THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

92-GT-52

Integration of Condition Monitoring Technologies for the Health Monitoring of Gas Turbines

CYRUS B. MEHER-HOMJI
Boyce Engineering International Inc., Houston, TX 77099

JIM P. CULLEN
Phillips Petroleum Company, Ekofisk Operations
Norway

ABSTRACT

Rapid advancements in gas turbine technology have created a need for advanced condition monitoring systems for critical applications of gas turbines. With a new generation of high temperature and high output engines (150-200 MW) the objectives of attaining a high availability and limiting degradation are of paramount importance. There are several condition monitoring techniques available to gas turbine users. Most publications tend to focus on a specific technique and do not address the need for integration of techniques. Several vibration problems that occur in gas turbines are manifestations of aerodynamic problems. To detect underlying problems of this nature, one is required to integrate performance, vibration and other condition monitoring data. This paper provides a comprehensive review of condition monitoring techniques and presents the thesis that for meaningful condition monitoring one requires the utilization of a variety of condition monitoring techniques coupled with an understanding of gas turbine design and its operational envelope. Case studies are provided to indicate the need for an integrated condition monitoring approach.

INTRODUCTION

With simple cycle thermal efficiencies in the 35 - 43% range a key issue is how one *retains* performance and limits degradation. Some important factors that are of relevance to condition monitoring are:

1. *Fuel Costs* - Fuel costs constitute a large part of the total gas turbine life cycle costs. The annual fuel cost for a 25 MW gas turbine is between 7 and 8 million dollars. Several forward looking corporations now demand that condition monitoring systems be used for performance degradation control. The importance of minimizing performance deterioration is highlighted by the following. In Norway, there is currently a CO_2 tax[1] on fuel of $3/MMBTU. Thus, fuel that cost $3/MMBTU now costs $6/MMBTU (i.e., a 100% increase).
2. *Availability* - This is a strong function of system design, fuel used and environmental factors. If properly implemented, condition monitoring can help in the attainment of high availabilities.
3. *Maintenance*- Hot section maintenance and inspection of a major source of unavailability in utility gas turbines. Condition monitoring techniques and instrumentation that can help detect degradation are therefore of value in reducing downtime. An accurate representation of machinery condition via a condition monitoring system can safely extend the interval between overhauls (TBO), minimize the number of "open, inspect and repair if necessary" routines and aid overhaul planning in the areas of manpower and spare parts requirements.

Several organizations with active programs of condition monitoring have reported maintenance savings of up to 30% compared to costs before the program was implemented. Additionally, the awareness of machine health promoted by condition monitoring greatly facilitates the diagnosis of identified problems. In fact, the two go hand in hand; the knowledge gains in problem analysis provides the database by which to judge new machinery, verify its performance, establish compliance with specifications and identify potential long range problems.

Gearboxes are critical components that are used in conjunction with gas turbines. Gear boxes are used in applications such as helicopters and other transports where mechanical integrity and warning of incipient failure is a must. Modern technological mission requirements for gear boxes relating to time between overhaul (TBO) and mean time to repair (MTTR) imply the need for Condition Monitoring to facilitate a change from the more conservative situation where individual gear boxes are removed based on life assessment to one in which removals are based on condition. Avoiding premature removals will increase the MTTR. Although gear box TBOs are relatively low, a large proportion of transmission assemblies suffer from early failure and have to be removed prematurely. A helicopter rotor and transmission can account for 18% of the helicopter maintenance cost after the engine (which accounts for 44%). The gearing and roller bearings are the critical life limiting items in the transmission. Several gas turbines in the industrial sector have drive gearboxes where successful performance is affected by factors such as alignment, torsional behavior, gear quality, installation factors(foundations, grouting) and lubricant quality.

Underlying Factors For Condition Monitoring Systems.

In North Sea pipeline operations, offshore platforms are designed to be very compact. This means a minimum number of spare parts are stored offshore. In some circumstances, no spare machine capacity may exist. The premium on bed space may preclude having machinery specialists situated offshore. When problems occur, it is vital that good quality information be available to the on-shore maintenance engineer. This can be facilitated by a condition monitoring system that permits real time tie in to onshore facilities.

[1] CO_2 is a "greenhouse" gas and the tax applies an incentive for efficient operation of the gas turbine.

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cologne, Germany June 1-4, 1992

Today, technology makes it relatively easy and low cost (compared with the cost of machinery and fuel) to acquire, reduce and present data about the condition of the critical machine trains. Using this tool, maintenance engineers are able to better understand how machines deteriorate in service. The deterioration is often marked by a loss in performance coupled with mechanical manifestations such as vibration. This is a key factor for the need to integrate condition monitoring technologies of performance analysis and vibration analysis.

It is the authors opinion (and the opinion of several researchers) that gas turbines will actually have to be scheduled for maintenance based on emissions considerations. This is a departure from the situation in which hot section maintenance was scheduled based on creep or low cycle fatigue considerations. Laws on NO_x emissions are being tightened, and this will make it even more important to limit degradation. Gas turbines create pollutants such as NO_x, carbon monoxide (CO) and unburned hydrocarbons (UHC). At low fuel/air ratios, the rate of production of CO and UHC is high due to the low temperatures within the combustors (i.e., low oxidation rates). At higher power levels however, reaction rates increase thus causing less of a problem with these two pollutants. NO_x production, on the other hand, is a strong function of flame temperature and their rate of production increases exponentially with flame temperature.

Simulation studies carried out by Singh and Murthy (1989) have shown the effect of operating degraded engines on NO_x production. Figure 1 shows the effect of a degraded compressor (reflected by a drop in non dimensional mass flow and drop in compressor efficiency) on NO_x production. As expected, the effect is greater at higher ambient temperatures. Hung (1991), describes a predictive emission monitoring system which calculates NO_x emissions based on ambient temperatures and turbine control parameters.

Selection of Condition Monitoring Techniques.

The choice of the condition monitoring philosophy (on line v.off line), particular approach and the diagnostic technique should be based on specific plant operational objectives, location of the machine (offshore, unmanned operation etc.), criticality of machines and the failure modes experienced. As *implementation* and acceptance of a condition monitoring system is a key issue, plant operational practices and maintenance philosophy must be considered at the early stages of a condition monitoring project.

AN OVERVIEW OF CONDITION MONITORING TECHNIQUES

A review of the major engine health monitoring techniques used is presented here. Table 1 shows available techniques and provides details on their implementation and integration.

Condition Monitoring Techniques - Gas Turbines

In order to implement condition based overhauls this one has to know details about the mechanical and performance behavior of the machine. An increase in the ratio of fuel costs to maintenance costs has caused some gas turbine operators to shift emphasis from monitoring mechanical health to monitoring engine performance. This is the case for some pipeline companies where turbine overhauls are driven by drops in thermal efficiency (Ried, 1977; Williams,1981; Saravanamuttoo and Mac Isaac, 1983).

The concept of a slow degradation of component strength or performance is the basis for condition monitoring systems. The condition monitoring system relies on a variety of sensors[2] that help in the observation of component degradation. With todays high speed computers and sensors, it is also possible to detect some of the underlying factors resulting in so called "instantaneous" failures. For example, acoustic doppler techniques have been developed to detect the resonance and cracks in large aspect ratio LP steam turbine blades (Leon and Armor, 1984; Simmons, 1986). Usage Monitoring is also important and in several cases must be integrated within a monitoring system.

