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ADVANCED DIAGNOSTICS FOR HELICOPTER ROTOR HEAD MANAGEMENT, INCLUDING THE USE OF EXPERT SYSTEMS

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1.0 INTRODUCTION

The requirement to meet vibration criteria for rotorcraft was examined in a recent paper by S T Crews (1). In it he illustrated the reason why minimal levels of vibration are demanded in helicopters. The subject was considered under three headings, human factors, equipment environment and rotating element criteria.

Much has been written about equipment to perform rotor track and balance. Essentially this consists of a number of accelerometers mounted in the fuselage and a rotor tracking device which provides data on the flap, lag and velocity of the blade at a single azimuthal position. The underlying requirement is to reduce the vibration (essentially 1R) in the fuselage while making the rotor blades all follow the same flight path. To allow for the differences which inevitably develop in the dynamic components the manufacturers permit a limited number of adjustments to the rotor. These include blade push rod, tab and blade/hub weight distribution adjustment. Beyond this the servicing consists of replacement of components.

The formulation of a series of criteria to perform rotor track and balance which are not aircraft-type specific is readily done. The particular response coefficients required in these relations can be obtained by calculation provided that a detailed dynamic model of the rotor and fuselage exist. Such models are becoming more generally available in helicopter design offices. Alternatively, or more probably in parallel with the theoretical model, experimental data can be used to provide the necessary information. The information can be used to provide information on sensor position which is optimum for the identification of faults. Furthermore, this technique is applicable to more than the first harmonic of vibration.

Subject to any regulatory authority mandatory requirements the vibration criteria for the helicopter can be specified in any form, e.g. as levels in particular directions at specific frequencies or in combined values such as the Intrusion Index referred to in Ref.1.

This approach to the problem obviously leads to a requirement for a flexible and intelligent capability for any equipment which is to remain in service for a significant period of time. This is particularly true in cases when the faults do not lie in the so-called "normal" group. An example is given in Ref. 1 for a UH1 helicopter which required 700 man-hours of effort to remedy the vibration problem as well as rendering the machine unserviceable from August to December. This paper therefore discusses some of the aspects of rotor monitoring which are additional to the standard diagnoses.

2.0 THE EFFECT OF BLADE FLEXIBILITY

The determination of blade behaviour and remedial action necessary to minimise rotor induced vibration in the fuselage is by determining the position of each rotor blade flight path. It is assumed that, if the blades are following the same flight path, then the forces induced into the hub and thus to the fuselage are the same. In the case of the articulated rotor no moments can be transmitted across the flapping hinge, but only shear force which gives rise to the vibration. The spatial position of the blade is therefore determined by the condition that the hinge moment is zero and it is quite easy to see that this condition alone does not demand a unique blade load distribution. Current methods of determining the blade position measures the location of one spanwise blade element. In most cases this is not an absolute measurement relative to the hub of the rotor but is the relative position of one blade tip to another. Generally this is an average position taken over a large number of revolutions. It is then assumed that the vibration can be associated with this track information on the basis that the dynamic response of all blades is similar. For many helicopters this assumption is correct. This was demonstrated in the trial conducted by SHL for the RAE Farnborough on their research Puma and reported in Ref. 2. The blade by blade passage of each blade showed remarkable consistency over the 2 minute period of each test condition.

The time averaged data for each condition for any blade is typified in Figures 1 and 2 which show the mean height of the blade at 3 spanwise stations and the calculated fraction of the tip deflection due to the first three modes. This information is averaged over 2 minutes and it is clear that the modal contribution to the tip deflection changes little. The magnitude of modes 2 and 3 is of the order of 10% of the total tip deflection. The contribution of these blade bending modes to the 1/rev vibration will be small as the natural frequencies of these modes is considerably higher than the rotor rotational frequency. The contribution of the modes to the tip deflection is not insignificant and if blade adjustments are made on the basis of errors in the tip deflection the change to the 1/rev vibration could be in error. This is particularly true if the modal response of the blades is different and may be one reason why split track is sometimes found to be necessary to reduce vibration in particular helicopters.

