Condition Monitoring in the Royal Navy

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SYNOPSIS

Selected monitoring techniques applied to significant equipment parameters will provide knowledge of an equipment's condition which, when combined with a sensible engineering judgement, can allow the immediate or future maintenance requirements to be decided. The RN operates a wide range of machinery in the many different classes of warship and submarine which make up today's Fleet and, for the last six years, it has been the RN's declared policy that the maintenance requirements of this machinery should be related to its condition. Previously a preventive maintenance system was operated where maintenance activities were carried out at prescribed calendar, or hours run, intervals. This was considered to have provided an over-insurance of equipment performance which was costly and did not necessarily reflect the true requirements of the equipments or systems concerned. The current upkeep and operating cycles of the surface warships are briefly described together with details of the shore support provided. Details are given of the various condition monitoring techniques currently applied to RN equipments, of the RN's experiences with these techniques, and of their application to a number of equipment types in RN service. The paper concludes with a statement of the work of the Ministry of Defence Research Establishments in the field of condition monitoring and an exposition of the future and likely intentions of the RN in this field.

INTRODUCTION

> 'The Carpenter should constantly examine the boats on the booms, quarters, and c., and report to the Senior Lieutenant on every occasion that they may appear to him to require repair.'
>
> Naval Officers Manual,
> Captain W. Nugent Glascock RN, 1836

For the past six years it has been the RN's declared policy that the maintenance requirements of the wide variety of machinery fitted in RN warships should be based upon considerations of an equipment's condition. The policy covers reciprocating and rotating machinery, marine boilers and heat exchangers, and to some extent ship systems. The upkeep requirements for all surface ship equipments and systems are now based on the following principles:

1. The maximum use of condition-based maintenance.
2. The critical examination of maintenance requirements against the operational needs.
3. Any overhaul or repair action to be taken at the lowest sensible level, ie repair by replacement of sub-assemblies.

Some equipments must have a low risk of failure for operational or safety reasons or their maintenance may be required to match a specific occasion such as docking. For these equipments maintenance based on calendar time, or hours run, and a degree of preventive over-insurance is accepted, although an extension to the time when a maintenance requirement becomes due may be granted in the light of certain inspections carried out by expert specialist teams. Mandatory safety checks such as the testing of overspeed trips on rotating and reciprocating machines continues to be carried out at prescribed calendar intervals.

Today the RN consists of 105 surface warships ranging from the latest CVS, the 'Harrier Carrier', HMS *Ark Royal*, with a complement of some 1000 men, to a Falkland Islands Patrol Vessel with a crew of 24; the Submarine Flotilla consists of 37 submarines ranging from the SSBNs with crews of 150 to the diesel powered *Porpoise* class with crews of 65. The means of propelling these vessels ranges from combined gas and gas (COGAG), with two Marine Olympus gas turbines per shaft driving the CVS, to a nuclear steam plant in the SSBNs and SSNs, to marine boilers and steam turbines in the older 'steam' frigates, and to medium-speed diesels in the smaller craft. The new *Type 23* class of frigate will be propelled by a diesel–electric drive for 'quiet' running and a combined diesel–electric and gas turbine (CODLAG) drive for high speeds. Various types of steering and ship's stabilisation systems are fitted and all ships and submarines provide their own hotel services for extended periods of operation away from their base ports.

Assisted maintenance periods (AMPs) lasting four weeks, which may coincide with leave periods,are programmed at nine or six monthly intervals for the bigger surface ships, and technical support during the AMP is provided by the uniformed Fleet Maintenance Units which are located, with their own shore workshop facilities, in the Naval Bases at Portsmouth, Devonport, Rosyth and Faslane. Docking intervals will vary for the different classes but for frigates and destroyers there will be a docking and essential defect (DED) period programmed at two or three yearly intervals and a refit or repair period, which may include considerable enhancement of the weapon fit, at intervals of four or six years, depending on the class of ship.

The maintenance system employed in these ships and in the

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submarines is known as the Maintenance Management System (MMS); certain checks, examinations or inspections are required to be carried out on an equipment at prescribed intervals, which are usually based upon the running hours of the equipment, either by the ship's staff or by a specialist uniformed Fleet team. Depending upon the results of these checks, or as a result of some deterioration in an equipment's performance, then corrective maintenance may be required. An example of the required maintenance operations, or 'Maintops' as they are known, for a boiler feed pump is shown in Fig. 1. Apart from basic servicing, it should be noted that the major maintenance operation of fitting an exchange pump is only carried out if certain pre-refit trials/inspections indicate the exchange to be necessary.

Included in the pre-refit inspections will be a vibration survey by a specialist Fleet team of vibration analysts. The maintenance of safety devices such as overspeed trips, relief valves, etc. is required to be carried out to a strict calendar or hours run schedule. A starred Maintop is one where undue postponement is likely to result in injury to personnel or in damage to equipment. Detailed requirements of each Maintop are contained in a job information card (JIC) unless the requirements are self evident.

It should be emphasized at this point that condition monitoring is neither an all embracing 'know it all' means of measuring the precise health of a machine nor does it rectify any deficiencies it reveals. It is an important and cost-effective means of obtaining reliable service from the many equipments which are in service in warships and submarines. There is no substitute for the engineering expertise of plant operators and for the rigorous scrutiny of plant and equipment performance which is achieved by the regular, routine and thorough checking of significant plant parameters.

CONDITION MONITORING TECHNIQUES

Vibration monitoring

The vibrations generated by running machinery will be transmitted to a surface where they can be sensed and, when measured as near as possible to a machine's bearings, an indication can be obtained of the machine's condition. By checking vibration levels at regular, chosen intervals, any deterioration in the machine's condition from a known base line will be indicated. Vibration measurements can thus provide an important part of a condition-based maintenance system.

It is now an established practice for a uniformed specialist vibration analysis team to measure the vibration levels at the bearings of all the reciprocating and rotating machinery fitted in warships as soon as the ship enters RN service and before and after a ship's DED or refit. These are known as base-line surveys.

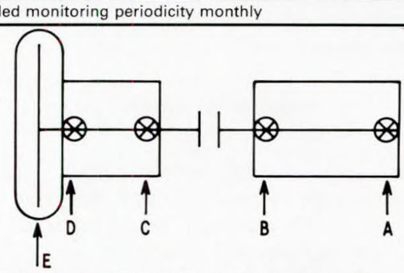
In the more modern warships where shipping routes are designed to allow important machinery, such as gas turbine change units (GTCUs) and diesel generator prime movers, to be exchanged in a ship's AMP, the specialist team will also carry out a base-line vibration survey of newly exchanged equipments on installation. The vibration measurements are checked and recorded and, provided they are satisfactory, a base line is established against which future routine measurements, recorded by the ships staff, can be compared. Any subsequent deterioration or trend of deterioration can then be monitored until a vibration level reaches an alert level when the reason must be identified from a full and thorough vibration analysis of the machine.

At present the Fleet is equipped with the Visin and the SPM 43A vibration monitoring equipments and the IRD 820M vibration analyser. The Visin provides a broad-band overall indication of vibration severity indicated by a colour code from white to red. The SPM 43A is used for the measurement of

MAINTENANCE SCHEDULE			BR NUMBER 3428	
Maint Op No	JIC	JOB DESCRIPTION	By WHOM	PER
1		Check lubricating water pressure.	SS	D
2		Lubrication routine – pressure governor.	SS	W
3		Drain sludge from lubricating water strainer, (Pump to be shut down).	SS	W
4		Lubrication routine – steam stop valve.	SS	W
5		Measure axial movement of rotor.	SS	M*
22	CM11	Take vibration readings and record in equipment log.	SS	M
8		Overhaul trip valve. Test hand and overspeed trips.	SS	4M*
7		Measure pump speed.	SS	6M
6		Overhaul governor and throttle valve.	SS	6M
9		Inspect lubricating water strainer.	SS	6M
10		Test differential pressure alarm.	SS	6M
11		Inspect overspeed and hand trip.	SS	6M*
12		Inspect turbine drain trap strainer.	SS	A
13		Inspect turbine centre pedestal.	SS	A
14	CM01	Inspect shock/vibration mountings.	SS	A
15		Overhaul lubricating water relief valve.	SS	A
16		Overhaul turbine casing sentinel valve.	SS	A
18		Inspect pressure/velocity reducing vessel.	SS	42M
21		Inspect and dimensionally check Non-return discharge valves.	SS	42M
19	NONE	Fit exchange pump (UXE) if M022 indicates.	D	42M
17		Overhaul rotating assembly.	SS	6000H
20		Deleted		
23	CM12	Carry out pre-refit trials/inspection in accordance with SEACL.	SS	PR
24	CM13	Carry out post-refit trials/inspection in accordance with SEACL.	SS	PR
ISSUE No. 4 October 1984		R3W/A	Side 1 of 1 Sides	
Schedule title Boiler feed pump weir TWL 20M and 20HS balances piston			Schedule number 3-4108-0000	

FIG. 1: Required maintenance operations for a boiler feed pump

Condition monitoring data form	Schedule No. 3-4946-0000 5-3111-0000	MMS form No. 6B/25 (March 1986)
Schedule title Girdle Stone evap p/ps & CFW booster p/p		
Equipment identity pump types ma 146, 147, 149, 169, 176 & 180		
Recommended monitoring periodicity monthly		



Note: All four evap pumps plus the shell are mounted on the same bedplate and therefore one mount reading will cover all four pumps.

