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Advances in condition monitoring

S Drew
YARD

SYNOPSIS

Recent developments in processor based condition monitoring (CM) equipment afford access to data in a format compatible with established and emerging data processing technology, permitting the integration of CM with maintenance management tools and management advisory systems.

Many of the component parts of these systems such as maintenance, process control and task scheduling packages are established. However, the integration of these packages with complex CM information requires the application of both conventional and knowledge based information handling techniques (IKBS).

This paper is based on work carried out over the last 2 years in connection with the application of CM techniques to propulsion and ancillary machinery for naval vessels. Over that period of time CM development work has also been carried out for applications on unmanned oil platforms and electrical generating equipment. It is on the basis of this experience, gained across a range of industries, that areas where the common interests of these industries may be met by the amalgamation of IKBS, traditional CM techniques, and the introduction of improved data collection methods, have been identified.

INTRODUCTION

Since the early 1970s condition based maintenance programmes have been employed in the continuous-process industries. From that time the application of condition monitoring (CM) as a predictive maintenance tool has been recognised by most industries. The level of acceptance has however been dependent on the cost benefits to the industry being demonstrated and on the need to comply with statutory requirements governing maintenance practice where safety considerations have been involved. For some, the uptake of new CM technology is continuous, driven by economic pressures at all operating levels. For others, such as the batch manufacturing industries, it has required government initiatives to promote the application of CM and predictive maintenance (PM) systems. In many industries the easy decision was to continue with time based maintenance programmes, CM techniques slowly being introduced, but with little impact on the effort directed to 'routine maintenance'. In the past the potential market for CM systems has been difficult to develop due to the factors identified above and also because in some industries of the absence of skills required to establish an effective CM programme. Another contributory factor has been the lack of awareness on the part of management to recognise the cost benefits of CM. There is however a general increase in awareness of condition based maintenance throughout British industry at this time. This is in part due to the availability since the early 1980s of compact processor based data collection equipment giving an impetus to the development of software products. These are allowing many industries to take the step forward of integrating existing CM techniques with processor based measurements techniques into a predictive maintenance programme.

At an early stage in the introduction of this form of CM technology it was recognised that there could be benefits by applying it as part of a marine predictive maintenance policy. Over the last 3 years a programme of work has been progressed on naval vessels to demonstrate and develop the application of digital data collection techniques applied to marine engineering equipment. This paper reviews the general CM requirements identified in this work, the advantages that may be gained from utilising digital data collection techniques for marine applications and where future software developments could assist in the integration of engineering support systems.

Stanley Drew completed an Engineering apprenticeship in 1969 which started with Simon Lobnitz on the Clyde and finished with Eadie Brothers in Paisley. After working on the development of measurement systems at Paisley College of Technology and obtaining an HNC in Mechanical Engineering at Clydebank Technical College, he joined YARD Ltd in 1978. Since joining YARD he has been responsible for the operation of the company's instrumentation and trials service. He is presently a Senior Consultant in the Systems Department participating in a number of industrial, offshore and naval condition monitoring projects.

PREDICTIVE MAINTENANCE REQUIREMENTS

The achievement of confident and accurate predictions on the maintenance requirements of a piece of equipment requires repeatable and accurate collection of equipment condition indicators on which to establish the rate of deterioration of the equipment. Conventional PM data which met this requirement have been derived from the human senses, oil analysis, vibration, temperature and pressure measurements, the measurement of electrical parameters, performance monitoring and a range of other physical measurements relating to specific