Figure 1

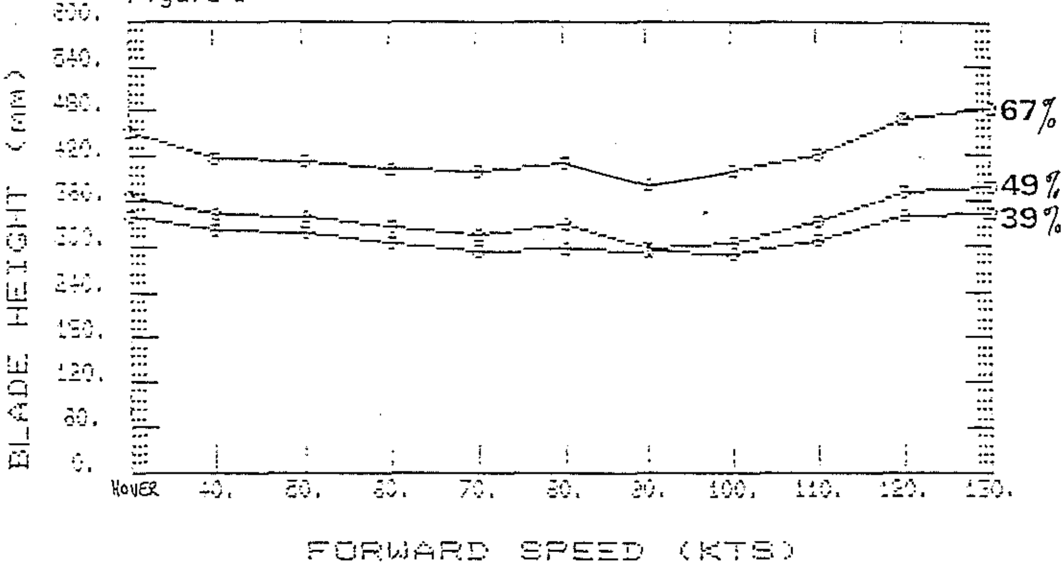


Figure 2

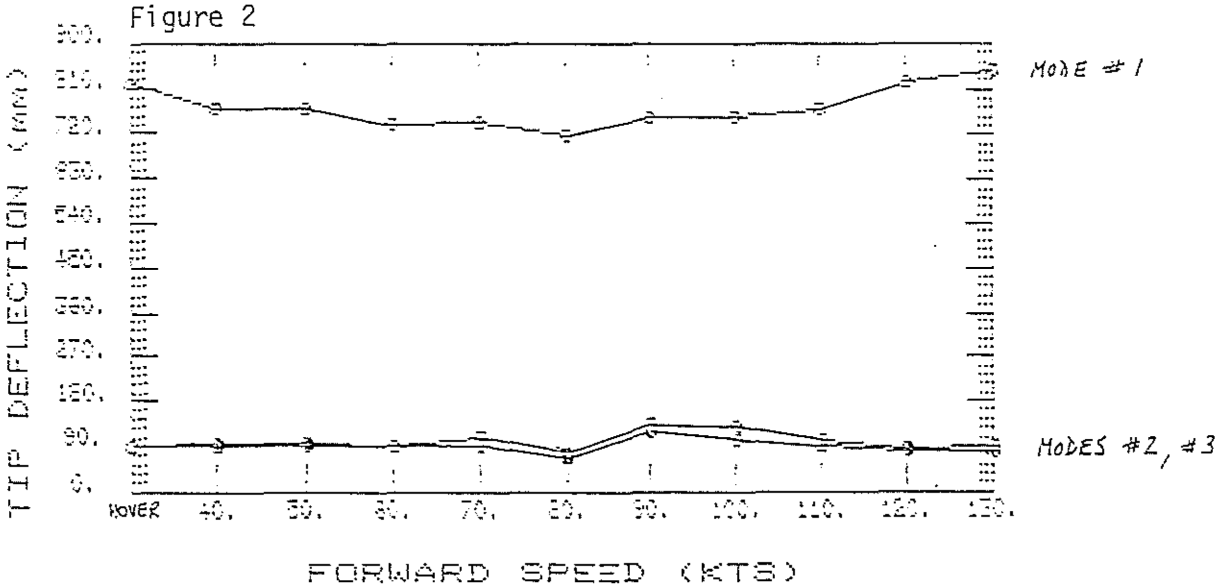


FIGURE 1 : Mean blade deflections

FIGURE 2 : Indicated modal content

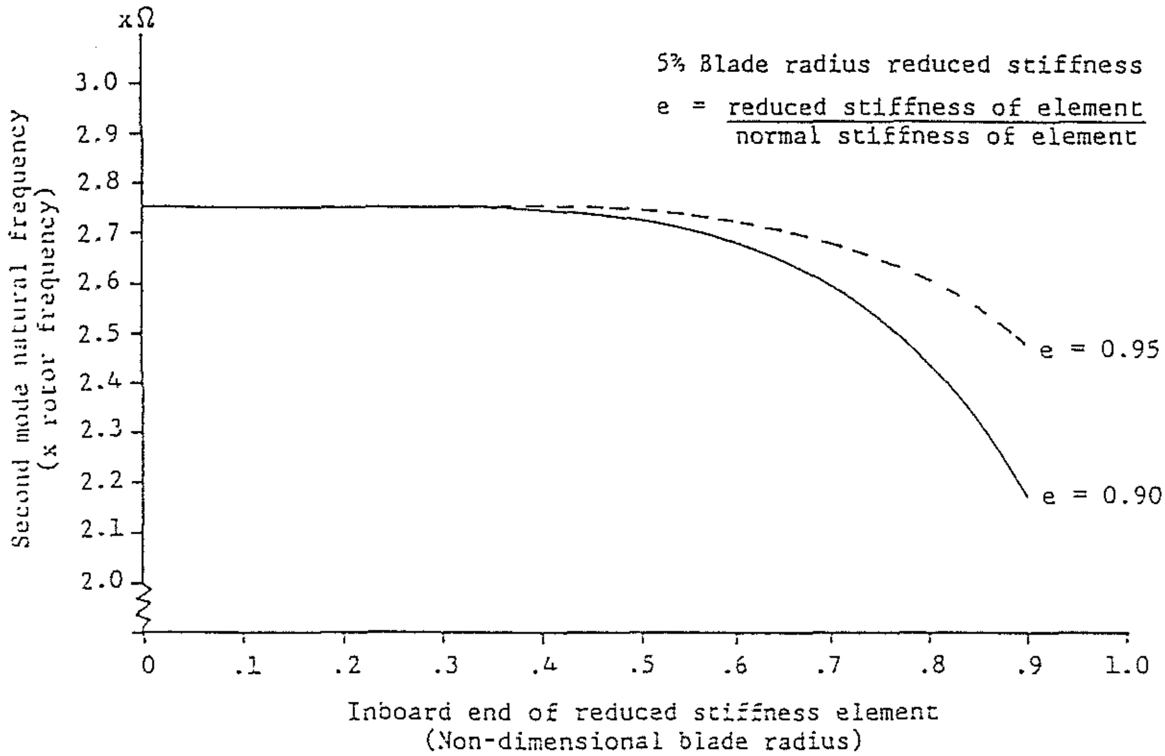


FIGURE 3 : Blade Natural Frequency Changes Due to Reduced Stiffness

3.0 BLADES

This particular problem of apparent inconsistency between consistent blade-to-blade track and low helicopter vibration levels could be overcome if the track data minimised the input of the harmonic blade bending. The second and third modes typically have nodes around 85% span. If track data is measured in this region this will minimise the input from these modes and the SHL Tracker is the only unit to have this capability.

4.0 CHANGE OF BLADE STRUCTURAL PROPERTIES

The steady change in blade construction from metal to composite has removed many long term problems but has substituted others. One area of concern is the degradation of the structural properties of composites due to impact damage. In particular, accidental low energy impacts which leave no easily detectable damage signs are causing some concern.

The local damage probably will produce local delamination, which may increase with cyclic loading. It is important to detect such changes sufficiently in advance to avoid possibility of blade failure.

Delamination will give rise to a local change in blade stiffness. There will be no change of mass. The blade bending modes will be affected in different ways. The rigid bending mode is little influenced by local blade stiffness - centrifugal stiffening being dominant. This is not true of the higher bending modes. The natural frequency is influenced by the magnitude and position of the local stiffness change, although the mode shape changes very little. A simple calculation indicates the change of the natural frequency of the second mode as a reduced stiffness element is assumed at various spanwise stations (Figure 3). A pronounced movement away from third harmonic excitation (3Ω) is found. The magnitude of the second mode response will therefore change. In the case of $e = 0.9$ (10% local stiffness decrease) the response to 2/rev forcing will increase as the defective section moves toward the tip and the mode frequency moves towards 2/rev. Other modes respond differently. For example, the third mode moves towards the 5 per rev excitation. The effect of inboard stiffness change for this mode is more pronounced than for the second mode. To develop diagnostics it is necessary to find a method of measuring the harmonic response of each blade and then comparing the blade to blade response with the predicted behaviour. The diagnostics are not simple and an expert system is of assistance. But first it is necessary to measure the modal mix in operation.

