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HELICOPTER ROTOR HEAD CONDITION MONITORING

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ABSTRACT

Condition monitoring of rotor heads on helicopters has traditionally depended on manual acquisition of data and subsequent analysis. This paper describes an automatic system which provides accurate track, lag and blade velocity information on every rotor revolution.

Interpretation of blade motion and fuselage mounted accelerometer data simultaneously for both steady and varying rotor speed tests leads to powerful diagnostic techniques. Interpretation of such data is illustrated.

An example of the use of the tracker for more detailed blade motion experiments in which the first three flap bending blade modes are determined is included. The real variation with time is illustrated from a continuous two minute recording.

A technology demonstration unit for use by helicopter manufacturers and operators is described.

1.0 INTRODUCTION

Low vibration levels measured in the fuselage of a helicopter are often taken to mean a good condition of the dynamic components. While this is generally true, it may be that the rotor components could suffer high stresses as a result of two mutually opposed faults as seen in the non rotating co-ordinate system. It is therefore important that in reducing the vibration level of a helicopter to a point which meets crew and passenger comfort levels, the method should not produce other problems.

A technique which is used is to reduce the vibration level in the fuselage simply by applying vertical and inplane balancing techniques. In the great majority of cases this is an acceptable technique, but there can be circumstances where it leads to undesirable results. A better technique is to identify the causes of the vibration and to solve these problems either by adjusting or replacing the relevant components. This philosphy is the one which Stewart Hughes Ltd. favour and which has been a major influence in determining the technology which they have developed.

Maintenance systems are necessary to keep helicopters in suitable flying condition. However, maintenance costs money and therefore anything which can be done to reduce that burden is to be welcomed. It has been stated that the cost of special maintenance flights can be as high as £5,000 per month (Ref. 1). Any reduction in that figure would clearly be of great benefit to the operator. It is also important in any maintenance activity that faults reported by the aircrew should be dealt with as quickly as possible. If equipment can be developed which can be installed on the helicopter for the next "fare paying" sortie and which can produce data that enables the maintenance engineer to diagnose the problem, this is highly desirable. It is also important that for faults which only occur under certain flight conditions the pilot shall be able to record data at the time when it occurs in order that the maintenance engineer is presented with accurate information with which to make a diagnosis.

A paper (Ref. 2) presented at the Ninth European Rotorcraft Forum by Dr. M.J. Andrew gave the Stewart Hughes' philosphy for tackling the diagnosis of helicopter main rotor faults. Since that date considerable progress has been made in demonstrating the feasibility of the technology and it is the purpose of this paper to report on some of these events.

Stewart Hughes' philosophy should be reiterated. For every fault that can be identified the basic physics underlying it need to be identified. From that analysis certain characteristics in terms of blade motion and/or vibration characteristics received within the fuselage are identified to correspond to a particular fault. Second, where possible these identifications should take place with the helicopter on the ground, thus enabling maintenance personnel to get the helicopter in the best possible condition without using any flight hours. Third, data taken in forward flight, possibly on a routine flight, is used to reinforce the diagnosis made on the ground. To achieve this result a combination of steady rotor speed and variable rotor speed tests have been devised and these represent a powerful suite of diagnostic tests. It must however be emphasised that this does not mean that Stewart Hughes Ltd. consider that they have a complete monopoly on diagnostic ideas and test techniques. In the last section, this philosphy, which has proved successful in many cases, has been applied to an equipment which can be used by individual diagnostic specialists to develop techniques which they consider are particularly suited to determine faults on particular helicopter types. Naturally, the ability to make a wide range of tests depends very critically on the equipment available. The use of (triaxial) accelerometers in helicopters is now widespread and nothing further need be said in this paper. However, the measurement of track, lag and blade velocity is something which up to the present time has left much to be desired in terms of repeatability and versitility in the measurement. The optical tracker which Stewart Hughes has developed opens new possibilities for the diagnostics engineer. Finally, the advent of reliable simultaneous blade motion and vibration information provides data which is suitable for interpretion using advanced computer techniques, including expert systems.

2.0 THE OPTICAL SENSOR

The tracking system is required to measure track height, lag position and velocity for each blade at a known azimuthal position on each revolution of the rotor. The underlying principle is triangulation. The optical sensor developed comprises two photosensitive elements in the image plane of a lens. From Fig. 1 it can be seen that each rotor blade passes sequentially through the field-of-view of the two photodiodes, and in so doing obscures the light from each of the photodiodes in turn. If the duration that the light is obscured from either photodiode is determined and the chord of the rotor blade is known then the local blade velocity can be determined. The period between the blade obscuring each of the fields-of-view of the two photodiodes coupled with the blade velocity and the included angle between the diodes allows the absolute blade height above a reference plane to be calculated. Hence relative blade track can be determined. Lag motion of the blades may be determined by relating the time at which the blade enters the first beam to the rotation of the rotor as measured by the shaft event marker.

The principle does not require modification of the rotor blades. All measurements are made automatically, continually and do not require any operator action. This sensor affords a versatility not achieved by previous track systems; it is light, compact and may be fitted directly to the aircraft. The system is "passive" i.e. it operates without EM or acoustic emission.

Such a simple system might be expected to have large uncertainties when it is appreciated that it is necessary to measure the time at which the blade occludes the light to one microsecond. In a recent trial conducted for the Royal Aircraft Establishment three trackers were flown on a Puma research helicopter. As part of the calibration of the equipment these three trackers were arranged to look at the same point on the blade. The outputs from these trackers were measured simultaneously on a tape recorder mounted in the fuselage of the aircraft. Figure 2 shows the uncorrected data taken from the three trackers over a period of approximately two minutes. No processing of the traces has been made. The rev by rev variations are seen to be very consistent throughout this period, and it may be concluded that the rev to rev variation shown in this figure is a representation of what the blade was actually doing. This is typical of the performance of the tracker. The ability therefore to determine the motion of the blade to an accuracy of ± 1mm in flap and ± 2mm in lag is clearly an important feature of this work. One should also notice the actual rev to rev variation in blade position as shown here.

From the Stewart Hughes tracker the data is available in numeric form for each rotor revolution so either the raw information can be inspected by the operator or, as is usually done in steady rotor speed testing, the signal is averaged over a chosen number of rotor revolutions to give a well understood scientific measure of blade track. Similar analyses are performed for lag and blade velocity with equally good results.

The present optical sensor is dependent on natural light. The tracker has been shown to to work over a wide range of lighting conditions, and the limits of the operational envelope are ascertained automatically. The optical sensor has been fully developed and proved for daylight operation. Stewart Hughes is currently working to develop a tracker which will operate throughout the twenty four hours.

