses, the Expert Computing System generates user friendly diagnostics which are unambiguous. The Expert System may also be interrogated by approved engineers who may need to know the reasoning behind the diagnosis.

Each of these four aspects of the Stewart Hughes technology will now be discussed.

2.0 ROTOR FORCES AND MOMENTS

Branwell (1) gives a comprehensive discussion of the resolution of the rotor forces and moments into the helicopter fixed frame of reference. The notation used is shown in Figure 1. He resolves the forces and moments on a flexible blade into three orthogonal forces and moments at the blade hub.

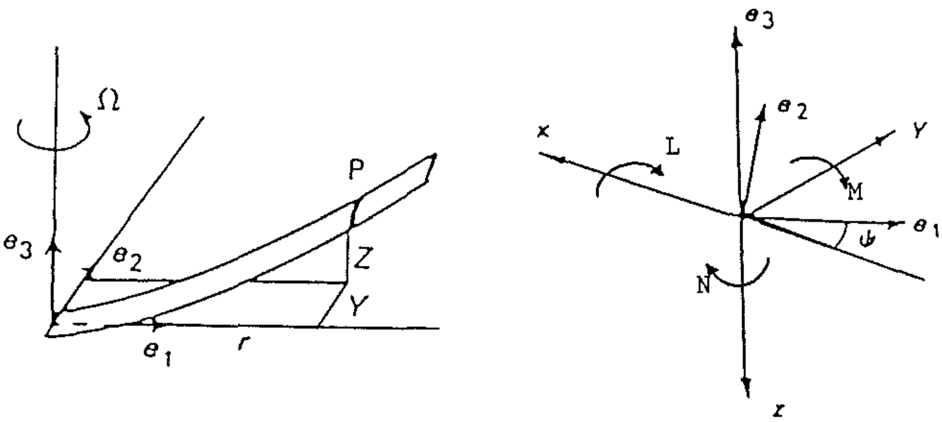


Figure 1. Notation of axes.

For an individual blade, the orthogonal shear forces at the blade root are,

$$R_1 = -\int_{r_1}^{R} \left(\ddot{Y}\frac{\partial Y}{\partial r} + \dot{Y}\frac{\partial^2 Y}{\partial t \partial r} + \ddot{Z}\frac{\partial Z}{\partial r} + \dot{Z}\frac{\partial^2 Z}{\partial t \partial r} + 2\Omega\dot{Y} + \Omega^2 r \right) m\,dr - F_1 \qquad (1)$$

$$R_2 = \int_{r_1}^{R} \left(\ddot{Y} - 2\Omega\dot{Y}\frac{\partial Y}{\partial r} - 2\Omega\dot{Z}\frac{\partial Z}{\partial r} - \Omega^2 Y \right) m\,dr - F_2 \qquad (2)$$

$$R_3 = \int_{r_1}^{R} \ddot{Z} m\,dr - F_3 \qquad (3)$$

where r_1 represents the radial position of the hinge and F_1, F_2 and F_3 are the component aerodynamic forces acting on the blade. These forces, now referred to body axes X, Y, Z where X is positive forward, Y positive to starboard and Z positive downwards, become for the k'th blade,

$$X_k = -(-R_{1k}\cos\psi_k + R_{2k}\sin\psi_k) \qquad (4)$$

$$Y_k = -(R_{1k}\sin\psi_k + R_{2k}\cos\psi_k) \qquad (5)$$

$$Z_k = -(-R_{3k}) \qquad (6)$$

The reactions R_1, R_2 and R_3 will similarly produce moments about the hub due to the offset of the blade hinges - or equivalent hinges in the case of non-articulated blades. These moments, L, M, and N (see Figure 1) when referred to fuselage axes become for each blade,

$$L_k = R_{3k}(eR\sin\psi_k - y) - (R_{1k}\sin\psi_k + R_{2k}\cos\psi_k)z \tag{7}$$

$$M_k = -R_{3k}(eR\cos\psi_k + x) + (-R_{1k}\cos\psi_k + R_{2k}\sin\psi_k)z \tag{8}$$

$$\begin{aligned} N_k = {} & (R_{1k}\sin\psi + R_{2k}\cos\psi)(eR\cos\psi_k + x) + \\ & (-R_{1k}\cos\psi_k + R_{2k}\sin\psi_k)(eR\sin\psi_k - y) \end{aligned} \tag{9}$$

where (x,y,z) denotes an arbitrary point in the fuselage.