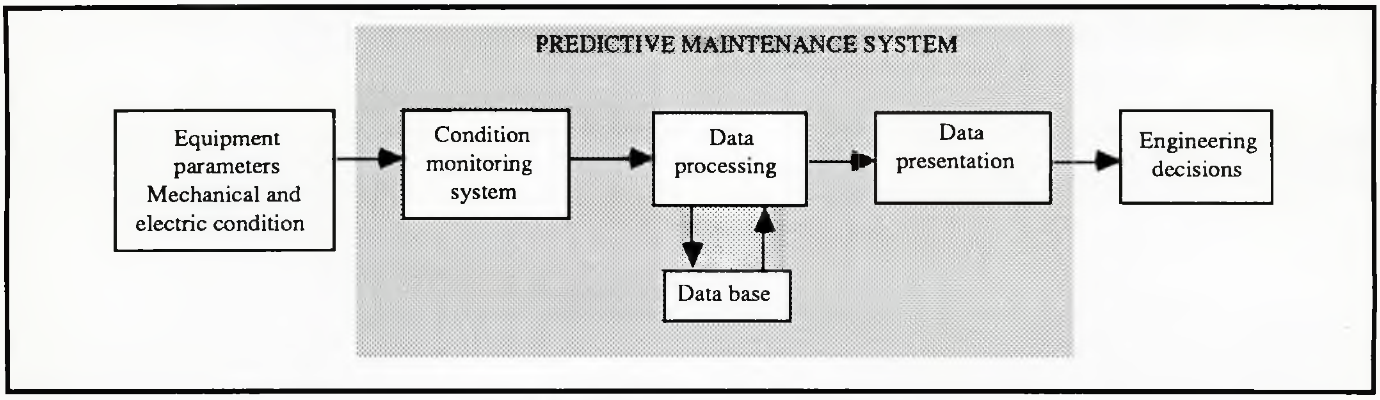

Fig 1: Predictive maintenance system

equipment. An example of this is the range of techniques applied in the Royal Navy.[1] Each of the above parameters can be represented by single numerical or qualitative statements which, when recorded over a period of time, establish a historical basis on which the engineer can predict when maintenance should be carried out. This has been achieved in the past without the need for computer based systems so the need for collecting data in a form compatible with computer based systems may not be immediately apparent.

The limitations of the above measurement methods are the importance placed on the ability of the operator to measure and record the data accurately and the level of effort required to carry out manual processing of the data to identify trends. It is these limitations that the introduction of portable data collector units (DCU) has overcome, establishing the environment that, when configured as a system with a low cost personal computer (PC), permits the development of effective data collection, processing, analysis and data presentation tools (see Fig 1).

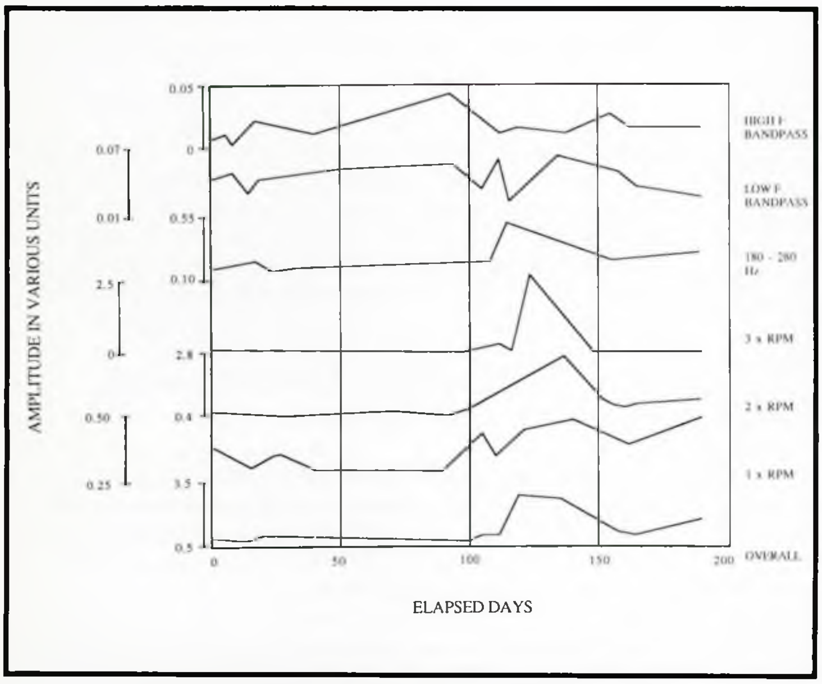

Fig 2: Rolling element bearing failure on marine electrical equipment

DIGITAL DATA COLLECTION

The DCUs presently available, that form part of the above system, generally have two modes of operation, diagnostic and semi-automatic.

In the diagnostic mode the operator of the DCU has available an instrument capable of:

1. vibration measurement.
2. FFT (fast Fourier transform) analysis with narrow based spectra displayed on a digital display.
3. real-time spectral displays.
4. infra-red temperature measurements.
5. a dynamic mechanical balancing capability.
6. an increased range of further options.

The interpretation of the data available from these analytical techniques requires a high degree of analytical skill that limits their handling to engineering staff.

In the semi-automatic mode the unit is programmed to instruct the operator to record data at pre-determined locations. On completion of data capture the unit indicates that data collection is complete and identifies the next data collection point. On completion of the data collection route the operator downloads the data to the central processing facility either directly from the solid state memory in the DCU or via a data bus, or by removing solid state memory cards from the DCU and entering them into a reader at the facility.

In contrast to the diagnostic mode of operation the application of the unit as a data collector in this semi-automatic mode requires a minimum of instruction and it may therefore be operated by unskilled personnel.

The data collected by the DCU in either mode during the collection route may consist of data derived from any or all of the following.

1. Fixed or mobile accelerometers connected directly into the DCU. Fig 2 shows typical vibration data identifying a bearing failure.
2. Analogue values from transducers connected temporarily into the DCU.
3. Parameter values entered via a key pad. Fig 3 shows typical values for a compressor interstage pressure entered by key pad over a period of 200 days.

