Articles

Vibrations in helicopters – reduction and monitoring

Terry Ford

The author

Terry Ford is an aerospace writer who has had many years of experience in the aerospace industry, latterly with British Aerospace, Weybridge, UK.

Abstract

Describes the Westland active control of structural response (ACSR) technique for reducing and alleviating vibration. Examines a refined coupled rotor/flexible fuselage model based on the ACSR approach. Reports on vibration health monitoring (VHM) which has been developed by Westland and details further work which is continuing in this field.

Aircraft Engineering and Aerospace Technology
Volume 69 · Number 2 · 1997 · pp. 119–125

One of the key problems facing rotorcraft designers is that of reducing vibration levels below specified limits. The increasing demands on flight envelope expansion, such as nap-of-the-earth flying, and high speed, high g manoeuvres, coupled with the need to improve systems reliability and reduce maintenance costs, has resulted in more stringent vibration specifications.

Rotorcraft, of course, have particular vibration problems compared to fixed wing aircraft. It is well-known that the principal contributors to vibration levels in the helicopter fuselage are the main and tail rotor systems, as well as the aerodynamic interaction between the rotor and the fuselage. The need for vibration reduction in helicopter design has led to the development of two fundamentally different approaches to vibration reduction and alleviation.

The first approach is passive, whereby use is made of vibration absorbers and vibration isolation devices. Another passive method involves careful structural dynamic design to minimize vibration in forward flight. A drawback of all such devices is that they may be optimized for a particular operating condition, and variations from normal operation result in performance degradation, since they are unable to adapt. Also, their performance is often constrained by considerations of parasitic weight and drag.

Active vibration alleviation

The second approach is based on using active control for vibration reduction and there have been several methods based on this philosophy. Two of the more recent ones show considerable promise. One involves an actively controlled flap (ACF) located at the outboard portion of the blade, which has been shown to achieve vibration levels comparable to higher harmonic control (HHC) while consuming much less power.

Another approach is active control of structural response (ACSR) which was initially developed by Westland and has been applied to several types of helicopters. The main principle of the active vibration alleviation techniques employed is that they apply controlled secondary excitations to cancel the effect of vibration generated by the primary uncontrolled excitations from the main rotor. Unlike passive techniques, active control is usually based on the feedback from sensors dispersed around the airframe, which will adapt the secondary excitation to account for

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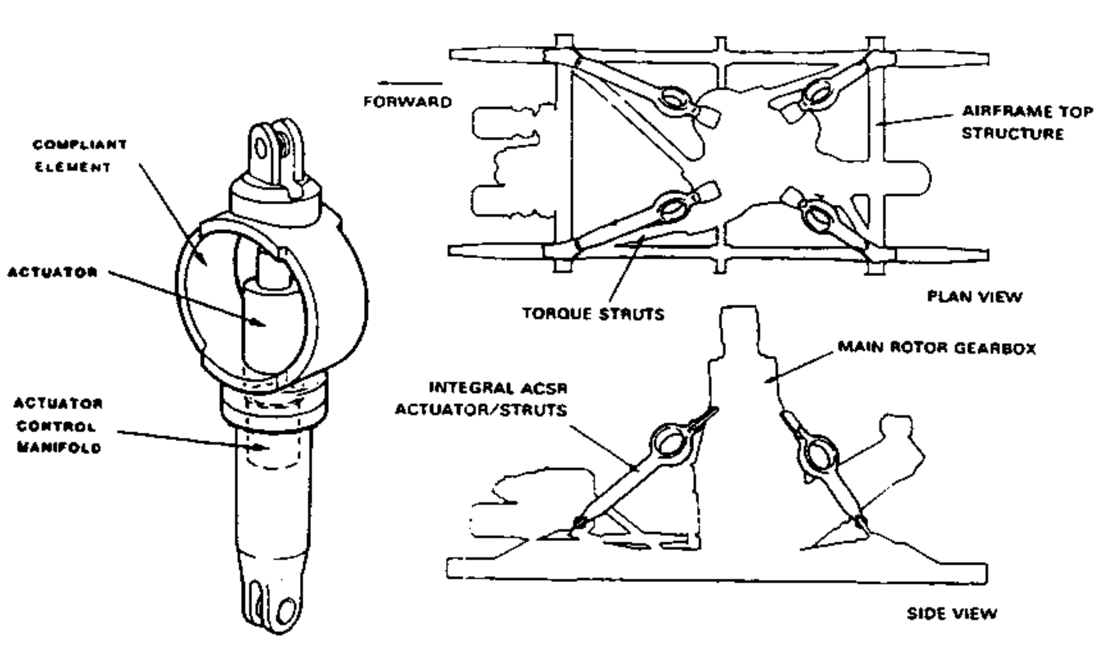
changes in vehicle operating condition. An amount of early work was concerned with attempts to cancel vibration at source and also, isolation of the airframe from the vibration source. Both of these efforts, however, suffered performance constraints.