If it is assumed that each blade is subject to the same forcing and has identical elastic properties, then it is well known that the resultant forces and moments transmitted into the fuselage are an integer multiple of the blade number b.

The *essence of the fault diagnosticians* use *of these* equations, however, is to consider what is measured in the fuselage and seen by measurement of blade motion when differences occur between blades. To demonstrate this, consider the simple case of b rigid blades, *for a ground running helicopter, where equations 1-6* simplify to:-

$$X_k = -((+M_b\Omega^2(r_{cg}+eR) + D\zeta - L\beta)_k\cos\psi_k + (-r_{cg}M_b\Omega^2\zeta + D + L\Phi)_k\sin\psi_k) \tag{10}$$

$$Y_k = -((-M_b\Omega^2(r_{cg}+eR) - D\zeta + L\beta)_k\sin\psi_k + (-r_{cg}M_b\Omega^2\zeta + D + L\Phi)_k\cos\psi_k) \tag{11}$$

$$Z_k = -(+L_k - (D\Phi)_k) \tag{12}$$

For a simple case where, for the k'th blade, an error of (ΔM) in blade mass M_b is postulated with r_{cg}, D and L remaining identical with the other (b-1) blades, then

$$\Delta\zeta \simeq \frac{-DR_d}{M_b\Omega^2 r_{cg} eR}\frac{\Delta M_b}{M_b} = \frac{-\zeta\Delta M_b}{M_b} \tag{13}$$

Similarly,

$$\Delta\beta = -\beta\Delta M_b/M_b \qquad \Delta M_b \ll M_b \tag{14}$$

Considering equation (10), the change in X force will be

$$\Delta X \simeq -\left(\Delta M_b\Omega^2(r_{cg}+eR) - \frac{D\zeta\Delta M_b}{M_b} + \frac{L\beta\Delta M_b}{M_b}\right)\cos\psi_k \tag{15}$$

A typical rotor blade has a value of $D\zeta/M_b = 0.2$ and $L\beta/M_b$ varies from 0 to 15 depending on the collective pitch setting, but $\Omega^2(r_{cg}+eR)$ is of the order of 4500 and therefore dominates for all values of collective pitch.

Similar expressions for ΔY, ΔL, ΔM and ΔN must be considered, examining their effect at the accelerometer position (x,y,z).

It must be stressed that the above analysis represents a gross oversimplification of the problem. For example, it ignores the transmission path of the vibration from the rotor into the fuselage, and the flexibility of the complete system, to name two factors which can affect the accelerometer signatures. Nevertheless, such models are extremely useful in ranking diagnostics and in understanding signatures from single and multiple faults.

An example of the use of the above equations to interpret 1R information with blade track and lag data is given in Figure 2. The measurement of blade pitching moment, as recorded on the non-rotating controls above the actuators, is introduced to evaluate a blade tab error which could otherwise be confused with a track rod maladjustment. Valuable as it is, this table represents only a small improvement on current practice and, therefore, non-steady rotor testing has been exploited.

3.0 NON STEADY ROTOR ANALYSIS

The previous equations have assumed that the rotor is rotating at a constant RPM, that no cyclic pitch is applied and that the rotor is in axisymmetric flight. Current fault diagnosis techniques remove the last of these constraints by making measurements in forward flight. This has operational and economic penalties as well as placing additional design contraints on the blade position measuring equipment, all of which should be avoided if possible. Stewart Hughes Ltd have therefore sought out a method which can be applied entirely on the ground.

When a rotor system changes its rotational speed, the natural frequency of its various modes of vibration change in a well understood manner. In the case of the lifting rotor, changes in the aerodynamic forces and moments also occur. In addition, the coupling terms resulting from, for example, chordwise mass imbalance effecting a blade torsion, is also a function of rotational speed. A series of equations, appropriate to the non steady rotational speed, has therefore been generated and used in a similar manner to the steady state equations referred to above.