The simplicity of these operations assists in producing repeatable, accurate data, without the requirment of skilled operators. The processing

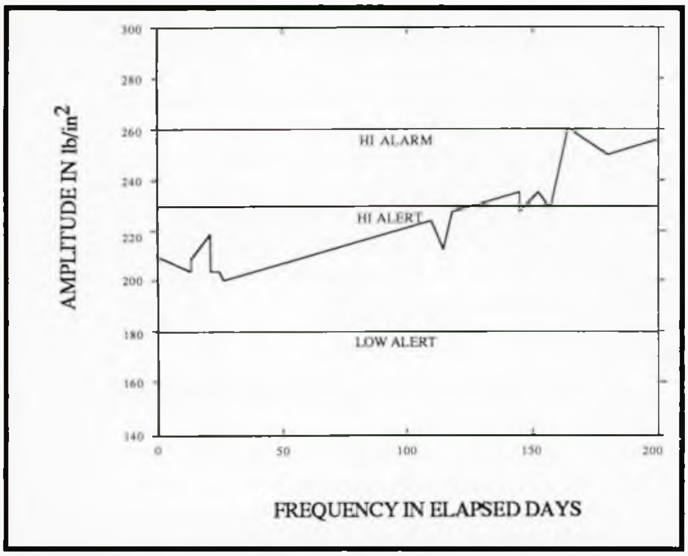

Fig 3: Air compressor interstage pressure increasing due to defective following stage value

power that is being applied by the DCU during semi-automatic data collection may not be apparent to the operator. For example:

1. vibration data is being sampled through anti-aliasing filters.
2. FFT data averaging is carried out.
3. storage of narrow band vibration data with over 3000 points for a selected frequency range is possible.
4. auto-ranging analogue to digital conversion occurs.
5. tachometer related data recording of synchronous data occurs.
6. times, dates and locations are tagged onto all data recorded.
7. data averaging is carried out.

The above list is not by any means exhaustive. However it does indicate the capabilities of a processor based system.

The hardware which together with the DCU completes the PM system is the computer and its peripherals (Fig 4). Typically the computer will be a PC, comprising processor and memory, display, key pad, floppy disc, hard disc memory and interface, and graphics cards. The peripheral facilities include printers and digital plotters to produce reports and modems to permit transfer of data to remote sites. All of these are standards facilities that require no further explanation except to note that the floppy disc drive is used to load the PM software package and to take back-up copies of the database to protect the data in case of computer memory corruption.

The impact which this combination of hardware has had on data collection is best seen in the way in which vibration data are analysed. Prior to the introduction of these developments vibration data was recorded as RMS (root mean square) values, hard copy traces of spectra, or in real-time format on magnetic tape recorders.

The limitation of using RMS values is that only a general indication of vibration levels is achieved. In many applications important spectral data are lost in the general high vibration levels dominated by the running speed of the equipment.

The second method, producing hard copy traces of spectra, has achieved excellent results in a wide range of industries both for analytical and maintenance purposes. The limitation of this technique is that all subsequent processing must be carried out manually.

The third method of data recovery, magnetic tape recording, has specific applications, particularly for complex analytical work requiring engineering expertise. The practical problems of using tape recorders in a marine environment for routine data recovery limits the application of this technique.

These vibration measurement and recording methods are rapidly being replaced with digital data collection methods, making the data compatible with analysis techniques previously reserved for high cost specialist instruments. The processing and digital storage of the data in the DCU ensures that the data is transferred to the computer without degradation and permits spectra to be displayed and trends to be identified by the PM system software.

SYSTEM SOFTWARE

The majority of existing preventive maintenance software products contain packages for carrying out four main data handling functions:

1. collections
2. storage
3. processing and presentation
4. reporting

The software package for the collection task permits data collection routes, parameter ranges, alarm levels and frequency ranges to be entered into the computer and downloaded to the DCU.

The storage task ensures that data download from the DCU are entered into memory with the correct labels attached to enable data recovery for subsequent processing.

Data processing and presentation are packages that take the data in digital form recovered from the DCU and present it in a form that permits the engineer to make maintenance decisions. In current systems these data are processed and presented to give:

1. alert and alarm limit excursion indication.
2. trending of data and prediction of rate of change of parameter values.
3. waterfall plots.
4. average trends.
5. narrow band and profile alarm checking of spectral data.
6. multiple spectra including baseline data.

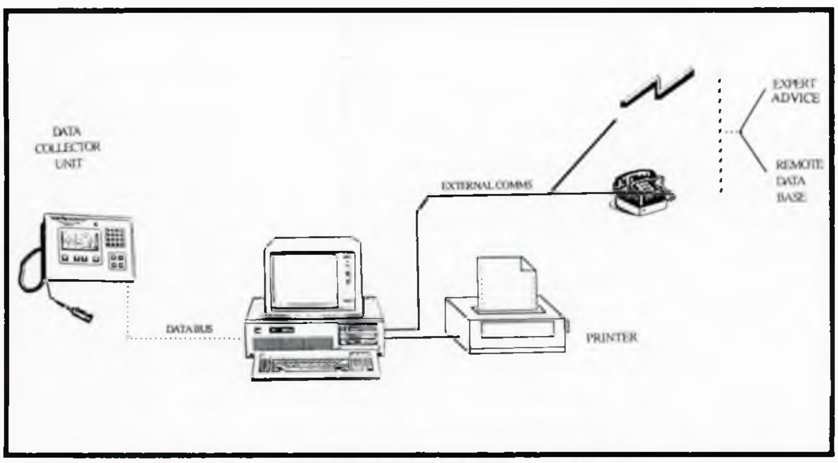

Fig 4: Predictive maintenance system

The reporting package combines the above facilities to present processed data in a form suitable for hard copy production.