The Westland active control of structural response (ACSR) technique has as its central element the adaptive control unit, which monitors vibration from a number of accelerometers, calculates and schedules the vibration reducing force demands to the ACSR actuators, and self-adapts its control algorithm to maintain performance against varying flight conditions and aircraft weight and centre of gravity. The system operates in the frequency domain on vibration at distinct harmonics of the main rotor fundamental frequency. Although the ACSR system configuration has been optimized for the control of the dominant blade passing frequency vibration, the system has been shown to have the potential to control other rotor-induced vibration harmonics.

Using microprocessor technology, analysis suggested that application of secondary vibrational excitations using hydraulic actuators could achieve the major reductions in vibration desired with much lower levels of power input. Structural rig work confirmed this, and a complete WG30 helicopter structure was then employed for a shake test, with ACSR hydraulic actuators installed between the gearbox and the main cabin, operating in parallel with the existing passive elastomeric treatment. Subsequent flight trials with this aircraft showed an 80 per cent reduction in vibration at the blade passing frequency in cruise. On the Westland 30, the ACSR control unit in the flight trials in 1987 received airframe vibration signals from 24 accelerometers located around the airframe, 17 in the cabin and cockpit, four on the engines, and three on the tail rotor gearbox. During the following year or so, extensive and very successful ground tests were undertaken on a Sikorsky S-76, again using dual point actuators. Six hydraulic units were installed in an experimental configuration to test the full range of possible actuator installation positions (see Figure 1).

On the Anglo-Italian EH101 helicopter, the ACSR installation employs four actuators which are installed on the main gearbox support struts. An extensive flight evaluation programme has been conducted on the EH101, which has shown the superior vibration-reducing capability of ACSR for a range of steady and manoeuvring flight conditions, at a variety of aircraft all-up weights. Average 5R vibration levels in the cabin and cockpit have been reduced by 75 per cent or more at the cruise speed of 140 knots, and by as much as 90 per cent in the cockpit. In particular, the vibration levels were generally reduced to below the target requirement of 0.15g throughout the forward speed range, and in some areas of the airframe levels were reduced to below 0.05g.

Figure 1 EH101 actuator installation



Further investigations

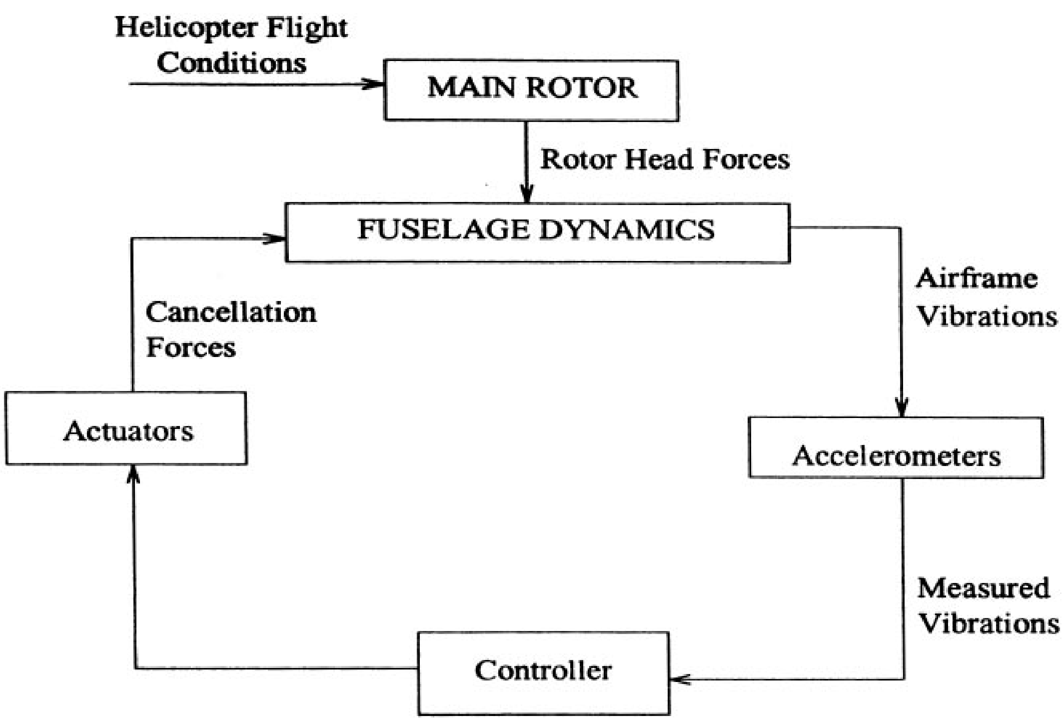
A schematic diagram of the ACSR system is illustrated (Figure 2). When applying this to the helicopter vibration reduction problem, the fuselage at selected locations is excited by controlled forcing inputs so that the combined response of the fuselage, owing to rotor loads and the applied excitations, is minimized. Recently, a modified variant of the ACSR approach, known as active vibration reduction (AVR), has been explored and flight tested.

