ADVANCED TRENDS IN PERFORMANCE MONITORING OF GAS TURBINES

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Introduction

1. The performance monitoring process of gas turbines requires technologies, skilled operators and communication to integrate all available data of the equipment condition, such as diagnostic and performance data, maintenance histories, operator logs and design data, to make timely decisions about the maintenance requirements of major/ critical equipment as well as predict defects. A variety of technologies can and should be used as part of a comprehensive and effective diagnosis of health of the gas turbine. Since mechanical systems or machines account for the majority of equipment, vibration monitoring is generally the key component of most performance monitoring systems. However, vibration monitoring alone cannot provide all of the information that will be required for an effective monitoring of gas turbine performance.

2. A comprehensive performance monitoring philosophy must be based upon monitoring and diagnostic technologies like Tribology, Thermography and Thermodynamic models (Process Parameter Analysis) in addition to vibration monitoring. When solutions emerging out of these technologies are employed in conjunction with one another as part of a larger system implementation, it enhances the diagnostic capabilities for assessing the nature, severity, location and cause of machinery performance changes. In the Indian Navy, the performance monitoring philosophy of gas turbines includes a combination of vibration monitoring, oil analysis and monitoring of process parameters. While the current system in the Navy is functioning well, there is an inescapable need to induct more advanced techniques as part of continuous improvement.

Aim

3. The aim of this paper is to study certain advanced performance monitoring techniques being used in the aero, industrial and marine applications of gas turbines.

Scope

4. The following advanced performance monitoring techniques being employed in the field of gas turbines have been discussed in this paper:-

(a) Vibration Monitoring through TORCH Analysis, application of Seismic transducers for vibration monitoring and good installation practices.

(b) Thermodynamic model based diagnostics namely Gas Path Analysis (GPA), Non Linear GPA (NGPA) and Kalman Filter methods.

(c) Soft Computing Methods/ Artificial Intelligent techniques based on Artificial Neural Networks (ANN), Fuzzy Logic and Genetic Algorithms (GA).

(d) Tribological monitoring techniques based on In-line X-ray Fluorescence (XRF), Innovative Wear Debris Analysis called Laser Induced Breakdown Spectroscopy (LIBS) and Real Time oil sensors.

(e) Thermography visualisation techniques based on Thermochromic Liquid Crystals and Infrared Thermography.

Performance Monitoring Technologies

5. A variety of technologies can and should be used as part of a comprehensive performance monitoring programme based on CBM philosophy. Since mechanical systems or machines account for the majority of plant equipment, vibration monitoring is generally the key component of most condition based maintenance programmes. However, vibration monitoring cannot provide all of the information that will be required for a successful performance monitoring programme[1]. This technique is limited to monitoring the mechanical condition and not other critical parameters required for maintaining reliability and efficiency of machinery. Therefore, a comprehensive performance monitoring philosophy must include a combination of monitoring technologies and diagnostic techniques. These include:-

(a) Vibration Monitoring
(b) Computer based Thermodynamic Models
(c) Artificial Intelligence Techniques
(d) Tribology
(e) Thermography
(f) Process Parameter Monitoring
(g) Acoustic Analysis

Advanced Performance Monitoring Techniques

Vibration Monitoring through TORCH Analysis

6. **Tracked Orders**. *TORCH* is an acronym coined by Rolls-Royce which stands for **T**racked **Or**der **Ch**aracteristics[2]. A ***tracked order*** is defined to be the amplitude of

[1] Implementation Strategies and Tools for Condition Based Maintenance at Nuclear Power Plants, International Atomic Energy Agency, Vienna, TECDOC – 1551, 2007

[2] David Clifton, Condition Monitoring of Gas-Turbine Engines, University of Oxford, 2006

engine vibration measured within a narrow frequency band centred on the fundamental or a harmonic of the rotational frequency of a shaft. During normal engine operation, most vibration energy is present within tracked orders centred on the fundamental frequency of each rotating shaft; we define these to be *fundamental tracked orders*. Significant vibration energy may also be observed at harmonics of the rotational frequency of each shaft. These *harmonic tracked orders* may be expected to contain less vibration energy than corresponding fundamental tracked orders during normal engine operation. This technique acquires data for the investigations and automatically identifies peaks in vibration spectra corresponding to fundamental and harmonic tracked orders, using measurements of the rotational frequency of each shaft. From these peaks, a time series of vibration amplitude and phase for each tracked order is generated.