All of these facilities have made the interpretation of the collected data more efficient, thus reducing the effort required to establish maintenance actions. Where further developments are required, however, is in the analysis of the data. Approximately the same level of skill is required at present to identify specific failure modes and resulting remedial actions as was required when conventional data collection methods were applied, little progress having been made in the development of systems which apply the analysis skill of the engineer to routine problems. In order to tackle the problem it is necessary to identify the manner in which a human engineer judges the importance and quality of the data which is being presented to him and subsequently uses his skill to determine any required remedial action. One possibility is the use of intelligent rule based systems at suitable stages in the analysis process.

When presented with the collected data the engineer will judge the quality of the data by comparing the values presented with those for a known operating condition. This validation process is complex for equipment with a large number of variable parameters. However, by encoding this expertise in the form of a rule based system to correlate data it is possible to interpret the data and present the engineer with significant features of it.

A further application of knowledge based systems lies in their ability to give assistance to the operator faced with a range of options when presented with CM data. This capability can be demonstrated by relating vibration spectra to known modes of failure for specific equipment. Harmonic values associated with balance, misalignment, gearing and electrical deterioration are typical of faults suitable for this application of a rule based system. To identify these fault modes from data derived from a single transducer location can be misleading. The application of knowledge based systems overcomes this by identifying possible fault modes and directing the operator or itself to examine supporting information for the diagnosis.

Conventional data processing techniques may also play a part in achieving efficient PM systems. Equipment performance monitoring has proposed little as a PM tool except in a few notable applications.[2] Conventional modelling, correlation and mathematical treatment of data may be used to achieve progress in presenting performance information in a form suitable for extracting trends in key operating parameters that are masked by variable operating conditions.

ANALYSIS TECHNIQUES

The establishment of a system that records CM data in a computer-compatible form permits the application of an ever increasing range of analytical techniques. A number of these are particularly appropriate for marine applications.

In the marine environment vibration data is degraded from two sources not encountered in land based systems: seaway induced motions and vibration induced in the subject equipment through the ship's structure by adjacent machines.

Application of a signal generated by a tachometer, relating the vibration spectra recorded to the running speed of the machine, ensures that the information required is not degraded by other sources. This technique also has application in monitoring variable speed machines, permitting time-averaged spectra to be recorded that would otherwise be confused by variations in the harmonic values of the machines.

Comparison of vibration data against known profiles collected from machines of the same type, can assist in the identification of machine faults, prevent premature stripdown of machines by indicating acceptable operational levels and provide data for acceptable operating conditions after replacement of equipment.

The ability to superimpose an envelope, indicating acceptable limits for specific frequency bands, can assist in the efficient analysis of data, focussing attention on frequencies that require further investigation. This can take the form of a general profile for the overall spectra or a profile for a specific narrow frequency band.

MEASUREMENT AND TRANSDUCERS

In the preceding discussion mention was made of a basic requirement of a CM system; that is the ability to collect accurate data. Over the same period that computer based PM systems have been developing, the reliability and accuracy of transducers and their signal conditioning electronics has increased considerably. The increase in reliability and accuracy relates to improved manufacturing techniques, sensor design and the reduction of discrete components required in signal conditioning electronics by the introduction of suitable integrated circuits. For the majority of applications these improvements have been applied to well established sensor technology for the measurement of temperature, pressure, vibration and displacement, with few new techniques appearing. The exceptions to this are in the application of non-intrusive techniques for monitoring the condition of electric motors and the advances that have been made in the development of infra-red temperature measurements.

The two forms of electric motor monitoring that have now been developed for commercial systems are stray flux monitoring and the monitoring of motor current anomalies. Both of these methods have benefitted from the development of processor based systems to produce practical measurement instruments capable of identifying the deterioration of internal components in induction motors.

The application of infra-red measurement methods to CM was for some time limited by the use of either simple hand-held electronic devices or complex gas-cooled systems. The development of a new generation of infra-red cameras capable of producing video format images for analysis, and comparison with baseline measurements, allows this measurement technique to be an effective CM tool.

SYSTEM INTEGRATION

While CM may be carried out as a stand-alone task it must be recognised that the PM function is not carried out in isolation of other scheduled tasks. For example it may be carried out as part of a production run or used for a limited time for shore based personnel to assist staff in their maintenance tasks.