As a gas turbine operates it will suffer from a wide range of factors causing deterioration. These include compressor efficiency degradation (fouling), seal leakages overboard leakages, drop in turbine efficiency, changes in turbine flow function, foreign or domestic object damage (FOD/DOD) and compressor blade erosion. Repeated compressor washings can partially restore performance losses, but at some time it is optimal to overhaul to restore performance. Reid (1977) has addressed the significance of fuel costs as a factor influencing the choice of time between overhauls for pipeline engines. Fouling is a major cause of performance deterioration and cycle efficiency loss in gas turbines. Some estimates have placed fouling as being responsible for 70 to 85% of all gas turbine performance loss accumulated during operation. Output losses between 2% (under favorable conditions) and 15 to 20% (under adverse conditions) have been experienced. Fouling of axial flow compressors can have several effects including aerothermodynamic effects, air flow distortion and compressor surge, blading integrity effects and associated problems[3]. These are discussed by Meher-Homji (1990). In studying the list of effects, is clear that early detection of fouling is important. This can be accomplished by performance analysis or by even simpler means of measuring intake depression (on fixed geometry machines). With steam injected cycles and cogeneration plants operating on variable IGV control (to maintain EGT), the control of fouling becomes even more critical as the operating line may be forced closer to the surge line due to the operational mode.

Performance Analysis. Modern turbines and compressors are monitored comprehensively for control and protection purposes. In fact, there is now a convergence between control systems, protection systems and condition monitoring systems. Interfacing (or combining) a condition monitoring system with a modern control/protection system is often only a matter of having an RS 232 or similar connection. This means that most of the information required for aerothermal analysis is readily available. Some machines may require the addition of some sensors for comprehensive aerothermal performance analysis. Several gas turbine operators are installing torque couplings on compressor and pump drives. Torque meters are now quite reliable and have accuracies of better than 0.75%. They can often give indications of surge and torsional vibrations and provide valuable information from a condition monitoring standpoint.

The aerothermal performance of a gas turbine provides valuable insight into its operating condition. Detailed approaches are provided in Boyce and Meher-Homji (1982), Boyce et al. (1989), Cullen (1988), Saravanamuttoo (1974), Muir et al. (1988), White (1988). It is important to integrate such a system with vibration analysis as several vibration problems are manifestations of underlying aerothermal problems. Some problems that can be detected/solved by an integrated condition monitoring approach include rotating stall in axial flow compressors and in centrifugal compressors (both in inducers and diffusers), rotor bows due to rapid temperature ramping, distortion or fouling related surge events (intake distortion) and plugged nozzles. Further, this technology provides insight into how efficiently fuel is being utilized and thus facilitates significant fuel savings if degradation is controlled. We include within performance analysis items such as EGT (or ITT) spread monitoring. This provides insight into hot section health. Figure 2 shows an improvement in EGT spread attained by fuel nozzle replacement on a Frame 5002 gas turbine. Actions such as this can significantly extend hot section life. Excessive spreads can occur due to a variety of reasons including excessive air leakages, blockage of nozzles, and cracks in the combustor liner/transitions.

[2] We include herein visual observations, borescope inspections and other approaches that may not utilize traditional field sensors.

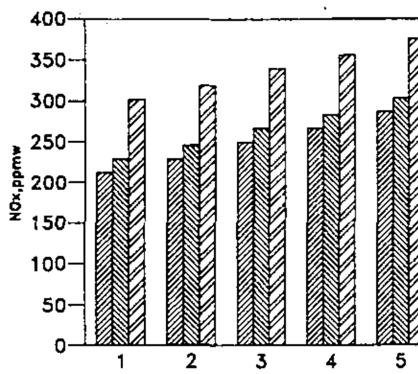
[3] Erosion, Corrosion, Cooling Air Passage Blockage, Unbalance, Foreign Object Damage.

TECHNOLOGY	GENERAL COMMENTS AS APPLIED TO GAS TURBINES	ON-LINE /OFF-LINE	FAILURE MODES/ DEGRADATION DETECTABLE	DATA PRESENTATION AND ANALYSIS	APPROACH TO INTEGRATING WITH OTHER CONDITION MONITORING DATA
VIBRATION ANALYSIS	By far the most popular technique for condition monitoring. Use proximity probes for journal bearings and accelerometers for detection of high frequency problems. Some manufacturers make special probes to monitor rolling bearing bearings. This technique has been applied with success to both steady state and transient data. Included herein are techniques such as shaft position monitoring, phase angle analysis etc. Torsional vibration is also a valuable diagnostic indicator. Torsiographs have been used for diagnostic purposes but are not full time analysis devices.	On-line systems are important for critical machines. Walk around data collectors have also been used.	Wide range of rotor dynamic and resonance related problems such as unbalance, misalignment, looseness, bearing problems, instabilities etc. Also possible so get qualitative information on some blading problems, and some performance related problems.	For diagnostic purposes spectral representation and time waveform analysis is important. Phase angle analysis and orbits are also very valuable. Interpretation is of importance and requires some skill. Meaningful trending is important taking into account dependance of certain factors such as load, RPM etc.	In order to view meaningful trends, baseline comparisons should be made to ensure similar power levels, &/or speeds. Corroborative trending with other mechanical parameters is invaluable. Bearing vibration may be checked with bearing temperature, thrust position with thrust bearing temperature and other operating conditions (eg. Pressure ratio). Step changes in vibration should be evaluated in contest of process changes, lube oil conditions. Certain vibrations such as seal oil induced vibration(≈40-50%RPM) can suddenly occur at a specific high load condition (on centrifugal compressors). Other problems such as insufficient tightness in bearing liner, cap or casing can appear or disappear with small changes in speed.
DYNAMIC PRESSURE ANALYSIS	This is an important tool though not often employed. Dynamic pressure can be measured at compressor locations or at the combustor. Can provide useful information regarding aerodynamic problems, instabilities, stall inception and at times blading damage. Another useful dynamic measurement is by strain gauges for blading vibration and stress. This is not however an approach that can be used for continuous operation.	Would require on-line monitoring because problems under consideration are very erratic and can occur very rapidly.	can be useful to detect problems such as pulsations, surge, stall, rotating stall, fouled conditions, blading problems etc.	Data can be viewed on an oscilloscope or by use of a RTA. Similar data presentation to vibration analysis as data is essentially dynamic. Qualitative evaluation is also important.	Useful when correlated with general performance parameters (flow , Pr ratio, water injection level, etc.) Correlate with vibration behavior at both high and low frequencies. Pulsations can be most troublesome when associated with resonances. Can be synthesized with noise analysis - often a low frequency rumble of a beat type phenomena. Pulsations can cause serious problem during surge.
MECHANICAL ANALYSIS	Included herein are a host of techniques and approaches such as bearing temperature measurement, casing differential expansion growth, ultrasonic detection of bearing wear and all analyses relating to the performance of the lubricating system and associated heat exchangers.	Can be either on-line or off line. For bearing temperatures, a rapid scan rate is required to detect transient problems such as surge, water ingestion etc.	Bearing distress or distress in lube oil systems.	Data can be presented in terms of tabulations or trends. Trend data may require some form of normalization. This is very parameter specific.	Bearing distress should be correlated with vibration, oil condition, debris analysis. In some cases, lube oil and bearing temperatures can be checked against acceptance zone plots which may be based on SHP, N1 etc. This is important with gearboxes where bearing temperatures may be highly load dependant. The effects of lube oil pressure and temperature can also be varied to see the effect on certain problems such as bearing and support excited vibrations, whirls, oil seal induced vibration, friction induced whirl and dry whirl
BORESCOPE INSPECTION (and other visual techniques)	An exceedingly important facet of condition monitoring and provides invaluable information of hot section condition. Included here are the "common sense" type of visual and walk around inspections. It is exceedingly important that troubleshooters do not loose the feel for machinery. Item such as feeling bearing caps, checking for foundation looseness, looseness in the bearing support system, obvious signs of misalignment and coupling problems should not be overlooked.	off-line inspection	Wear, cracks, hot section distress, abnormal fouling, heavy oxide deposits, missing blade tips, cracks, corrosion, erosion, coating flaking, FOD/DOD	Documentation is via photographs or video. Analysis by an experienced individual required. Useful as an aid to making difficult value judgements.	This information must be considered qualitatively with other condition monitoring data. The synthesis is therefore done by the engineer and involves value judgements.
NOISE ANALYSIS	Has been applied to helicopters but is not used extensively on rotating machinery for diagnostic purposes. However, some recent work has shown its use in troubleshooting of steam turbines. The use of microphones in gas turbine inlet ducts has also been used for rub detection during shutdown. On a simple level a mechanics stethoscope can also provide useful for detecting rubs during shutdown (creep induced)	Can be either off-line or on-line. Noise analysis equipment has been used for specific troubleshooting work and not for continuous monitoring.	Wide range of problems such as gearing problems, airflow distortion, etc.	Can be analyzed in terms of frequency content using a RTA	Can be valuable for corroborating evidence in case of aerodynamic excitations, flow induced vibration and gearbox problems -intermediate and frequencies associated with the gear mesh (also for casing drumming)
SPECTROMETRIC OIL ANALYSIS PROCEDURE (SOAP)	SOAP has been applied in marine, industrial and other applications. Requires the regular collection of oil samples. Care must be taken during sample transportation. Good at detection of fretting, sliding wear, micropitting and water ingress. Unable to detect cracks or fractures that do not release tell tale debris. Analysis costs much cheaper than ferrography. Limitation of technique is that it gives no indication of particle size and cannot be used for sizes greater than 10μ. Another problem is the time between sampling and analysis.	This is an off-line approach and involves taking of oil samples.	Wear particulates in the lube oil system	Requires experts to analyze. Sophisticated analysis equipment required.	Use along with other indicators of wear such as vibration, bearing temperature etc.
PERFORMANCE MONITORING AND GAS PATH ANALYSIS TECHNIQUES	Important specialty for large critical applications or in situations where energy costs are of importance. Several mechanical problems are manifestations of aerodynamic problems. We include under this head items such as trending, monitoring of EGT (or ITT) spreads and profiles. It is important to view the data both quantitatively and qualitatively. This can include the use of performance map based data analysis, checking of VSV schedules etc. Also included here are a host of performance related techniques related to *transient behavior*.	Can be performed in either an off line mode or on-line. Normalization and correction of data is important for meaningful calculations.	Deterioration in performance. The extent to which faults are isolatable to specific components depends on the sophistication of data analysis, instrumentation integrity and several practical factors including symptom masking and data scatter effects. *Transient analysis* of aerothermal parameters is useful to detect a host of problems relating to the hot section, start ignition system and several other problems.	Data can be presented in terms of tabulations, performance maps or trends. Trends are valuable to detect deterioration provided some form of data normalization is done to discriminate between off-design effects and deterioration effects.	Corroborative trending with vibration is often very valuable. Examination of effect of speed on vibration is most important for diagnostic purposes. Examination of performance data when there is a step change in vibration is important. Rapid starts, rapid loading can induce bows, excessive temperatures can set up casing distortions and induce misalignment. Foulants on the compressor can cause increase in unbalance and upon shedding, can cause step change in vibration.

