HEALTH AND USAGE MONITORING

BY

COMMANDER P. J. KNOWLING, MSC, CENG, MIEE, RN
(Directorate General Aircraft (Navy))

ABSTRACT

To date, Health and Usage Monitoring has been used almost exclusively on aircraft, but now it is beginning to enjoy much wider use on ground-based equipment and there appear to be considerable benefits to be gained from its application. Nevertheless, there are many pitfalls which await the unwary user, and this article proposes a strategy for determining a Health and Monitoring System Requirement, giving examples of difficulties experienced by other users where appropriate. The article then goes on to give an overview of the more common Health and Usage Monitoring techniques, describing their advantages and disadvantages.

Introduction

The Fleet Air Arm has been actively involved in applying Health and Usage Monitoring techniques to its aircraft for many years. However, there has recently been a rapid increase in the number and quality of Health and Usage Monitoring systems available and they are now also starting to be used by both civil helicopter operators and industry. This progress has primarily been as a result of recommendations made by the Helicopter Airworthiness Review Panel (HARP) which was set up by the Civil Aviation Authority in 1983 to look into civil helicopter operations following a series of highly publicized fatal accidents involving helicopters operating in the North Sea. The Panel reported in 1984, and as a result of one of their recommendations the pace of research in this area has increased rapidly and systems of varying maturity are being marketed aggressively to a wide range of potential users.

Whilst the initial impetus was based on improving the airworthiness of the UK civil helicopter fleet, other industries are increasingly beginning to recognize the potential benefits of Health and Usage Monitoring. Foremost amongst these are the North Sea Oil Companies who are using Health and Usage Monitoring extensively to reduce their planned maintenance costs; and at least one major motor manufacturer is investing large sums of money in a health monitoring system which will form part of the Quality Assurance process on his gearbox production line.

This article, which is based on the lessons learnt by the Fleet Air Arm in applying Health and Usage Monitoring techniques, is primarily intended to address the application of these techniques to equipment other than aircraft. It offers some observations on the potential benefits and pitfalls of adopting Health and Usage Monitoring, and proposes a strategy which it is believed should provide a sound and pragmatic approach to the application of Health and Usage Monitoring in any engineering field. Finally, an overview is provided of the most common Health and Usage Monitoring techniques that are currently available.

What is Health and Usage Monitoring?

Before proceeding, however, let me clarify what I mean by Health and Usage Monitoring. Health and Usage Monitoring is a term which is widely used to describe what are, in fact, two quite separate maintenance philosophies, Health Monitoring, and Usage Monitoring. For the purposes of this article, *Health Monitoring* can be considered to be the process by which the need for a maintenance action is determined by continuous or regular periodic observations of the system; whilst *Usage Monitoring* is the process by which components having fixed lives are monitored by direct measurement of their in-service use.

From these definitions it can be seen that, as maintainers, we have been employing Health and Usage Monitoring for years and I believe this is an important point to recognize. What these new techniques should be offering is a more efficient and effective means of maintaining our equipment and we should be seeking to implement them as part of the overall maintenance strategy for our equipment.

WHAT CAN HEALTH AND USAGE MONITORING DO FOR YOU?

I believe that the first, and most important question that must be asked is; what can Health and Usage Monitoring do for me? Well, quite simply, it should *reduce the life cycle costs of your equipment*. Whether or not you actually achieve this holy grail will depend on a number of factors:

- How you go about defining your system requirement.
- Which Health and Usage Monitoring techniques you choose to satisfy your system requirement.
- How your Health and Usage Monitoring system is developed, introduced to service and supported whilst in service.

First of all, how do you go about defining your system requirement? Well first and foremost, it is important you look on Health and Usage Monitoring as part of your overall maintenance strategy. Health and Usage Monitoring is not an alternative to investing in reliability. It should not be used to overcome design deficiencies, nor should it be used to overcome quality assurance problems during manufacture or assembly. Health and Usage Monitoring should simply provide the most cost-effective means of maintaining a system once it has been introduced into service.

The prime objective of your strategy should be to use Health Monitoring to place as many components as practical onto On-Condition Maintenance. If this involves a change to the equipment's lifing policy, the Design Authority should be involved from an early stage as difficulties can arise, especially where the Design Authority and Engineering Authority are not the same organization. Where On-Condition Maintenance is not practical, whether it be on the grounds of safety, cost or technical risk, Usage Monitoring will need to be employed. In this case there are two options available—Direct Load Usage Measurement, or Parametric Usage Measurement. With the former, the damaging loads which consume the life of the component are measured directly; whilst with the latter, some easily measurable parameter such as operating time or power for example are monitored and life usage estimated by a parametric analysis which attempts to correlate the parameters measured to actual damaging loads which were applied.