It will be appreciated that chordwise mass imbalance gives rise to a torsional moment on the blade which alters the lift and hence the track of the defective blade - the torsional moment will vary approximately as Ω^2 , but will also depend on the collective pitch (coning angle) of the rotor.

A defective blade tab will also give rise to a torsional moment of the blade which will vary as Ω^2 (ignoring compressibility effects). Assuming, in the first instance, linear aerodynamic characteristics of the blade section, the torsional moment due to a tab error will be largely independant of collective pitch. This feature provides one mechanism, among others, for differentiating between tab and chordwise mass irregularities.

The transient excitation of natural frequencies - for example, a ground resonance mode - is a well known phenomenon experienced on helicopters during start up and shut down. Lag dampers are introduced to control the amplitude of the blade inplane motions. Measurement of the blade motions during such transitions yield information on the health of the lag dampers. With regard to the

MAIN ROTOR IRREGULARITY	S Y M P T O M S									
	NER ZERO-LIFT COLLECTIVE PITCH SETTING					POSITIVE COLLECTIVE PITCH				
	1R in plane	1R vertical	lag error	BTTE	BPMV	1R in plane	1R vertical	lag error	BTTE	BPMV
Mass imbalance on the blade flexural axis	*		*			*		*	*	
Mass imbalance not on flexural axis (untwisted blade)	*		*			*	*	*	*	*
Track rod error	*	*	*	*		*	*	*	*	
Blade tab error	*	*	*	*	*	*	*	*	*	*
Lag damper fault	*		*			*		*		

KEY - BPMV = Blade pitching moment varying
BTTE = Blade tip track error
* = Symptom indicator