Table 1. CONDITION MONITORING TECHNOLOGIES AND THEIR INTEGRATION.

TECHNOLOGY	GENERAL COMMENTS AS APPLIED TO GAS TURBINES	ON-LINE /OFF-LINE	FAILURE MODES/ DEGRADATION DETECTABLE	DATA PRESENTATION AND ANALYSIS	APPROACH TO INTEGRATING WITH OTHER CONDITION MONITORING DATA
FERROGRAPHY	A labor intensive technique restricted to ferrous metals. Seems to work of well for ball bearings. Can provide warning prior to detection using vibration.	Off line	Wear	Requires the use of optic a densitometer or high resolution microscope. Analysis is via ferrograms. Skilled analyst required to interpret data. Some automated systems using image analysis have been developed.	Use along with other wear indicators for corroborative evidence
MAGNETIC CHIP DETECTORS	Often a complementary technique used with SOAP. Chip detectors have to be removed at periodic intervals. Picks up particles typical of spalling and fretting. Only picks up magnetic material. Oil monitor filters will pick up non-ferrous debris as well. Optimal location of chip detector is often traded off for accessibility. Risk of improper installation (or non installation of plug) is significant due to periodic removals. Introduction of fine filtration can negate effectiveness. As a practical matter, MCDs have been applied to aeroengines (see oil debris monitoring)	Off-line. Requires periodic inspection.	Wear in oil wetted parts.	Visual inspection. Data (count) can be trended. Larger particles can be analyzed via microscopic examination (or SEM).	Use with other indicators such as vibration.
OIL DEBRIS MONITORING	Looks at metal debris with sensors located in the scavange lines. Appropriate for gearboxes and for engines utilizing rolling element bearings. Some sensors have been developed that are non intrusive. Has been successfully applied to aircraft, marine and industrial gas turbines. Can detect ferrous debris in a wide range of sizes. Digital display of counts available.	can be on -line. Commercial on-line monitoring systems available.	Wear	Digital displays and trend capability exists. Particles can be classified by sise and number.	Use with other wear indicators
USAGE MONITORING	Applied to lifed parts that are subject to LCF and Creep. Usage algorithms can vary in complexity and typically, a compromise is forged between simplicity and accuracy. This has been extensively used in the maintenance management of aircraft engines.	Data has to be gathered by an on-line system to account for engine excursions, cycles etc.	Damage to disks, hot section blading and other lifed parts.	Usually requires design equations involving transient thermal stresses and complex empirical/experimental data on damage assesament. More difficult with combined damage modes such as creep, thermal fatigue, corrosion etc.	Hot section component life is important and should be integrated with other condition monitoring parameters and off course, borescope inspections. In land based gas turbines, some estimates can be made based on the number of starts, trips and by accumulating engine time at different EGTs. A hot end pyrometer gives valuable information on hot section temperature.
PYROMETRY	An important technology which should become more popular. It enables determination of hot section metal temperatures. Can be used for control purposes. Valuable diagnostic tool that has been used on an on-line basis. Enables determination of improper cooling, excessive hot section life consumption and temperature profile problems.	Can be either off-line or on-line. Measurement by a hand held pyrometer is possible. For critical machines, on-line prefered.	Blade cooling problems, poor temperature profiles, improper control of firing temperature etc.	Can have computerized readouts and graphic capability to get data on blades, peak temperatures, and excursions from average temp, max blade temperature etc.	This data can be integrated with aerothermal analysis to provide an insight to hot section condition and for maintenance planning.

Table 1(Con't). CONDITION MONITORING TECHNOLOGIES AND THEIR INTEGRATION.



DEFRADATION No.	% LOSS IN COMPRESSOR EFFICIENCY	% FALL IN NON-DIMENSIONAL MASS FLOW	AMBIENT TEMPERATURE
1	1	2	−15C
2	2	4	+15C
3	3	5	+45C
4	4	8	
5	5	10	

Figure 1. Oxides of Nitrogen as a function of LP compressor degradation. Singh and Murthy (1988).

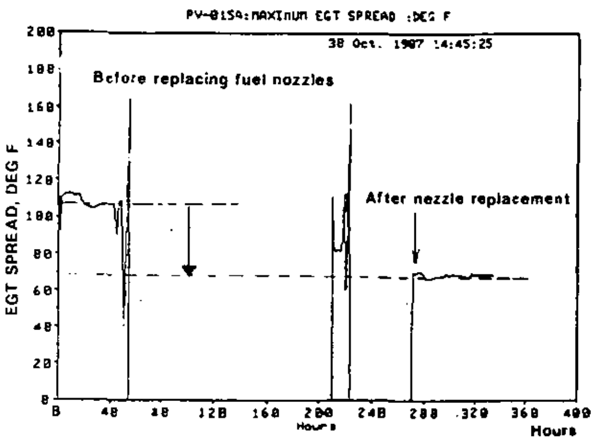


Figure 2. Drop in EGT spread attained by nozzle balancing.