While the application of the tracker was originally conceived as a technology entirely geared towards obtaining diagnostic information the recent experiments with the Royal Aircraft Establishment have shown that it can give other indications of blade motion. The use of three trackers mounted on the Puma 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.

Examples of the tracker records obtained at a forward flight speed of 110 knots over a test period of about two minutes are shown in Figure 3. It will be noticed that for much of the time the three curves show remarkable similarity. However, at position A on Figure 3 it will be noted that there has been a marked change in the relative blade position determined from two of the trackers. From the data already shown in Figure 2 where the three trackers were all looking at the same blade position and over a two minute period showed remarkable consistency, it may be inferred that this difference is due to the blade bending being excited differently. The bending of the blade in terms of the first three modes for point A and point B is shown in Figure 4. It will be seen that while the rigid body or first mode is little changed, the amount of second and third bending mode does vary very significantly. This ability to be able to take data over long periods and subsequently to interpret it in this way is important and it warns that snapshot examinations of blade behaviour may be misleading if taken in isolation.

3.0 THE USE OF NON STEADY ROTOR SPEED TESTS

In Reference 2 Dr. Andrew indicated that non constant rotor speed tests were proving to be extremely useful in interpreting faults which were occurring in rotor systems. This early promise has been totally born out by the work which has followed the presentation of that paper and it is appropriate that a little more detail about the technique should be given.

In every case where a fault has to be diagnosed the philosphy must be to look for a rotor condition which emphasises the particular fault. Three very simple examples of the way that this idea may be applied will now be illustrated.

When a rotor is perfect except that one blade has been misadjusted so that its root pitch differs from that of the other blades the rotor is said to be out of track. The result is that one blade will fly higher or lower than the rest and this effect is independent of the rotor rpm as long as that is sufficiently high that the weight of the rotor blade is insignificant. Thus, an out of track rotor blade will fly a constant distance above or below the height of the other rotor blades irrespective of the rpm. On the other hand, if the rotor blade is fitted with tabs the twisting moment induced on the blade due to the tab varies roughly as the square of the rotor speed. Thus, the rotor blades, which are all identical except that one has a tab or tabs deflected in a particular direction, will exhibit rotor track heights where the blade with the error in the tab will move progressively nearer to the other blades or further away from the other blades depending on the initial conditions and the sign of the moment produced by the tab as the rotor speed is changed. Two such examples, one showing a set of blades with only a track rod error and the other a set of blades with only a tab error, are shown in Figure 5. Data like this can be used to determine multiple track and tab faults and also to give an estimate of the magnitude of the correction which is required.

Lag damper malfunction may be detected in a different way. It is worth repeating that the objective of every test should be to exercise a particular rotor component. Lag dampers can be exercised either by forward flight or by the application of cyclic pitch. If cyclic pitch is applied on the ground then the blade is forced to oscillate about its lag hinge. In the case of non articulated rotors like the Lynx, because there is an inherent lag stiffness in the system, the fundamental lag frequency and the once per rev rotational frequency cross at some intermediate frequency between full rotor revs and zero. This resonance can be used to demonstrate that a lag damper is deficient. It should be pointed out that the interpretation of traces such as the one shown in Figure 6 depends on a further understanding of the basic physics. The phenomenon seen is not the classical steady state situation of a mass spring damper system being excited at a fixed frequency. Second, because one is only sampling the information at one point in the whole of the revolution of the blade one does not see the complete time history. If one is approaching the resonance from above, in a run down, then the amplitude of oscillation will build up as the revs decrease. The amplitude of oscillation will clearly be a function of the rate at which the rotor is running down.

The motion of the blade for a slow run down speed will initially be the forced response at the initial frequency. As the rotor frequency approaches the resonant frequency the phase of the forcing function and the motion will change. If the run down is sufficiently slow the response will approximate the pseudo steady state case. A peak amplitude will occur at about the resonant frequency. As the run down speed is increased the blade motion is unable to respond quickly to the phase change of the forcing term and so the amplitude of blade motion decreases as the resonance is approached. The apparent resonant frequency is therefore above the true value.

Mr. P. Michie at Stewart Hughes has produced a computer simulation of this situation and his diagrams are shown in Figures 7, 8 and 9. The upper diagram in each case shows the time history of a simple spring mass damper system during run down, the decrease in rotational frequency being a linear function with time between 3.5 and 1.5Hz. The lower illustrations show the value of the lag of the blade as it would be sampled by the tracker at a particular azimuthal station on each rotor revolution. The figures show that the type of record produced is very much a function of the way the rotor runs down and therefore it is important, not only for rotor tests but for all dynamic tests where this type of sensor is used, that the technique should be controlled. Further processing of the data is performed in order to make the changed response clearer.

In the case of helicopter rotors there is a further complication which needs to be safeguarded and this concerns the application of power during run down. In many cases as the rotor slows down the freewheel is re-engaged, and for a limited length of time the rotor becomes driven rather than freewheeling. Naturally this has an effect on the lag of the rotor blade and information such as this has to be included in the interpretation of the records. This has been accomplished by Stewart Hughes. Thus, what at first sight appeared to be a simple classical resonant system problem is more complicated and this is the reason why Stewart Hughes has been interested in expert type programmes to aid the maintenance engineer in diagnosing the faults which may be present.

4.00 THE ROTOR ANALYSIS DEMONSTRATION SYSTEM (RADS)

Stewart Hughes, having developed the basic building blocks which enable the rotor diagnostician to obtain reliable, real time data on blade motion which can be coupled immediately with vibration information, have gone one step further and have produced an equipment which utilises the technology that is now available.

The rotor analysis demonstration system does not constrain the maintenance staff to a formal routine. The system shown in Figure 10 has three basic components. These are a tracker to sense the position and velocity of the blades, a data acquisition unit which processes and records that information in ways most suited to the test which has been set up, and a small hand held computer, currently a Husky, which is the controlling mechanism of the whole system, and also the data store for the information when it has been processed.