7. **TORCH Vibration Signature**. This can be defined as the vibration amplitude and phase of a tracked order measured over a range of speeds of the corresponding shaft. Amplitude and phase of tracked order vibration are measured across the speed range [0% to 100% maximum speed] of the corresponding shaft. This speed range is subdivided into equal bins designated as *B*. Typically, for a *B* = 400, each bin corresponds to a 0.25% sub-range of the maximum shaft speed. Within each bin, *b* = 1 to *B*, the mean and variance of vibration measurements occurring within that bin's sub-range of shaft speeds are computed. Phase and amplitude of vibration are considered separately, resulting in two TORCH vibration signatures for each tracked order. Vibration phase measurements are known to exhibit high variability within some sub-ranges of shaft speeds. Separation of vibration phase and amplitude signatures allows analysis of vibration amplitude independent of vibration phase, which may otherwise dominate the analysis due to this high variability[3].

8. The benefit of the application of this method to engines is the identification of engines that have maximum vibration amplitude below the contractual limit, during “pass-off" testing or “acceptance tests” (which would thus be released into service), but which go on to suffer vibration-related faults. This method provides a more accurate assessment of abnormality than comparison of vibration levels to a simple threshold. Increasing accuracy of engine assessment allows better control of engine maintenance and, if used during pass-off testing, better achieves the goal of determining if an engine is fit for release into service.

Use of Seismic Transducers and Good Installation Practices

9. The seismic transducers used on aeroderivative and industrial gas turbines are specially engineered to withstand extreme temperatures and g-forces encountered[4].

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[3] David Clifton, ibid

[4] Mel Maalouf, Gas Turbine Vibration Monitoring – An Overview, *ORBIT (*Vol.25 No.1), 2005

While the high surface temperatures of gas turbines are readily apparent and are rarely overlooked, high g-forces incase of aircrafts and roll & pitch incase of ships are encountered on these machines. This introduces a number of mechanical fatigue concerns in the instrumentation system which are responsible for more than their fair share of false alarms and trips. Mitigation of such issues would require special installation considerations for sensors, cables and connectors. Fortunately, these can generally be overcome by careful installation practices explained in the succeeding paragraphs.

10. **Use of Solid state transducer**. Velocity transducers using moving-coil technology are sometimes used for gas turbine seismic measurements. Due to the very aggressive forces and surface temperatures encountered on gas turbines, the moving parts in such sensors degrade and have a limited useful life. Unfortunately, they do not degrade linearly, and it is difficult to predict when they will fail. For this reason, it is advised to use solid-state accelerometers which are not susceptible to this type of degradation since they do not employ moving parts. Also, moving-coil sensors are designed to measure vibration in one axis only. However, gas turbines sustain considerable vibration in all three axes, and this cross-axis vibration is particularly damaging to moving-coil sensors, accelerating their fatigue.

11. **Transducer with Integral Cable**. The connection between the accelerometer and its extension cable is a very common source of failures. As a high-impedance device, it is particularly sensitive to dirt, oil, or other debris that can invade this connection. Also, when a connector is located on the engine, the high forces can tend to loosen the connection. Both of these lead to intermittent connection problems which result in noise and “spiking” in the signal, often causing false alarms and even false trips. Ideally, a transducer with an integral cable is recommended. This allows the connection between the sensor and the removable cable to be located off the engine, where vibration and contaminants that serve to compromise this connection are less of a problem. When this is not possible, it is very important to keep this on-engine connection tight and to protect it from contaminants.

12. **Secure Anchoring of Cable**. Regardless of whether an integral cable is used, it is extremely important to anchor the cable securely. When not anchored adequately and at frequently short intervals, the cable can vibrate behaving like a miniature piece of unsupported piping leading to high-cycle fatigue at the connector or anywhere along the cable. This can lead to high-cycle fatigue at the junction between cable and sensor, even when this is a permanent molded or welded connection. Another common problem is that the cable will chafe against another part of the machine, eventually wearing out the cable and causing noise or other intermittent

problems. When clamping the cable, it is recommended to use clamp inserts that will not degrade and can sustain the surface temperatures encountered[5].