Both direct and parametric methods are discussed further on pp. 428–429. A careful comparison of the two techniques on the basis of life cycle costs is recommended before making any decision on the approach to be taken.

Another important factor when developing your Health and Usage Monitoring system requirement, is that your final choice should demonstrate a reduction in the overall maintenance effort. This is particularly important at the point of operation where the Health and Usage Monitoring system should be looked upon as an aid to maintenance and not a hindrance, if it is to be accepted and used effectively. In this respect it should be borne in mind that no equipment will be totally reliable and the introduction of additional sensors, wiring and electronics will introduce a maintenance penalty. For a system to be acceptable this penalty must be more than offset by demonstrable benefits in maintainability. It is possible that these could come from reductions in scheduled maintenance or an increase in mean time between replacement of components, but wherever these benefits come from you must satisfy yourself that your maintainers will, on balance, be better not worse off as a result of the introduction of Health and Usage Monitoring.

It is also important that your Health and Usage Monitoring system should be more reliable than the system it is monitoring. To achieve this, the reliability together with the probability of detection and probability of false alarm should be quantified in the requirement. If buying 'off the shelf' evidence of demonstrated in-service reliability, detection rates and false alarm rates should be sought. If the intention is to develop a new system, the method by which the system's reliability, probability of detection and probability of false alarm are to be demonstrated should be specified in the contract, together with the penalties which will be invoked if the contractor fails to achieve them. An appropriate reliability growth programme should be offered by the contractor in his tender. The importance of investing time and effort in getting the requirement, specification and contract accurate and watertight cannot be overstated. Few Health and Usage Monitoring systems have been introduced into service to date without significant reliability problems, and experience indicates that for a single simple technique, the probability of a false alarm is likely to exceed the probability of detection of a defect. You can see that unless great care is taken during the design, development and testing of the system, there is a very real chance that its credibility will be lost through the excessive generation of false alarms. There have been repeated examples of this actually occurring in service; both the Sea King gearbox magnetic chip detectors and elements of the Harrier Information Management System (HIMS) on the Harrier GR5 have been disabled as a result of false alarms causing many unwarranted and often unwelcome premature terminations of sorties.

A Failure Mode and Effects Analysis should be carried out on any system you propose to monitor, in order to identify those failures which you would wish to see detected. These failure modes should then be analysed further to determine likely fault propagation rates, and suitable Health Monitoring techniques with response times compatible with these propagation rates.

Once you have identified potential Health Monitoring techniques, you should satisfy yourself that they provide:

- Advance warning of failures or potential defects. The aim should be to provide safety critical information to maintainers before it becomes noticeable to operators. Ideally the warning should be far enough in advance to allow replacement parts to be ordered, delivered, and then fitted as a planned part of the programme.
- A clear rejection signal for developing failures such as wear or fracture.
- Suitable corroborating techniques such as trending, Non-Destructive Testing or visual inspection as appropriate to achieve an acceptable probability of detection and probability of false alarm.

Once these Health Monitoring techniques have been identified, the probability of detecting the faults and the probability of false alarms can be estimated and the Health and Usage Monitoring strategy amended as necessary to achieve the requirement. If as a result of this iterative process, it is decided that Health Monitoring is impractical, the next stage is to consider Usage Monitoring and amend your maintenance and logistic philosophies to cater for it. In short, when defining the Health and Usage Monitoring system, the approach should be, what do we need to do to maintain this equipment, and how will Health and Usage Monitoring help us to achieve this; and not, we have this super Health and Usage Monitoring system available, how are we going to use it?

One final consideration is that of the processing of recorded data, which can impose a huge burden on operators. It is estimated that the latest generation of Integrated Health and Usage Monitoring systems will record in excess of 1 Megabyte of data on each flight. Therefore, if the maintainer is not to be drowned under a sea of data it is essential that a suitable strategy for handling the data is developed and the data handling system is in place when the Health and Usage Monitoring system is introduced into service. Many Health and Usage systems will be generating vast quantities of data, therefore the need for recorded data should be considered critically and justified. Much work remains to be done to resolve this problem and make best use of that data.