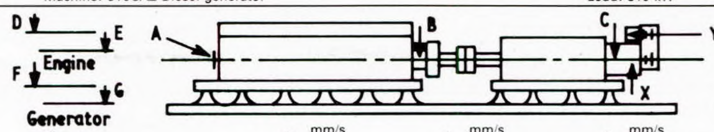
IRD 811 vibration				IRD 811 spike energy (rolling element bearing)			Above and below mount readings	
		Level in mm/s						
Pick-up point	Position	Normal average level	Alert level	Pick-up point	Position	Limit S/E *g*	If below mount reading is greater than 25% of above mount reading inform Section Senior Rating	
A	H V A	4.0	6.0	A	H V	0.8		
B	H V A	4.0	6.0	B	H V	0.8		
C	H V A	4.0	6.0	C	H V	0.8	Symbol	Identity
D	H V A	4.0	6.0	D	H V	0.8	→	Pick-up point
E	H V A	4.0	6.0	E	H V		×	Plain bearing
F	H V A			F	H V		⋈	Thrust bearing
G	H V A			G	H V		⊗	Anti-friction bearing
H	H V A			H	H V		─┤├─	Coupling
Issue No Original March 1986				*Note:* H = Horizontal, V = Vertical, A = Axial				

FIG. 2: Example of a condition monitoring data form

H.M. SHIP
Date: 14 March 84
Equip. used: IRD 820
Operator: CPO MEA(M) March
Main assy. R.P.M. 1200

Machine: 8YJCAZ Diesel generator

Load: 310 kW



Mounts: D mm/s 40; E mm/s 0.5; F mm/s 23.5; G mm/s 1.5

Pick-up position		Filter out		Filter in																											
		S/Eg	mm/s	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm	mm/s	cpm
A	H		18.5	3	0.6k (½ × rpm)	1.4	1.2k (1 × rpm)	12.5	2.4k (2 × rpm)	2.6	3.1k	1.2	3.6k	1.7	4.9k	3.6	6.1k	1.4	7.2k	2.8	8.5k			1.4	10.5k	2	12k	2	14.9k		
	V		17	0.4		0.6		11.8		1.6		1.6		0.5		2.3		1.4		2.1		1.7	9.6k								
	A		22/25					1.4				1.2		1.1		1		3				1.6									
B	H		30					26		4		3				2		2		2								1	15k		
	V		21					18						1				1						1	10.5k						
	A		11/12	0.5				4.4		1		2.5		1		1.9		3		1.8		1.2									
C	H	0.14	27	1				24				3						2								2	12k	3	15k		
	V	0.12	17	0.5				14.8		2.5				1.2		2		1		1.1		1								2	29k
	A		10					7.5		2		0.8		3				1.6		1.5		1.3						1.6	14.2k		
X	H	0.1	38	1				34		4		5				3		2													
	V	0.09	24					19		4		3				3		4													
	A		11					5.8				1				5		4													
Y	H	0.06	65					60								9		10													
	V	0.01	34					25										12													
	A		20					14		2				10																	

Exhaust temp (°F)				
CYL	1	2	3	4
A Bank	570	520	580	620
B Bank	610	490	560	460

Note: cpm = cycle/min, mm/s = velocity, S/Eg = spike energy, H = horizontal, V = vertical, A = axial.

FIG. 3: Typical vibration analysis readings for a diesel generator

rolling element vibrations, and the meter has a scale indicating in units of AdB.

In 1985 four *Type 22* frigates conducted a trial using a small hand-held vibration monitor supplied by IRD Mechanalysis UK Ltd and designated the IRD 811. This monitor indicates, on a meter scale reading, overall vibration levels in metric units of displacement (μm peak to peak), velocity (mm/s) or acceleration (**g** peak); a 'spike energy' facility can also be selected for the measurement of the vibration levels of rolling element bearings. Usually, vibration velocity provides the best overall indication of a machine's condition, however, for vibration measurements of machinery where the fundamental shaft speed is below 600 cycle/min displacement provides the best measure. For machinery where significant vibrations are experienced at frequencies above 60 kcycle/min the use of acceleration units is recommended. Each of the four frigates was provided with two IRD 811s and supporting documentation for the trial, which consisted of a list of the machines required to be monitored, the periodicity of monitoring each machine (generally monthly), and a data form for each machine. The data forms gave details of the monitoring points, the normal average vibration levels, and the alert levels at which a full vibration analysis would be required. An example of a data form is shown in Fig. 2.

The trial proved to be successful and all classes of surface warship are now being issued with IRD 811s and the supporting documentation applicable to the ship's machinery fit. The 'normal average levels' and the 'alert levels' have been derived from the records held by the Fleet Vibration Analysis Unit, and although it is not possible in this paper to provide details of the limiting levels for all the machines fitted in all RN warships, a broad outline is given in Table I. Note that the figures quoted in the table apply to machinery which is generally mounted on a bed plate supported by resilient mounts designed to reduce the effect of underwater explosions.

Vibration analysis

The IRD 820M vibration analyser provides an indication of vibration levels in the same units as the IRD 811 both on a print out and on a meter scale reading. The instrument is used to conduct the full vibration analysis required when an alert level is reached. An analysis of the vertical, horizontal and axial vibration measurements recorded at each bearing will then allow a diagnosis to be made of the cause of the high reading. Using the IRD 820M overall or 'filter-out' facility, measurements are taken for each recorded position, a discrete or 'filter-in' analysis over the full frequency range of the instrument is then carried out. A discrete frequency analysis can be defined as an examination of peaks of vibration and the frequencies at which they occur over a very wide frequency range. It does not mean that you avoid telling your Captain what the results are!

The key to identifying the source of machinery vibrations is frequency, and a guide to the cause of vibrations in very broad terms is given in Table II. Note, however, that it takes a Chief Artificer joining a specialist Fleet Vibration Analysis Team about one year to become a confident and competent analyst after having completed all the necessary courses and gained a great deal of practical experience.

Table I: A broad outline of vibration limits in RN warships

Equipment	*Vibration limit*
All motor-driven auxiliaries including fans	9 mm/s (discrete at fundamental speed)
All turbo-driven machinery	6.5 mm/s (discrete at fundamental speed)
Rolling element bearings	0.5 **g** spike energy (may be as high as 1.0 **g** spike energy in some applications)
HP air compressors	20–35 mm/s depending on type (overall filter-out readings)
LP air servo air compressors	35 mm/s (overall filter-out readings)
Refrigeration compressors	6–12 mm/s depending on type (overall filter-out readings)
Air conditioning compressors	5–15 mm/s depending on type (overall filter-out readings)
Auxiliary boiler auxiliaries	9 mm/s (discrete at fundamental speed)
Main steam turbines	6.5 mm/s aft bearing, 13 mm/s fwd bearing
Main steam turbine gearboxes	6.5 mm/s (discrete at fundamental speed)
Paxman diesel generators	5 mm/s at ½ × rev/min 7 mm/s at 1 × rev/min 12 mm/s at 1½ × rev/min
Olympus gas turbines	80% limit defined in engine Book of Reference
Tyne gas turbines	80% limit defined in engine Book of Reference
Resilient mounts	At least 50% reduction above and below mounts

Notes:
1. A 'filter-out' reading gives an indication of overall vibration amplitude.
2. Fundamental speed is the speed of rotation of the machine.
3. A discrete is a peak of vibration amplitude at a stated frequency or speed.

Table II: A guide to causes of vibration

Cause	Amplitude	Frequency	Remarks
Imbalance	Proportional to imbalance. Largest in radial (horizontal or vertical) direction	1 × rev/min	For large overslung rotors high axial amplitudes will also result.
Misa-lignment	Large in axial direction: 50% or more of radial vibration	1 × rev/min usual; 2 and 3 × rev/min sometimes	Best found by appearance of large axial vibration; dial test indicators should verify results. Misalignment can be confirmed by phase analysis.
Rolling element bearings	Unsteady unless recorded in spike energy	Several times rev/min but probably not an even multiple of rev/min	In many cases several high vibration amplitudes at a number of high frequencies. Vibration not usually transmitted to other parts of machine, the defective bearing is therefore usually the one nearest to the part where highest amplitude occurs. Use of spike energy facility provides steady reliable readings.
Journal bearings,			
Wiped bearings	Vertical unusually high compared with horizontal	½ or 1 × rev/min	
Oil whirl		Slightly less (5% or 8%) than ½ × rev/min	
Lubrication		High frequencies not likely to be multiples of rev/min	
Eccentric journals	Usually not large	1 × rev/min	If on gears, largest vibration in line with gear centres. If on electric motor or generator, vibration disappears when power is turned off. If on pump or blower, attempt to balance.
Gearing defects	Low	Very high: gear teeth × rev/min	
Mechanical looseness	Amplitude at 2 × rev/min more than ½ that at 1 × rev/min	2 × rev/min	Loose mounting bolts or bearing holding down bolts.
Defective drive belts	Erratic or pulsing	1, 2, 3 and 4 × belt rev/min	Can result in higher amplitudes in direction parallel to belt tension.
Electrical defects	Disappears when power turned off	1 × rev/min or 1 or 2 × synchronous frequency	Caused by electrical defects resulting in unequal magnetic fields.
Aerodynamic or hydro-dynamic forces		1 × rev/min or number of blades on impeller × rev/min	Cavitation, recirculation or flow turbulence indicated by random vibration probably over a wide frequency range.
Reciprocat-ing forces		1, 2 and higher orders × rev/min	Firing stroke of ICE engine must be known; high vibrations at other multiples of rev/min may occur which reflect the number of firing impulses/revolution.

Vibration analysis of diesel engines

An analysis of the vibration measurements recorded from a 500 kW medium-speed (1200 rev/min) Paxman diesel generator provides an example of the process followed by the vibration analyst.

High vibrations from this machine were reported by the ships staff and a full vibration survey was therefore carried out by a specialist vibration analyst. The engine was run up and loaded to 310 kW on the ship's load. The IRD 820M was first used to record overall 'filter-out' vibration levels and then 'filter-in' print outs were obtained for points A, B, C, X and Y, using the velocity mode (mm/s peak) in the planes indicated in Fig. 3. At the same time cylinder exhaust pyrometer temperatures were recorded.