The tracker has already been described. The data acquisition unit consists of a facility to take the data from the tracker or trackers (two can be fitted at the same time) together with once per rev information from two sensors, for example, one on the main rotor and one on the tail rotor, or, in the case of a tandem rotor, one on each main rotor shaft, to verify that that data is good and to process that data in a suitable way depending on whether it is a steady rotor revs or a varying rotor revs test. In addition, up to eight channels of accelerometer signal can be taken. These are done in two banks of four and any number of accelerometers within each bank of four can be sensed and analysed simultaneously. The way in which the signals are processed depends on the test which is being conducted. In the case of the non steady rotor revs test, the tracker information is retained throughout the whole of the run up and the run down. This enables track lag and velocity of the blades on every revolution to be stored in the Husky and to be displayed in flight if so required. No accelerometer data is recorded but it would be possible for example to take the maximum value of acceleration and the rpm at which this is achieved if it was so desired. In the case of steady state data the data acquisition unit acquires a number of consecutive revolutions of rotor data, from which the mean values of track, lag and velocity for each blade are stored in the Husky. The number of revolutions which can be taken can be varied from one up to one hundred and twenty four and this is specified in the programme which is set up in the Husky before the flight. Simultaneously with the acquisition of data from the tracker the four channels of accelerometer information are analysed to give vibration information up to 70Hz. This information is recorded currently in terms of particular rotor orders which have been specified by the test engineer before the flight and the information is given in the lower orders as amplitude and phase and for the higher orders simply as amplitude. To give some indication of what this means in practice, for an aircraft like the Westland Lynx, this enables up to the sixteenth rotor order of the main rotor to be obtained.

The processed information is stored in the Husky which can be removed from the aircraft because the Husky has its own battery powered memory. The information can be interrogated on the Husky display or taken to any one of several alternative systems. These systems are, typically, a dot matrix printer, a personal computer, which of course can then be used for subsequent processing, or the Mechanical Systems Diagnostic Analyser (MSDA) which has been developed by Stewart Hughes and which can be used for other advanced analysis and interpretation of diagnostic data.

The RADS system may be operated as follows. The diagnostic engineer prior to flight programmes into the Husky the various test conditions which require examination. The information regarding the aircraft condition is also included for future reference. The equipment is then ready to be taken to the aircraft. The tracker is installed, ideally viewing the forward part of the rotor disc, the data acquisition unit may be placed anywhere in the aircraft where space exists and uses aircraft power supplies. It is connected to the tracker, accelerometers and tacho sensor. A cable is then taken from the DAU to the Husky which, for example, may be situated within the pilot's cockpit. The Husky may be operated in a simple mode to collect data, the Husky display being used to advise the pilot of test details. The amount of description shown is at the discretion of the test engineer who has specified the programme. The pilot presses any key on the Husky to secure the data when he is on condition. If tests are not satisfactory for any reason they may be repeated. The limit to the number of individual flight conditions depends on the mix between non steady and steady tests but some forty steady state tests can be accommodated without having to down load the information from the Husky computer. If the equipment is being operated by a test engineer in the air then he has an option to examine the data on the screen. In that case after each test is complete the information is presented on demand. The trends which summarise the information from all the tests that have previously been taken may also be inspected. The flexibility of the equipment, its ability to be operated on a routine flight without the need to carry a specialist test engineer (or to occupy valuable cockpit or cabin space) or alternatively to be operated by a test engineer and to have the information presented in an unambiguous and accurate form for examination on the spot has been illustrated.

Finally, the RADS system can be coupled to either a PC computer or to an MSDA, and the information can be down loaded and examined by an Expert System. Although aide memoirs, for example, gradients of transient curves, are presented to the engineer on the Husky, it has already been shown in paragraph 3 that the interpretation, for example, of lag damper data, is not simple. It is in these roles that the expert type of programme is exceedingly valuable, as has been found in the work which has been done for the Royal Navy.

6.0 IN CONCLUSION

The development of a small, lightweight, cheap blade motion and position sensor which requires no human intervention has altered the whole technology of rotor diagnostics. The coupling of such rotor information with vibration data has now moved to a point where a large number of integrated diagnostics can be developed. Several of these are already available at Stewart Hughes.

In operational terms the development of the tracker and RADS has given great flexibility to the maintenance staff in that data can be obtained on regular flights, so reducing if not entirely eliminating, the need for special maintenance flights. Data can be taken by aircrew in conditions where they have problems. The equipment is small, requires no more than normal inputs, is flexible and can be adapted by the test engineer to meet an extremely wide range of operating conditions. In particular, the ability to take non steady rotor speed data on the ground has proved a valuable additional source of diagnostics.

The application of science to rotor condition monitoring has therefore moved a whole step forward with the development of this technology.

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2. M.J. Andrew. The Diagnosis of Helicopter Main Rotor Faults. **Ninth European Rotorcraft Forum, Strasa, Italy,** 1983

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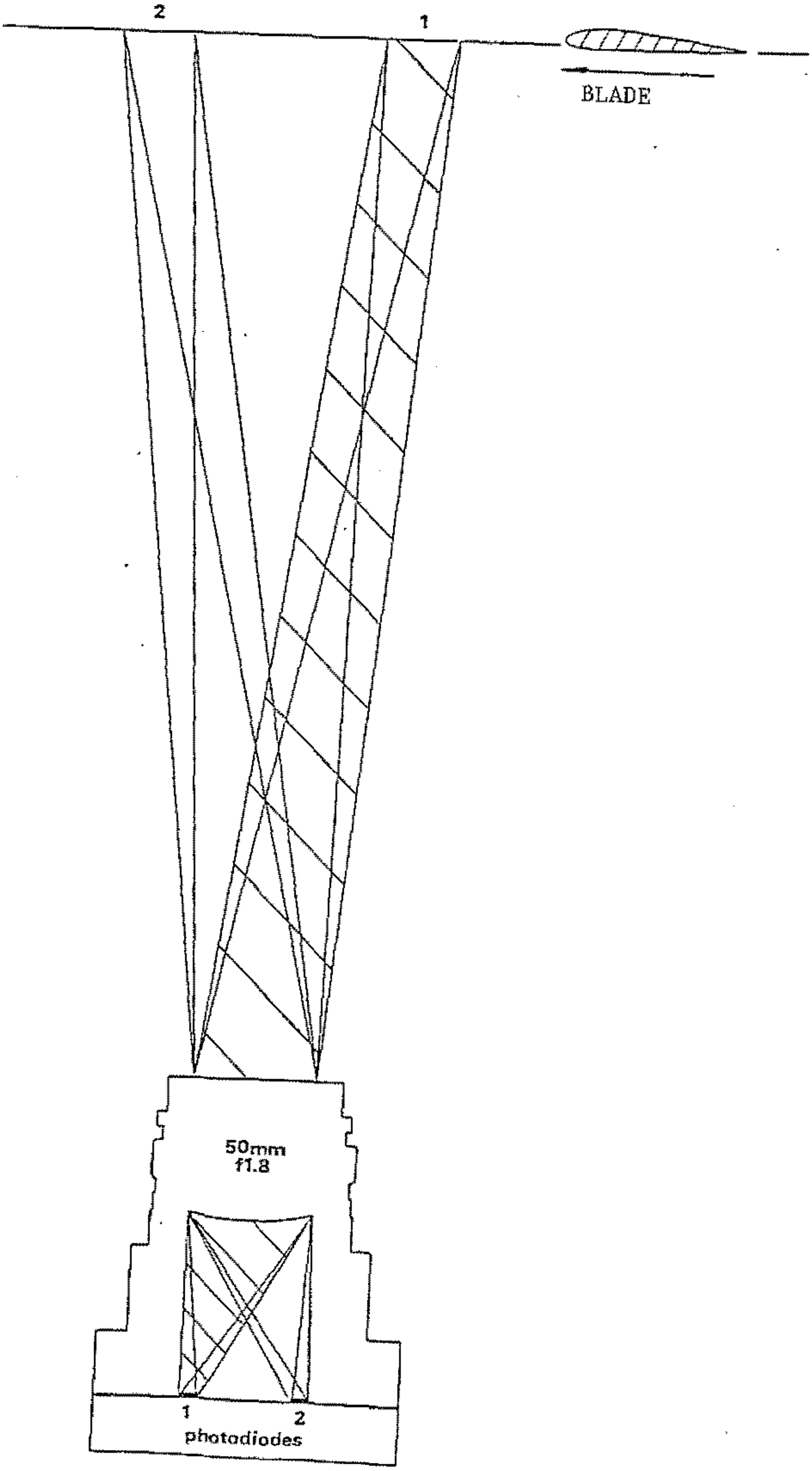