While the application of the SHL tracker was originally conceived as a technology entirely geared towards obtaining maintenance diagnostic information the experiments with the Royal Aircraft Establishment (Ref. 2) have shown that it can

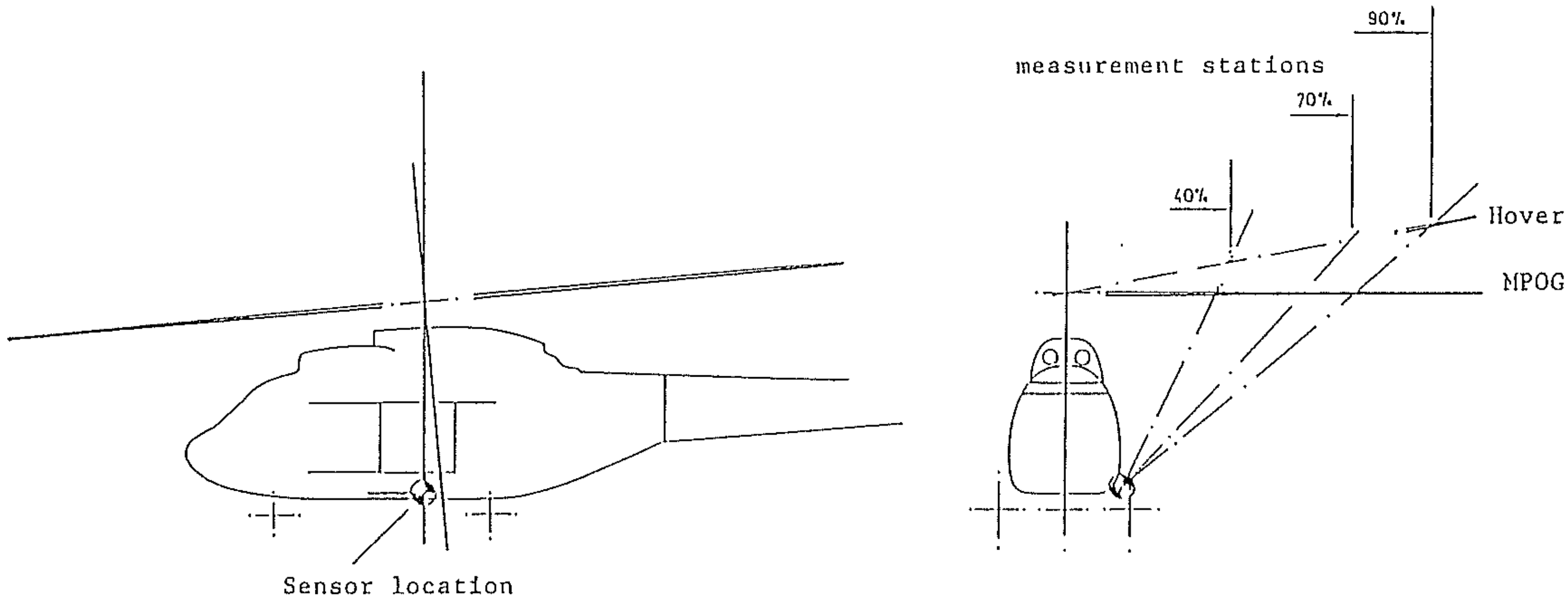


FIGURE 4 : Installation of sensor assembly on Puma

give other indications of blade motion. The use of three trackers mounted on the Puma (Figure 4) enabled an indication of the blade bending modes at a particular azimuthal position to be determined. To do this three trackers were sited so that they looked at the blade at approximately 40%, 50% and 65% of the blade radius.

From work conducted by the Royal Aircraft Establishment the non-rotating mode shapes of the Puma blades were known. Knowing the position of the flapping hinge and the rev by rev position of three points on the rotor blade, simple analysis allowed the first three flapping modes to be fitted to these four points. This was done either on the basis of the average position of the deflected blade over the whole of a two minute test flight, or using the data appropriate to a particular revolution.