Transient Analysis. There is considerable work being done in the area of transient analysis relating to both performance and vibration data as presented by Meher-Homji and Bhargava (1992). Significant condition monitoring information is available by examining the profile of startup acceleration, coast down times, EGT response during light off and other transient behavior (Merrington, 1988; Muir et al., 1988; White, 1988)

Vibration Analysis. Vibration is a good indicator of machine mechanical health.. With the correct choice of sensors and analysis techniques, vibration analysis is an excellent condition monitoring tool It is further enhanced when used in conjunction with other condition monitoring techniques. Some turbine suppliers provide the minimum sensors (in terms of numbers, frequency ranges etc.) with the main objective of protecting the turbine from catastrophic failure. These sensors are not always successful in meeting this minimum objective. Several manufacturers will provide one or two accelerometers or seismic probes, often filtered to cover only the unbalance frequency (1 X RPM). Thus the operator will often have to add sensors to get the best information for a good maintenance strategy. Experienced troubleshooters will most often review the vibration data in conjunction with performance data to arrive at a "root cause" of a problem.

Dynamic Pressure Analysis. The use of dynamic pressure transducers has worked well to detect certain blading instabilities and compressor instabilities. This is an important facet of condition monitoring that has not received much attention. Loukis et al (1991a) has examined the use of sound, innerwall dynamic pressure and casing vibration to detect certain gas turbine faults.

Lube Oil Debris Analysis. A number of methods are currently available. Several aeroengines have magnetic chip detectors. Debris analysis has been most valuable on gearboxes and engines having rolling element bearings. A wide range of debris analysis techniques are available which can be both intrusive or non intrusive. Details can be found in Lucas and Anderson (1989), and Tauber and Howard (1984).

Spectrometric Oil Analysis Procedure (SOAP) Collacott (1977) has provided a detailed treatment of SOAP as a maintenance tool. It is an off-line technique that often can fail because personnel problems and cycle time limitations. This is especially true in offshore operations where the manpower is of a more transient nature. Experience in offshore operations shows that most off-line schemes usually fall into disuse.

Borescope Inspection. This is an important and valuable condition monitoring tool[4]. It is usually carried out at fixed intervals dependant on the machine with a video camera being used to record results. Borescope inspections are usually very quick and result in a minimum loss of turbine availability. For borescope inspections it is important to have well trained personnel and clear cut procedures defined in concurrence with the machinery manufacturer, to ensure full coverage of the critical components. By using a video camera to record the inspection one can enlist expert outside help to interpret the data. Eddy current checking is also being done to detect cracks.

Usage Monitoring. Experience has indicated that a mere time count of life limited parts is not effective. Life is strongly dependant on the manner in which the engine is used (EGT history, No. of starts and trips). The algorithms to calculate life usage are typically proprietary and require the knowledge of detailed design information. Because of this, it is difficult for industrial users to conduct any form of sophisticated usage monitoring.

[4] Borescope inspection can show up component cracks, erosion, corrosion and buckling.

Advanced Gas Turbine Monitoring Techniques. There are several sensors and monitoring techniques under development or under test at this time. These include:
Optical Pyrometry: By use of an optical pyrometer it is possible to actually measure the metal temperatures of the 1st stage nozzles and rotating blades. It is possible to obtain profile data from such a sensor. There are some industrial gas turbines that have applied optical pyrometry on a full time basis Kirby et al.(1986). Data from an optical pyrometer has been tied into a on-line real time monitoring system Barnes (1989). Pyrometry as applied to gas turbines is covered by Beynon (1981), Kirby (1986 and Barber (1969).
Combustor Acoustics Monitoring: There is a possibility that monitoring of acoustic outputs from a turbine combustor can provide useful diagnostic information pertaining to flame patterns, low frequency pulsations or combustor instability as stated by Dolbec et al. (1986). There are also combustor viewing systems that permit representation of flame images on video screens.
Exhaust Gas Debris Monitoring: This technique utilizes a sensor located in the exhaust duct of the gas turbine and can detect the passage of wear particles (eg. rubbed seals, blades, coating wear, ingested material etc.). Information may be found in Pipe and Fisher (1988), Cartwright and Fisher (1991).
Clearanceometers: Probes have been developed that permit measurement of rotating blade clearance (Simmons, 1990).

Condition Monitoring Techniques - Gear Boxes.

As is the case with gas turbines, a host of condition monitoring techniques are available for gear box monitoring (Meher-Homji et al, 1989) and are summarized below.

Vibration Analysis Techniques:

Spectral Analysis. This is useful for detection of classic rotor dynamic problems such as misalignment, unbalance, sub-synchronous problems, intermediate frequency problems and gear mesh problems. As reported by Mitchell (1982) in industrial gear boxes, high gearing forces usually imply highly loaded bearings and hence a low probability of sub-synchronous vibration. However, during part load, it is possible for these bearings to experience sub-synchronous vibration.

Cepstrum Analysis. A cepstrum is defined as the spectrum of a logarithmic spectrum. Cepstrum analysis is a useful tool for determining periodicity in a spectrum and analysis of the gear mesh sidebands which indicate deterioration. Randall has described the application of Cepstrum analysis for gear box diagnosis.

Shock Pulse Metering. Shock pulse meters detect mechanical impulses caused when rotating elements encounter discontinuities in bearing races. It operates in the high frequency range.

Statistical Signal Analysis and Time Domain Averaging. While spectrum analysis is a common method for vibration condition monitoring, there is an interest in the use of statistical analysis, especially for roller bearings. There has been success reported in the use of Kurtosis (normalized 4th moment) for bearing condition monitoring because it is independent of operating conditions (Dyer and Stewart, 1978; Martins and Gerges, 1984). The Kurtosis method is based on the fact that with defects, the high frequency pulses created by the raceway striking a ball tend to alter the completely random vibration signal (from a normal bearing) to one in which the Kurtosis component increases. Time domain averaging incorporates phase, as well as amplitude information. Synchronous time domain averaging can be used to isolate vibration signals generated from individual gears. Obviously for phase measurements, shaft encoders are required. Page and Hernandez (1989) describe tooth-by-tooth techniques that permit an enhancement to the time domain averaging method.

Usage Monitoring

In helicopter service there are times when very heavy torque excursions occur for short durations. In order to maintain endurance limits, transmissions are typically certified on a safe life basis based on a fixed number of flying hours. By monitoring torque, it is possible to move towards a condition based retirement policy.

Oil System Monitoring

This includes oil system operation monitoring, oil debris monitoring, and oil condition monitoring. An interesting analysis made by Hunt (1987) in which he concludes that no single condition monitoring technique is applicable, but that a combination of condition monitoring techniques would go a long way in satisfying gear box monitoring needs. This view is also supported by Astridge (1987) who reports success in using both vibration analysis (specifically the 6th moment) in conjunction with a debris monitoring technique. In the case of roller bearings, Stewart (1976) has conducted a set of experiments where he has postulated the use of vibration analysis and debris analysis. Another correlation type of investigation has been reported by Kyhnell and Stecki (1984). A comparative analysis of techniques has been made by Lewis (1984)on large gear boxes. In general, the conclusions all point to an integrated approach as being the best.

INTEGRATION OF CONDITION MONITORING TECHNIQUES

In order to plan maintenance for machinery problem rectification, one requires good insight into the operating condition of the machinery. With predictive maintenance, small incremental maintenance actions are used to delay the need for major maintenance intervention. For example, if ignored at an early stage, an increasing temperature spread in the combustion/turbine module may lead to premature failure of the 1st. stage nozzle or even turbine blades. Maintenance action such as nozzle balancing can alleviate the problem. Sometimes, a combination of symptoms may be needed to pinpoint problems. A broken inlet guide vane mechanism, may cause increasing vibration as well as loss of compressor efficiency or possibly even surge.

Blading vibration and failures are one of the most complex problems in gas turbines due to the complicated blade dynamics and interaction of factors such as blade quality, environment (salt, temperature), erosion/wear and fatigue effects. An integrated condition monitoring approach involving performance and vibration monitoring can be of help here. While vibration and performance monitoring cannot predict blade failures, often the underlying causes (air flow distortion, surge, nozzle bowing/blockage etc.) can be detected, thus providing a chance to avoid the failure. The use of performance and vibration monitoring for reduction of blading problems has been described by Meher-Homji and Focke (1985). There has also been work done in the area of using dynamic pressure to detect blading problems. Details on blade diagnostic work is provided in Loukis et al. (1991b).