Despite success with the ACSR system, some limitations have been encountered when compared with earlier tests. This emphasizes the importance of an analytical simulation capability that can provide fundamental understanding needed for the successful implementation of the ACSR approach. A refined coupled rotor/flexible fuselage aeroelastic response analysis suitable for the modelling of vibration reduction based on the ACSR approach has been developed. The work aims to: describe a coupled rotor/flexible fuselage aeroelastic response model, including the actuators required for the simulation of an ACSR system on a typical helicopter; present a recently completed vibration reduction study employing a disturbance rejection scheme based on an internal model principle (IMP) for the controller; and determine the sensitivity of the actuator forces needed for vibration suppression to changes in the location of the sensors, which measure the location of the vibration levels in the fuselage.

The coupled rotor/flexible fuselage model has a provision for incorporating an ACSR platform. This platform consists of a rigid rectangular plate inserted between the rotor and the flexible fuselage. At the four corners of the platform, the model can accommodate high frequency force actuators, which produce very small displacements but considerable force. Provision is made for measuring accelerations at a discrete number of fuselage locations. Currently, the sensors are placed at the pilot seat, mid-cabin and rear cabin locations, and measure the vibration levels at these positions. A complete mathematical model describing the active controller for these actuators, together with results illustrating their potential for vibration reduction, has been prepared.

The results presented for the coupled rotor/flexible fuselage model are based on a combination of parameters intended to model approximately an MBB BO 105 helicopter operating at a weight coefficient of $C_w = 0.005$, with a soft-in-plane four bladed hingeless rotor. Results have been obtained for blade tip responses, vibratory hub loads, fuselage accelerations at various locations of interest, control forces needed to achieve vibration suppression, actuator displacements, and

Figure 2 Helicopter system schematic for ACSR



power consumption. The sensitivity of the control forces and actuator power requirements to the location where the baseline vibration is measured, have also been studied.

In summary, a refined coupled rotor/flexible fuselage aeroelastic response model for vibration suppression study has been formulated. The fuselage contains a provision for the modelling of a novel type of ACSR vibration suppression device. The fuselage is represented by a fairly elaborate finite element model, which accounts for the effect of important non-structural masses. The coupling between the rotor and the fuselage is accomplished implicitly by satisfying force and moment equilibrium at the hub. The approach combines a non-linear rotor model, where the non-linearities are due to moderate blade deflections, with a flexible fuselage represented by a linear finite element model.

A controller based on internal model principle (IMP) is implemented in conjunction with a coupled rotor/flexible fuselage model. Numerical results indicate that the controller based on IMP can reduce vibration levels below 0.05g for all fuselage locations considered. In addition, the proposed controller does not influence the vehicle airworthiness, since the actuators are implemented in the non-rotating system.