Consider the way that the blade bends in flight as shown by the three traces (Fig. 5) each of 2 minutes duration showing the deflected position of the blade at the three spanwise locations. These are for the hover, 50 knots and 110 knots. The almost constant blade shape, the whole making slight vertical displacement, is obvious in the hover - a not wholly unexpected result. The effect of forward speed is shown in the comparison of the traces in the three illustrations. The variation of the modal bending on a rev by rev basis becomes greater as the forward speed increases. If one blade has a different modal mix from the others in the rotor, then using an analysis similar to that made on the Puma coupled with information from a modelling of the effect of possible blade defects, the probable blade damage can be indicated. Trending such information will indicate the progress of such a fault.

The three trackers used in this demonstration can be replaced by a single unit containing three optical sensing units so giving a compact sensor if required.

If however the redistribution of stresses caused a torsional deformation of the blade, the blade loading will be changed. The tab is fitted to the blade to correct for such a deformation. In most helicopters the tabbing facility consists of one tab unit which is divided into a number of individual items, which can be separately adjusted. Some helicopters have a number of tabs which are located at different spanwise stations and which offer greater opportunities for correcting the blade twist over a range of forward speed. The necessary adjustments would be easier to make if the twist of the blade was known. The SHL tracker has been adapted to provide this information and this is described in Ref. 3

5.0 FAULTS IN THE CONTROL SYSTEM

The helicopter control system achieves its objective by directing the thrust of the helicopter rotor in the appropriate direction. The rotor blade flapping is controlled by variation of the blade pitch control. It is possible to relate the response of pilot's inputs to the motion of the helicopter measured by instrumentation mounted in the fuselage. However, this is strongly affected by many factors, which include AUW, centre of gravity, aerodynamic drag, tailplane setting etc. It is theoretically possible to measure all of these parameters and to use them in a full stability and control model of the helicopter and then by determining any deviations in the response to diagnose faults. Such a process is complicated as well as expensive to implement.

In order to make the problem more tractable, the control element can be divided into the non-rotating and the rotating components. In the non-rotating case instrumenting the input from the pilot's controls and the output at the non-rotating element of the rotor pitch change mechanism can be measured and compared with the expected response. This will include allowance for inputs from any stability augmentation system or autopilot. The techniques for diagnosing faults are reasonably well developed in this case. The rotating members of the control system present a different problem.

The rotor has a rapid response to control inputs, typically reaching its final flapping value in much less than half a rotor revolution after the control input. It is possible to measure the response of the rotor to a control input by measuring the change in rotor flapping with sensors fixed to the fuselage.

The basic mathematical model of rotor control is given in the basic helicopter textbooks. These show that for a rigid blade with constant chord and density, flapping about a hinge offset a non-dimensional distance 'e' from the centre of rotation, the equation of motion is :

$$\frac{d^2\beta}{dt^2} + \Omega^2(1+E)\beta = M_A/I$$

Here, β is the flapping angle, Ω the rotational speed, $E = 3e/2(1-e)$, M_A the aerodynamic lift moment and I the blade moment of inertia both about the flapping hinge. M_A contains the inputs from the pilot's controls as well as the effect of flight condition (ie speed, climb etc). Solving this equation shows that the flapping motion is composed of an infinite series of harmonics of the rotor rotational frequency. The most important and the only ones to effect the rotor control are the first harmonic terms. There are, therefore, two major terms which influence the rotor control, namely the constant (or coning) term and the longitudinal and lateral tilt.

Assuming that these are the only flapping terms of significance, then a minimum of three tracking stations spaced around the disc azimuth is required to relate control inputs and coning and cyclic flapping response.

A tracker system, such as that developed by SHL, which measures absolute blade position relative to the fuselage is required. The motion of each blade can then be related to the control input and any differences determined. These differences will not be based on a single control input but will be the result of constant monitoring during a flight, possibly supplemented by specific test inputs. The blade to blade differences will be indicators of faults particular to a blade-specific control component, whereas overall deviations from the model indicate whole rotor components. The use of different flight conditions adds further inputs to assist in the resolution.

It must be remembered that the model indicated above is over simplified in that it does not take any account of the motion of the fuselage to the blade flapping (eg pitch and roll), the natural variations of the individual blade motions due to gusts, variable interference one with another etc. These can be minimised by relating the fault to a number of test conditions which can be gathered in a short time during a flight. There is also the possibility that the control system will contain variable rate terms and possibly non-linear responses as part of the design. Mathematical models of most of these effects have already been used by the designer and could be incorporated to find out the difference in response obtained from that predicted. Again, this is a major computer exercise which is likely to be too big for airborne application. This whole problem is one where artificial intelligence may offer an attractive solution for the coming generation of aircraft.