Figure 2. 1R VIBRATION AND BLADE SYMPTOMS ARISING FROM ROTOR IRREGULARITIES DURING A GROUND RUN/HOVER TEST

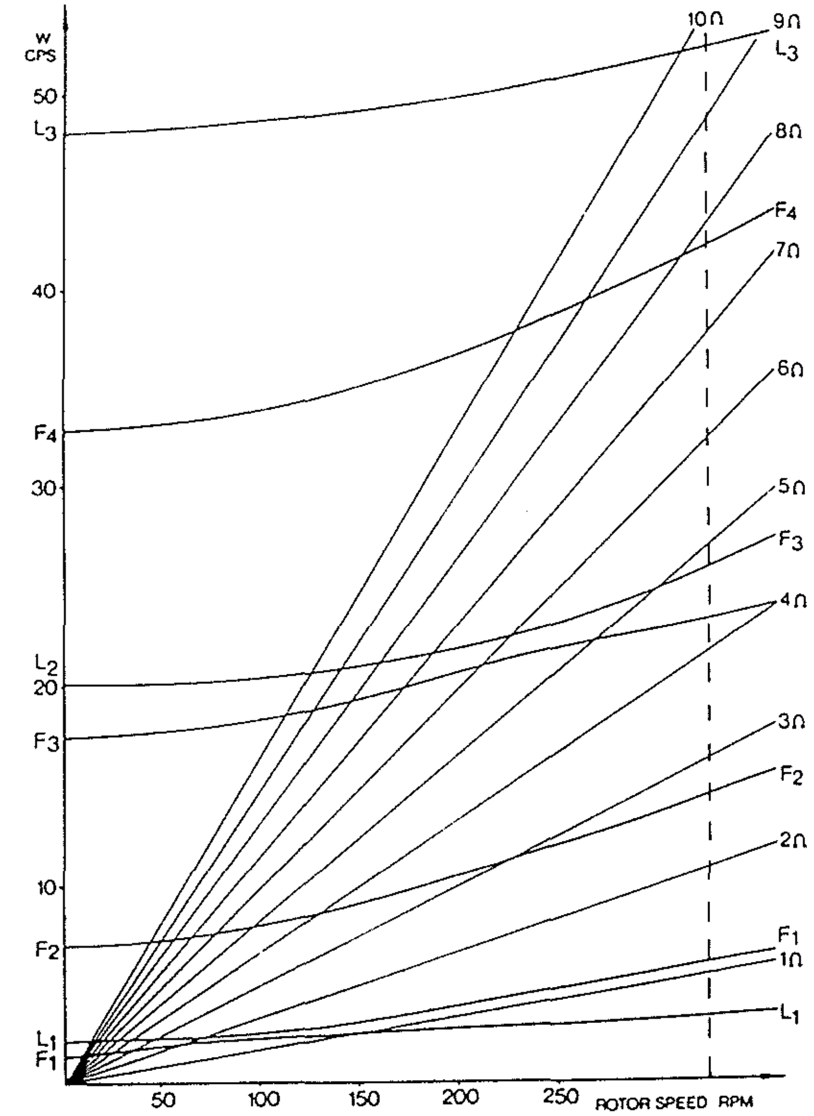
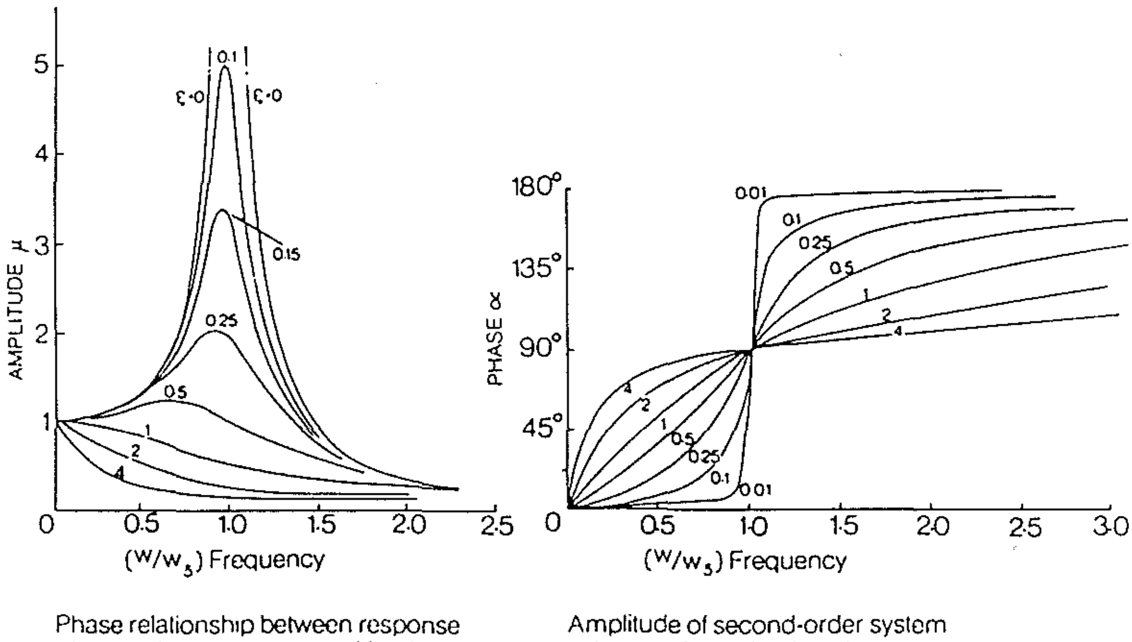


Figure 3. Full scale Lynx main rotor natural frequencies.



Phase relationship between response of second-order system and forcing function

Amplitude of second-order system to harmonic forcing function

Figure 4. Mass-spring-damper characteristics.

semi rigid rotor head of the Lynx helicopter,however, the rotor once per rev (1R) and the fundamental lag frequency (L_1) become coincident at approximately 2.5htz (see Figure 3). At and near to this resonant condition where $w/w_\zeta = 1$, differences in the lag damping efficiency between blades is most marked, as can be seen by the amplitude and phase characteristics of a second order mass spring damper system shown in Figure 4.

Some typical records taken from a full scale, ground running Lynx helicopter, with cumulative blade tab errors and a soft lag damper defect are shown in figure 5 and 7 respectively.

It is worth noticing the additional information given on these non steady trends.For example, the gradient apparent on Figure 6 suggests the blade drag characteristics are varying in a different manner from the other blade (Figure 7).

The ability to obtain such records is dependant on the necessary analysis equipment available. The following section describes the Stewart Hughes equipment used during the diagnosis of helicopter rotor faults.