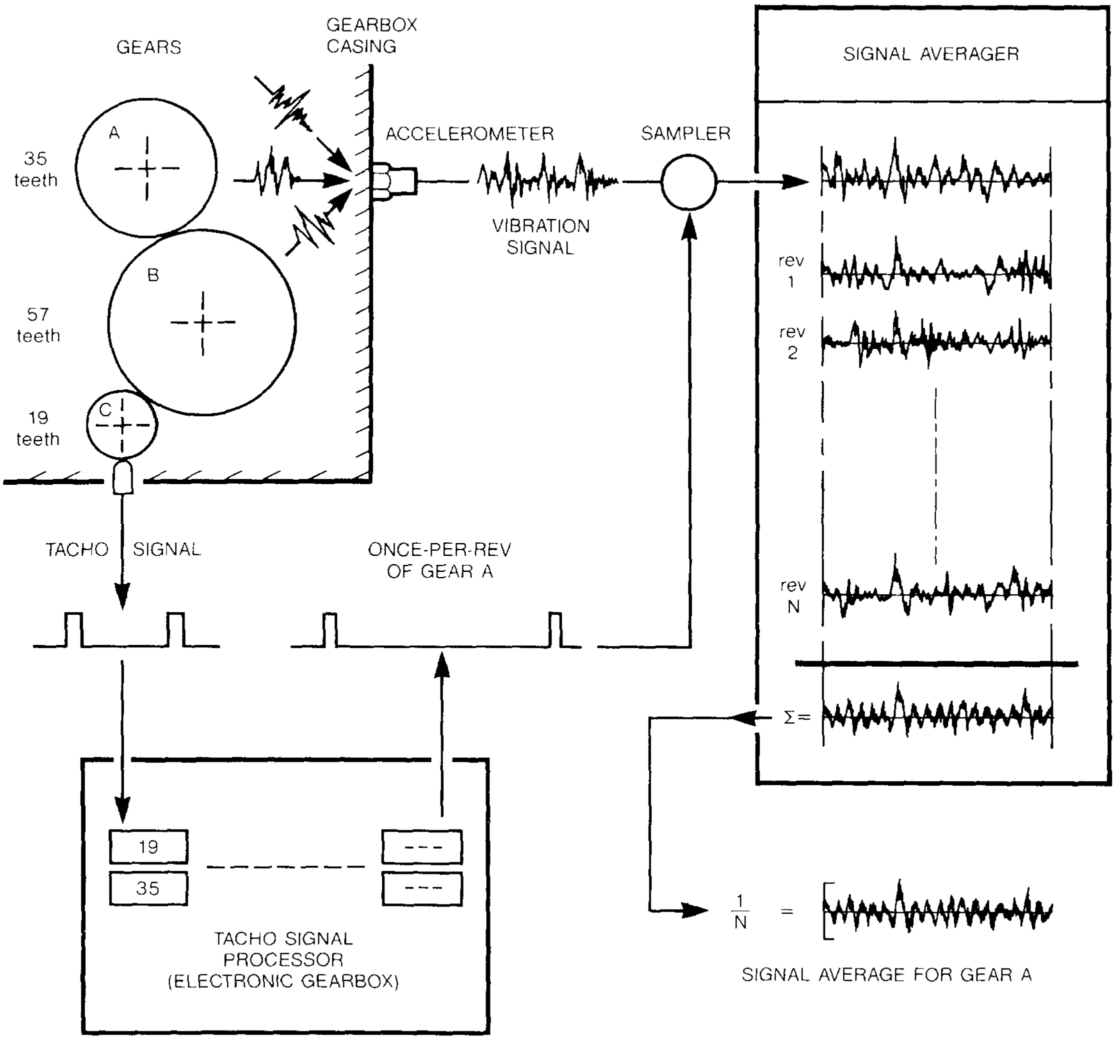

FIG. 1—A TYPICAL VIBRATION ANALYSIS SYSTEM APPLIED TO A GEARBOX

HEALTH AND USAGE MONITORING TECHNIQUES

Vibration Analysis

One of the most powerful techniques for carrying out Health Monitoring of gearboxes, engines, transmissions and other vibrating structures is Vibration Analysis. The technique involves the measurement of the equipment's vibration by a series of accelerometers mounted at suitable positions on the equipment. This raw vibration signature is then processed to identify any abnormalities. There are many signal processing techniques available, ranging from simple frequency domain filtering to identify known forcing frequencies, to signal averaging, fast fourier transforms and numerical analysis to optimize the probability of detection and false alarm rate. A typical system which monitors the condition of a 35 toothed gear within a gearbox is shown diagrammatically in FIG. 1 and described below.