The AI approach that appears to hold much promise in this area is Confluence Analysis (Ref.4). This is a knowledge representation technique specifically aimed at the time behaviour of measurable quantities in physical systems. It is based on manipulating **qualitative** differential equations, called confluences, using sign algebra. Anyone who went to college before the advent of digital computers will associate it with the hand method for finite element analysis.

The major attractions of this approach are (a) the formal method of deriving rules, and (b) the design office origin of the rules. The fact that the control system is a flight critical item seems to make this type of approach more appealing.

The time behaviour of a single quantity, A, is represnted by identifying one of the three 'sign values', +ve, -ve or 0, with the change in the quantity over a time interval depending on whether the quantity has increased, decreased or remained steady.

TABLE 1

1R Vibration and Blade Symptoms Arising from Rotor Irregularities During a Ground Run/Hover Test

Main Rotor Irregularity	SYMPTOMS									
	Near 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 (spanwise)	*		*			*		*	*	
Mass Imbalance Not on Flexural Axis (untwisted blade) (chordwise)	*		*			*	*	*	*	*
Track Rod Error	*	*	*	*		*	*	*	*	
Blade Tab Error	*	*	*	*	*	*	*	*	*	*
Lag Damper Fault	*		*			*		*		

KEY: BPMV = Blade Pitching Moment Varying
BTTE = Blade Tip Track Error

* = Symptom Indicator

The time behaviours of the measured inputs (eg stick movement) may then be connected to the measured outputs (eg track sensor) by the **causal physical laws** applicable to the system. This can be programmed easily into a computer using any one of the standard AI languages, or C for that matter.

Whereas most expert system shells and structures have been derived from fields where there is no underlying quantitative theory, eg medicine, this approach seems to offer a great deal to engineers dealing with systems governed by well-understood physical laws.

Whether or not implementation of the system takes place under the laws of implicative (non-modal) or causal (modal) logic is an interesting matter for debate.

6.0 THE APPLICATION OF ARTIFICIAL INTELLIGENCE TO DIAGNOSTIC PROBLEMS

Mention has been made in the previous sections of the place of Artificial Intelligence or Expert Systems. The application of the more sophisticated techniques, such as the 'Confluence Technique' previously mentioned or the use of sophisticated pattern matching techniques such as applied in linguistics are currently being actively pursued by Stewart Hughes Ltd. There is also a place for Expert Systems in the simpler field of diagnostics applied to Rotor Track and Balance. The value for such an application is underlined in Ref. 5 which includes the statement 'In spite of the difficulties imposed by the real-time environment, diagnosis is a particularly fruitful area for application of AI'.

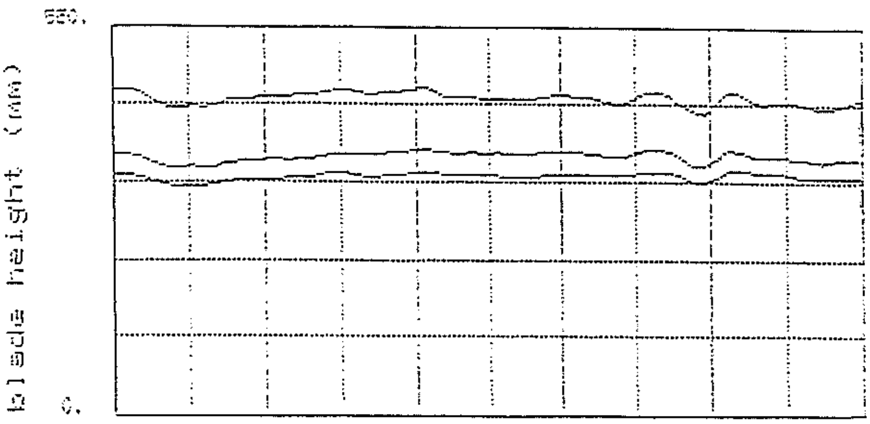
Stewart Hughes have been active in this field for some years and have found some of the valuable attributes of Expert Systems. The first system implemented diagnosed faults from Table 1 which is taken from Ref.6 The system was extremely simple and was written and tested in under one week. The system was rule based and used a data base which was keyboard driven by the user having to answer questions like -

> 'Is there an IR in-plane vibration at near zero left collective pitch."