13. **Proper Design of Brackets**. It is very important to ensure that transducer mounting brackets will faithfully transmit the vibration of the machine to the sensor without introducing their own vibration characteristics. A bracket that may seem "stiff " may infact be stiff in only one axis, and attention must be paid to stiffness not only in the measurement axis, but all other axes as well. Surface finish is also an important consideration with accelerometers. Small imperfections on the mounting surface, whether directly on the machine or on an intermediate bracket, can introduce strain (force) into the accelerometer, distorting its signal since it is inherently a force measuring transducer.

Model Based Diagnostics

Gas Path Analysis Methods

14. One of the popular and pioneering tools for gas turbine engine supervision and sensor diagnosis is the Gas Path Analysis (GPA). The GPA algorithm can be summarized into the four main steps namely, measurement normalization, reference value generation, estimation of performance deviation and diagnosis decision. The GPA method is based on thermodynamic relationships where one of the main objectives is to estimate deterioration in gas path components from a number of measured sensor signals. These signals and resultant equations could be used to estimate steady state and transient variations in the performance parameters for an arbitrary gas turbine engine during most conceivable sets of input conditions.

15. **Linear GPA**. There are two types of Gas Path Analysis namely Linear GPA and Non Linear GPA. LGPA is simple and quick, can identify faulty components & quantify the amount of degradation and it can handle more than one faulty component at a time[6]. LGPA assumes a linear relationship between measurements and independent parameters. However, in practice, this relationship is non-linear and assumption of linearity can introduce errors as large as the fault itself resulting in low accuracy. In an attempt to eliminate the errors associated with linearity assumptions, the Non-Linear GPA (NLGPA) technique has been developed.

16. **Non-Linear GPA**. NLGPA process seeks to solve the non-linearity component numerically by calculating a first estimate of degradation from the simulated performance data. This step gives an interim independent parameter change. A

[5] Mel Maalouf, ibid
[6] Giovanni Bechini, Performance Diagnostics and Measurement Selection for On-line Monitoring of Gas Turbine Engines, Cranfield University, 2007

percentage of this change (typically 66%) is used to calculate the change in measurements and arrive at a new interim baseline performance. A new measurement deviation is defined from this baseline and this process of iteration is continued until the change in independent parameter becomes increasingly smaller. Some of the GPA based diagnostic systems developed by the leading OEMs of gas turbines include COMPASS by Rolls-Royce, SHERLOCK by Pratt & Whitney and TEMPER by General Electric.

17. **Kalman Filter Method**. This method is used to estimate the health of the engine components in the presence of measurement noise and sensor bias. A KF processes all available measurement data and prior knowledge about the system to produce an estimate of the desired variables with the statistically minimized error[7]. The KF based linear algorithm involves a prediction step and the correction step. Extended Kalman Filter (EKF) and the Iterated Extended Kalman Filter (IEKF) are the filters designed for non-linear systems. Some of the advantages of KF method are listed below:-

(a) Low computational time
(b) Good multi-fault capabilities
(c) Prior knowledge
(d) Measurement noise is taken into account
(e) Optimality

Soft Computing Diagnostics

Artificial Neural Networks (ANN)

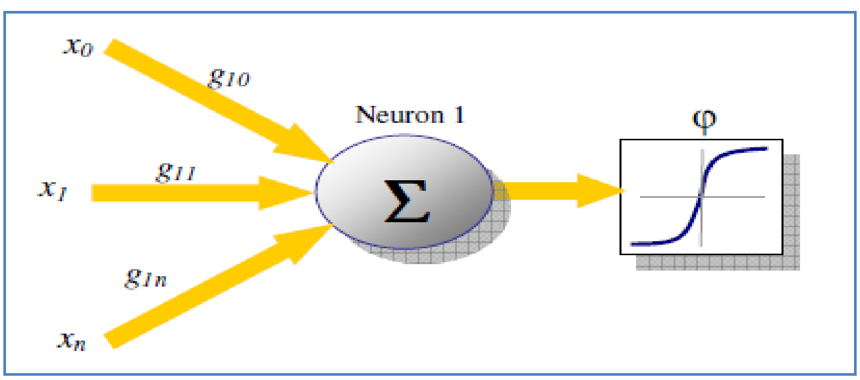

Fig 1 Neuron

[7] Changduk Kong, Review on Advanced Health Monitoring Methods for Aero Gas Turbines using Model Based Methods and Artificial Intelligent Methods, International Journal of Aeronautical & Space Sciences 15 (2), 123–137 (2014)