The high vibration levels recorded throughout the machine gave cause for concern but in order to pin-point the defect accurately it was necessary to conduct a second survey with the machine running at no load. A quick-look diagnosis indicated that the engine had suffered damage/failure to the secondary balance weights and the associated gearing and it was recommended that the engine should not run except in an operational emergency. The diagnosis of the cause of the high vibrations for this type of engine included consideration of the following.

Half-order vibration

Vibration at a frequency of half engine speed (600 cycle/min) should be negligible, ie less than 2.00 mm/s. It is caused by faulty combustion, which can usually be confirmed by exhaust pyrometer temperature readings being either high or low, or with a large variation between cylinders. A limit of 5 mm/s half-order vibration (vibrations at half running speed) is set by the engine maker but corrective action to adjust the engine's combustion must be taken at lower vibration levels if exhaust temperatures are not within permitted limits.

First-order vibration

Vibration at a frequency of once times engine speed (1200 cycle/min) is caused by imbalance or misalignment. Static imbalance is usually indicated by high vibration levels in the radial planes and dynamic imbalance is indicated by the presence of axial as well as radial components. Misalignment is indicated by high vibration levels in the axial plane, usually accompanied by a second harmonic, and can be caused either by mechanical misalignment between the engine and generator or by defective resilient mountings causing the engine raft to twist.

The limit for first-order vibration (vibrations at engine running speed) is 7 mm/s.

Second-order vibration

Vibration at a frequency of twice the engine speed (2400 cycle/min) may be caused by:

1. Mechanical looseness: usually indicated by high vibration levels in the vertical plane.
2. Torsional vibration: indicated by high vibration levels in the radial planes with smaller components at 2½, 3½, 4, 4½ and 6 times engine speed caused by defective torsional vibration dampers. The amplitude of this vibration is load related and will attenuate considerably with a reduction in electrical load.
3. Secondary balance: most Paxman engines are fully balanced for external primary and secondary forces and couples. Paxman 8YJ engines are fitted with secondary balance weights driven from the crankshaft to overcome these secondary forces. Vibration caused by imbalance is proportional to speed and is not load related but in certain circumstances load may affect vibration amplitudes. Secondary balance problems are indicated by high vibration levels in all radial planes both when a machine is on and off load.

The limit for second order vibration is 12 mm/s.

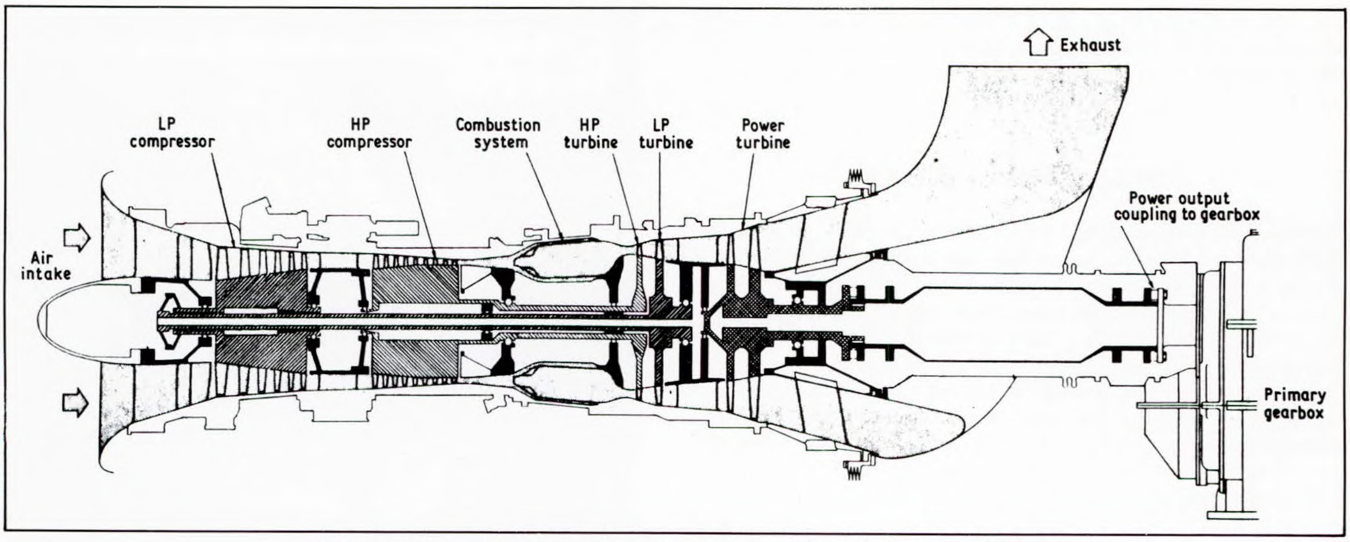


FIG. 4: Main assemblies and bearings of a marinised Tyne gas turbine

Third-order vibration

Vibration at a frequency of three times the engine speed is rare unless poor combustion is present. However, 3.6 kcycle/min is equivalent to the electrical line frequency (60 Hz) and so third-order vibrations may indicate problems within the electrical generator.

Exciter

Because of the position of the exciter, which is mounted on a bed plate affixed to the top of the overhung generator and casing, vibration amplitude levels tend to be higher than those experienced on resiliently mounted machines. The running speed of the exciter is 2400 rev/min (twice the engine speed). Problems encountered on the exciter are:

1. Unsatisfactory rolling element bearings indicated by spike energy amplitudes above 0.8 ***g*** S/E.
2. Misalignment between the generator and the exciter indicated by high amplitudes in the axial plane at a frequency of once times exciter speed.
3. Damaged drive belt. Belt defects cause vibration at frequencies which are multiples of the belt speed, which may be measured using a strobe light or calculated if the length of the belt, the pitch diameter of one pulley and the pulley speed are known:

$$\text{Belt (rev/min)} = \frac{\text{Pulley pitch diameter} \times \pi}{\text{Belt length}} = \text{Pulley (rev/min)}.$$

Problems causing vibration of the engine or generator accentuate vibration levels of the exciter.

Clearly the aim of any condition-based maintenance system is to predict when levels of vibration may be such that the machine may be damaged. In the above case of the diesel engine the failure of the secondary balance weights had already occurred when the 'expert' was called in. His presence then became necessary in order to locate the source of the problem and if he had incorrectly diagnosed the cause of the high vibration then a great deal of nugatory effort could have been expended in an attempt to remedy the problem.

Vibration analysis of gas turbines

A case history of a newly installed Tyne engine in HMS *Cardiff* provides an example of a vibration analysis which almost certainly saved the engine from subsequent damage. Marinised Tyne gas turbines are installed as the 'cruise' main engines in the *Type 21* and *Type 22* frigates and in the *Type 42* destroyers. Tynes are fitted with installed vibration transducers, one mounted on the gas generator (GG) casing, ie above the HP and LP compressors in Fig. 4, and a second on the power turbine (PT) casing. Vibration levels in units of displacement peak to peak are continuously indicated separately for the gas generator and the power turbine on gauges in the ship control centre (SCC).

For the Tyne in HMS *Cardiff* the installed vibration monitors indicated high vibration levels on initial run up of the engine in the ship, which the specialist vibration analyst investigated, using an IRD 820M, as part of the 'on installation' survey. Readings were taken at full power and these indicated a high amplitude of vibration at the LP spool speed measured at the gas generator end and a high vibration at the HP spool speed measured at the power turbine casing. A knowledge of the usual amplitudes and sources of vibration when an engine is newly installed and, in particular, recognizing that it is unusual to record high amplitudes at HP spool speed resulted in the engine being rejected. It was subsequently found that the rotating assemblies were out of balance, especially the LP turbine and the HP compressor.

The experience of the Fleet Vibration Analysis Unit suggests that the following considerations should be taken into account when analysing Tyne gas turbine vibration records:

1. Primary gearbox vibration fundamental is often transmitted to the GG pick up position.
2. The LP spool speed is almost invariably the predominant vibration and harmonics are usually evident.
3. Negligible vibrations are generally present at PT spool speed.
4. Some vibrations at HP spool speed are often evident but of low amplitude.
5. Auxiliary drive frequencies from the left-hand and right-hand wheelcases are sometimes observed at the GG transducer.
6. Transient vibrations are occasionally observed at LP frequency.
7. Vibration levels at the GG transducer are invariably higher than PT levels because of engine support arrangements.
8. The most important factors in minimising Tyne vibrations are the optimum alignment of the engine and the condition of the engine supporting arrangements.

Summary

The RN's experience with the Visin and SPM 43A was not altogether satisfactory: the colour scale of the Visin is too coarse and the fact that the SPM 43A's main application is for rolling element bearings limits its use; additionally, the units of AdB tend to inhibit the enthusiasm of the average RN Stoker for this equipment.

The combination of the IRD 811, supported by realistic documentation, and the IRD 820M should allow the measurement and analysis of vibration levels to play a significant part in the maintenance required by a knowledge of a machine's condition.

REAL-TIME ANALYSIS

Real-time analysers (RTA) are used extensively in industry and the specialist Fleet Teams are now equipped with Hewlett Packard 3561A dynamic signal analysers. This technique allows instantaneous vibration levels over a wide frequency range to be displayed on a cathode ray tube display. A printer attachment can provide hard copy of the results. The technique is particularly useful in the analysis of gas turbine vibrations where the HP and LP compressor speeds can be very similar and the RTA will differentiate clearly between the two. The Hewlett Packards are also useful for the analysis of very-low-frequency vibrations and of transient causes of vibration.

TORSIONAL VIBRATION ANALYSIS

Electrical power in the gas-turbine-drive warships is provided by Paxman diesel prime movers running at a constant speed of 1200 rev/min. These diesel engines are fitted with viscous fluid torsional vibration (TV) dampers, the efficiency of which can be measured either by sampling the viscous fluid, provided a sampling point is provided and accessible, or by conducting a torsional vibration analysis.