- the answer being yes or no.

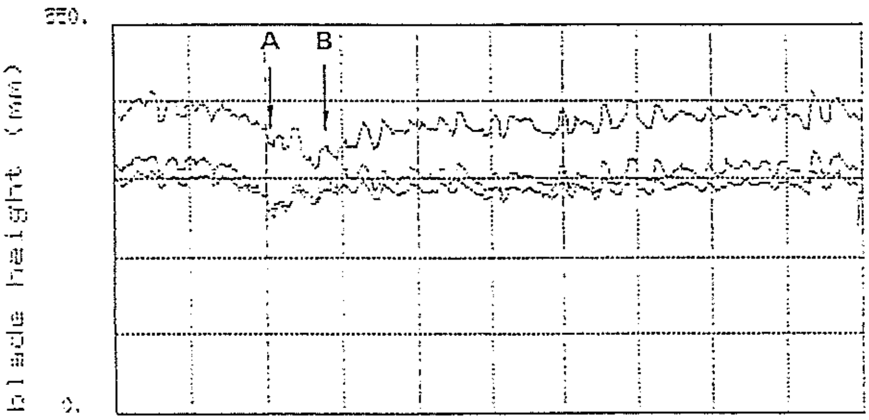
The system did not require all questions to be answered but only those needed to prove a rule. Thus any answer 'NO' precluded certain faults and it was not necessary to investigate further any other factors which might confirm that that fault was true or false, ie forward chaining was used.

Inspection of Table 1 shows that each fault had a unique set of symptons to identify it, which is the ideal situation.