The numerical simulations show that the control forces for vibration reduction required by the actuators depend on the control algorithm employed. The simpler control algorithm denoted as ACSR needs substantially larger forces than the control algorithm based on the IMP, to achieve a similar level of vibration reduction. It has also been shown that fairly large control forces are needed for vibration reduction; however, these are accompanied by small actuator displacement. The overall power consumption needed for vibration suppression is small. The sensitivity of the control forces in the actuators and the associated actuator power consumption depend on the locations where the baseline vibrations are measured. This dependency, however, is not severe.

Health and usage monitoring systems

Health and usage monitoring systems (HUMS) for helicopters have progressed in recent years from development and demonstration of prototype equipments to large scale implementation in various parts of the world. The harsh environment of the North Sea, where rotorcraft are engaged in support of the oil industry, has provided the UK with the background for the amassing of service experience.

A number of techniques are available to monitor helicopter and other transmission systems which potentially have a wide range of defect conditions, albeit with a low probability of occurrence. These include vibration monitoring, temperature monitoring, wear debris monitoring, and oil analysis. A combination of techniques are usually used, each particularly suited to certain defect classes. We shall be mainly concerned here with vibration monitoring and analysis.

Westland started developing vibration health monitoring (VHM) for helicopter transmissions some 20 years ago, since it has the potential to: detect and locate cracks and other defects without a debris signature, which would not be found by other sensing systems; detect and locate defects in rotating components, gears, shafts and also bearings; and complement other health and usage monitoring technologies.

The Westland VHM package combines data acquisition and diagnosis, examining changes in the dynamic characteristics of the transmission system. Defects modify the dynamic behaviour of components and change the vibration spectrum of the system. These modifications are automatically assessed for location and severity by the diagnostics element, which identifies signals associated with faults in the transmission at an early stage, before serious damage occurs.

Development and details

The first exploitation of VHM on civil helicopters in commercial operation was implemented on the Westland W30 in the 1980s. VHM was undertaken on a regular basis and used to extend the transmission time between overhauls (TBO). Government-sponsored civil and military flight trials have been conducted in various parts of the world and demonstrated the effectiveness of the Westland technique.

A major operator, Bristow Helicopters, and its other partners, GEC-Plessey and MJA Dynamics, developed the integrated health and usage monitoring system (IHUMS) around the Westland VHM package, and this has been in operational service for some time on the North Sea fleet. All new helicopters now have to be fitted with a health and usage monitoring system. The Westland VHM system is also an integral part of the HUMS on the EH101 helicopter.

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Vibration monitoring is used to detect and locate defects which do not produce debris, such as cracks and imbalance, and defects which result in wear and imbalance, such as bearing degradation, tooth pitting, and sculling. VHM has the potential to detect a wide range of defects such as those involving fixed axis gears (spur, helical, bevel, conformal) and epicyclic gears (sun, planet, annulus), as well as shafts, splines and couplings, bearings, and structural cracks and other modes of distress if they influence the dynamic characteristics of the transmission.

Vibration analysis is vital and the methodology adopted by Westland is based on the fact that certain defects will alter the dynamic characteristics of rotating components, which in turn will alter the dynamic characteristics of the transmission. If such changes can be detected and located, then the potential exists to determine and identify the early degradation of such components.

Vibration is typically monitored using accelerometers mounted on the gearbox casing. The signal characteristics range from low frequencies (helicopter shaft rotation is typically 4 Hz) through to harmonics of high speed input stage gear meshing with frequencies of perhaps up to 50 KHz. The signals measured contain frequency characteristics from: rotor blade, propeller or fan rotation and harmonics, all gear meshing frequencies and harmonics, bearings, and certain accessories such as fans and gear pumps.

Westland analysis techniques have been developed bearing in mind that the ability to detect defects at an early stage depends on the utilization of the information contained within the signal characteristics at the high frequencies.

Methodology and diagnosis

Analysis requires extraction of information from components which are synchronous in nature, such as gears and shafts, as well as asynchronous information from components such as bearings. For synchronous components, characteristics are determined by signal averaging, which extracts from a combination of vibration sources solely those components synchronous with the rotational frequency of the selected shaft. The signal averaging process is undertaken for each shaft contained within the transmission, the process using azimuth sensing which allows synchronization of the vibration acquisition process.