The torsional vibration analysis technique consists of fitting a toothed wheel on to the free end of the crankshaft (a suitable arrangement is achieved using the Econocruise system shown in Fig. 5 and recording torsional vibrations transmitted by a proximity probe sensing the movement of the toothed wheel. The amplitudes of torsional vibrations at significant orders (or multiples) of engine speed are then measured either for a number of 50 rev/min steps of engine speed ranging from 1050 to 1300 rev/min say, or by tracking these vibrations as the machine runs down to stop. An analysis of these measurements will give an indication of the TV damper effectiveness, as shown in Figs 6 and 7.

Torsional vibration analysis is relatively new to the specialist vibration analysis teams and at present this technique is continually being improved and developed with considerable help from Paxmans and the Admiralty Research Establishment at Pyestock.

CALIBRATION OF VIBRATION INSTRUMENTS

The accuracy of the measuring instruments used in any condition monitoring system is of fundamental importance. In the past vibration measuring instruments have been returned to the manufacturers for calibration as well as repairs. It is now intended that check calibration facilities for the IRD instruments held by ships and bases will be set up at Portsmouth and Devonport. These check calibration centres will be operated by the specialist Fleet Vibration Analysis Unit. It is intended that initially instruments will be check calibrated at six monthly intervals.

FIG. 5: Arrangement of Econocruise system for vibration analysis

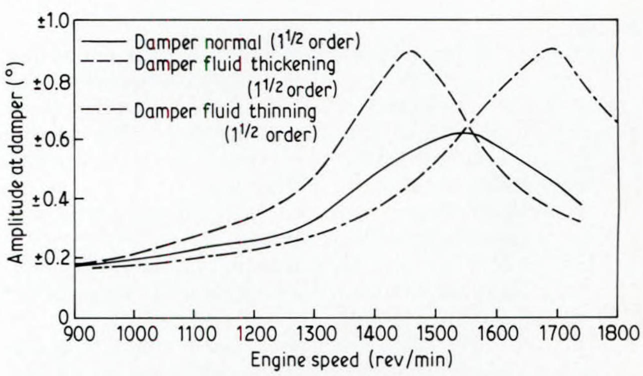


FIG. 6: Calculated 1½ order torsional vibration amplitudes at damper, showing normal, thickening and thinning fluid for full-load excitation

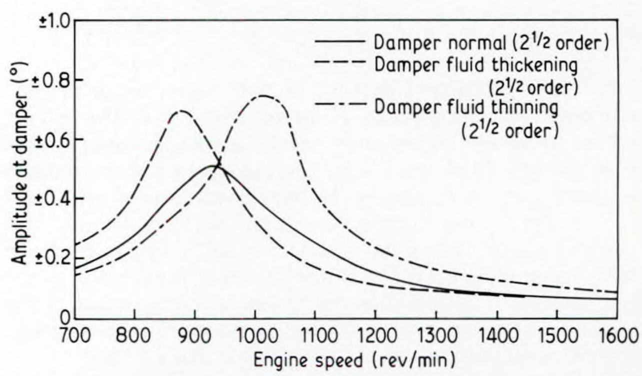


FIG. 7: Calculated 2½ order torsional vibration amplitudes at damper, showing normal, thickening and thinning fluid for full-load excitation

VIBRATION UNITS OF MEASUREMENT

The units chosen to indicate vibration amplitude range from the ubiquitous and logarithmic AdB to metric, or imperial, peak, RMS, average or overall values. The units indicated by the IRD equipments have already been described and the important point to be made is the obvious one that it is essential that both machinery manufacturers and their customers use the same units to define base-line and limiting levels. It is also sensible for the instruments used for monitoring or analysis of vibration levels to employ the same units as those used to 'pass-off' equipments from the manufacturer.

The use of the logarithmic decibel unit for machinery health vibration measurement is not regarded by the Fleet Vibration

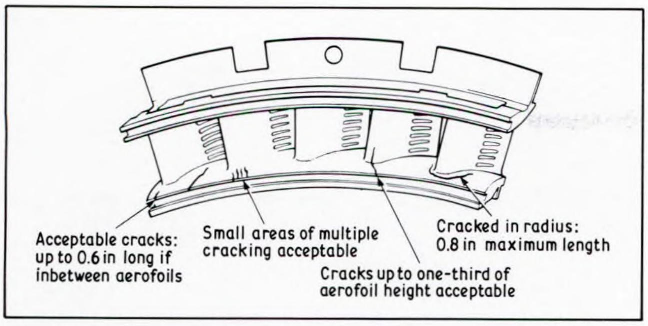


FIG. 8: Leading edge view, including inner platform, of HP nozzle guide vane showing cracking limits

Analysis Unit as being the best choice: it is difficult for operators to imagine a 'decibel' and the linear units used by IRD at least have the merit of being familiar. Although logarithmic scales contain more information than linear scales they also require a high degree of expertise to interpret, for example an increase of 3 AdB represents a doubling of the vibration amplitude.

Frequency is almost invariably indicated in cycles per minute (cycle/min) or cycles per second (cycle/s or Hz) but the alternative means of expressing frequency in octave bands is sometimes used. The IRD machines use cycle/min which, again, the 'non-scientist' finds easy to understand.

TRAINING AND PERSONNEL

A specialist team known as the Fleet Vibration Analysis Unit is based at Portsmouth with a Lieutenant Commander as the Unit's full time officer in charge. An outstation of the Unit is based in Devonport and similar teams operate in Rosyth and Faslane. The Team in Portsmouth consists of a Warrant Officer and five Chief Artificers and that in Devonport of a Warrant Officer and four Chief Artificers. The Chief Artificers join the Unit having already obtained considerable experience of operating machinery and they then develop their skills in the analysis of vibration measurements.

There can be few vibration analysts in the country who can match the expertise of these Chiefs once they have attended the courses provided by IRD Mechanalysis and also obtained essential experience in the field. In addition to their vibration analysis work, members of the team attend balancing courses at IRD where they are trained to correct imbalance in rotating machines using IRD balancing equipment. In the course of one year the Fleet specialist teams carry out vibration checks on over 3000 machines.

In each ship of frigate size and above there should be at least one Artificer who has attended a one week vibration analysis additional qualification (ADQUAL) Course at HMS *Sultan*, the Marine Engineering School of the RN in Gosport.

ENDOSCOPES

Regular and thorough internal and external inspections of equipments can provide an indication of a machine's condition. In the RN the internal examination of gas turbines, in particular, through access points, which may penetrate more than one casing, is carried out using endoscopes.

At present all gas turbine ships hold a simple rigid boroscope for use by the ship's staff. A specialist Fleet Team known as the Gas Turbine or COGOG Team is equipped with Olympus IF8D3 flexible fibrescopes supplied through Keymed Ltd.

At 5000 h running for the Tyne and 4000 h running for the Olympus gas turbine main engines an examination called a 'lifex' is conducted by the specialist team using a fibrescope. The lifex will allow extensions in service of the gas turbine of 500 h depending upon its condition. Successive inspections at 500 h intervals are then similarly carried out.

An example of the value of these inspections occurred when a lifex endoscope inspection of a Tyne engine in HMS *Alacrity* was carried out before the ship sailed for a deployment away from the UK. The inspection showed that one of the HP nozzle guide vanes was severely eroded and the engine was withdrawn from service, thus almost certainly preventing a subsequent catastrophic failure.

In future all of the gas turbine ships will be issued with fibrescopes and also a Book of Reference (BR) which contains coloured photographs of the internal parts of the gas turbines obtained from these inspections, together with details of the permissible limits of damage such as the extent of blade cracking.

An example of some HP turbine nozzle guide cracking limits is in Fig. 8. When these limits are exceeded then the engine may be exchanged for repair or further inspection may be carried out after a further 250 h running time to check the cracks for propagation. Provided the further inspection shows that the crack length has stabilised the requirement to recheck can be relaxed at the discretion of the operator up to a maximum of 500 h running. Ultimate crack acceptance limits are not known but those quoted in the BR provide excellent guidance and further experience of engine strip reports of both 'lifed' and rejected engines may allow further relaxations.

The fibrescope uses mains electrical supplies and a 35 mm Olympus camera can be attached to provide a permanent colour record of the inspected parts. In particular the fibrescope will allow a more extensive examination to be made, by ships' staffs, of the combustion chambers, which are especially vulnerable, and of rapidly wearing components.

Again, training of the operator is essential. At present the COGOG team attend a two day course at Keymed and then operators require some five working days carrying out inspections in the field to become fully competent and capable. When the fibrescopes have been issued to ships' staffs training of operators will be carried out at HMS *Sultan*.

MAGNETIC CHIP DETECTORS AND DEBRIS TESTING

Magnetic chip detectors are fitted into gas turbine bearing oil scavenge lines and to the oil return lines of some of the auxiliaries in the more modern warships. The Tyne engine, for example, has four chip detectors installed in the oil system.

The 'mag plugs' collect ferrous materials washed along with the oil and regular inspections of the collected debris provides an early indication of the impending bearing failure. Detectors are monitored daily throughout the life of the gas turbine. During the running-in period of a new machine swarf remaining from the engine build may be picked up and will be included with the magnetic 'fines' (minute particles of metal worn by normal abrasion from relative movement of components) and any foreign particles washed from the oil ways. After this initial wear the plugs should only pick up fines, which should not vary in quantity, and any major magnetic particles picked up will then provide an indication of deteriorating bearings.