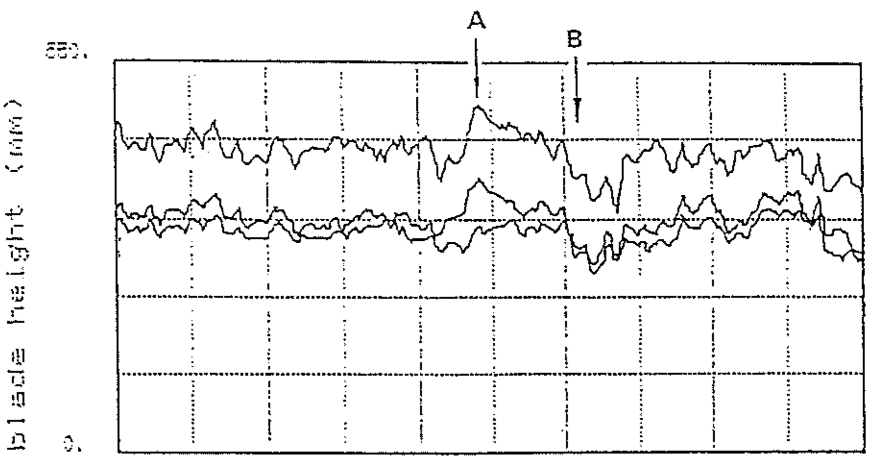
(a) Hover time

Figure 5a



(a) 50 knots time

Figure 5b



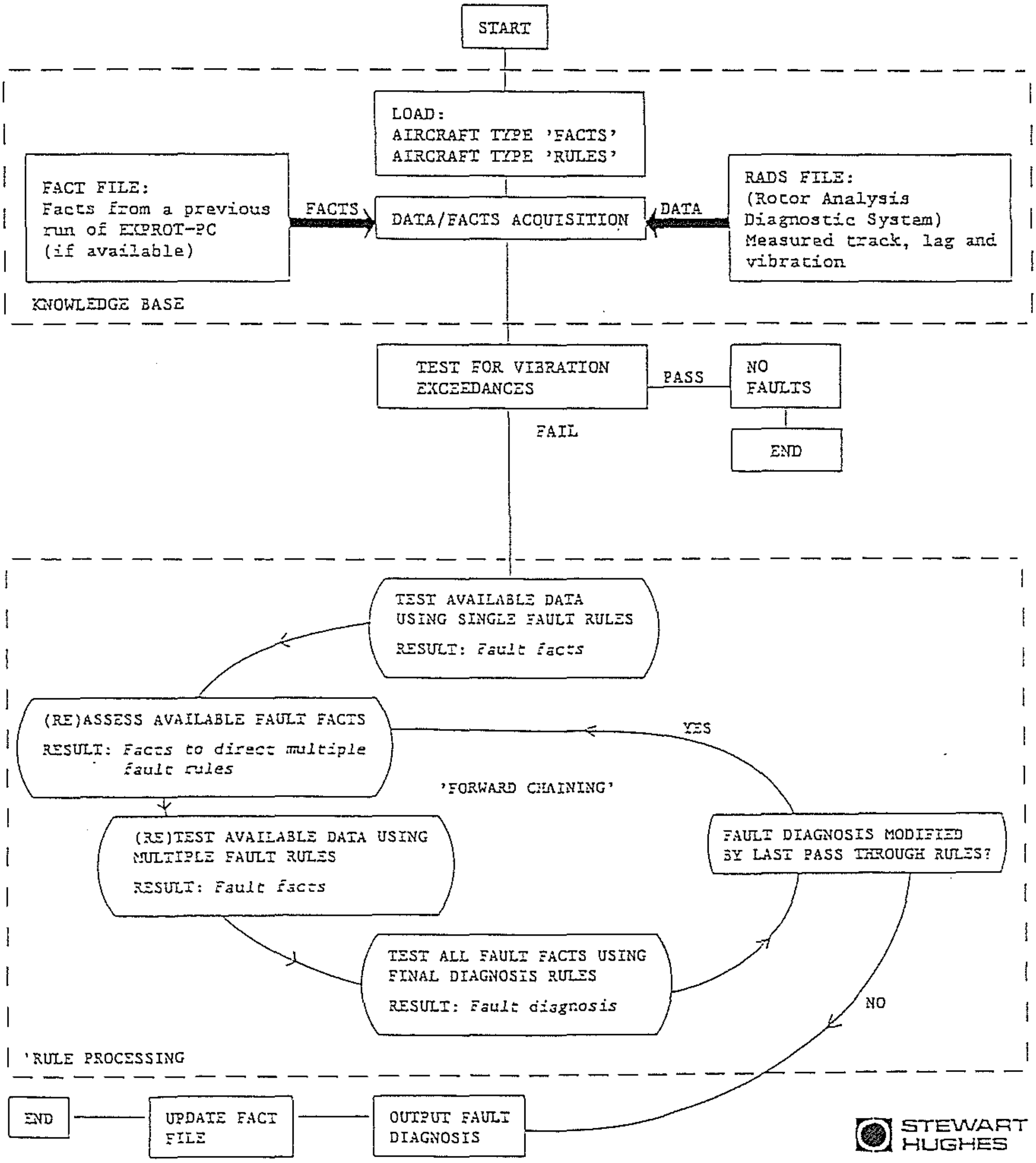
(a) 110 knots time

Figure 5c

FIGURE 6

EXPROT-PC

HELICOPTER ROTOR EXPERT SYSTEM



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The system was over simple - it did not cover such problems as validating the data to be analysed, the determination of significant symptoms nor the magnitude of the faults present.

One of the latest Expert Systems is presented in Figure 6.

The initial portion of the Expert System first loads the information available. There is no such thing as a standard test pattern, the data available being a function of the states operated and the data obtained. Implicit in the first, and enclosed within the pecked on lines on Fig 6, is the assessment that the data is good. This will include heuristic knowledge gained from the pilot that the test was contaminated due to, say, an unscheduled manoeuvre as well as rules which assess the consistency of data through the envelope flown.

The diagnostic box - marked *rule processing* - involves two sets of rules. The first relate specific faults to particular patterns at individual or groups of tests. From this a short list of potential faults is determined but it is dangerous to assess the magnitude of any one fault if some other faults are also present. This is done in the multiple fault rule Expert System. These faults are used to 'correct' the data by the amount of the correction recommended and then to repeat the exercise. This is done until consistency is obtained, or until a preset maximum permitted number of passes through the rules has failed to produce consistency. In the latter case this information is output with the final diagnosis obtained. Further developments to the Expert System are being made to extend the diagnosis.

It is obvious that this System is not aircraft specific in concept or implementation but does require numerical values or objective criteria for the type under examination.

7.0 CONCLUSIONS

This paper has shown that in addition to the previously published techniques for rotor track and balance the technology developed by Stewart Hughes Ltd can be applied to determing information about faults developing in the rotating blades, hub and control system of a helicopter.

An indication of the value of Artificial Intelligence to these problems is included.

8.0 REFERENCES

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