18. Work on the artificial neural network has been motivated from its inception by the recognition that the human brain computes data in an entirely different way to that of the conventional digital computer. A neural network can be defined as a massively parallel distributed processor made up of simple processing units, which has a natural propensity for storing experimental knowledge and making it available for use. Neural Networks (NNs) or Artificial Neural Networks (ANNs) have been applied in gas turbine propulsion diagnostics. The typical feed forward network, also named Multi-Layer Perceptron (MLP), comprises three layers: the input, hidden and output layer. Each layer is made of a set of neurons. For the hidden and output neurons, the output or activation value is computed.

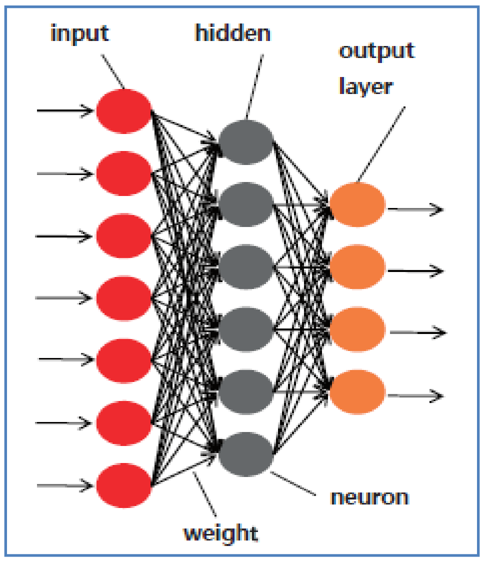

Fig 2 Feed-Forward Neural Network with one Hidden Layer

19. Feed-Forward Back-Propagation Neural Networks (FFBPNN s) are one of the NNs commonly used in gas turbine engine fault diagnostics. They can be used for fault detection, fault isolation and fault quantification. Gas turbine component faults can be quantified with FFBP NN which has a similar configuration to that used for fault isolation, where the number of neurons in the output layer is equal to the number of gas turbine component parameters and where the deviations of these parameters are to be quantified. The training samples are expressed with component parameter deviations and measurable parameter deviations. Once the neural network is trained and used in the application, it will provide the component parameter deviation for each new measurement set.

<u>Fuzzy Logic</u>

20. Fuzzy Logic is a particular rule based approach founded on formulation of a novel algebra, typically used in the analysis of complex systems and to enable decision-

making processes to be performed[8]. Fuzzy engineering is the specific research area investigated inorder to model engineering processes with fuzzy systems. These are able to provide appropriate approximations of various phenomena if enough rules are defined. The quality of the approximation is strictly related to the quality of the rules. Fuzzy engineering can be implemented according to a three step procedure aimed at defining the system architecture. The first step is the identification of the input and output variables. The second step is aimed at selecting the right membership functions for these variables. The third step relates the output sets to the input sets through fuzzy rules.