A quantitative evaluation of the debris picked up is conducted using a debris tester. This is an eddy current device which compares the quantity of debris against a standard calibration piece. A cumulative record is kept of the results of successive debris tests. Where readings exceed a stated limit or when large chips are picked up, samples are sent to the Naval Aircraft Materials Laboratory (NAML) at the Royal Navy Aircraft Yard, Fleetlands, in Gosport for analysis. This laboratory facility determines the material of the fragments, which indicates the source of the debris. A decision can then be made as to whether to reject or retain the engine in service.

An example of the debris picked up on a magnetic plug is shown in Fig. 9.

ULTRASONICS

Although warships propelled by all gas turbines have been in service in the RN since 1975, the older steam ships will be required for some years to come. These are mostly *Leander* Class frigates where the propulsion steam turbines are supplied with steam from main boilers operating at 550 lbf/in^2 at 750–850 °F.

A uniformed Fleet specialist team, the Central Boiler Inspection Unit (CBIU), based at Portsmouth has the task of inspecting all boilers in the RN. These range from the controllable superheat main boilers in the steam frigates to the auxiliary boilers providing low pressure (100 lbf/in^2) saturated steam for water distillation plants and domestic heating in the gas turbine ships.

Formal inspections of main boilers are carried out when a ship comes into refit, which is at three yearly intervals for the steam frigates. The inspection assesses the durability of boiler tubes and pressure parts; both the superheaters and the economisers are 'lifed' at 12 years.

The durability of boiler tubes is decided by a measurement of the tube wall thickness using ultrasonic measuring equipment. Two types of analyser can be attached to the ultrasonic probes, one giving a graphical display on a cathode ray tube (A screen) and the other indicating tube wall thickness on a digital read-out.

The A screen is used as an initial check of wastage gradients in a boiler tube and the digital read-out is then used to measure the minimum tube thickness accurately. A prediction can thus be made of the life remaining of the tube.

The ultrasonic equipment used is self-contained and robust. It is fitted with built-in rechargeable battery packs and is supplied by Wells Kraut Kramer. The USK7 flaw detector A screen and CL204 digital thickness meter are used with Sonatest Comparigauge internal and external probes. Training is conducted at Kraut Kramer's Head Office at Letchworth where a full two week course will lead to a qualification to Level II of the American Society of Non-destructive Testing.

In the hands of a trained and experienced operator the ultransonic equipment can be extremely reliable and the durability and remaining life of boiler tubes can be predicted with confidence.

GENERAL

Although some condition monitoring techniques are described above, a number of routine tests such as diesel engine and main gearbox lubricating oil tests and feed water tests in boiler systems continue to be carried out at regular laid down intervals. Any of these tests can be regarded as indicators of machinery, plant or system condition.

By careful scrutiny of significant and accurately measured parameters, and by observing trends of deterioration, certain conclusions can invariably be made as to the cause of the deterioration and thus the condition of the machine concerned. A visual observation at regular intervals, which is hourly for running machinery in the RN, will indicate the obvious: the leaking pump seal, the sudden change in a discharge pressure or in a vibration level indicated by the noise made by the machine. All of these can be regarded as condition monitoring; they can equally be described as sound engineering practice.

The basic rules of condition monitoring can be seen to be first measure the amplitude of a base-line reading for a significant machine parameter, decide if the base-line reading is acceptable, and, if it is, monitor that parameter and note any deterioration until maintenance is required to correct the deterioration. The trending of deterioration levels should allow, with experience, a prediction to be made of a time when an unacceptable level will be reached and the required corrective maintenance action can then be programmed to be carried out at a convenient moment before that time.

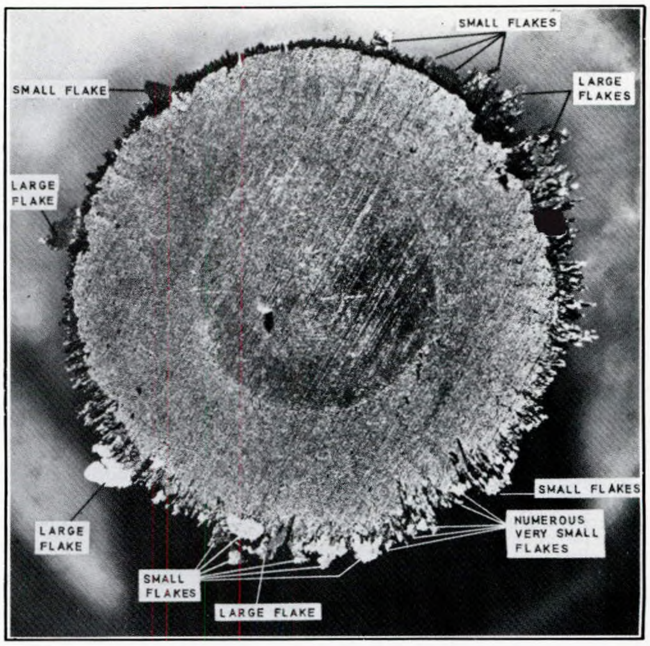


FIG. 9: Debris picked up on a magnetic plug

CONDITION MONITORING APPLICATIONS

Diesel engines

Considerable advances have been made in recent years in the application of linear vibration analysis techniques to diesel engines. The torsional vibration analysis technique for torsional vibration damper testing has already been briefly described.

The Paxman diesels in service in RN warships are fitted with individual exhaust temperature pyrometers at each cylinder head which can provide an indication of the combustion conditions of the cylinders. A trial is currently being undertaken which aims to set sensible limits for the spread of exhaust temperatures of all of the cylinders of an engine. Figure 10 shows the temperature limits permitted at various loads for a 16 cylinder Paxman Ventura engine. Readings of each cylinder's exhaust temperature at the usual ships loads of 350 or 450 kW are compared with a known base line for each cylinder and a temperature variation of 100 °C from that base line is then required to be investigated.

Crankcase pressure measurements can provide early identification of piston ring failure. At present routine checks are required to be made by a U-tube manometer fitted to one of the crankcase doors. However, this manometer will also be affected by compartment ventilation and the long crankcase breather pipes which vent to the upper deck. An alternative method of ascertaining piston ring wear is by the measurement of the flow of vapour passing from the crankcase to the breathers venting to the upper deck. This will shortly be available to the Fleet Diesel Team when they take delivery of an AVL Blow By Meter 413.

Paxman diesel top overhauls are carried out in situ at 6000 h intervals and major overhauls, which require the engine to be removed from the ship, are carried out at 12 000 h intervals. These overhaul intervals are now being extended for a number of engines in service and the life before overhaul is being progressively increased depending upon the results of linear and torsional vibration checks, endoscope inspections through cylinder head injector holes, measurements of piston ring blow by, and careful scrutiny of the engine performance records.

Weekly tests are carried out on the lubricating oil for acidity, carbon content, viscosity, water content and abrasive content.

Gas turbines

Vibration monitoring using both installed vibration monitoring equipment and the portable analysers described above is used extensively for the health monitoring of gas turbines. Use of magnetic chip detectors has also been referred to.

Performance checks of gas turbines are regularly undertaken at laid down intervals. These include:

1. Compressor delivery pressure against compressor speed. An indication of compressor blade tip wear can be obtained by regularly monitoring the compressor discharge pressure at a speed chosen to be at 75% engine power.
2. Turbine entry temperature spread. An indication of burner malfunction will be obtained by observation of the reading of the individual probes fitted to each combustion chamber.

At six monthly intervals the performance of the propulsion gas turbines is checked at sea. Records of the many instrumented plant parameters are taken at full power and the ship is manoeuvred ahead and astern. All of the results are recorded, compared with previous readings of engine pass-off tests, ship's acceptance trials, and full power and manoeuvring trials, and a final report is forwarded to the Fleet COGOG Team for scrutiny.

Pumps

Condition monitoring techniques applicable to the many types of motor driven pumps in service include vibration measurement, performance analysis and motor current measurements.

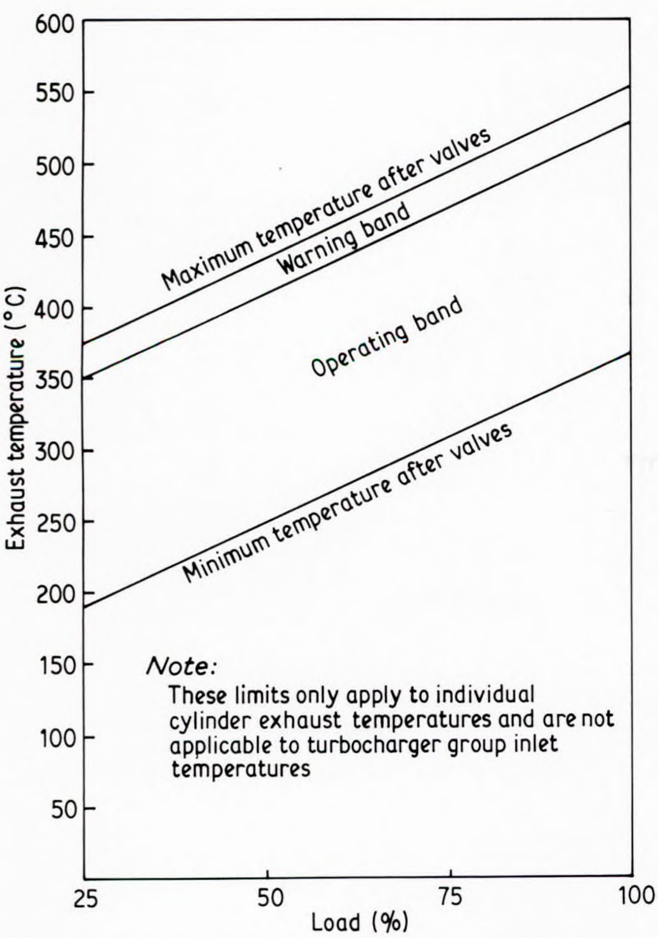


FIG. 10: Exhaust temperature limit for a 16 cylinder Paxman Ventura diesel engine

CURRENT DEVELOPMENTS IN ADMIRALTY RESEARCH ESTABLISHMENTS

A number of condition monitoring techniques are being developed either in the Admiralty Research Establishments (AREs) or by private firms.