Most operators of critical unspared gas turbines have been in situations in which machines which are known to be in distress have to be operated. In this situation, all possible insight is valuable to help keep the machine operational until a convenient outage can be taken. The maintenance engineer must know if the machinery is capable of achieving this requirement and must be able to provide management with solid reasons why the machines need to be shut down for overhaul. Trend curves, vibration spectra, exhaust temperature spreads, oil analysis and borescope inspection results are invaluable in making such decisions. No single technique can cover all the essential data. As a general rule (and there may be exceptions), if the performance, efficiency, vibration, borescope, and EGT spread results are acceptable, then a major inspection can be avoided, regardless of how long it was to the last inspection. This has been our experience with turbines and compressors offshore. Prior to the implementation of condition monitoring systems, it was quite normal to carry out a major inspection every 40,000 hours on industrial gas turbines.

Obviously, the above techniques do not provide all the information on the condition of a machine. Creep life, for example is not measurable by vibration or performance analysis or in a borescope inspection. Similarly some catastrophic failures occur because of high cycle fatigue, without any pre warning. Creep life can however be estimated if some record of load/firing temperature is maintained. Some fatigue mechanisms (low cycle) can be estimated from start/stop and trip events.

Expert Systems and Neural Nets.

Some of the skepticism towards expert systems occurs because engineers believe that their long experience with machinery diagnostics cannot be summed up in a few rules of inference, no matter how powerful the inference machine. A study of the reasoning processes in diagnostics and implications to expert systems is made by Meher-Homji (1985a,b). Expert Systems generally imply a deterministic approach to machinery behavior. In reality, chaotic rules are often more appropriate. A machine may run perfectly well at one set of conditions but may suffer seriously from a small change in these conditions. This is certainly true of some high discharge pressure compressors. Expert Systems are of use in dealing with sub-problems such as trending, data validity checking and diagnostics. They are also valuable in integrating condition monitoring data in order to obtain meaningful diagnostics. A review of possible roles for expert systems is made by Doel (1990).

There has recently been considerable work done in the area of the application of neural nets for monitoring and diagnostic applications (Wang, 1990; Weiskopf, 1990; Kamal et al, 1987). The training of a neural net may, however, require a considerable number of faulty engines. Another computer related technological development is the use of hypermedia which could provide users with fast access to text and figures related to troubleshooting and maintenance of gas turbines.

CASES SHOWING THE NEED FOR AN INTEGRATED APPROACH IN CONDITION MONITORING

Maintenance & Overhaul of Off-Shore Gas Turbine Compressor Trains

This case pertains to a GE Frame 5002 Type H (ISO rated at 22.4 MW) two shaft gas turbine driving a Dresser-Rand centrifugal compressor(back to back configuration) in off-shore pipeline service. The trains are located at the Ekofisk off-shore complex. As major overhauls on a Frame 5002 gas turbine can typically take 3 months, there is a very strong incentive to prolong time between overhauls if integrated condition monitoring data does not indicate distress.

The No.1 bearing of this turbine exhibited an increase in vibration that was picked up on the condition monitoring system and analyzed as unbalance. The machine had run for over 40,000 hours since its last major inspection and the performance of both the gas turbine and the pipeline compressor was poor which was ascertained using a condition monitoring system. A decision was made to dismantle the turbine and gas compressor for an investigation. The 16 stage gas turbine axial compressor was found to have foreign object damage (FOD) on the first 8 stages. The blading was severely eroded in the latter 6 stages. The rotor was removed and sent for repair. A spare rotor taken from another gas turbine (the replacement rotor had 20,000 hours running time) was installed to replace the damaged compressor.

Figure 3a shows a trend in turbine ISO corrected horsepower which indicated a decline prior to the overhaul. The recovery after the overhaul is evident. Figure 3b shows a trend showing a drop in gas turbine compressor pressure ratio and the improvement attained when the replacement rotor was installed. Figure 3c shows the deterioration that occurred in the flow capacity of the centrifugal compressor before the overhaul. An increase in polytropic efficiency is also noted as shown in Figure 3d. This increase in polytropic efficiency was attributed to the replacement of the damaged interstage seals and the cleaning for the pipeline compressor. An improvement of about 40% in the vibration level at the compressor inboard bearing was also noted as shown in Figure 4.

At the same time, an inspection of the gas pipeline compressor revealed damaged interstage labyrinth seals and dirt in the compressor. The seals were replaced and the unit cleaned. After the major inspection was completed, the unit was started and immediately had a vibration problem on the No.1 bearing. As it was known that the turbine high pressure *rotor* was in good condition and well balanced, the coupling condition was investigated. It was found that inadvertently, an old accessory coupling (with high unbalance) had been installed instead of a new one. The old coupling was replaced

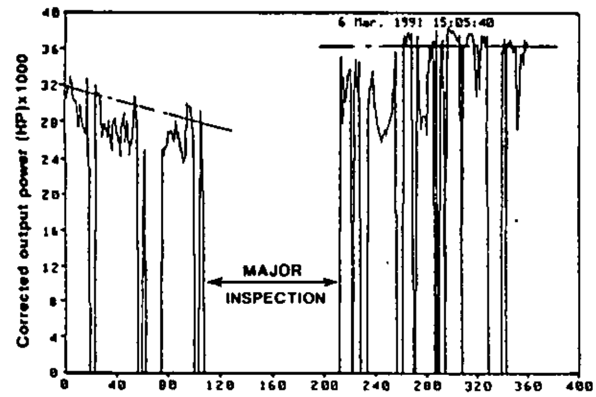


Figure 3a. Turbine corrected HP before and after major inspection.

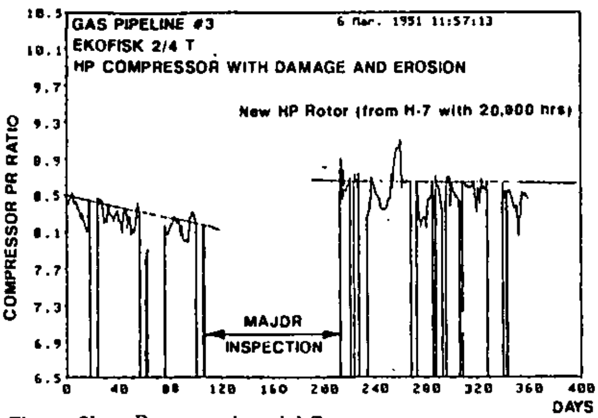


Figure 3b. Recovery in axial flow compressor pressure ratio.

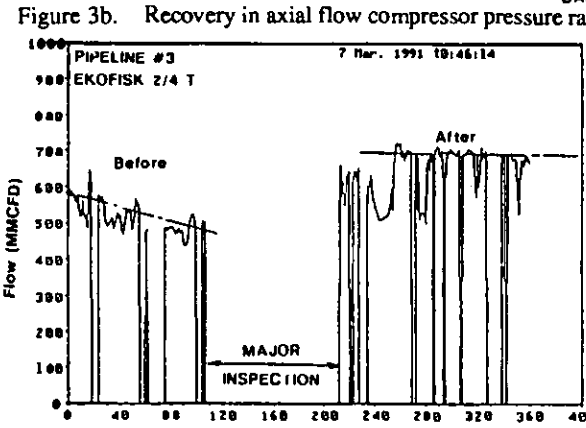


Figure 3c. Pipeline Compressor Flow capacity

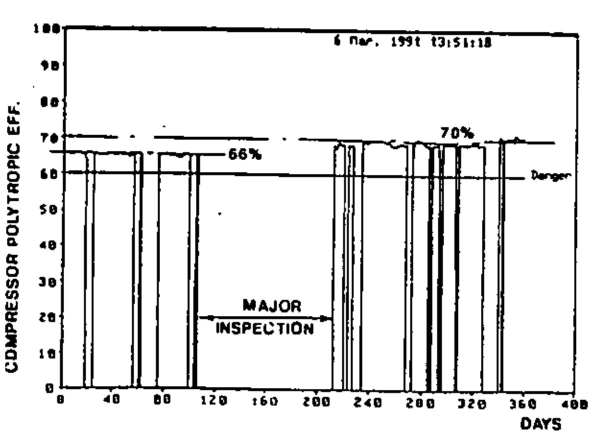


Figure 3d. Polytropic efficiency of pipeline compressor.