FIGURE 1: TRACK SENSOR OPTICAL GEOMETRY

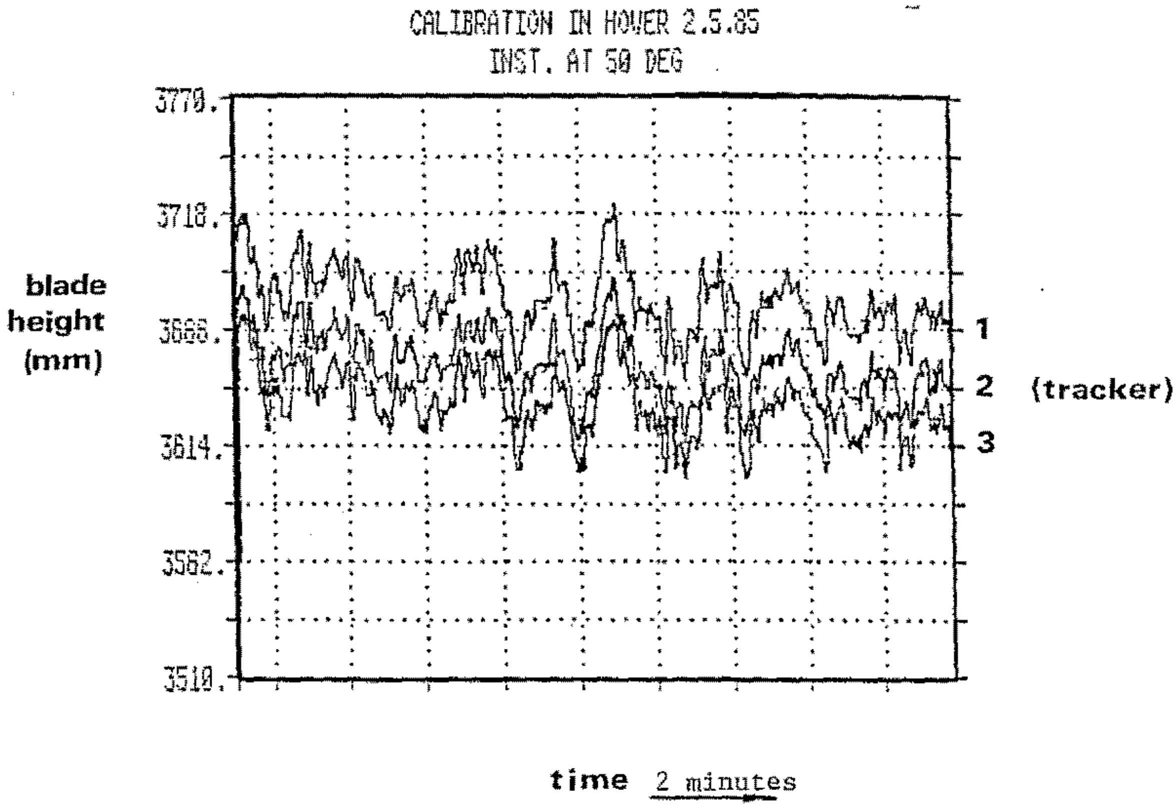
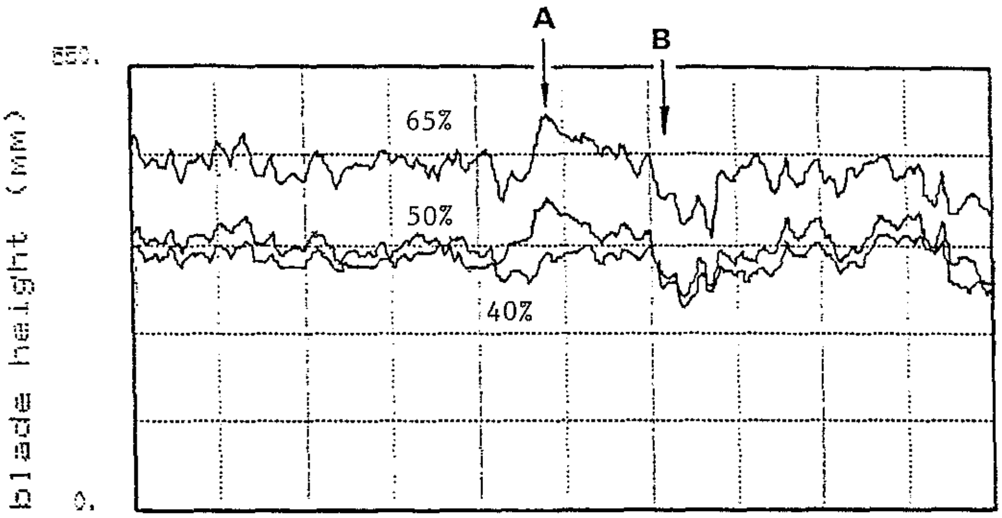