In the AREs work is being carried out on oil debris analysis for gas turbines and the Naval Aircraft Materials Laboratory at Fleetlands have an excellent facility used by the Fleet Air Arm for the spectrometric analysis of oil samples. On-line oil debris analysis of main gearbox oil systems which will continually monitor particles in the system is also being assessed.

Vibration analysis techniques continue to be improved with the development of signal processing of vibration data methods as a technique for systems health monitoring. The torsional vibration analysis of reciprocating machines is constantly being progressed.

In the gas turbine field gas path debris detection systems are about to be evaluated. These give an indication of blade problems as soon as debris is produced thus allowing an engine to be stopped prior to major damage.

In the field of hydraulic pumps and systems work is being done on the accurate measurement of flow, pressure and temperature. A versatile sensing cable, manufactured by Raychem Ltd, which converts sound, vibration, input, pressure, stress or strain into electrical signals is also being evaluated.

THE FUTURE

A major condition monitoring trial is about to be started on 12 selected equipments, including gas turbines, centrifuges and hydraulic pumps, in a number of ships and submarines. The trial is expected to last three years during which time a considerable quantity of data will be obtained from the chosen parameters for the selected machines. An analysis will be made of the data collected.

The aim of the trial is to assess the various condition monitoring techniques used. The trial includes a requirement for strip reports to be completed at a chosen time for the monitored equipment in order to relate the collected data to the true condition of the machine. The ultimate aim of the trial is to allow corrective action to be taken to restore the performance of the machine and to prevent its failure, thus improving its availability.

There is no question that certain condition monitoring techniques such as vibration measurement and analysis should, and will, be more extensively used in future as quality control techniques before equipment acceptance from manufacturers and as an installation check when an equipment is first fitted into a ship. All machinery manufacturers should have a vibration analysis department and a customer, such as the RN, should be able to agree pass-off vibration levels with the manufacturer as a matter of course and as part of the acceptance procedure. Manufacturers of equipments should agree with their customers the base-line vibration levels which they should demonstrate. They should also agree on the alert or danger levels when corrective action should be taken.

Equipment designers can be criticised for their failure to build in to their designs measures such as the means of easily correcting imbalance; also considerations such as the provision of connections and fittings on bearing caps to accept portable vibration monitoring devices should become an essential part of machinery design in future.

As microprocessor-based engineering management systems are develolped they can provide excellent storage and analysis facilities for data obtained from condition monitoring. It is intended that the specialist Fleet Vibration Analysis Unit will, at some time in the near future, be equipped with a system which will allow vibration data to be stored on a tape or disc. Data may be obtained from portable electronic data gatherers such as the Scientific Atlanta Data Trap, the IRD 818, or the

Palomar 'Microlog', can then be retrieved and analysed, and alert values can be checked and possibly adjusted. The system should include a facility to transfer the data by telephone between the expert teams in the four main Naval Bases.

CONCLUSIONS

A condition-based maintenance system has been operated in the RN for some years, and the system will be considerably improved as the new vibration monitoring and analysis equipments and fibrescopes enter service. The major trial of condition monitoring about to be started should enable an assessment to be made of many of the various techniques now available.

Any financial investment into these techniques and their application in practice must be compensated by overall savings in the cost of operating the machinery and equipments fitted in the ships of the Fleet. Much still requires to be done in establishing the various base lines, alert levels, limits and levels at which corrective action becomes necessary. It will be appreciated that this paper describes only the RN's experience of condition monitoring applied to equipments fitted in ships and submarines. The Fleet Air Arm is also developing the same techniques with considerable success.

It has been the policy in the RN that uniformed teams should be formed to provide shore support and inspection and analysis expertise to ships and submarines at laid down intervals and to investigate particular problems. This policy is considered to be fully justified. Senior technical ratings, led by technical officers who can concentrate on a specialised but narrow field of engineering, can ensure that the highest standards are achieved and maintained.

A considerable and increasing investment in both portable and permanently installed ship-borne monitoring equipments, supported by the expert advice and direction provided by the Fleet Engineering Staffs, the specialist equipment sections of the Design Authority at Bath, and the Admiralty Research Establishments, will ensure that the maintenance of machinery based on a knowledge of its condition will continue to provide a cost-effective means of ensuring that our warships and submarines are both reliable and available wherever and whenever they are required.

Discussion

Rear Admiral D. R. SHERVAL (Chief Staff Officer (Engineering) to C-in-C Fleet): I was particularly attracted to part of Mr Riley's paper on the spare-parts register and the use of spare-parts consumption data to identify availability, reliability and maintainability problems. In the Royal Navy we are not intending to hold ship registers centrally and update them to reflect day to day usage of spare gear.

However, considerable work has been done on ensuring that usage data is fed back to allow spares holdings to be reduced by eliminating the high percentage of spares that are seldom, if ever, used and concentrating on the remainder. This, of course, should result in increased availability for spares that are required and a reduction in overall cost. This feedback is also used to highlight spares usage for a given equipment. Abnormal consumption acts, therefore, as a trigger to initiate an investigation into the underlying reasons.

I would now like to turn to Dr Thomas' paper and develop a point which follows from the very clear demonstration of the efficacy of condition monitoring when a problem has been identified. Commander Thorne noted that a full survey of HMS *London* was being conducted at an early stage in her life to establish a base line. I believe that the identification of trends in health monitoring is an important step leading to the ideal of an accurate, predictive capability for the technique. This, I believe, is the next major step forward required in this important area.

J. L. BUXTON (Lloyd's Register of Shipping): Mr Riley mentions in his paper that Classification Societies may credit items of machinery for survey without opening out when it can be shown that a good planned maintenance and condition monitoring system is in regular use.

Currrently, Lloyd's Register of Shipping has 21 shipowners who make use of approved PM schemes as an alternative to the CSM Survey cycle and there are a total of 184 ships, of all types, adopting this type of survey procedure. Accordingly, it is thought worthwhile to expand on Mr Riley's general point and briefly explain what is involved in gaining the Society's approval for PM schemes and how they operate in relation to classification surveys.

In order to gain approval, the following information should be submitted for appraisal.

1. A numbered index of the machinery items to be included in the scheme. This index should at least include all those items which appear on the 'Master List of Surveyable Items'. No doubt it will also cover many items which are not required for classification and this is, of course, perfectly acceptable. The indexing system should be such that cross reference to the LRS machinery survey codes can be made. It should also indicate those items to be dealt with on preventive maintenance and those on condition-based maintenance.

2. The maintenance schedules and maintenance descriptions for each item. Maintenance descriptions should at least cover the minimum opening up necessary to enable a satisfactory examination to be carried out. The extent of work to be carried out should also be indicated but it is not necessary for approval purposes to include the very detailed job descriptions; a few samples will suffice. Where machinery items are maintained on a condition basis, the monitoring to be used should be described and details of the equipment submitted. The limits of deteriorated condition should be stated and these may be derived from manufacturers' recommendations, applicable severity criteria as defined in standards, eg VDI 2056, or the Owner's required limits when these are more severe.

3. The reporting and data recording facilities. These should be sufficiently comprehensive to enable a Surveyor to satisfy himself that the PM scheme is being operated correctly and is up to date. Reporting and recording may take the form of simple planning charts to the more complex interactive computer-based systems, but no matter which type of scheme is devised, it should have flexibility. Objectives may not always be met and breakdown maintenance will always be with us. The scheme should cater for outstanding maintenance and clearly indicate those items which are overdue and the proposed new schedule.

Having examined the maintenance programme and given its approval, the Society requires a list of Approved Chief Engineers liable to sail on each vessel covered by the PM scheme. On receipt of these details a 'Certificate for Operation of an Approved Maintenance Scheme for Machinery' will be issued. An entry will also be made on the Quarterly Listings 'Approved Planned Maintenance Scheme Annual Audit Due' in order that the Society's Surveyors will know on what basis surveys are to be carried out.

In practice the scheme operates as follows. The ship's Chief Engineer may carry out surveys at sea or in port (wherever is most convenient) and he is no longer restricted to ports or places where the Society is not represented.

At the time of the Annual Classification Survey an audit of the PM scheme is carried out by a Surveyor to ensure that it is being operated correctly in accordance with the conditions of approval. When the annual audit is held, confirmatory surveys are carried out on those items to be credited which have been examined by the Chief Engineer during the preceding year. It is not necessary to have confirmatory surveys carried out after each Chief Engineer's examination, his reports may be filed and dealt with annually.

To facilitate harmonization with Statutory Surveys the annual audit of the PM records may be carried out at any time in the period three months before and after the due date. At the time of the annual audit written details of any breakdown or malfunction of the essential machinery are to be made available. After satisfactory examination of the records, confirmatory surveys and a general examination of the machinery Interim Certificates are issued in the normal way for those items which have been credited for class. The dates for items credited are aligned to the date of the confirmatory survey regardless of when the Chief Engineer carried out his examination.

Where condition monitoring of suitable items has been incorporated in the maintenance scheme, and it can be shown that the condition and performance of these items are within the approved specified limits, they can be credited for survey without opening up.

The broad scheme outlined above offers benefits to both the shipowner and Lloyd's Register of Shipping:

1. Less inconvenience to the ship's staff.
2. Fewer Surveyor visits to deal with CSM items.
3. An improvement in standards
4. Better reliability and defect data.