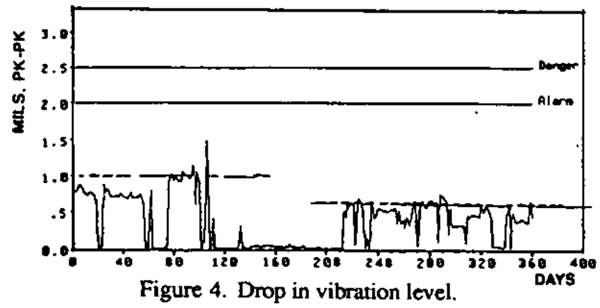


Figure 4. Drop in vibration level.

with a new one. Figure 5 shows the dramatic drop (approximately 75%) in vibration after replacement of the accessory coupling. Figure 6 shows the 8 mil pk-pk vibration spectrum predominantly at 1 X running speed of 84 Hz (5056 RPM) that occured with the old coupling. The arrow on the figure indicated the reduced amplitude attained with the new coupling installed. This case highlights how decisions can be made by the use of an integrated condition monitoring approach evaluating both performance and vibration data.

In the past, there have been cases of self excited vibration on pipeline compressors, which have required careful monitoring of process conditions to determine the onset of this phenomena and also the use of the transient data capture to determine the exact frequency of the critical and the damping capability of the bearings. Usually with sub synchronous type vibration problems, there are many variables which can contribute to the problem. It is therefore necessary to have as much data as possible including aerodynamic, rotordynamic and static data (such as oil temperature, shaft to bearing clearance). Often, in such cases, one can successfully operate the compressor by adjusting these parameters without resorting to major redesign. Obviously, this calls for an *integrated* evaluation of both performance and vibration data.

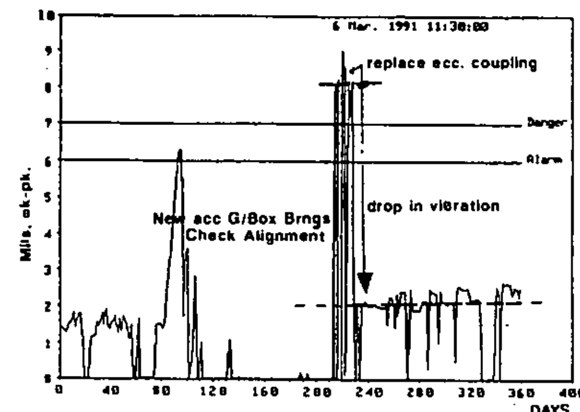


Figure 5. Drop in vibration level with new acc. coupling.

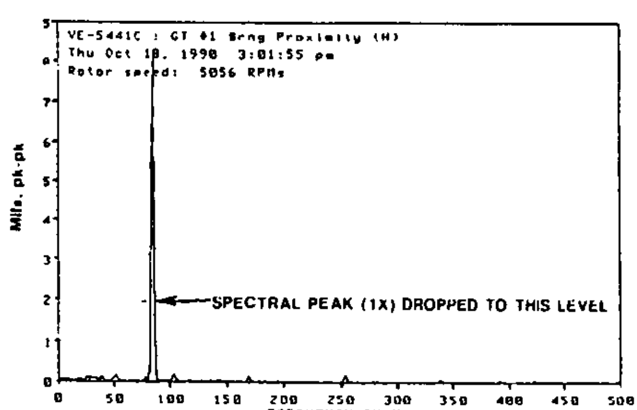


Figure 6. Vibration spectra showing high 1X RPM peak with old coupling and level attained upon installation of new one.

Industrial Gas Turbine Exhibiting Bearing Sub Harmonic Resonance

A large industrial gas turbine (mechanical drive service) experienced high amplitude, low frequency vibrations at around 10 Hz. The high vibration behavior was very time dependent and erratic and experienced on both the No. 1 and 2 bearings. Detailed vibration studies, correlation with basic performance data, and examination of dynamic pressure indicated that the problem was a bearing subharmonic resonance caused by deterioration in the bearing and bearing support structure. By using dynamic pressure measurements in the exhaust duct it was determined that the problem was being accentuated due to exhaust rumble (pulsations). Again, in this case, information from both vibration and dynamic pressure pulsation data were integrated to arrive at a diagnosis. Figure 7 shows some vibration cascade data pertaining to this.

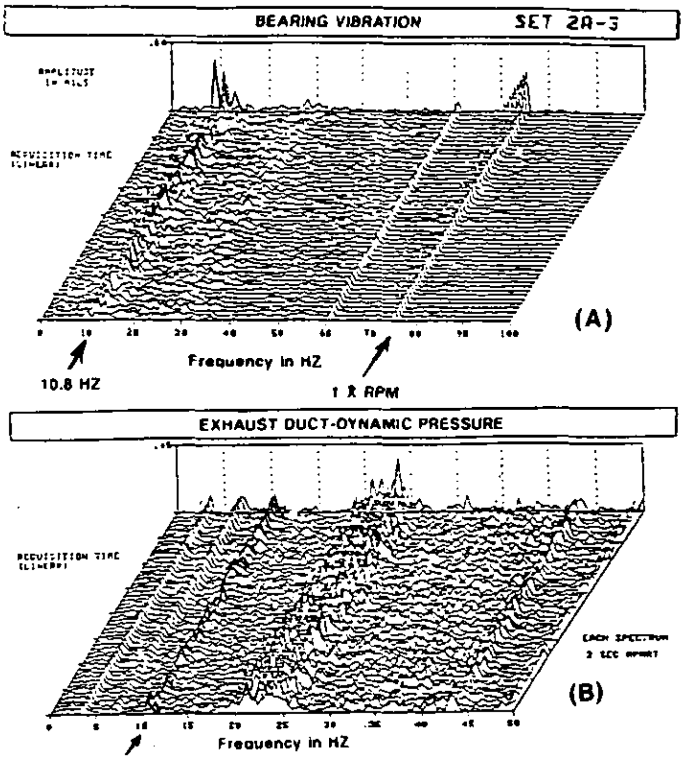


Figure 7. (a) Vibration cascade at GT bearing showing low frequency excitation. (b) dynamic pressure cascade taken at exhaust duct.

Random Vibration Trips on a Centrifugal Turbocharger

The turbocharger consisted of a single stage centrifugal compressor and an axial flow turbine operating at approximately 10,200 RPM. The unit had a vibration switch for protection which constantly tripped the unit at random times. The integrity of the vibration switch itself was checked and was found acceptable. A vibration analysis was performed by taping high frequency accelerometer data (see Figure 8). Analysis of the data on a Real Time Analyzer showed that the spectrum in the full frequency range was being excited (white noise exciation). All the peaks and the base value of the spectrum would rise during this event. This occured several times a minute. The taped vibration signal was also put through an audio device so it could be monitored on headphones. This combined form of analysis indicated the following:

1. The impulsive forces that were causing the excitation were random in nature and not speed dependant. They occured as the machine ran. The problem was also tracked at different performance conditions (RPM) to see if there was any correlation.
   Corresponding to the excitation of the spectra, a distinct audible sound could be heard.
2. Trips were initiated by a loud sound (and excitation of the spectra)
3. During coast down, this phenomena persisted on a random basis.
4. After shutdown (i.e., 0 RPM), the impulsive forces still occured for a duration of about 1 minute and they finally died out.