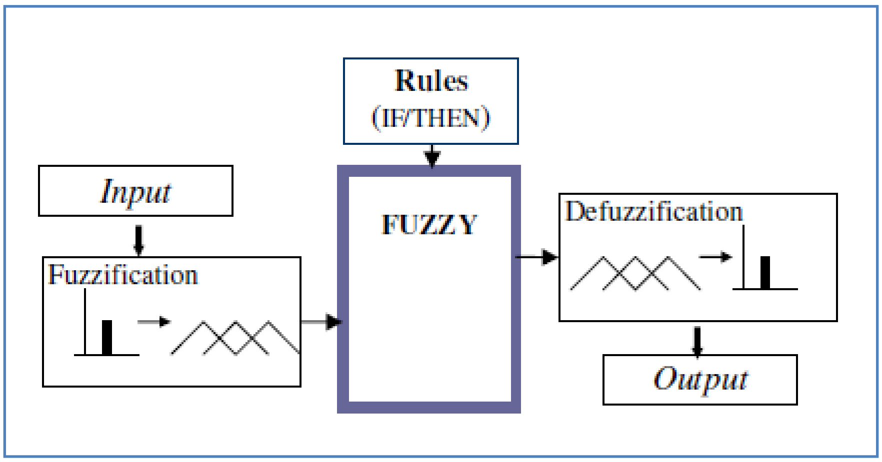

Fig 3 Fuzzy Logic Diagnostic System

21. In a diagnostics system, the input variables are the elements of the set of measurements and the outputs the performance parameters representative of health of the engine. Rules that relate input space and output space are generated by using an engine performance model or taken from real-life data of faulty engines. The typical fuzzy logic system shown in Fig. 3 involves fuzzification, fuzzy inference and defuzzification by using a fuzzifier, an inference engine and a defuzzifier respectively. First, the engine measurements enter the fuzzifier where they are mapped into fuzzy sets using membership functions. The core of the diagnostics process is carried out in the inference engine, where the fuzzy sets obtained from the fuzzifying process are mapped into fuzzy fault sets. The rules are of the IF & THEN type and contain other operators like AND, OR etc.

Genetic Algorithms

22. Genetic Algorithms are used in diagnostics mainly due to their outstanding optimization capabilities, which allow them to find the solution to extremely complex functions with multiple maxima and minima. GAs mimic the process of evolution to solve problems. First, a population of possible solutions is created at random. Each of

[8] Changduk Kong, ibid

these solutions or ‘strings’ is examined in turn using an evaluation function inorder to find the ‘fitness’ of each string. The strings are then combined or ‘mated’ according to their fitness. Mutation is also introduced to add variety to the population and allow combinations other than the original ones to emerge, eventually converging towards the solution.

23. In the GA diagnostics process, firstly the current power setting and ambient conditions are used as inputs to an engine model, which gives an expected set of measurements corresponding to the current operating point. These are compared with actual engine measurements and the deviations are combined into an ‘objective function’. The role of the GA is to minimize that objective function or find a degraded operating point in the engine model that corresponds to the actual measurements. The GA generates a population of solutions with random levels of degradation. It then evaluates the solutions by calling the engine model and retrieving the sensor values corresponding to that level of degradation. The deviations are compared and those closest to the current operating point are selected as parents for the next generation.

Tribology Based Monitoring – Advanced Wear Debris Analyses

In-Line X-Ray Fluorescence Spectroscopy (In-Line XRF)

24. Conventional x-ray fluorescent spectrography system has an x-ray tube which is used as a high intensity source of primary x-radiation. The generated x-ray beam strikes the surface of the specimen to be analyzed, causing excitation of its characteristic radiation. These characteristic secondary x-radiations are scattered from a crystal surface, and, by suitable collimation and selection of the Bragg angle of reflection (dispersive analysis), the radiation is separated into its component wave-lengths. The number of photons scattered at each Bragg angle in a given period is proportional to the amount of each particular element present in the specimen. Intensity monitors are generally either Geiger or proportional detectors.

25. X-Ray fluorescence spectroscopy is now being developed as an in-line sensor for real time quantitative analysis of wear and additive metals[9]. XRF systems have been extensively used in laboratories for elemental analysis. In-line XRF systems work on the same principles as their laboratory counterparts. An x-ray source is imparted on the oil flow and a detector reads the x-ray emissions from the flow. The resulting data is analyzed and the elemental content is displayed. This system performs a quantitative detection of 12 elements in the parts per million range. The In-line XRF system is being further developed at the Pacific Northwest National Laboratory (PNNL) for additional applications.