It should be stressed that the survey procedures outlined are primarily intended for owners who already have in existence a viable PM system. LRS would not recommend an Owner to attempt to set up such a scheme solely on the basis of the benefits to be gained through classification. In order to function correctly, careful consideration must be given to the manner in which reports and recording procedures are kept under control and the training of both ship and office-based staff. To be successful, planned maintenance must have as its driving force a cost-saving incentive, which requires good organization and the firm commitment of the company's staff.

Finally, I have a question for Dr Thomas and Commander Thorne. Throughout the presentations dealing with vibration monitoring some stress has been given to the importance of defining acceptable limits of vibration. Could the authors give their views on the significance of change in vibration and the rate of change? For example, assume a base-line signature produces a first order vibration level of 1.3 mm/s and the alert level is defined as 7.0 mm/s, what sort of increase in the base-line reading would be cause for concern? Or can it be taken that even though the reading has increased, but remains below 7.0 mm/s, everything is okay?

J. P. P. PILLAI: One Classification Society reported recently that 95% of ships classed do not operate any formal planned maintenance system, so there is a very wide scope in this area. The techniques used and advantages have been spelled out by the three authors. However, the following areas have not been addressed:

1. More and more shipowners today are employing crews of the Third World, where competence levels are well below those of First World crews. However, their willingness to work compensates to some extent for their low competence. The main criteria for employing these crews are the lower crew costs.
2. Office bureaucracies that are set up to service planned maintenance systems probably cancel out any hoped for cost savings. Minimum manning also applies to 'Head Office'. Shipowners are trimming the staffing levels, and more work is expected from the retained staff.

Hence, ship operators should keep in mind the following basic criteria before creating and adopting a planned maintenance system for their fleet:

1. Clarity of purpose.
2. Delegation of authority.
3. Motivation to work.
4. Economy of effort.

L. F. MOORE (Leslie F. Moore Associates): I think that Dr Thomas has his tongue in his cheek when he states that 'forecasting when a machine or structure is likely to fail and to establish the reason for the failure. Today this can be achieved by using vibration analysis techniques'. Surely the word 'frequently' should come before 'can be achieved' as a number of other techniques are also necessary for this idealistic state to be possibly achievable.

I would disagree with the statement that 'vibration analysis has now developed into a precise science in which the acceptable magnitudes for different machines and structures are well defined'. In most of the various standards which specify vibration criteria the text specifically states that the vibration limits quoted are for guidance only and that circumstances may permit lower or higher values. In particular the allowable vibration levels in structures incorporating welded joints are very poorly defined (as I have found from bitter experience), and in this connection it would be interesting to know if the author uses dynamic strain guages to establish the severity of structural vibration, in particular for applications such as in Case History 2.

In Test 1 of Case History 1 it is stated that the 'main holding-down bolts were tightened'. It would be of interest to know if this was the result of taking vibration measurement above and below the bolted joints and, if so, the magnitude of the differences measured. Also in this case history it would be of interest to know why no attempt was made to improve the resonant condition of the engine stays which was causing a problem.

Referring to Case History 4, my sympathies are with the author regarding the lack of knowledge of some manufacturers concerning balancing. Even worse than the case where a manufacturer thinks that his product does not require balancing is, in my opinion, the manufacturer who produces a pile of balancing characteristics which are obviously ridiculous to those who have some knowledge of balancing but can be completely misleading to a novice.

At the end of Case History 6, Dr Thomas contradicts his earlier statement of 'vibration analysis has now developed into a precise science' when he states 'in theory, one would not expect this to happen'. In my own limited experience there are a number of aspects of vibration work which are still very empirical.

In Case History 8 it would be of interest to know what type of vibration exciter was used to excite the pipework and the magnitude of the force used. If this information is available I think a large number of people will be surprised at the small forces involved. This is a particular case where I would be interested in knowing how acceptable vibration levels were determined as I would have thought that the measurements of dynamic strain guages would have been more appropriate in this case.

Concerning Ref. 4 in the bibliography, is there an English translation available of VDI 2063?

Commander Thorne mentions the use of the SPM 43A for the measurement of rolling element vibrations. Could he please let us know his success rate when using this instrument and also if he has tried other techniques for finding an answer to this tricky problem?

I am of the opinion that the vibration limits given in Table I of the paper are 'peak' values as distinct from the RMS values used in the paper by Dr Thomas. If this is the case I think that this should be clearly stated as all British and International standards use RMS values for machinery vibration velocity, and it will be necessary to divide the values in this paper by 1.414 for comparison with RMS values. Also I am reasonably certain that the IRD instruments referred to in the paper do not indicate true peak values but RMS values converted to peak values assuming that the waveform is truly sinusoidal, unlike some meters which indicate a true peak value and are used in the application of some vibration standards. It is unfortunate that with their purchasing power the Royal Navy cannot persuade their suppliers to conform with International standards.

While on the subject of measurement units, would it be possible for us to be informed of future Royal Navy policy regarding the 'ubiquitous and logarithmic AdB'. For a number of decades the reference quantity for vibratory acceleration level (AdB) has been 10^{-5} m/s^2 RMS and the reference quantity for vibratory velocity level (VdB) 10^{-8} m/s RMS, but International Standard ISO 1683, 1983 (which has been approved by the UK but not yet adopted as a dual-numbered standard) now gives these values as 10^{-6} m/s^2 RMS and 10^{-9} m/s RMS, respectively.

I get the impression that these reference levels have been changed by some 'purists' who have not used these units in practice, especially as the title of the standard is 'Acoustics – Preferred reference quantities for acoustic levels' which was produced by an ISO 'acoustics' committee as distinct from one of their 'vibration' committees. Unless a powerful body fights for the retention of the old reference levels there could be a lot of confusion in the future.

It is appreciated that 'torsional vibration analysis is relatively new to the specialist vibration analysis teams' but could Commander Thorne let us know if they have used these techniques to determine internal damage in reciprocating machines such as broken valve plates in refrigeration compressors, as this sort of damage is not readily identified by conventional vibration and other measurements.

R. IVES (Shell International Marine Limited): I would first like to compliment each of the authors on the quality of the papers presented. Each paper addresses in its own particular way a subject that is both topical and pertinent: topical because every European shipowner is currently preoccupied with cutting maintenance and manning costs to remain competitive and pertinent because most recurrent maintenance problems are either due to or manifest by excessive vibration.

The observation I would make is that the three papers tend to confirm once again the view that the marine industry as a whole has yet to recognize the widespread benefits which the development and adoption of a single set of internationally acceptable vibration standards would provide to all concerned. That is standards that are neither too stringent for a builder to accept nor too lax so that the owner has either retroactively to call on the services of vibration specialists to identify and rectify fundamental problems (often at considerable cost) or to face repeated repair and maintenance costs throughout the life of a ship.

That this is the current situation is evident from the fact that throughout the three papers and the discussion reference has been made to various vibration 'standards', ie standards acceptable to the equipment manufacturers, standards developed by Bureau Veritas, by ISO, by ABS, by DNV, by the Military and by individual owners.

On the other hand, Dr Thomas' paper provides a brief insight into the real world in which, despite the proliferation of 'standards', a shipowner invariably finds by default that it is necessary to incorporate additional stiffening to (a) a radar mast and (b) a diesel engine 'in order to reduce vibrations to an acceptable level' and of the need to rebalance a number of instrument air compressors on several ships in order to reduce repeated bearing and crankshaft failures and the associated repair costs.

We have also learned from Commander Thorne of the work recently undertaken by the Admiralty to develop vibration measurement and analysis techniques and, more particularly, to establish yet another set of vibration limits as a means of quality control on new vessels.

The situation suggests that the proliferation of vibration 'standards' (which incidentally have little in common) has, if anything, been counter-productive in that collectively they are seen by both builders and owners as a minefield.

Conversely, if, as has been asserted, vibration monitoring and analysis is such an established science that well founded quality control limits might now be defined for a spectrum of marine equipment and a ship as a whole, then the time is surely ripe for the development and adoption of such a set of limits by the whole industry.

K. GRAHAM (Shell Tankers (UK) Limited): I would welcome the views of both Dr Thomas and Mr Riley with regard to the labour intensiveness of a manual vibration analysis system. In my company's experience, after instigating a system of vibration monitoring, it is clear that on reduced manned vessels the engineers see the routine gathering, recording and analysing of information as taking up a disproportionate percentage of their time.

The obvious answer is a data collector, as long as the machine is reliable enough in the hands of a totally unskilled operator to give the repeatability necessary to determine accurate trends. I would like to ask the authors if they know of such a machine on the market today. This would then release the engineer for more important tasks, which would of course include consulting the computer to determine the condition of the machinery.

All this is today, but surely now is the time to be developing systems which are permanently installed and require no manual information gathering. New building specifications should include such systems as standard if health monitoring of machinery is to be relied upon as a replacement for the watchkeeper, or at least as a means to operate with reduced manning.

Dr Thomas emphasized the need for proper training before being able to operate a vibration monitoring system and diagnose some of the more obvious faults. He did not specify a time period, although the training course operated by VCI is of two days duration. Commander Thorne suggested that it takes about one year for a Chief Artificer to become a competent analyst.

Whilst it is appreciated that Dr Thomas will not produce a 'competent analyst' in two days, there does seem to be a large difference in the amount of training involved prior to the 'tools of the trade' being handed over to the operators. I would ask both Dr Thomas and Commander Thorne whether they have any comments to make in this respect.

Authors' replies

R. J. Riley

In reply to Mr Graham, many companies have been unsuccessful in introducing condition monitoring systems. My experience shows that this is due to:

1. Engineers themselves. Basically engineers enjoy any excuse to tamper with machinery.
2. Lack of Head Office commitment to or an understanding of condition monitoring.

BP Shipping overcame this by making a corporate decision that condition monitoring was to be successfully implemented and operated. This ensured that both Head Office and fleet personnel became committed to the objectives.