Several candidate causes were considered. An examination of the turbocharger drawings showed that the unit was water cooled. The water was forced in to the bottom of the casing and exited at the top. A hypothesis was formed that flashing of the water into steam was causing the impulsive forces. To test this hypothesis, two tests were conducted. First cooling water at nominal conditions was pumped in. Using a stethoscope, the number of impulsive noises of 40/minute was counted. In the second test, the flow and pressure of the water

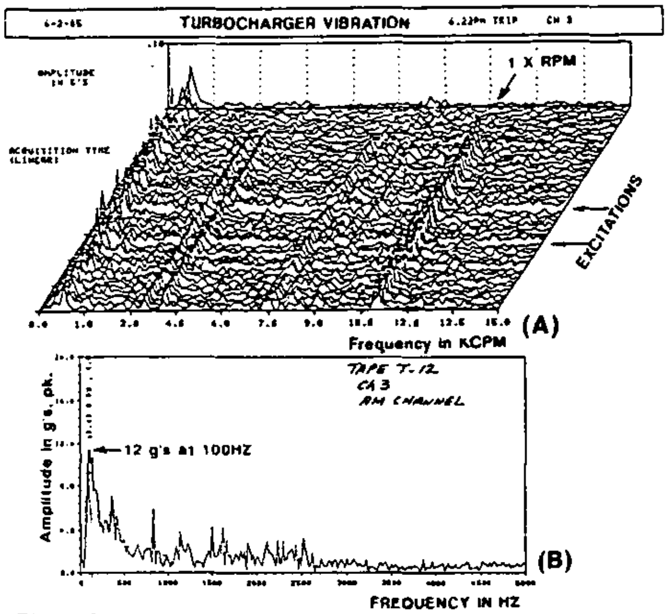


Figure 8. (a)Cascade representation of impulse events (see arrows). These corresponded to audible noises within turbocharger. Frequency range = 250 Hz.
(b)Spectrum captured on peak hold showing level of 12 g's at ≈ 100 Hz. Frequency range = 5 KHz.

were increased. Under these conditions, no impulsive sounds were audible. The flashing of water into steam (due to a casing design modification) was what was exciting all natural frequencies that caused the full spectrum to be excited which when severe, caused a vibration trip. This case shows how both vibration, noise and performance were used in an integrated fashion to troubleshoot an elusive problem.

CONDITION MONITORING FOR A GAS TURBINE MAINTENANCE MANAGEMENT

In the case of large gas turbines a satisfactory compromise in terms of maintenance strategy is to carry out preventive maintenance at what may be irregular intervals, but to determine these intervals by the actual condition of machines at the time.

Condition monitoring permits an accurate assessment of the machine condition thus providing the opportunity to optimize maintenance actions to minimize fuel consumption and control maintenance costs. The problem is a complex one and calls for a detailed understanding of gas turbine degradation, condition monitoring and optimization. It is important to note that in reality this problem is multi-objective in nature and involve solutions that *"satisfice"* i.e., *solutions that are non-optimal but meet most goal aspiration levels*. It is possible to link condition monitoring with multiobjective optimization and utilize knowledge based systems to modify the factors that are used in the optimization models. Meher-Homji. et. al. (1991) have provided a treatment of this concept.

CLOSURE

A thesis has been presented that for critical high speed turbomachinery and gearboxes no *one* technique can provide all the answers pertaining to machine condition. An integration of techniques is required and the information obtained by different techniques must be synthesized. While expert systems are becoming popular, their application should be limited to areas where a rule based system approach makes sense i.e., when algorithmic solutions are impossible or intractable. Expert systems are of value in synthesizing condition monitoring information. The choice of which set of condition monitoring technologies should be utilized is a complex decision involving economic, technical and human factors. As systems for condition monitoring are merged with control systems, opportunities will exist to apply several techniques and approaches in an integrated fashion. These include a *set* of condition monitoring techniques, expert systems to deal with sub problems, such as validity checks, trending and diagnostics and data synthesis. Additionally, neural networks (for learning and classification of data) will be investigated and will probably coexist with expert systems as hybrid systems. Hypermedia applications will also be of value to users. Decision support systems including a merging of condition monitoring technology and multiobjective optimization will be applied for maintenance management. We believe this level of sophistication will be appropriate on large scale critical plants. These approaches would enable a close to optimal maintenance and outage schedule by considering a multitude of factors.

Regardless of the technological advances in condition monitoring technology, a key issue for the successful implementation of any condition monitoring approach is for the user to have a thorough understanding of the machines performance characteristics and health related mechanical behavior.

REFERENCES

Astridge, D.G., 1987, "HUM-Health and Usage Monitoring of Helicopter Mechanical Systems". International Conference on Condition Monitoring (Condition Monitoring '87) Swansea, March/April, 1987.

Baristo, N.A., 1988, "A UK. Perspective on Engine Health Monitoring Systems for Future Technology Military Engines", ASME Paper 88-GT-148.

Barber, R., 1969, "A Radiation Pyrometer Designed for In-Flight Measurement of Turbine Blade Temperatures", SAE Paper No. 690432, April 1969.

Barnes G., Hawthorne, D, Boyce M.P., Wooldridge, B., Meher-Homji, C., 1989, "On-Line Condition Monitoring of Two Westinghouse CW 352 Gas Turbine Compressor Sets", Proceedings of the 8th NRCC Symposium on Industrial Applications of Gas Turbines, Ottawa, September 1989.

Beynon, T.G.R., 1981, "Turbine Pyrometry - An Equipment Manufacturer's View", ASME Paper 81-GT-136.

Boyce, M.P. and Meher-Homji, C.B., 1982, "Aerothermal- Mechanical Health Monitoring and Diagnostics of Turbocompressor Sets", Proceedings of the Eleventh Turbomachinery Symposium, Texas A&M University, December 14-16, 1982, Houston, Texas.

Boyce, M.P., Meher-Homji, C.B. and Mani, G., 1983, "The Development and Implementation of Advanced On-line Monitoring and Diagnostic Systems for Gas Turbines", 1983 Tokyo International Gas Turbine Conference, paper IGTC-94.

Boyce, M.P., Meher-Homji, C.B. and Mani, G., 1989, "A Diagnostic Methodology for Condition Monitoring of High Speed Turbomachinery". Proceedings of the 1989 Condition Monitoring and Preventative Maintenance Conference, Society of Tribologists and Lubrication Engineers, May, 1989, STLE Publication SP-27.

Cartwright, R.A., Fisher, C., 1991, "Marine Gas Turbine Condition Monitoring by Gas Path Electrostatic Detection Techniques", ASME Paper 91-GT-376

Collacott, R.A., 1977, Mechanical Fault Diagnosis, Chapman and Hall Ltd 1977

Cullen J.P., 1988, "Operating Experience with Type H Industrial Gas Turbines on North Sea Platforms", ASME Paper 88-GT-247

Di Pasquale, F., "Field Experience with Quantitative Debris Monitoring", SAE Paper No.: 871736

Doel, D.L., 1990, "The Role of Expert Systems in Commercial Gas Turbine Engine Monitoring", ASME Paper no: 90-GT-374.

Dolbec, A.C., et.al., 1986, "Advanced Diagnostic Instrumentation for Combustion Turbines", 1986 American Power Conference, Chicago, Illinois, April 1986.

Dyer, D. and Stewart R.M., "Detection of Rolling Bearing Malfunctions by Statistical Analysis". Journal of Mechanical Design Vol. 100, pp 229-335, 1978

Fisher, C., 1988, "Gas Path Condition Monitoring using Electrostatic Techniques", AGARD Conference Proceedings No. 448, June 1988.

Hung, W.S.Y., 1991, "A Predictive NOx Monitoring System for Gas Turbines", ASME Paper 91-GT-306.

Hunt, T.M., 1987, "Vibration or Oil Debris Monitoring?" Journal of Condition Monitoring, Vol.1, Number 1, 1987.

Kamal S.Z., Meher-Homji C.B. and Mistree F., 1987, Event-based Learning for Monitoring Rotating Machinery, Second International Conference on Applications of Artificial Intelligence to Engineering Problems, Boston, August 1987.

Kirby, P.J., Zachary R.E., Ruiz, F., 1986, "Infrared Thermometry for Control & Monitoring of Industrial Gas Turbines", ASME Paper 86-GT-267.