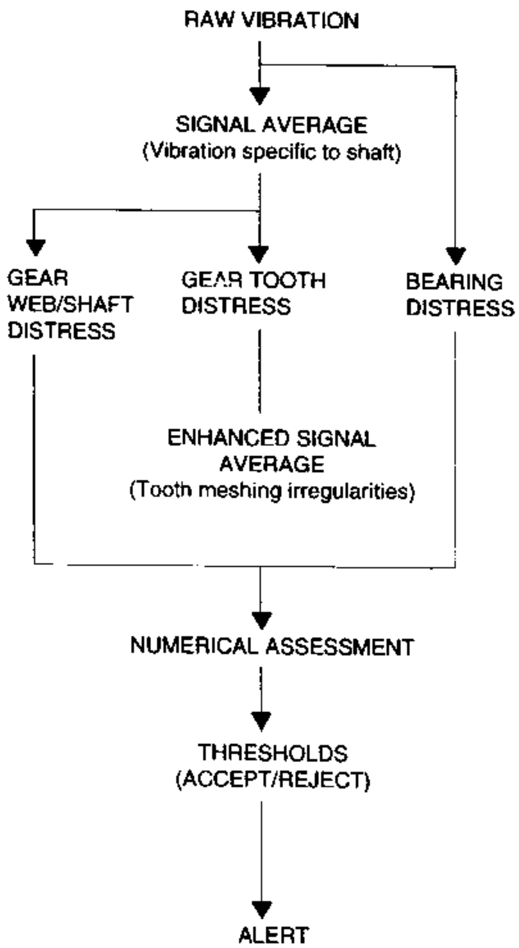
Subsequently, the signal average can be filtered and processed to improve the diagnostic capability for shafts and gears. The resulting enhanced signal average is accomplished by transforming the signal into the frequency domain, suppressing extraneous vibration characteristics and transforming back into the time domain. Defects in bearings are detected by processing asynchronous components in the vibration signal after removal of gear and shaft related frequencies.

Subsequent to analysis, numerical assessments of parameters undertaken and compared with alerting thresholds. Should parameter values be greater than the pre-determined thresholds, then an alert status signal can be given (see Figure 3). Effective diagnosis of defects requires that the signal conditioning and processing identifies information pertaining to potentially serious defects while, at the same time, the likelihood of false alerts is kept at a low, acceptable level.

Variability effects

Despite the success of helicopter monitoring, unsubstantiated indications have been an important issue for gearbox diagnostics. Most