4.0 THE HARDWARE DEVELOPED AT STEWART HUGHES LTD

The application of the steady and transient helicopter rotor analysis relies heavily upon the hardware developed at Stewart Hughes Ltd. The output from a unique blade tracking device and accelerometers mounted in the helicopter fuselage supply the monitoring/analysis package with the raw information on the blade motions and dynamic characteristics of the helicopter. The monitoring/analysis package, known as the Mechanical Systems Diagnostic Analyser (MSDA), is detailed in the following section.

4.1 The Mechanical Systems Diagnostic Analyser (MSDA)

The design of the portable MSDA was initially based on the experience gained after a number of years of usage of a large mini computer based system, vis DEC 11/40. Incorporating advanced analogue and digital circuitry, the MSDA uses the universally accepted DEC LSI 11/23 micro processor with 256 Kbytes of RAM backed up with two hard discs offering a further 10 Mbytes of non-volitile memory.

The analogue processing takes the form of discrete analogue units, such as the enveloper and filters etc. After this initial real time processing (the exact sequence of which is predefined by the user), the signal is passed through the analogue to digital converter. The digital side of the machine is centered around an executive processor which controls hardwired array and acquisition processors, providing exeptionally fast data analysis and subsequent interpretation. The analysis and interpretation routines, driven by an exisiting library of software application packages, or a package written by the user, offer a unique multifunctional analysis and diagnostic capability. Results are

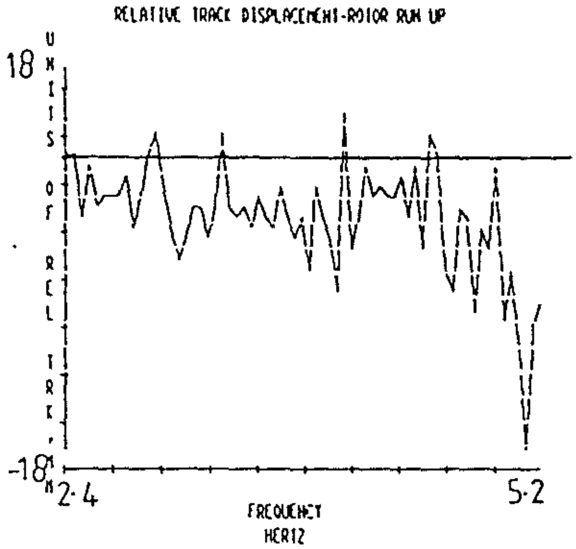


Figure 5. Non steady blade track trend with cumulative tab errors.

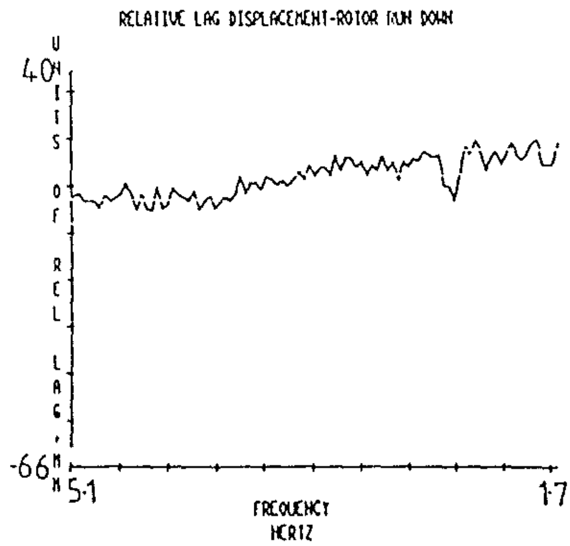


Figure 6. Non steady blade lag trend with an accetable lag damper.