P.J. Kirby, 1986, "Some Considerations Relating to Aero Engine Pyrometry", 67th AGARD Symposium on Advanced Instrumentation for Aero Engine Components, May 1986.

Kyhnell, B.T. and Stecki, J.S., 1984, "Correlation of Vibration, Wear Debris, and Oil Analysis in Rolling Element Bearing Condition Monitoring". Condition Monitoring 1984, Ed. Jones, M.H., Pineridge Press, Swansea, U.K..

Leon, R.L., Armor, A.F., 1984, "Detecting Resonant Blade Vibrations in Turbines", EPRI Conference on Incipient Failure Detection in Power Plants, October 1984.

Lewis, D.C., 1984, "Machine Health Monitoring at MRDE", Condition Monitoring, '84, Ed, Jones, M.H. Pineridge Press, Swansea, U.K..

Loukis, E, Mathioudakis, K., Papathanasiou, A., Papiliou, K., 1991, "A Procedure for the Automated Gas Turbine Fault Identification Based on Spectral Pattern Analysis", ASME Paper 91-GT-259

Loukis, E., Wetta, P., Mathioudakis, K.,Papathanasiou, A., Papailiou, K., 1991, "Combination of Different Unsteady Quantity Measurements for Gas Turbine Blade Diagnosis", ASME Paper No: 91-GT-259.

Lucas M., Anderson D.P., 1989, "Developments in Instrumentation & Automation in Techniques for Machine Condition Monitoring Through Oil Analysis", Proceedings of the 1st International Machinery Monitoring & Diagnostic Conference, Las Vegas, Sept 1989

Martins, L.G., and Gerges, S.N.,1984, "Comparison Between Signal Analysis for Detecting Incipient Bearing Damage". Condition Monitoring 1984, Ed Jones, M.H. Pineridge Press, Swansea, U.K..

Meher-Homji C.B., 1990, "Gas Turbine Axial Compressor Fouling - A Unified Treatment Of Its Effects, Detection & Control", ASME Publication IGTI-Vol.5 1990 ASME Cogen Turbo IV, August 27-29, 1990

Meher-Homji, C.B., Bhargava, R, 1992 "Condition Monitoring and Diagnostic Aspects of Gas Turbine Transient Response", 1992 ASME Gas Turbine Congress, Cologne, Germany, June, 1-4, 1992.

Meher-Homji, C.B., Meher-Homji, F.J. and Chinoy, R., 1989, "Vibration and Debris Analysis for Condition Monitoring of Gearboxes: An Integrated Approach," Proceedings First International Machinery Monitoring and Diagnostic Conference, Las Vegas, Nevada, September 11-14, 1989.

Meher-Homji, C.B., 1985a, "A Feasibility Study in the Application of AI Techniques for Turomachinery Diagnostics", ASME Paper No. 85-GT-102.

Meher-Homji C.B., 1985b, Reasoning Foundations for Machinery Diagnostics - Thought Process & Expert Systems, Proc. Symposium on New Technology to Improve Mechanical Readiness, Reliability & Maintainability, National Bureau of Standards, April 16-18, 1985, Cambridge University Press, 1987.

Meher-Homji C.B., Focke A.B., 1985, "Performance & Vibration Monitoring for the Prevention of Gas Turbine Airfoil Failures", 6th Bi annual ASME Conference on Failure Prevention & Reliability, September, 1985 ASME Vol H-331.

Meher-Homji, C.B, Mistree, F. Karandikar, S., 1991 "An Approach for the Integration of Condition Monitoring and Multiobjective Optimization for Gas Turbine Maintenance Management", Proceedings of the 3rd International Machinery Monitoring and Diagnostic Conference, Las Vegas, December 9-12, 1991.

Merrington, G.L., 1988, "Identification of Dynamic Characteristics for Fault Isolation Purposes in a Gas Turbine Using Closed Loop Measurements, AGARD CP 448, 1988.

Messenger, G., Thibedeau, R., 1989, Gas Path Debris Monitoring Test & The National Research Council", Proceedings of the 8th Symposium on Industrial Applications of Gas Turbines, Ottawa, September, 1989.

Mitchell, J.S., 1982, "Continuous Monitoring of High Speed Gearing". Proceedings of the 11th Turbomachinery Symposium, December, 1982, Texas A&M University.
Muir D.E., Saravanamutto, H.I.H., Marshall, D.J., 1988, "Health Monitoring of Variable Geometry Gas Turbines for the Canadian Navy", ASME Paper 88-GT-77
Muir D.E., Rudnitski D.M., Cue R.W., 1988, "CF-18 Engine Performance Monitoring" AGARD Proceedings CP-448, 1988.
Page, E.A., Hernandez, W.C, 1989, "Vibration Analysis Pinpoints Gear Defects", Power Transmission Design, March, 1989, pp 43-46.
Pipe, K., Fisher, C., 1988, "Recent Advances in Engine Health Management", ASME Paper 88-GT-257.
Randall, R.B., "Cepstrum Analyzers and Gearbox Fault Diagnosis". B&K Application Note 233-80.
Ried, D.E., 1977, "Impact of Increased Fuel Prices On Gas Turbine Operation and Maintenance", Proceedings of the 2nd NRCC Symposium on Gas Turbines Operations and Maintenance, Calgary.
Saravanamuttoo, H.I.H., Mac Isaac, B.D., 1983, "Thermodynamic Models for Pipelines Gas Turbine Diagnostics", ASME Paper 83-GT-235
Saravanamuttoo, H.I.H., 1974, "Gas Path Analysis For Pipeline Gas Turbines", Proceedings of the 1st NRCC Conference on Gas Turbine Operations & Maintenance, October 1974.
Simmons, H.R., 1986, "A Non-Intrusive Method For Detecting HP Turbine Blade Resonance", ASME Paper No. 86-JPGC-Pwr-36.
Simmons, H.R., et al., 1990, "Measuring Rotor & Blade Dynamics using an Optical Blade Tip Sensor", 1990 ASME Gas Turbine Conference, Brussels, Belgium.
Singh, R., Murthy, J.N., 1989, "A Computational Study of Some of the Implications for Gas Turbine Design and Maintenance as a Consequence of NOx", 18th CIMAC Conference, Tiajin, China.
Society of Automotive Engineers "Guide to Oil System Monitoring in Aircraft Gas Turbine Engines", Society of Automotive Engineers, Aerospace Information Report , AIR 1828.
Stewart, R.M., 1976, "Vibration Analysis as an Aid to the Detection and Diagnosis of Faults in Rotating Machinery", International Conference on Vibration and Rotating Machinery, Cambridge, September, 1976, I. Mech.E..
Tauber, T.E., Howard, P.L., 1984, "QDM - A Smart On-Line Debris Monitoring System", Condition Monitoring '84, Ed. M. Jones, Pineridge Press, 1984.
Velentini, E., Ferrari, M., "Measuring Temperature of Rotating Blades in a Gas Turbine with an Infared Pyrometer", Quaderni Pignone No. 46.
Wang, S.S., 1990, "Diagnostic Expert System For Industry", Proceedings of the 2nd International Machinery Monitoring & Diagnostics Conference, October 22-25, '90 LA, California.
Weiskopf F.B., Arcella, F.G., Lin, J.S., Newman,R.W.,1990, "A Hybrid System Approach for Machinery Monitoring & Diagnosis", Proceedings of the 2nd International Machinery Monitoring & Diagnostics Conference, October 22-25, '90 LA, California.
White, M.F., 1988, "An Investigation of Component Deterioration in Gas Turbines using Transient Performance Simulation", ASME Paper 88-Gt-258.
White, M.F., 1988, "An Investigation of Component Deterioration in Gas Turbine Using Transient Performance Simulation", ASME Paper 88-GT-258, ASME Gas Turbine & Aero Engine Congress, Amsterdam, June 6-9, 1988.
Williams, L.J., 1981, "The Optimization of the Time Between Overhauls for Gas Turbine Compressor Units", 4th NRCC Proceedings on Gas Turbine Operations and Maintenance, Sept., 1981.