To assist in the planning and the scheduling of tasks a large number of PC based management, planning and maintenance packages are available. At the present time the PM system and the maintenance and management packages are operated in parallel with computer based store systems and computer aided engineering tools. All of these systems have an underlying requirement for data from the other systems. This is achieved at present by manual transfer of data.

However, with the encouraging developments in knowledge based systems and computer networking capabilities, the development of an effective maintenance management

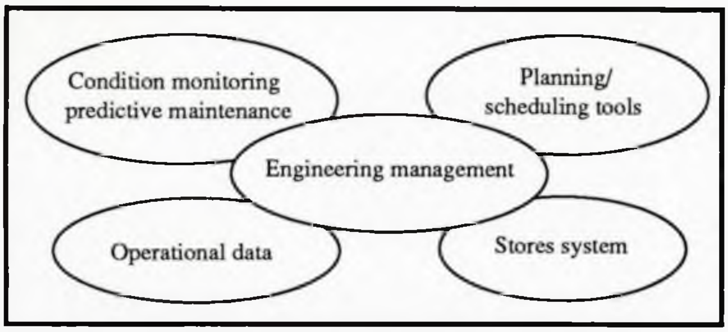

Fig 5: Computer based engineering management systems

system, based on the principle of PM, but with the capability to respond to external influences, is an achievable target (Fig 5).

There are currently a number of separate projects underway concerned with the establishment of an integrated engineering management tool including knowledge based systems for:

1. data validation.
2. interpretation of equipment data from remote locations.
3. production scheduling tools.
4. monitoring of production equipment for preventive maintenance.

CONCLUSIONS

From the above it may be said that we are, in fact, only part way through a further evolutionary cycle of PM. However, it is possible that the same conclusion would have been reached had the subject been reviewed at any time in the last 10 years. The pressure to achieve cost savings and reduce downtime by the application of PM techniques ensures that new technology in this field will be considered by the engineer and that the commercial development of PM tools will continue. At the present time this development work is taking place in the processing of CM data, and mainly directed at the portable data collector market. Fortunately, much of this technology is applicable to the processing of data from continuously monitored systems. When the cost of permanently installed equipment for continuous monitoring is effectively reduced by the application of distributed data collection methods and increased intelligence at the sensor, then a new market area will again give impetus to the development of PM tools.

Recent developments in computer based data collection and processing which achieve additional cost savings over conventional data monitoring methods can be recognised in two main areas.

1. The early detection of forms of equipment deterioration which would previously have gone undetected until failure, permits the extension of maintenance periods based on the confidence that the equipment condition is established by monitoring key parameters. This ability to identify trends at an early stage also ensures that the efficient scheduling of maintenance tasks can be established.
2. Data available from the CM systems permits the content of maintenance tasks to be established, permitting efficient use of labour and facilities. These decisions on the form of maintenance required can be confirmed by transmitting the collected data to a second analysis facility for expert analysis.

A further advantage of computer based systems is perhaps not one with which a cost saving can be directly associated. The advantage is the acceptance of CM systems and equipment that previously, although adequate for analysis applications, had neither the reliability nor ease of use that encouraged engineers to apply them to routine applications. This will be overcome with the introduction of computer based systems which will establish the conditions for future CM development and maintenance systems.

REFERENCES

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2. D C Warkmen, 'BP's performance monitoring system for marine diesel applications', *Trans IMarE(TM)*, Vol 95, Paper 41 (1983).

Discussion

G D Ashley (Mobil Oil Company Limited) The author has commented on the justification for the cost of installing condition monitoring equipment. If overhauls or surveys are condition based rather than time based then a reduction in downtime, savings in overhaul costs and increased cargo carrying time can be expected.

As Mr Drew has stated, a number of studies are currently in hand. One such study is to assess the condition of lubricated machinery by a full analysis of oil including wear metals and contaminants. Major oil companies have traditionally offered an oil analysis service. In the last few years this has been extended to include spectrometry to monitor wear metals produced by normal rubbing wear.

A more recent improvement has been the ability to automate a system designed to measure and identify magnetic particles, produced by more destructive types of wear, by means of a rotary particle depositor and ferrography.

Has the author carried out any investigative work using oil analysis to monitor the condition of lubricated machinery?

S Drew (YARD) As identified by Mr Ashley, oil analysis can be applied as a CM technique without incurring additional installation costs. In its various forms oil analysis has been recognised for some time as an effective CM tool by marine, offshore and industrial companies. A benefit of the debris analysis technique developed to identify specific materials and their physical form, is the ability to monitor inaccessible bearing surfaces in complex equipment and identify the source and rate of debris production, a key factor in condition monitoring bearing systems.

Our own experience of applying oil analysis as a CM technique suggests that where further work is required is in linking the real-time vibration data with the non-real-time oil analysis information, linking the rate of deterioration of bearing surfaces as indicated by oil analysis with the physical performance of the equipment.

I C Ball (Alfa-Laval Engineering Limited) Could the author give some indication of the order of costs which could be saved using condition monitoring techniques?