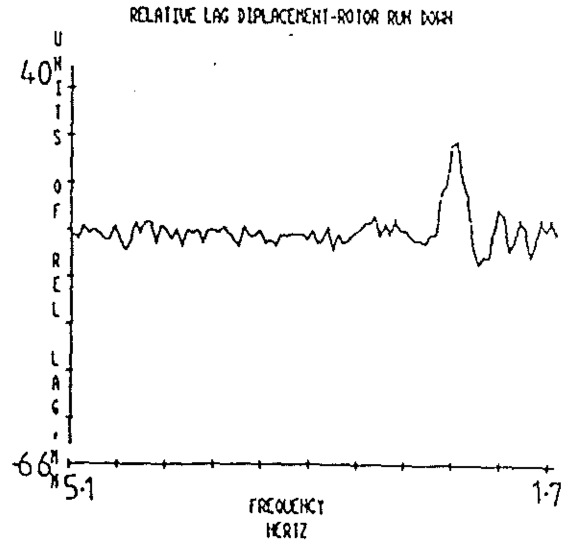


Figure 7. Non steady blade lag trend with a soft lag damper.

presented on a display screen in either alphanumeric or graphical format. Hard copies may be produced via a built in thermal printer.

One application of the MSDA , pertinant to the helicopter, is the analysis and interpretation of the signatures produced by the blade tracking device - the operation of which is described next.

4.2 The Passive Rotor Blade Tracking Device

To ascertain the degree of helicopter rotor symmetry, a device was required to produce electrical signals (for MSDA processing purposes) proportional to blade flap, lag and instantaneous velocity. For operational reasons, the system was not allowed to use electromagnetic radiation. The result was a passive optical tracking system which uses two receptors, separated by a known angle, and capable of registering a blade pass. Figure 8 shows a schematic representation of the electrical pulses emitted by the tracking device. Knowing the time a blade takes to travel the distance between the sensitive 'beams' of the receptors, the time for a blade chord to pass through one 'beam' and the time between successive blade passes through a beam, each blade's flap, lag and instananeous velocity may be computed. This data may be presented in absolute or relative terms, rev by rev, or after a predefined number of averages.

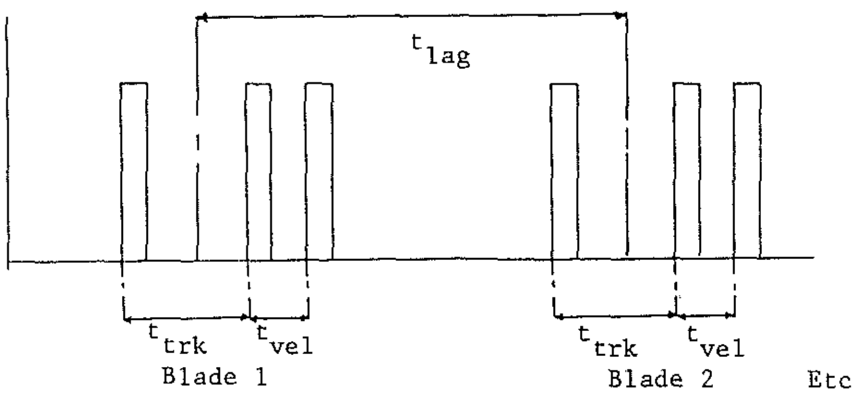


Figure 8. Schematic representation of the blade tracker pulses.

5.0 APPRAISAL OF THE NEW ROTOR DIAGNOSTIC TECHNOLOGY

The non-steady blade track and lag trends shown in Figures 5-7, identify blade tab and lag damper irregularities. Both these faults are much more difficult to pinpoint using steady state analysis. Equally a blade chordwise mass imbalance, possibly resulting from water ingress, may be interpreted from steady state analysis as a pure mass imbalance (1R inplane vibration) and a track rod malajustment (blade track spread and 1R vertical vibration). Acting upon these conclusions could, as in the case of water ingress, temporarily reduce the effect without removing the cause. Changes in the mass and/or location of the water would produce new 1R inplane and vertical vibration signatures. This is one example of 'a rotor in track one day and out the next' scenario. However, the application of the non-steady analysis prevents such situations arising by identifying the cause of the problem.

Although this paper has concentrated on 1R signatures, both higher harmonic and non-harmonic signatures are also used in making a diagnosis. Furthermore, forward flight blade track and vibration information, if available, can be analysed and is especially important if fine resolution is necessary, particularly so when pinpointing small blade tab errors.

6.0 DATA INTERPRETATION USING EXPERT COMPUTING

Applying the multifunction capability of the MSDA to the conditioning/processing of the accelerometer and blade tracker signatures results in a vast data base of information. To exploit the full diagnostic potential of the acquired data, a high level of expertise is necessary. Expert computing provides a mechanism for defining a structure in which such expertise, represented by a series of rules, may be efficiently handled.