A Typical System

The vibration signature is acquired by accelerometers attached to the gearbox casing. An accelerometer can receive vibration signals from a number of gears depending on its position. A reference signal is produced by a tachometer attached to one of the shafts within the system. This reference signal is then used to generate trigger pulses at the revolution rates of the gears which are being monitored. These trigger pulses are then used to sample the vibration signal once every revolution of the gear shaft being monitored, and to synchronize the sampling to the shaft rotation. Next, typically five to ten of these samples are summed and averaged to suppress random and non-synchronous signals such as those produced by other shafts in the gearbox, so providing a discrete signature for the 35 tooth gear.

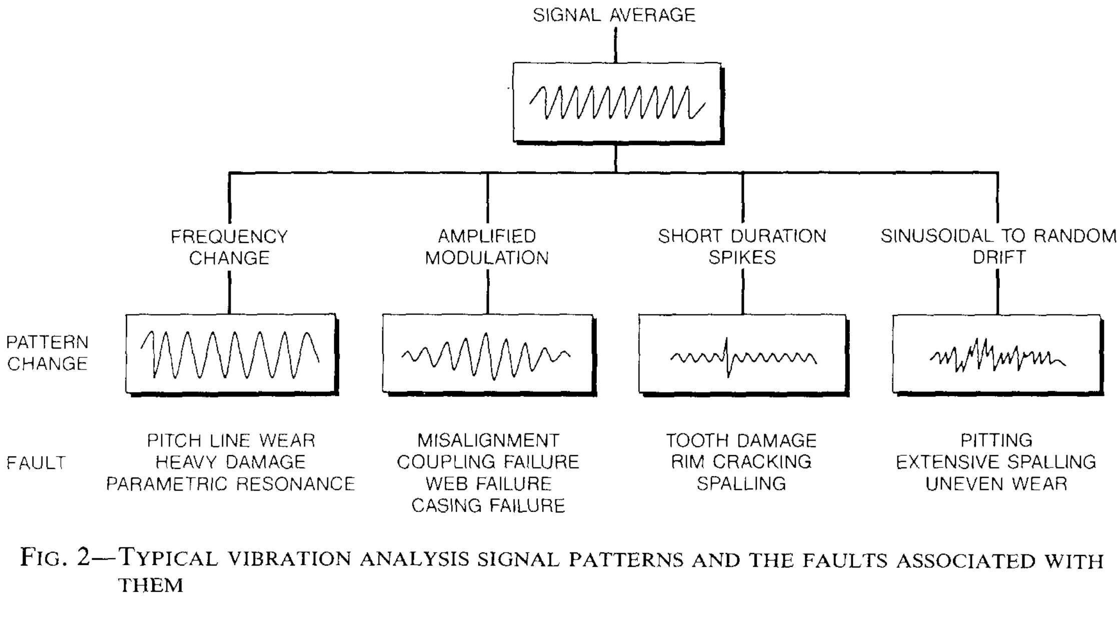

FIG. 2—TYPICAL VIBRATION ANALYSIS SIGNAL PATTERNS AND THE FAULTS ASSOCIATED WITH THEM

This shaft signature is then processed to measure energy levels and specific diagnostic patterns examples of which are shown in FIG. 2, together with the faults they are likely to indicate. Faults are identified by analyzing these energy levels and patterns over several passes and various parameters are also cross-referenced to increase the probability of detection and reduce the probability of false alarm. Using this technique, the following typical gearbox faults can be identified:

(*a*) gear mesh quality;

(*b*) gear alignment;

(*c*) fractured or damaged teeth;
(*d*) tooth pitch errors;
(*e*) bent or damaged shafts;
(*f*) cracked shafts;
(*g*) housing or case misalignment;
(*h*) brinelled raceways;
(*i*) scratched or dirty elements or raceways;
(*j*) damaged elements or raceways.

FIG. 2 shows the ways in which some of these are identified.

Cost-Effectiveness

The cost-effectiveness of Vibration Analysis depends primarily on using it to put gearboxes onto on-condition maintenance. However, there is evidence to suggest that the reliability of adjacent equipment, and in particular electronic equipment, will be increased if vibration levels are reduced.

An attempt was made by the US Army as long ago as 1973 to quantify the potential benefits of reduced vibration levels in helicopters. A head absorber which reduced vibration by 54% was fitted to a group of helicopters whilst a second group acted as a control. When the equipment failure rates and unscheduled maintenance man-hours for the two groups were compared, it was found that the group fitted with the head absorber showed a 48% reduction in equipment failure rate and a 38.5% reduction in unscheduled maintenance. It was estimated that this was equivalent to a 10% reduction in the life cycle cost of the aircraft concerned.