S Drew (YARD) A number of studies carried out in the heavy engineering and mining industries have quantified the cost savings achieved in specific applications. For more general applications, such as for marine operators, the savings to be achieved by reducing maintenance effort and spares holdings, specifying remedial actions to limit secondary damage and the efficient scheduling of effort, is limited by the range and complexity of the equipment to be monitored and the installation, training and equipment costs incurred to establish a CM system. All of these variables must be considered when assessing the cost benefits of applying CM for each specific application. As yet we have insufficient information to permit a general indication of the order of cost savings.

I C Massey (Student, Humberside College of Higher Education) How much value do you attach to the use of a continuous water-in-oil monitor (in-line) in condition monitoring systems?

Please include your comments on water-in-oil monitors.

S Drew (YARD) On a number of air compressor plants which we have surveyed for the application of CM, water-in-oil contamination has been identified as a problem with regard to interpretation of information available. Off-line oil analysis has quantified the level of contamination present. However, since the equipment monitored consists of variable duty machines, it has not proved possible to establish a trend. The presence of on-line monitoring equipment when linked with other parameters would permit us to overcome this problem.

B H Thomas (Vibration Consultants & Instrumentation Limited) Mr Drew, in his presentation, clearly expounds the advantages of using a data collector system for vibration. As a matter of interest VCI have successfully installed many condition vibration monitoring systems including data collectors in ships and on land based structures.

Data collector systems are not quite so easy to install and use as may first be imagined. We would therefore recommend that new potential CM users could save many hours of heartache and frustration by employing experienced consultants to set up the initial system. This system would include the appropriate limits, alarm levels and routes, etc, for each machine. Once this has been completed, the continuation of the programme could then be carried out by the user's own staff, with possibly some external advice as and when required.

We would re-emphasise the author's comment that the programmed data collectors are useful instruments for the collection of a wide range of vibration criteria by non-skilled personnel. However, such systems in the final analysis still rely on competent vibration engineering skills to interpret the results processed from the personal computer.

It is interesting to note, however, that for full detailed 'trouble shooting' projects, manual systems have advantages over the pre-programmed data collector units.

As a general guide, in terms of overall time taken for the collection and analysis of data, we have found that there is very little difference between computerised and manual systems.

S Drew (YARD) I fully agree with the comment that interpretation of the CM data collected by either manual or automatic systems requires a high level of skill to obtain maximum benefit from the data, and to optimise subsequent actions, than is often appreciated. We are only now seeing the introduction of systems that go some way towards reducing the level of skill required. For specific trouble shooting tasks I would agree that the analyst requires the flexibility to manually program the analyser, and is a task separate from the basic CM routine.

M H P Hembling (LR) I thank the author for a most interesting paper. The possibility of a system capable of prognosis, as opposed to diagnosis, has already been raised. I would like to question the necessity of prognostication.

From the moment a piece of machinery commences operation, components start to wear. By taking regular readings, the slope of, and therefore the position on, the wear curve can be determined. It has been stated that there are diagnostic systems already available which can detect the onset of a major breakdown. So it would appear that the problem lies in how little wear can be detected and in determining the acceptable wear limits for each component.

From this argument, it could be deduced that there is still a lot to be achieved from the 'fine tuning' of the diagnostic systems currently available.

S Drew (YARD) While we are seeing developments in the interpretation of vibration data by automatic means, the need to transform the data presented into engineering actions, requires an understanding of the operation of the system and the interpretation of other supporting operational information. It is in this area that further work will be required if we are to make full use of the presently available diagnostic systems.

D A Hughes (Student, South Tyneside College) The paper is most interesting in that its main conclusion is that the key to the fitting of CM equipment is the economy brought about by cost savings and reduced downtime. However, a reduction in machinery downtime is not a direct contribution to cost-cutting but rather an indirect one through reduction in manning levels. Whilst this may be possible on naval vessels it may be difficult to attain in the merchant fleet where manning levels are already minimal.

The paper concentrates on data received from vibration sensors. Vibration monitoring is a useful CM technique, but in many cases it is the performance of the machine that the operator is interested in. In the case of a simple centrifugal pump, for example, it is not sufficient to know the vibration levels as these may be quite acceptable when the pump is incapable of delivering the required amount of water. With this in mind, would the author therefore agree that vibration measurements should not be relied upon as the sole method for CM, but should be integrated with other methods as part of an overall CM system?

Additionally, vibration signatures are difficult to identify in the marine low speed diesel engine and so other methods of CM, such as on-line wear debris monitor for the lubrication oil, may be required. Therefore would the author like to comment on the possibility of integrating the system as described in the paper with other CM techniques?

I would agree entirely with the author that at the present time we do not have enough data to determine pre-failure conditions, particularly in the field of monitoring diesel engines. Does the author know of any current research, especially on lubrication oil monitoring, which would enable lead time to failure in the running gear of diesel engines to be identified?