They then ensured, by careful system design and training, that condition monitoring became accepted as a tool which assisted the engineer in his work. The design also ensured that speedy data collection and analysis could be easily undertaken. In operation the BP manual system data collection could normally be achieved for each machine in under 15 min.

Mr Graham is correct in assuming that time is greatly reduced when data collectors are used. Recent projects we have been involved with in the BP Shipping and Gulf Beau Drill fleets have indicated that for 12 machines the time for data collection can be reduced from 180 min using manual collection to 35 min using data collectors. This, as can be seen, is a considerable saving in manpower effort.

The data collector used in the case outlined above was an IRD 818, the software packages giving system management being one within the Marine Management Centre PMS suite.

Dr B. H. Thomas

Mr Buxton raises a very important question because, in my opinion, change and more so rate of change of vibration is more significant than, say, a limit of 7.0 mm/s in determining whether or not a machine problem is developing.

If a warning limit of 7.0 mm/s was established for a particular machine and a gradual change in the vibrations occurred of 1 mm/s per month, then we would suggest that measurements should be taken more frequently. Where the initial vibration was, say 4.0 mm/s then, assuming a linear increase, it would be approximately three months before the vibration reached the warning level.

On the other hand, if the rate of change in vibration is very rapid this suggests that a problem has occurred and is worsening quickly, in which case the machine should be stopped and examined as soon as possible.

In reply to Mr Moore, ideally, to forecast the time when a machine is likely to fail, one would need to know the previous vibration trend. By knowing this information, if a change of vibration occurs over a period, then the time to failure can be estimated, but clearly one should make sure that the machine is rectified well beforehand.

However, where no trends are available, there are various other precautions one can take, such as:

1. Compare the vibration levels on the suspect unit with a similar machine, if one is available.
2. VCI have established a vibration standard which is based on measurements from hundreds of vessels and is in line with VDI 2056. If the vibrations on a suspect machine are outside

this standard, then we would recommend that the machine should be examined further.

Sometimes other techniques such as oil analysis or pressure measurements are necessary, but in many cases vibration techniques alone will pinpoint a problem. One important exception is thrust wear for which an axial indicator is essential.

The tests employed by my company all have a scientific basis and are designed to produce specific responses. Many of the techniques we use have been developed by ourselves and we find that generally the results give clear cut and well defined solutions.

It should be noted that for each of my case histories it was possible to present only a small portion of the overall measurements and tests. Therefore, in Case History 1 one would automatically check the vibration levels above and below the holding down bolts as a matter of course. In fact, very many more measurements were taken around the structure and base of the machine than have been shown.

Also, it was not the stays which were resonant, but the structure onto which they were attached. As this was a new vessel, extra stiffening of the structure was really the responsibility of the shipyard.

Mr Moore makes an interesting point, as sometimes vibration tests produce the opposite results to what one would initially expect. However, in my experience, where this has been the case there has always been a definite reason for this happening; often the reason has only become apparent after the completion of the tests. In Case History 8, the exciter used for the test comprised a rotating flywheel mounted between two bearings. The diameter of the flywheel was 6 inches and the exciting force approximately 6 oz inches.

Concerning Ref. 4 and VDI 2063, I would suggest that the BSI would be the best organization to advise on an English translation.

Mr Ives has made an excellent point and I agree with his comments about the marine industry recognizing a single set of internationally accepted standards. There does seem to be a void in this direction because most standards do not specifically tabulate values for machinery or structures. In fact, Ref. 1 in my paper was produced for Shell International Marine to meet this requirement. Clearly, a detailed practical standard for the marine industry should be adopted universally as soon as possible.

In response to Mr Graham, when manual system analysis was first introduced, there was a disproportionate percentage of engineering time spent collecting the data. The main reason for this was that initially every machine on board was checked every month. Most programmes have now been changed to fall more in line with the requirements of the Classification Societies so that the major machines are monitored every two to three months and the others are spread over a period of six months to one year, depending upon their relative importance. However, if a change of vibrations is noted, then they should be monitored more regularly.

In the long term, data collector systems with memories will probably help to reduce the manual content of such a programme, but at the present time very few data collectors have been widely used in a marine environment. Our investigations have indicated that with many makes there are still problems associated with the data collector and associated software. We are convinced that if data collectors are to be fully accepted by marine engineers, then they must be relatively easy to use.

I would agree with Mr Graham that the best system for vibration measurement would incorporate permanent monitors on all the machines so that their condition can be assessed continually through, say, a central process unit. Unfortunately, at the present time, this is a very expensive method. The accelerometer costs alone would be large.

With regard to training, most merchant fleet operators have to ensure that the time for a vibration course is limited to about two days, for commercial reasons. From past experience we believe that this is sufficient to give marine engineers a good basic training and understanding of the subject. The VCI course is of a very practical nature and has been developed in conjunction with the marine industry. On completion, the engineers will be able to operate a monitoring programme, analyse basic problems, and carry out simple balancing. Most of the more senior Shell marine engineers have taken part in this course and we understand that they have found it very beneficial. As Mr Graham has also attended the VCI course, perhaps he is really in a better position than myself to judge its effectiveness.

In addition, my company has developed an advanced course for the marine industry with the object of promoting a more detailed understanding of analysis and trouble-shooting techniques. This is carried out in a special purpose-built laboratory which is equipped with a range of ex-ship machinery which has been donated by Shell Tankers (UK) Ltd.

With the above training, which we feel is adequate for the purpose, most marine engineers will be able to solve many vibration problems. For the most difficult problems, specially trained vibration engineers will be required, where the training for a fully qualified vibration engineer is much more extensive. At VCI we look for engineers who have had a recognized apprenticeship, worked for two to three years in a marine or land-based industry, and have a formal qualification of about degree standard. We then expect to train each person for another three years before we consider them to be fully competent to deal with very complex problems.

Cdr R. W. Thorne

In reply to Mr Buxton, the 'alert level' represents an overall vibration level which, when reached, will require a full vibration analysis to be carried out. It will be noted that monthly monitoring is carried out of overall or 'filter out' vibration levels using a small hand-held monitoring instrument not an analyser — the 'alert level' is not a limiting vibration level. In a monitoring system where overall vibration levels are measured at monthly intervals clearly an increase in vibration amplitude from, say, 1.3 mm/s to 5 mm/s, ie an increase of 3.7 mm/s in one month, would, if continued at the same rate, exceed an alert level of 7 mm/s before the next monthly reading is taken.

This demonstrates the need to scrutinize carefully the results of the measurements taken, note any increases and, when a trend of increased amplitude is developing, first increase the frequency of measurement checks and then carry out a full vibration analysis as necessary in order to determine the cause of the increase.

I agree with Mr Pillai's statement.

Mr Moore's general statement has my full support. In the RN, acceptance, alert and limiting vibration levels are almost entirely obtained empirically and the values are then adjusted in the light of experience.

In the RN, the use of somewhat dated SPM 43A equipment has suffered from difficulties experienced in the initial tuning of the instrument, which is by an audible signal. However, limited success has been achieved in the past with the identification of rolling element bearing defects.

Introduction of the IRD 811 and the IRD 820M instruments will allow the 'spike energy' facility to be used for the measurements of rolling element bearing vibration levels. It will be appreciated that the 'spike energy' facility, in effect, enables measurements to be taken of only those high-frequency vibrations which are a feature of rolling element bearings, although care must be taken that high-frequency gear mesh vibrations are not influencing the readings taken. Limiting values are still being decided although the instrument manufacturer recommends a value of 0.8g as a limit.

Representative, worn rolling element bearings are examined in one of the Admiralty materials laboratories and the condition of the bearing is then directly related to the spike energy vibration level measured before removal. In time, and again empirically, limiting vibration values for the wide range of these bearings and their various fits in the RN should be reasonably accurately defined.

It is confirmed that the vibration limits in Table I of my paper are 'peak' values, as was previously stated in the paper when describing the IRD 811 and the IRD 820M. Peak vibration amplitudes at a particular frequency can be divided by 1.414 to obtain the RMS value, but overall 'filter out' levels cannot similarly be simply converted.

The RN has not chosen to persuade its suppliers to confirm with so called 'International Standards' and the existence of such 'standards' in turn is questioned. It is appreciated that ISO 2392 expresses standards in RMS values.

For a vibration measurement and analysis programme where limiting values are decided empirically and where all the RN's experience has been obtained using peak values, it seems sensible to continue using such values and, of course, this enables the RN to continue to use the considerable quantity of vibration data now held. It is recognized that RMS values can be considered to represent a measure of energy which peak values do not. However, this discussion could and should be the subject of a separate paper.

IRD supplies instruments which indicate vibration amplitudes in either RMS or in peak values as the customer requires. It is confirmed that the IRD instruments indicate RMS values converted to peak values.

Future RN policy regarding the AdB is that for machinery health monitoring and for machinery vibration analysis the AdB will not be used, but there are applications, for example the reduction of radiated noise into the water, where machine bed plate vibration levels are measured in these units. This particularly applies in the submarine service.

The RN has not yet used torsional vibration analysis techniques on any machines other than diesel generators. Clearly as the RN's experience increases then applications such as the one quoted in the question will be explored.

I fully agree with Mr Ives statement.

I am not personally aware of full details of a data collector performing as Mr Graham requires; however, companies such as IRD would certainly be in a better position to answer the question. Such a data collector should, of course, perform in such a way that preset alarms warn the operator when a trend becomes significant and before the machine has suffered damage. Again, the data to be collected would by no means be of vibrations only.

The one year quoted as being necessary for a Chief Artificer to become a competent and confident analyst allows the Chief to carry out full linear analysis of complex machines, to balance rotating machinery and, in effect, to make major decisions regarding the need for and the required repair action when the condition of machinery deteriorates and where an incorrect diagnosis can prove extremely expensive. Much of the year is spent on the 'job' where essential 'in the field' experience is acquired.