[9] Carl S. Byington and David C. Schalcosky, Advances in Real Time Oil Analysis, Penn State University Applied Research Laboratory

Laser Induced Breakdown Spectroscopy (LIBS)

26. A new, innovative diagnostic tool with the capability to analyze large metallic particles and oil-borne wear debris in a single instrument has been developed to allow non-subjective decisions concerning machinery operating condition[10]. Utilizing Laser Induced Breakdown Spectroscopy (LIBS), this new tool empowers informed maintenance decisions based on the quantity, alloy type, size and shape of debris particles and concentration (PPM) of oil-borne particulate wear. Digital image capture in combination with an innovative spectroscopy system is used to automatically and rapidly analyze collected debris. The intent is to minimize equipment downtime and unnecessary repairs, allow for more efficient planning of maintenance actions, reduce false positives and provide confidence to equipment operators with respect to safe and reliable operation of their machinery.

27. This LIBS technology can replace larger laboratory atomic emission spectrometers for detailed elemental composition in the field or at the plant. In addition, large particulates can be individually sized and analyzed by specific alloy type – not just element composition. Particles can be from filters, around filter housings, in oil samples, from ferrograms, etc. Field trials are currently being conducted in cooperation with the United States Air Force (USAF) to prove the benefits of the technology in an operational environment and to potentially replace the older atomic emission analysis technologies currently in use for oil analysis. Collaborative projects are also on-going with the United States Army (USA) through the Army Oil Analysis Program (AOAP) and the RIMFIRE (Reliability Improvement Through Failure Identification and Reporting) program to demonstrate the benefits of the new technology. This new technology is also currently in use by gas turbine Original Equipment Manufacturers (OEM) as well as major airlines.

New Developments in Real Time Oil Sensors

28. Real time sensors provide the ability to conduct continuous monitoring. Real time sensors enable the integration of diagnostic and prognostic maintenance systems. Developments in real time sensors have been divided into two paths, true real time sensors and near real time systems[11]. True real time systems are placed either directly in the system flow, or in a rerouted flow branch. They can be connected directly to monitoring systems to allow for continuous real time monitoring and diagnostics. Near real time sensors bring laboratory procedures onsite to allow for quicker response time. Some near real time systems still require oil sampling, but the tests only take a matter of

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[10] Hill Robert, Lawrence Ronn H, Toms Allison M, A New Approach to Elemental and Wear Debris Analysis, Society for Tribologists and Lubrication Engineers Annual Meeting, 2016

[11] Carl S. Byington and David C. Schalcosky, ibid

minutes to complete. Alternatively, some near real time systems can be connected to monitoring systems for lubricant diagnostics and prognostics.

29. Some of the recently developed and commercially available Real Time Oil Sensors are mentioned below:-

(a) ***Kavlico Oil Quality Sensor*** works on the principle that the dielectric constant of oil changes as it degrades or becomes contaminated. As the quality of oil deteriorates, the sensor measures its dielectric constant and outputs this information in the form of a voltage that is correlated to the quality of the oil.

(b) ***Lubrigard Dielectric Sensor*** works on a similar principle as the Kavlico sensor. It uses high frequencies to measure the dielectric constant of the lubricant and provides real time qualitative analysis of oil quality.

(c) ***Oil Condition Monitor (OCM)*** is a real time optical system for the measurement of oil condition acidity (TAN), water content, thermo-oxidative degradation, fuel/ coolant dilution and antioxidant depletion. The OCM features a miniaturized infrared spectrometer that tracks pre-established wavelength regions.

(d) ***MetalSCAN*** unit is a through-flow sensor that is installed on lubricant lines upstream of the oil filter. The sensor uses a magnetic coil assembly to detect and categorize metallic particles by size and type (ferrous or nonferrous). The minimum detectable particle size is determined by the bore size of the sensor. Currently, systems are designed to detect particles as small as 50 microns.

(e) ***Quantitative Debris Monitor (QDM)*** QDM creates a magnetic flux field, which detects the presence of debris. When the debris disturbs the field, a voltage output is produced. This voltage is correlated to the mass of the debris.

(f) ***IQ Debris Monitor*** provides a continuous analog output proportional to the amount of debris accumulated and can sense a change in debris accumulated as small as 0.1 mg of magnetic material.