FIGURE 2: PERFORMANCE OF 3 TRACKERS VIEWING THE SAME BLADE STATION



(a) 110 knots

FIGURE 3: MEASURED BLADE DEFLECTIONS REFERENCED TO HINGE

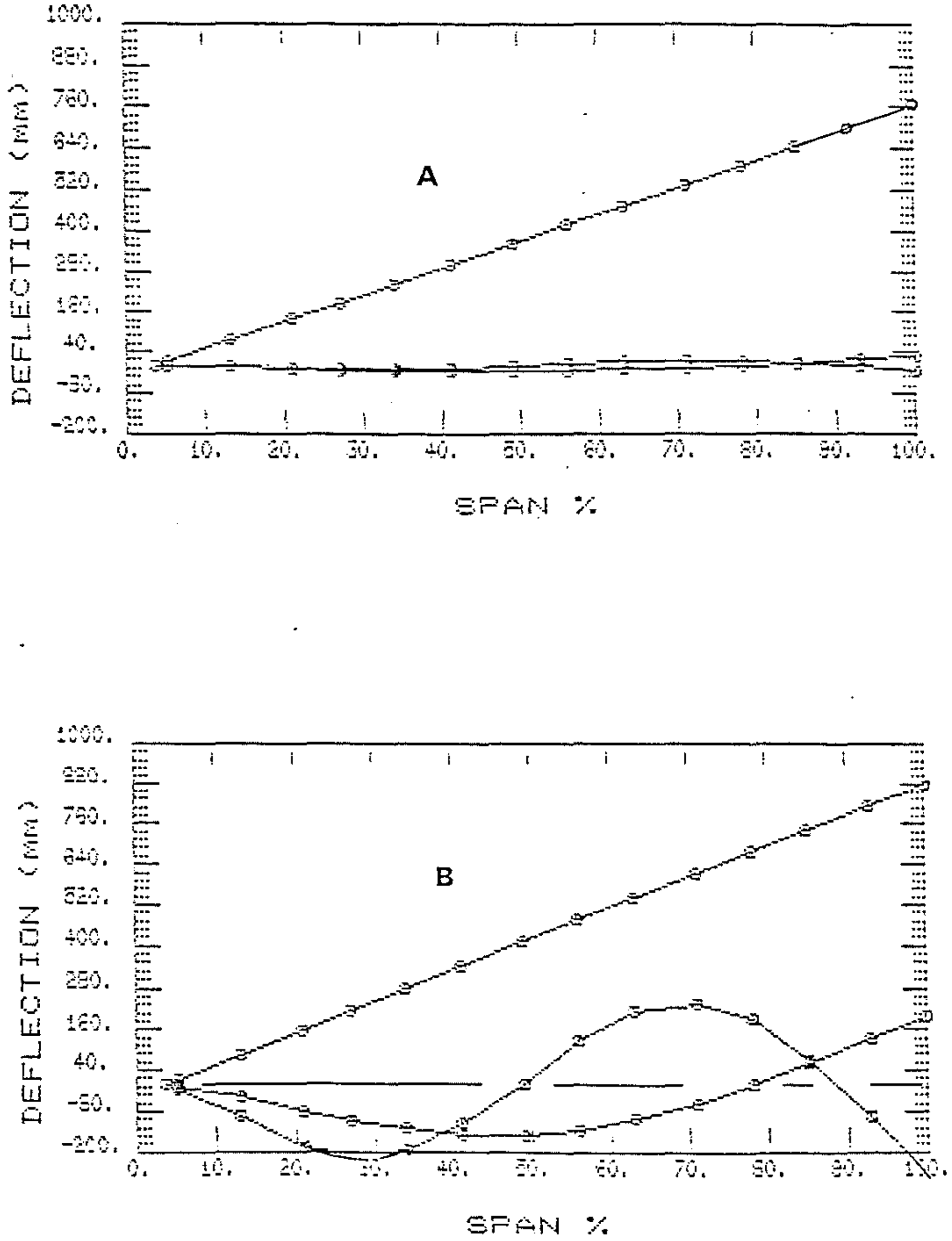


FIGURE 4: COMPARISON OF MODAL BEHAVIOUR ON DISTINCT REVS AT 110 KNOTS, SEPARATE EVENTS 'A' AND 'B' (SEE FIGURE 3)