Figure 3 Vibration analysis and diagnosis

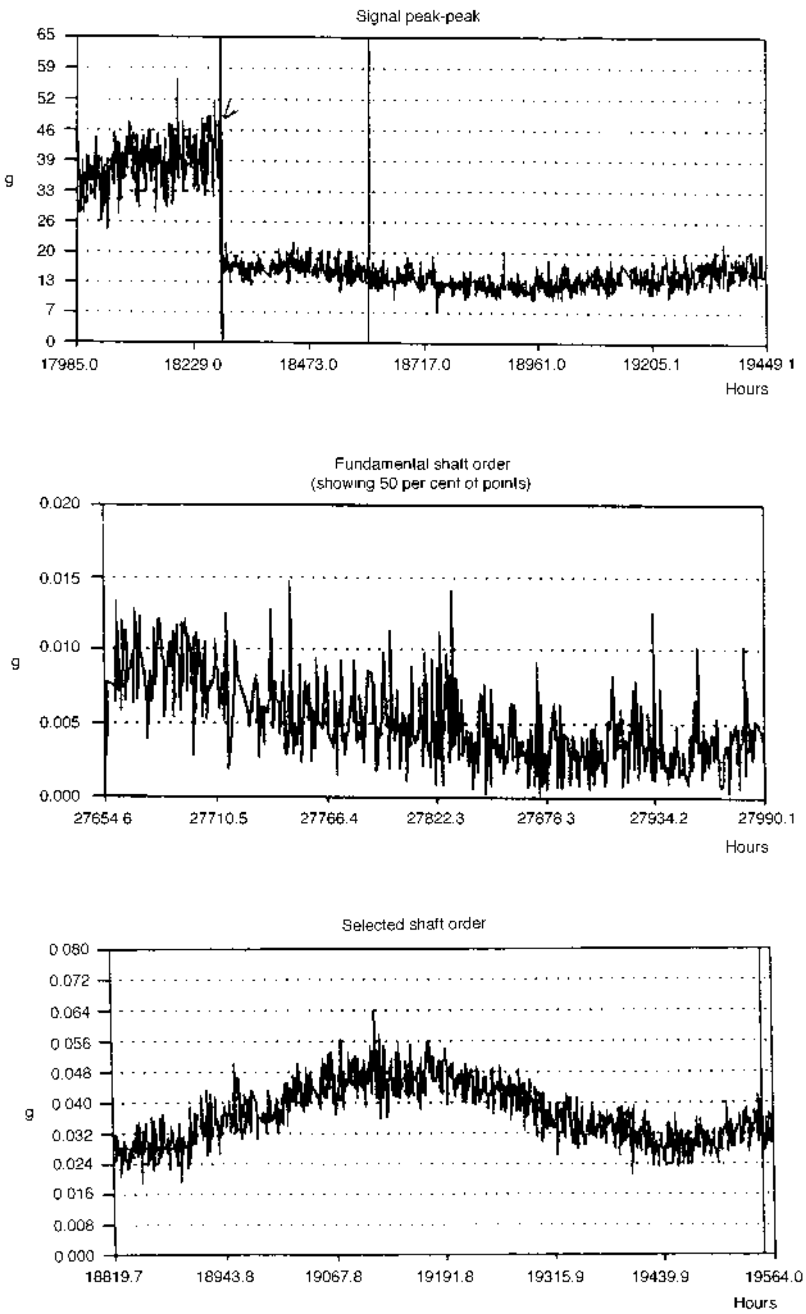


of the problems encountered have related to instrument integrity, but the underlying variability of diagnostic parameters has become of increasing importance as installation problems are overcome and a wider range of data are available.

Gearbox vibration signatures show variability, which can be caused by various factors. Variation in the operating conditions of the gearbox is one, as well as external influences from the remainder of the helicopter. Variations can occur in the external conditions, as well as those caused by small, in tolerance, variations from one gearbox to another. Also, inherent variability can arise from the highly non-linear nature of the gearbox dynamic system. In some cases, identifying the level of a rejection threshold is a compromise between achieving an adequate probability of timely rejection while minimizing the number of unwarranted rejections.

The integrated health and usage monitoring system referred to collects vibration data from, typically, seven accelerometers fitted to the main rotor gearboxes, and one each to the intermediate and tail rotor gearboxes. The onboard data acquisition and processing device provides for preconditioning, filtering, ana-

Figure 4 S61 – long term trends in various parameters



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logue to digital conversion and, where required, reduction to signal averages. The vibration signals are transferred to a ground station computer where a wide range of parameters is calculated for each. Values of certain of the parameters derived both from raw vibration data and signal averages are used to make an assessment of the integrity of the signals. This is essential, since the likelihood of instrumentation defects exceeds that of gearbox defects. Only when signal integrity has been validated are the parameters used for gearbox diagnostics.

Acquisition of transmission vibration data can be initiated by the pilot. More usually, the acquisition cycle is automatically triggered when the aircraft comes into a predefined flight window which may be defined by collective pitch, engine torques, bank angle and rate of climb. The precise window depends on the aircraft type, but is selected to identify straight and level flight under normal cruise conditions. During a typical flight, which will include rotors-running turn round at one or more rigs, between three and five sets of signal average signatures are collected for each of the main drive shafts in each of the gearboxes.

Both short-term and long-term trends have been investigated. For the former, there has often not been any evidence of systematic variation from flight to flight. Long-term trends from various parameters on an S61 aircraft are illustrated (Figure 4). The lowest trace is of particular interest, showing a long-term cycle variation. If this trace had been observed part-way through, it could well have been misinterpreted as a clearly increasing trend. For this particular example, a relationship with operational or other factors was not able to be found.

Further work is continuing to:

- examine the relationship with operating condition (using flight data recorder information);
- assess in greater detail the influence of maintenance actions;
- review the relationships between individual monitoring parameters;
- implement automated techniques to identify significant long-term trends in parameter values; and
- attempt to generalize the particular observations made.

Two important conclusions of immediate relevance to HUMS are: the necessity of correctly recording disturbances to gearboxes (a wide range of maintenance actions) if the diagnostics applied rely on relative changes; and the need for repair authorities to investigate otherwise unexplained long-term trends in parameter values which might be associated with changes in the condition of the gearbox.