S Drew (YARD) The recognition that applying CM may not result in further reduction of manning in the merchant fleet is a valid point. I would however suggest that we look to the reduction of secondary damage and the scheduling of maintenance tasks by support staff, based on a knowledge of equipment conditions, when assessing where the benefits from CM may be attained in this industry. While recognising that vibration monitoring has a major role to play in any industry with a large number of rotating pieces of equipment, the use of process and performance data should not be ignored. I would hope to see future CM systems developing the relationship of these parameters to give a more integrated systems approach to monitoring equipment.

The monitoring of low speed diesel engines has been the subject of a number of research projects. These have considered both the measurement of parameters required as CM indicators and also analytical methods specific to diesel engines. The results of these two research areas were to be brought together for the development of a monitoring system for diesels. We are not aware of any published results of this work at present.

W N Watson (MOD) I do not share the apparent pessimism of the author (implied in his address but not in the paper). I believe that far from there being little advance over the recent past there has been a significant improvement in many areas – and there are more exciting advances in the pipeline and expected any minute.

The data collector has evolved rapidly to the extremely sophisticated machine described in the paper. It is probably nearing its final form – although there are moves to make it smaller still. There is some argument (with which I am in agreement) that it is becoming too complex and attempting to become all things to all men. This trend may have the effect of negating one of its principal advantages, that of reducing the skill level required to collect the data. However, attempts to put 'intelligence' into the collector are progressing well and should reduce the risk of this occurring.

It is questionable, however, whether there is a need to combine all the functions described into one box. I believe, as does the author, that it would be better to separate the function of data collection from that of analysis, thus allowing the data collection to be carried out at a low skill level whilst freeing the powerful computerised analytical capabilities of the machine to be used by the maintenance specialist. Whilst this would mean the purchase of two instruments, I believe that the cost would be justified by the ability to further enhance the capabilities of the analyser which would no longer be constrained by the need to keep its size to the absolute minimum – although portability would still be a major consideration.

The major advances in the last 5 years have been made in the field of data handling. When data collectors were first introduced the emphasis was almost entirely on vibration analysis. The ability of the software to determine changes in the vibration spectrum was severely limited and in many cases still depended on manual analysis and input. The ability of the software to trend and compare was also minimal and user-friendliness was generally poor. Since those early days the software has improved markedly. There are many more functions available to the user and just about any combination of data can be extracted and compared. Furthermore, much more emphasis has been put on gathering, collating and using process parameters in conjunction with the vibration data which obviously remains the predominant feature of these systems.

Regrettably little advance has been made to date in prediction of time to failure (which is the real crux of CM) although the use of polynomials as opposed to straight line methods has resulted in some improvement in accuracy. Over the same period the learned institutions have invested a great deal of effort in the determination of condition using data other than vibration. Great strides are being made in infrared (as mentioned in the paper), oil debris monitoring, sound as a diagnostic tool, signal averaging, and many other techniques. Much work has been done to determine algorithms which will allow performance to be monitored as an indicator of condition, particularly in the field of variable speed and power machines such as diesel and gas turbines.

The development of transient response characteristics together with pattern recognition techniques is well advanced. Many of these developments are either available now, or will be in the very near future. There is space within the current software to incorporate these new techniques and work is well under way to build them into the process which offers the most promise for the next step forward – expert systems. Indeed several companies now market an expert systems to be incorporated into their software package as an optional extra – those companies which do not yet offer this facility are working hard and fast to do so. These systems still rely heavily on vibration but as the new techniques are developed they will undoubtedly be included.

It should be pointed out that the idea that sufficient information, the years of expert experience, can be programmed into a black box, so making the expert redundant, is, and will remain for the foreseeable future, a total myth. What it will do is relieve the expert of the drudgery of sorting out and analysing the data for the obvious, giving him a choice of say three possibilities and allowing him to make the best decision using all the available information. It will significantly improve efficiency and performance and save time.

The latter point brings me to my final comment. CM and condition based maintenance are only a part of the overall strategy of the management of maintenance. This is an area that we have sadly neglected in this country for many years. The advent of the computer means that we now have a powerful tool to aid us in the efficient management of our art. The software systems are easily integrated, as described, into a maintenance management package. Whilst there is not yet, as far as I know, a knowledge based management system available, there is on the market at least one British maintenance management system capable of the automatic transfer of data between its various elements, including CM. The existence of this and similar programs is a very beneficial spin-off of the rush to develop CM but I believe it will become the principle area of development in the future.

I have done a lot of research into the cost benefits of condition based maintenance. Everyone has a 'gut feeling' that it ought to save money but I have yet to find a clearly documented proof of quantifiable and justifiable savings. There are many wild claims made for CM – not least by the equipment manufacturers. Savings as high as 80% of maintenance costs have been granted. Close inspection of these claims show that either the company did not truly know their maintenance expenditure or, as is more often the case, did not have a maintenance management system in place before the introduction of CM. By introducing a management system of any sort they were bound to get substantial savings and to be better placed to quantify expenditure. My research to date indicates that if a company is operating a sound management system the changeover from preventative to predictive maintenance will lead to savings of around 7–10%. However, savings will only be achieved if a systematic approach is taken to the introduction of condition based maintenance.