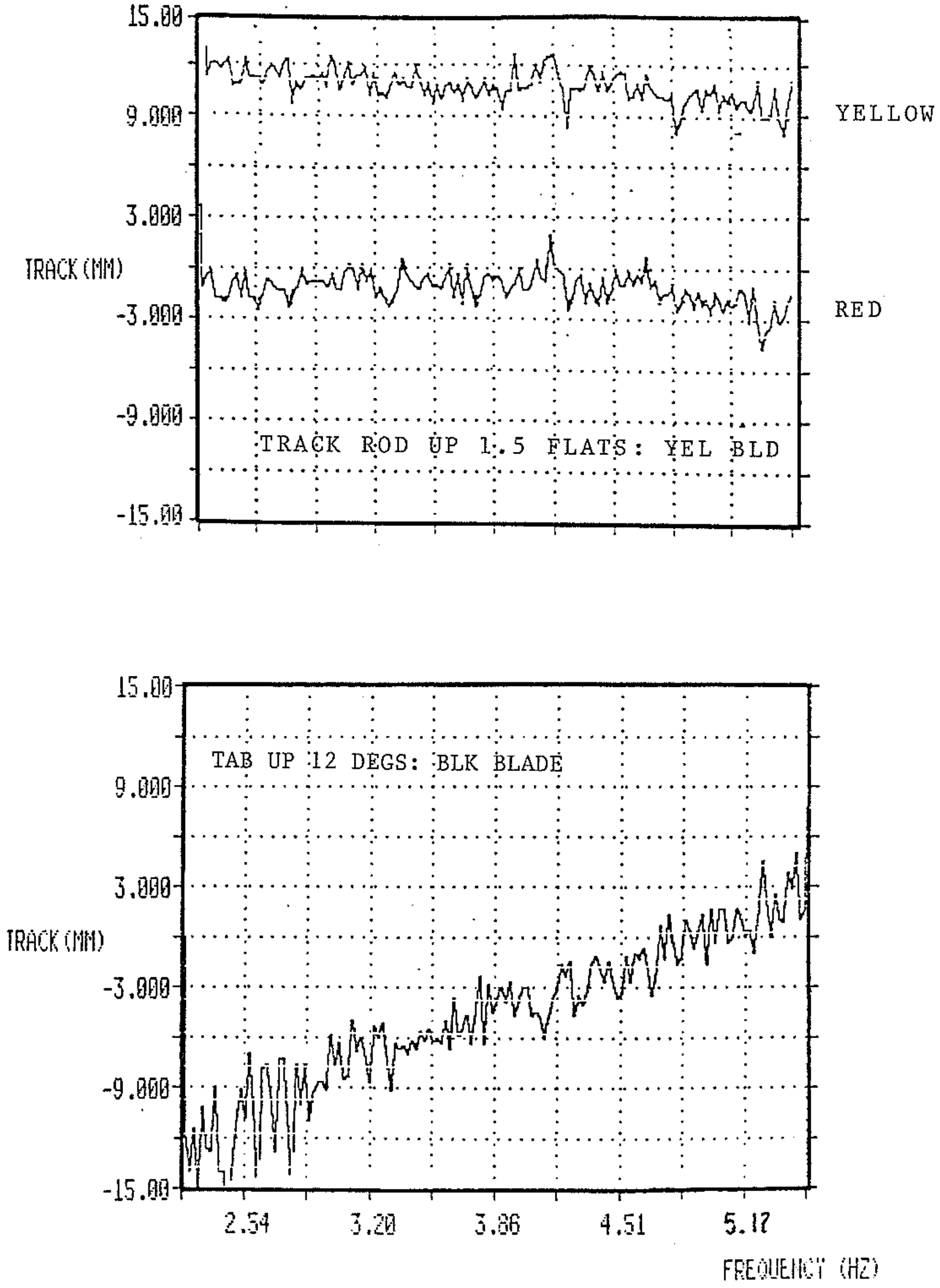


FIGURE 5: ROTOR RUN-UP TRACK TRACES:
BLADE TO BLADE COMPARISONS

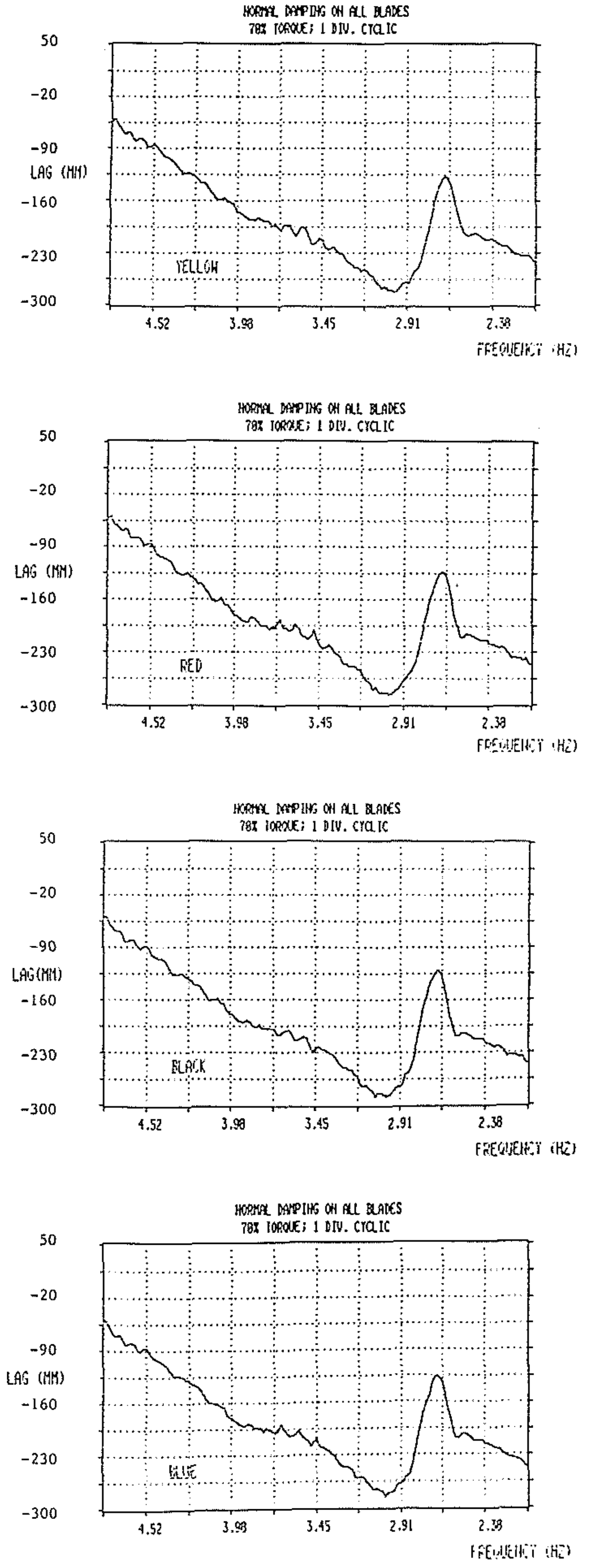
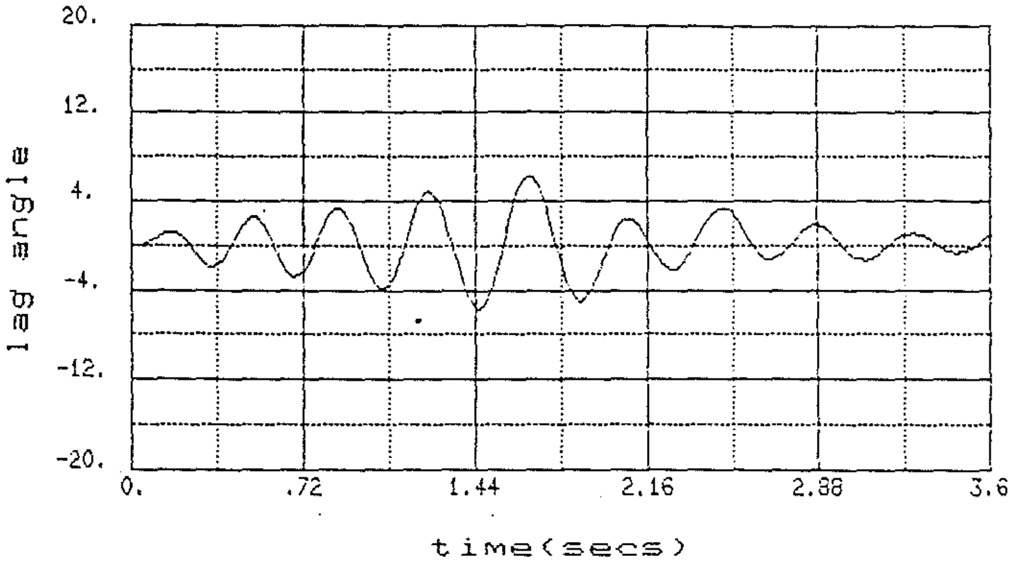
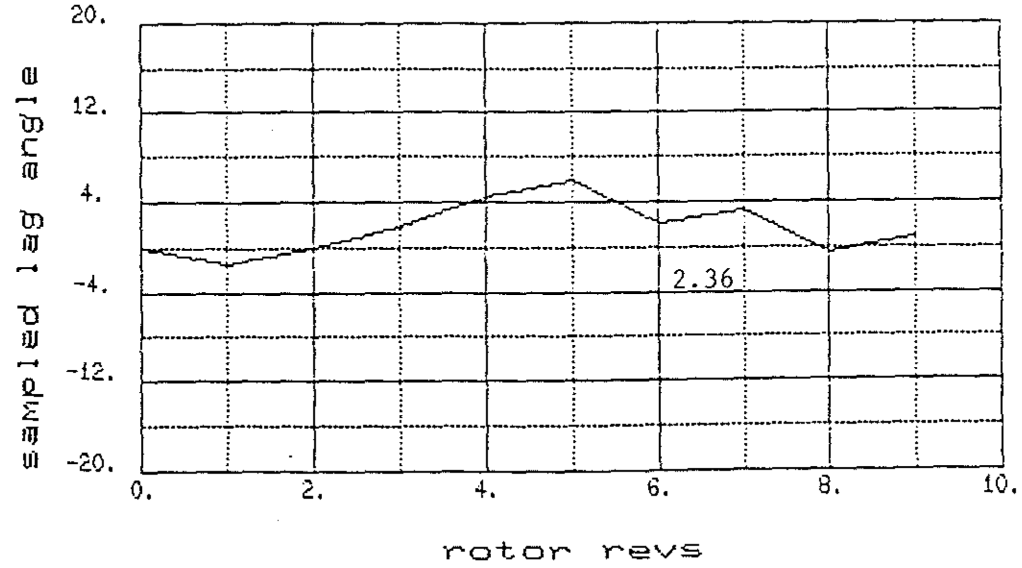