Also, in 1989, 702 Naval Air Squadron embarked on an intensive rotor track and balance programme which significantly reduced the vibration levels experienced on their aircraft. Subsequent comparison of the reliability of the various aircraft systems before and after this programme showed a 12% increase in reliability of the avionic equipment.

Probably the most comprehensive Naval trial of Vibration Analysis equipment was carried out by the Fleet Air Arm in 1988 and 1989. This showed that there may be teething problems with the initial installation of prototype equipments that could lead to a loss of confidence in the system. Appropriate development with service involvement, including trial installation, is essential to ensure that any fleet fit has high reliability from the start.

Vibration Analysis is being marketed as the Health and Usage Monitoring technique which offers the greatest cost benefit. The range of hard-headed business organizations that are investing in this technique vouches for its potential. My only word of caution would be, to be clear what it is you want Vibration Analysis to do for you, and what benefits you expect it to provide, before committing your scarce funds.

Wear Debris Monitoring

Rolling contact fatigue of bearings and gears cannot be completely designed out of a gearbox or engine and therefore some random failures resulting from it must be expected in service. Fortunately, damage propagation rates tend to be low and therefore the problem can be effectively contained by the routine analysis of debris in the oil system. The wide range of particle shapes, sizes and materials that can be generated however, calls for a variety of monitoring techniques. The most common faults generate relatively large ferrous particles with leading dimensions ranging in size from 500 μ to 1 cm or more. Magnetic Plugs will collect these particles but rely on skill and experience of the maintainer to interpret the resulting debris.

Where gearboxes or engines produce non-ferrous debris or debris with a leading dimension of under 15 μ, oil analysis has proved a very powerful technique. The main problem with this technique however, centres on the quality assurance of the oil samples. It is essential that maintainers implement strict routines to record accurately the quantity of oil that has been added to the system since the last sample was taken, and of course it is critical that samples from different sources, such as two identical gas turbines for example, are not confused. Currently, samples are returned to a central analysis laboratory such as the Naval Aircraft Materials Laboratory (NAML) at RNAY Fleetlands in Gosport. In the case of Fleet Air Arm Aircraft, maintenance advice based on the analysis of the sample and trending of previous samples is forwarded to operating units by signal. Work is under way to develop automatic analysis equipment for use at the operating unit. However, as there is no evidence to suggest that fault propagation rates are high enough to require such a system, and it would be unable to benefit from the enormous data base which has been built up at NAML, it is questionable whether a case exists to introduce such a system.

The Fleet Air Arm has been using these Wear Debris Monitoring techniques with considerable success for many years. Our experience is that they should be capable of detecting wear in:

(*a*) Major components such as gears, splines, shafts and bearings (usually ferrous materials).

(*b*) Important components such as bearing cages (frequently copper-based), interface plating (copper and silver), hubs (sometimes titanium), locking washers (aluminium), casings (magnesium or aluminium), seals (cast iron, rubber or carbon) and plain bearings (tin, lead, copper).

If it is decided to introduce a Wear Debris Monitoring system, the following requirements should be taken into consideration:

(*a*) Sensors should have a high catch efficiency, and preferably be placed in the sump or exposed to full oil flow.

(*b*) All debris should be retained for examination and for pump protection.

(*c*) All routinely removable sensors should have self-sealing housings.

(*d*) Where quantitative debris measurement is necessary, remote indication should be provided.

(*e*) Debris analysis should provide a quantitative output.

(*f*) Analysis techniques should include trending of results.

Some very interesting work which is now under way is looking at the application of machine learning techniques which use all of the data in the database to provide a more effective trigger to critical changes or patterns in the data. The technique involves pattern recognition and operates without any prior knowledge about the data or its origins. Experiments with these techniques using large data bases such as those at NAML have been successful in identifying previously undetected faults, and they appear to offer a potentially very powerful analysis tool for use with large databases. Progress in this area will be monitored with interest.

Visual Inspection

Visual Inspection is, of course a tried and tested Health and Usage Monitoring technique and it still has a role to play today, particularly in the confirmation of defects identified by other techniques, or the triggering of other, more comprehensive Health Monitoring or Non-Destructive Testing. Indeed, in some cases, this may be the only way of achieving acceptable probabilities of detection and false alarm. It is essential however that there are clear and preferably quantitative criteria on which to base acceptance or rejection. A good example of this is the use of Wear Debris Atlases providing pictures of harmful and harmless particles at meaningful magnifications to assist with the assessment of wear debris from magnetic plugs and filters.