First, you must develop your policy. Are you going to go over totally to condition based maintenance? Indeed can you? Are there areas in which you are legally required to carry out time based maintenance? Do you have sufficient redundancy in key areas to risk an unpredicted failure? These and many other questions must be asked and answered before you even start to consider what equipment or manpower will be required. You must carry out an engineering audit of your plant and systems. To do this you must determine the criticality of each machine and place it in one of the following three categories.

1. Equipment which, because of its importance or its lack of redundancy, or because of legal requirements, must remain on a preventative time/calender based maintenance system. This does not mean that it will not benefit from CM but this will be for health monitoring and availability reasons and not for maintenance purposes.
2. Equipment which can be maintained by condition. This will generally be that which either has sufficient redundancy within the system or the failure of which will not catastrophically affect the plant or process. This equipment should comprise the bulk of the plant if condition based maintenance is to be cost-effective.
3. Equipment which can be allowed to run to failure. These will have a maximum of redundancy, or their failure will have little or no effect on the operation of the plant, or their replacement is such a quick and simple task that CM effort is not justified.

Having completed this task such equipment should be studied to determine its fault pattern. It will be necessary to determine which faults are likely to occur, where and how they might be detected, and especially whether they can be predicted – it is of little value collecting data if it is not going to tell you anything. Once this exercise is complete it should be possible to determine if CM and condition based maintenance will be of value. Then the cost of equipment, the cost of modifying the plant to produce data (fitting monitoring points, etc), and the cost of employing consultants (only the smaller systems are capable of being set up in-house and a consultant will be the cheapest option in most cases), should all be considered.

If, having carried out this audit, it can be shown that there is any saving in maintenance costs, then condition based maintenance should be chosen, preferably coupled with a computerised maintenance management system from the start – experience indicates that the increase in availability and reliability which accompanies condition based maintenance will significantly increase the maintenance savings.

S Drew (YARD) I would hope that in view given reflects the progress made in developing CM analytical methods, particularly regarding vibration analysis, in comparison with the progress made in developing the applications of the analysis to solving engineering problems. My thanks to Cdr Watson for highlighting the total engineering approach required for the successful application of CM, the need for a clear policy and engineering audits to establish requirements, and only then deciding on the relevance of CM to each application. The outcome of this approach, whether CM is taken up or not, will be a sound understanding of maintenance requirements and an increase in equipment reliability.

P S Katsoulakos (LR) The author is to be congratulated on this very realistic description of current developments in the field of condition monitoring for marine machinery and equipment.

The success of any condition monitoring system will be dependent on two aspects.

1. Quality of information (extent of instrumentation, accuracy and reliability of sensors).
2. Intelligent information processing.

With respect to the first issue, and in particular sensors, I would like to ask the following questions.

1. What is the author's experience with infrared temperature measurements?
2. Have the authors any practical experience with oil debris monitors?
3. What kind of sensors are most needed to improve our diagnostic capabilities?

S Drew (YARD) We have for some time had an interest in infrared measurement techniques as a diagnostic tool with applications for both electrical and mechanical equipment. The limitation on early infrared systems was that the systems usable by one man gave only a relative indication of temperature or a single spot measurement. The systems available to give measured variations in temperature across equipment required two operators and gave limited hard copy records of the images viewed.

The introduction of infrared equipment, operating without the need for cooling mediums, operated by one man, and giving hard copy records in video format, has greatly increased the application areas for this technique. Industrial applications, utilising fixed infrared measurement equipment, have demonstrated the technique as a CM tool particularly when applied to refractory linings in ovens. Initial investigations in other areas suggest that the primary application will be for investigation of faults and surveys of equipment, while the ability of the system to indicate trends and process data automatically, will permit CM applications to be developed.

As identified in response to other questions it is apparent that oil analysis is an effective CM tool. Our own limited experience of utilising oil analysis as a CM tool has highlighted the requirement for a fast response when samples are submitted for analysis, and the need to follow a well defined procedure for taking samples to ensure that trends are not distorted by external contamination or sampling practice. The level of expertise required to relate the analysis data to specific faults could be reduced by the introduction of suitable information technology.

In our work to date we have seen little need to develop new sensor technology for CM applications. Where benefits could be achieved is in the repackaging of existing sensors to reduce cost, maintenance and calibration requirements and produce a standard output suitable for connection into a digital network. If costs can be reduced by this approach, then manufacturers of marine equipment may find it appropriate to include suitable transducer installation points, further reducing the cost of installing permanent monitoring systems with intelligence local to the machine. Further work is needed in the communication system required to minimise the cost of this type of system. However, success could result in the next step forward for condition monitoring.