FIGURE 6: ROTOR RUN-DOWN LAG TRACES - NORMAL CONDITIONS OF DAMPING

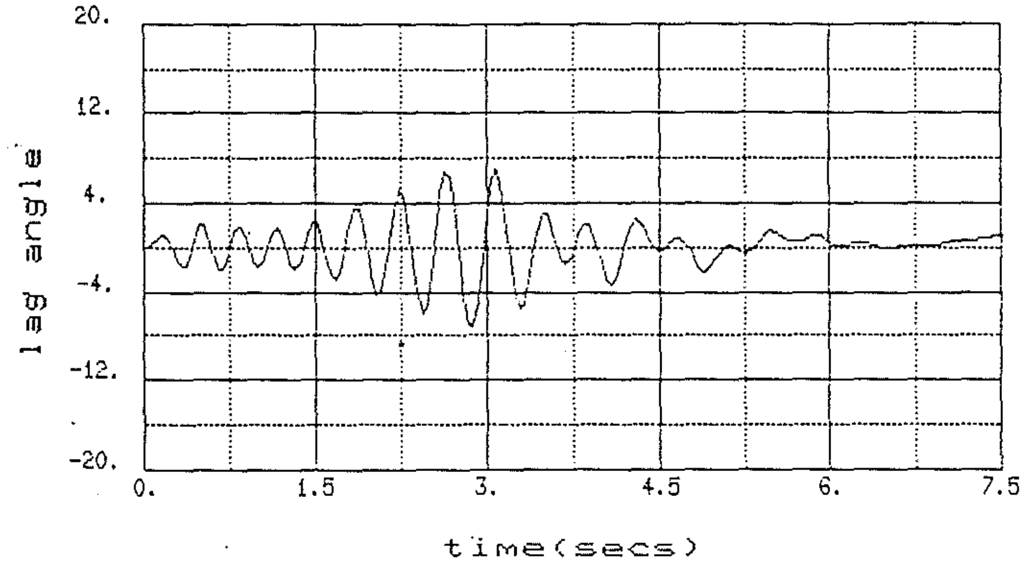


a. Blade response around the azimth

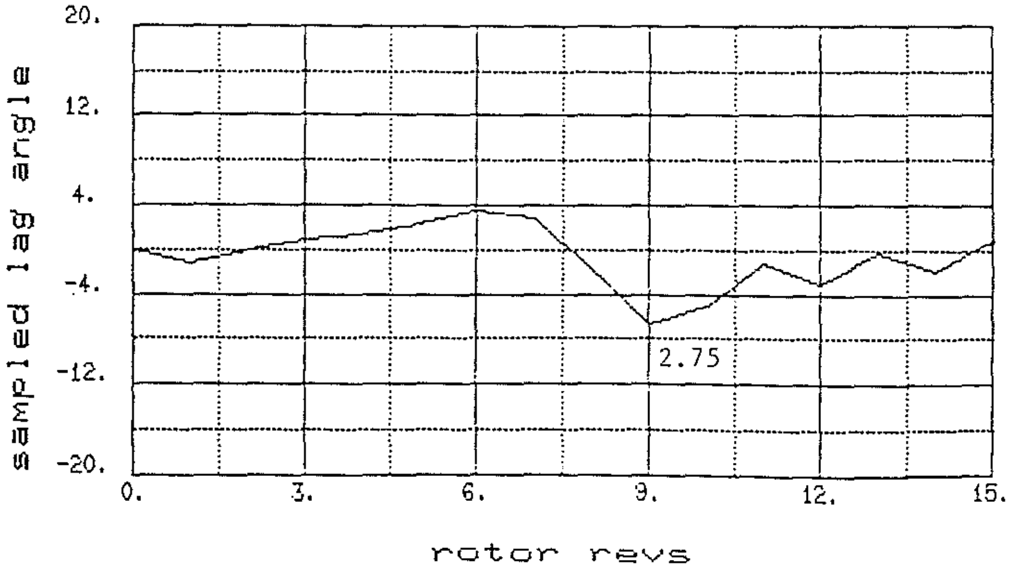


b. Blade response as seen at one point of azimuth

FIGURE 7: ROTOR RUN-DOWN LAG TRACES

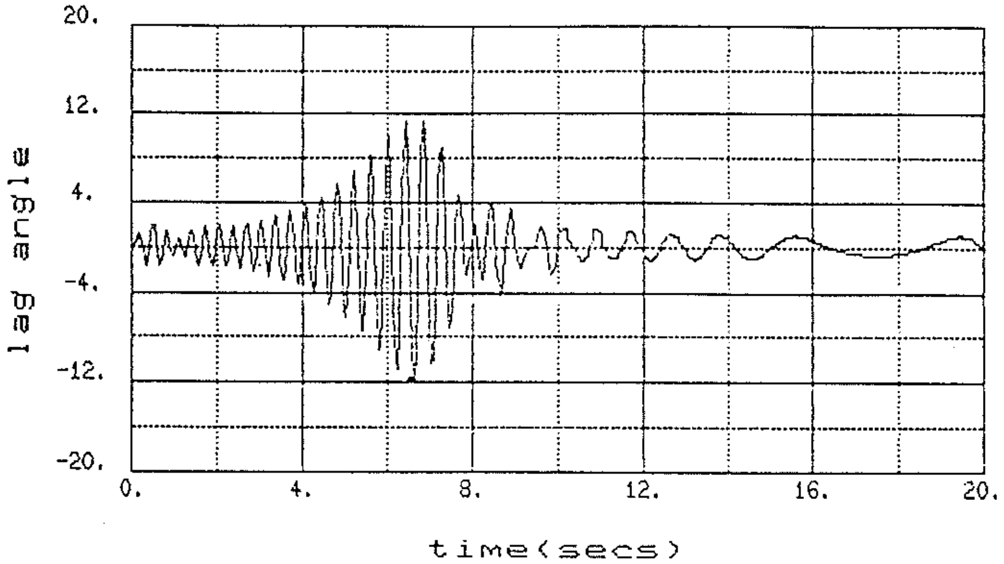