Contents and Pressure Gauging

Contents and Pressure Gauging are the classic methods of Health and Usage Monitoring of oil, hydraulic and fuel systems. The primary problem which is likely to be encountered with these systems is fluid leaks from fractured pipes; over-torqued unions and filter housings, damaged and unseated seals and so on. Accurate and reliable gauging coupled with conscientious visual inspections is still and is likely to remain the most effective technique for monitoring these oil systems.

Temperature Monitoring

Thermocouples have been used to good effect in a number of integrated Health and Usage Monitoring systems to monitor the condition of bearings, and Thermal Imaging may have a role to play in the future, although its use is currently limited to static installations and test beds.

Engine Performance

The routine monitoring of engine performance has proved to be a most effective Health Monitoring technique for gas turbines. Wherever possible, this monitoring should not interfere with normal operations. It may be preferable to consider conducting less accurate but less intrusive monitoring on a regular basis and use trending techniques to trigger a more comprehensive dedicated performance assessment when required. This technique has been used to good effect over a number of years in our helicopter fleet.

Usage Monitoring

As I have already said, there are two approaches to fatigue usage monitoring:

- Direct measurement of the loads applied to the structure.
- A parametric approach whereby easily measured parameters are used to calculate fatigue usage by referring back to either the designer's original stress measurements or data from load measurement trials.

The dilemma with Usage Monitoring is that direct measurement of the fatigue life usage of a component can be very expensive and, at first sight, parametric usage monitoring can seem a cheap and attractive option. However, there are a number of factors which need to be considered which could make the total cost of ownership higher if Parametric Usage Monitoring is used.

First and most significant, as Parametric Usage Measurement does not measure fatigue life usage absolutely, there will inevitably be a measurement error which the designer must allow for. As a result of this safety factor, there will always be some fatigue life remaining on a component when it is replaced. Furthermore, an equipment's employment is likely to change during the course of its service life and may well give rise to loads or loading rates that differ substantially from those anticipated at the design stage.

In the early days of operations in the South Atlantic the RAF were concerned that they were abusing their Sea Kings by operating them outside the original design envelope. They therefore carried out a limited Operational Data Recording exercise. This served to demonstrate the conservatism with which lives were originally determined. For instance, the design envelope assumed that 51% of time would be spent above 88% torque when in reality only 2.8% of the time is spent above 80% torque. More importantly from the fatigue damage point of view, the design envelope assumed the aircraft would spend 2% of its time at 111% torque when in reality there was no occurrence above 110% torque and only 0.135% occurrence above 100% torque, and in practice the aircraft recorded no fatigue on components lifed against torque throughout the whole trial. This exercise, which admirably demonstrates the value of revisiting original design criteria from time to time, is now being repeated throughout our aircraft fleet. Direct Load Usage Monitoring of all equipment will, of course, avoid the problem; but at a cost.

The Ministry of Defence has recently conducted a series of Operational Data Recording Trials to compare the actual fatigue damage consumption on various aircraft types with the original design assumptions. These trials began as simple parametric logging exercises and later developed into direct load measurement. The conclusion reached from these trials was that it was not possible to correlate the direct loads measured in the later exercises to the parametric measurement carried out in the earlier exercises. Therefore, as the lifing policy will have to make allowance for any uncertainty in the usage measured by reducing the life of the subject component, there will be a significant cost penalty in adopting Parametric Usage Monitoring which may well cancel out its cost advantage over Direct Load Usage Monitoring.

Built-In Testing of Avionics

Up to now we have concentrated exclusively on mechanical systems, but it must not be forgotten that the Health Monitoring of electronic and electrical systems can be equally as important. The discussion of the benefits and potential problems associated with In-Built Check Out Systems (IBCOS) and Built In Test Equipment (BITE) deserves an article to itself. Suffice it to say here that it is essential to take them into consideration when developing the Health and Usage Monitoring strategy for a system.

SUMMARY

This article only scratches the surface of this very large subject. But, hopefully, it gives an indication of the potential benefits and dangers associated with Health and Usage Monitoring. If there were one single message that I wished to get across from this article, it would be that the procurement of Health and Usage Monitoring Systems is no different from any other major project in that investment up front, in getting a clear and accurate requirement and ensuring what you buy meets that requirement, will pay dividends in the long run.