(g) ***Electromesh Indicating Screen*** provides a warning of ferrous and nonferrous conducting debris particles. Debris particles bridge the gap between strands to close a circuit. Oil flow passes through the screen with minimal pressure drop. The Electromesh screen is effective at detecting non-magnetic conducting particles i.e., aluminum, bronze, magnesium and Babbitt.

Recommendations

Implementation of Thermodynamic Performance Monitoring Models

30. The most important ends to be achieved through performance monitoring of GTs are ***high reliability*** and ***high efficiency***. The time tested and proven means adopted by the leading OEMs of GTs all over the world to achieve these ends is Thermodynamic modeling. The techniques covered in this paper form the foundation or the bottom most layer on which the thermodynamic performance monitoring models can be built and tailor made as per the requirement. Research in the open source clearly brings out that each and every OEM which pioneered the GT technology like GE, Rolls Royce, Pratt and Whitney etc. built up their performance monitoring philosophies on thermodynamic modeling.

31. With the induction of LM 2500 gas turbines, Navy is attempting to undertake a typical performance monitoring using “Cycle Deck Method” provided by the OEM. The results obtained from the above mentioned software is positive and a good insight into thermodynamic performance of the gas turbine is being achieved. However, when it comes to the eastern origin gas turbines, the performance monitoring is generally limited to trending of thermal parameters and comparing them with promulgated limits. The current analysis in this case is simply leading us to a Go/ No-Go decision making. Therefore, it is time the Thermodynamic Modeling techniques are adopted for performance monitoring of all the gas turbines targeting higher efficiency and reliability. We may start with modeling a smaller engine like GTG, test the efficacy of the model, critically evaluate the benefits/ shortcomings and subsequently expand the scope and span of this technique for main engines.

Vibration Monitoring

32. **Phase Analysis**. As part of vibration analysis, three parameters namely amplitude, frequency and phase are to be monitored. However, presently the vibration analysis undertaken in the Navy restricts to amplitude and frequency only. Inorder to enhance the accuracy of the analysis and pin point the incipient defects, there is an essential requirement to address phase analysis. Therefore, phase analysis has to become integral part of every vibration analysis to understand the health of the GT better and consequently take decisions on its operability. The existing gas turbines are not provisioned with arrangement for undertaking phase analysis. Therefore, there is a requirement to design and develop exclusive fixtures/ adaptors for facilitating phase analysis.

33. **Proximity Sensors and High Temperature Transducers**. The gadgetry employed for vibration monitoring currently is limited in their capabilities. Vibration

readings are restricted to measuring casing vibrations and towards the cold section of the GT, ie, Compressor. The options of employing the proximity probes for vibration measurement need to be explored. Similiarly, transducers which can withstand high temperatures must be inducted for vibration measurement so that signature from the Turbine section can also be captured and not confine to Compressor alone.

Tribology

34. The present tribological investigations of GTs in the Navy include testing the physical properties of the lub oil and Spectrometric analysis of the wear debris. Wear physics with analysis of geometry & dimensions of the wear debris and establishing the mechanism, cause and effect, is a diagnostic tool commonly employed in GT industry. Therefore, we must extend our Wear Debris Analysis from SOAP analysis to other diagnostic tools of Tribology. Further, the existing equipment in Dockyard Laboratories may be augmented to undertake advanced analyses brought out in the paper. Specific assistance for analysis, when required, can be sought from laboratories of agencies like HAL, BHEL and GTRE which deal with gas turbines.

Conclusion

35. Performance monitoring constitutes a key practice to ensure operational availability, efficiency and reliability of the gas turbine engines. Timely diagnosis of defects and prognosis of health of GTs go a long way in offering considerable savings in terms of cost, time and effort. There exist different methods and techniques of carrying out performance monitoring of gas turbines. The proper selection and combination of these techniques determines the productivity of the performance monitoring philosophy. Correct performance information provides the plant with relevant, actionable information that can help identify the cause and location of overall performance degradation. The performance monitoring techniques covered in the paper enjoy widespread acceptance in aero, marine and industrial applications of gas turbines. Therefore, we may select the appropriate techniques or a right combination of them, which could be tailor made to operational & maintenance requirements of the Navy and enhance the robustness of the performance monitoring philosophy followed currently.

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