a. Blade response around the azimuth

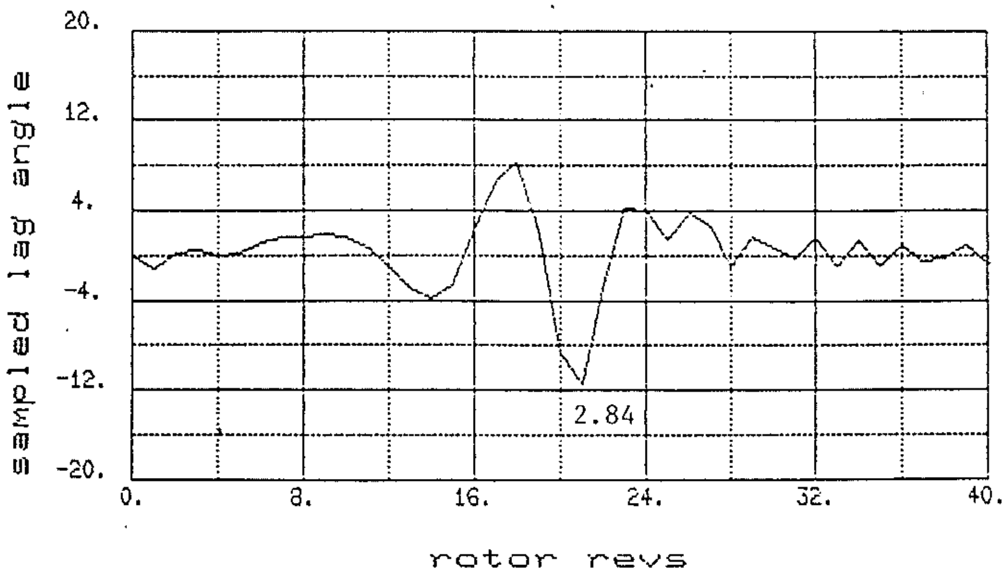


b. Blade response as seen at one point of azimuth

FIGURE 8: ROTOR RUN-DOWN LAG TRACES

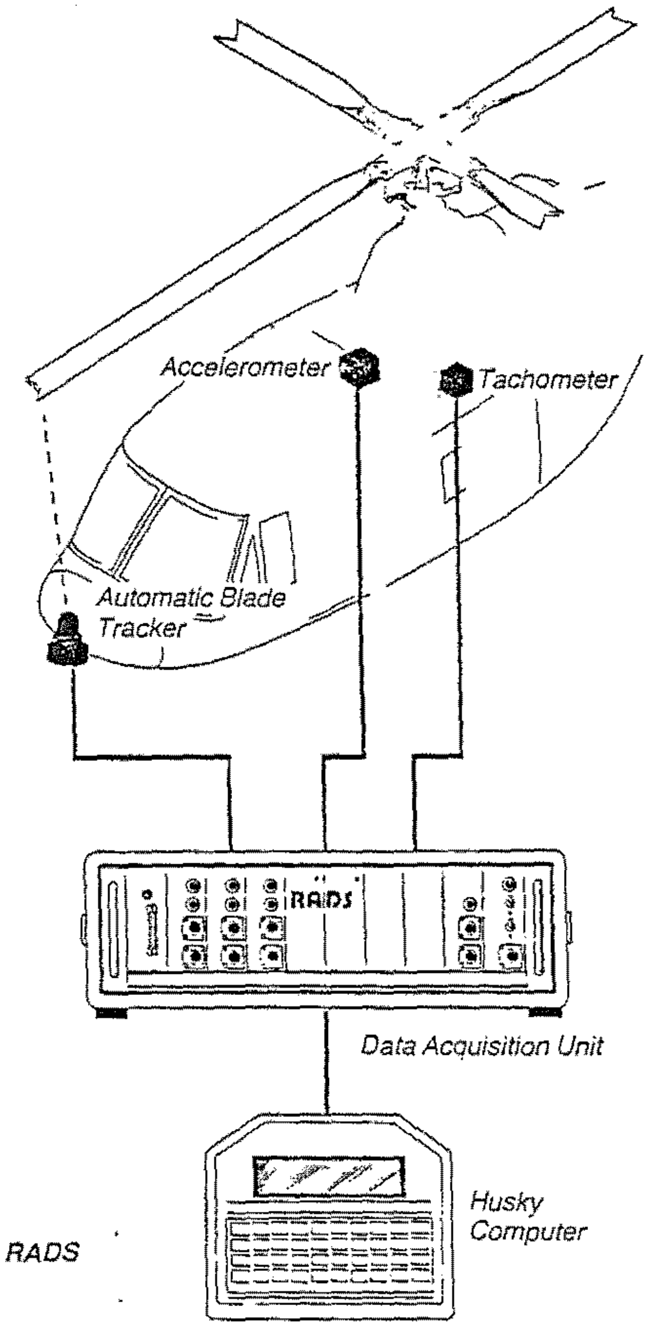


a. Blade response around the azimuth



b. Blade response as seen at one point of azimuth

FIGURE 9: ROTOR RUN-DOWN LAG TRACES



RADS

FIGURE 10