The Expert Computing language, used by the MSDA, is Prolog-1. By allowing the user to interrogate the system in his own language, the 'Expert' may be consulted efficiently. When necessary, the 'Expert' may be easily updated by simply implementing the new rules, without rewriting the software. A schematic illustration of an Expert System is given in Figure 9.

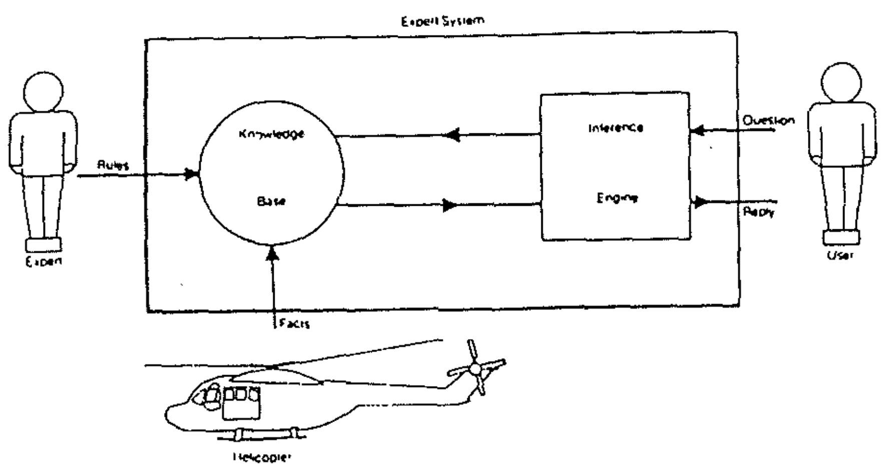


Figure 9. Block diagram of an Expert System.

Although preliminary developments of the Expert System may require some human interaction to acquire the appropriate data, the eventual aim is to produce a system which manages data acquisition, conditioning, processing and diagnostic interpretation without human intervention. Thereafter,a facility will be provided to allow a full interrogation of any result or conculsion drawn including, if required, a step by step account of the rules used to make a diagnosis.

7.0 CONCLUSION

The limitations of traditional fault finding techniques using steady state analysis, largely based on experience, can hinder the rapid diagnosis of helicopter rotor faults. This results partly from the inadequate resolution of the currently used equipment, partly from the lack of a knowledge base derived from sound physical principles and partly from the inability to discriminate between a number of rotor faults occuring simultaneously. For example, an incorrect steady state diganosis can be made as a result of a combination of faults producing near vibration cancellation (and therefore not detected), or a vibration summation more characteristic of another fault.

In rectifying these current limitations, the approach adopted at Stewart Hughes Ltd has produced a number of developments.

First, a unique suite of hardware including a passive optical blade tracker, measuring blade track, lag and instanteous velocity, coupled with a monitoring/analysis/diagnostic package, named the Mechanical Systems Diagnostic Analyser (MSDA). This multifunctional portable, analogue and digital computer (see section 4.1) performs all the tasks necessary to make a diagnosis.

Second, the use of non steady rotor analysis which is carried out entirely on the ground, and may be applied to pinpoint blade track rod malajustments, errors in blade tab settings, blade chordwise mass imbalance and lag damper defects.

Third, the generation of a Expert Knowledge Base derived from experience already gained using more traditional equipment, and enhanced by rules based on sound physical principles.

Fourth, the use of Expert Computing to provide a mechanism for defining a structure in which diagnostics may be performed efficiently. Provision is also made to allow a system to be rapidly generated, easily updated and fully interrogated by the user.

Ultimately, a more specialised version of the MSDA will be produced, dedicated to helicopter diagnostics. This single unit, micro based 'first line analyser', will be substantially smaller and cheaper than the current MSDA.

The technology presented herein complements other proven technological advances at Stewart Hughes Ltd. The combined technologies have the resources to diagnose faults in the main rotor, gearbox and transmission systems, offering a complete helicopter diagnostic package.

8.0 ACKNOWLEDGEMENTS

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