Application Note

Aeroderivative Gas Turbines

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Vibration early warning system (VEWS)

Conventional engine shut-down systems for vibration protection of aeroderivative gas generators and power turbines are usually not appropriate for protecting the machines against primary component damage or malfunction. Consequences often seen are substantial secondary damage to the engine as a result of, for example, ball or roller bearing failure. Other effects may typically be various blade or vane damage, root fretting or blade rubbing.

Conventional engine shutdown systems do not activate until a certain unbalance is released. The nature of the signals related to bearing and blade-pass are too small in energy and lie in too high a frequency range to be monitored by conventional engine protection systems.

This application note discusses the importance of the early detection and trending of vibration from primary component damage and taking necessary actions to prevent secondary damage to the engine. The use of SKF systems for this application is considered together with the potential benefits of expanding the system to integrated performance monitoring.

Aeroderivatives – overview

The aeroderivative (derived from aero engine) gas turbine is basically an aircraft engine adapted for use in marine and industrial applications. The major difference between the applications is that the energy normally used for jet stream propulsion is absorbed by a power turbine, thereby converting "forward thrust" into rotational energy. The power turbine will deliver the available energy to the driven equipment via a shaft connection. The engine has the following main components:

- **Compressor(s)** – Which may consist of a single unit or two, a low pressure "fan" and a high pressure "compressor"
- **Combustion chamber** – Either "annular" (one continuous ring) or "can-type" with individual chambers distributed around the circumference, and fuel injection system
- **Gearbox** – To connect a starter unit and drive a lubrication system
- **Turbine(s)** – Which may consist of a single unit or two, a low pressure and a high pressure
- **Power turbine** – Multiple stages to convert as much jet stream energy as possible

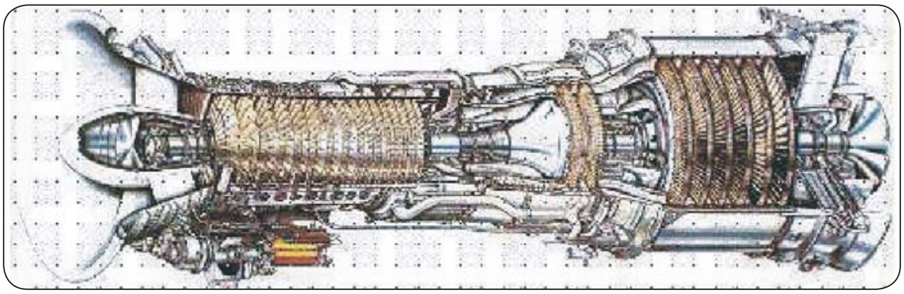

Fig. 1. Aeroderivative gas turbine layout.

The compressor and turbine, for a given stage, are all mounted on one shaft supported by bearings; this is known as a "spool". An aeroderivative engine usually has one or two spools. A key feature of the aeroderivative is the fact that the bearings are ***rolling element bearings*** for radial shaft support and thrust.

The use of aeroderivative gas turbines is still a growing market. In particular, the use of aeroderivatives in offshore applications is dominating. There is also an increase in the application both for onshore power plant and for propulsion machinery for commercially operated fast ships. Long pipeline installations also benefit from the aeroderivative. Typical of many installations are strict requirements for plant availability and unscheduled shutdowns, and with a time-based preventative maintenance strategy. In offshore installations in particular, the standby or spare unit is becoming less frequent.

The conventional set-up for protection and monitoring of a gas turbine is normally based on two elements:

- Thermodynamic condition monitoring
- Vibration protection by means of velocity readings

Such programs can be of great value in preventing unscheduled engine shutdowns and may contribute to cost benefits, increased availability and a better understanding of the behavior of the machine. Please note that only the application of vibration analysis systems will be discussed in this application. Thermodynamic condition monitoring is considered a mature technology in this context.

The traditional concept of protecting the engine from rolling element bearing secondary damage is to use on-line chip detectors. These are simply magnets placed in the lubrication system to capture metallic particles and are visually inspected periodically. In many cases, chip detectors may prevent the machine from severe secondary damage. However, due to primary damage already inflicted on the bearing raceway, there may be an unforeseen and sudden interruption of the operation of the installation, with the reduced engine availability as a result.

New and overhauled installations may suffer from contaminants in the turbine package lubrication system, which may lead to degradation of the bearings. By the use of vibration analysis techniques, the degradation of bearings can be traced at a much earlier stage than when spalling from the bearing reaches the chip detectors.

Spalling is one of the first stages of bearing failure, and in the early stage there is only microscopic metallic material breaking away from the raceway. This is the primary damage phase and can occur months before failure. It should be noted that when larger particles are released from the race surface, a total breakdown may occur within minutes or seconds, thus requiring an immediate action. This is the secondary phase, illustrated by **fig. 2**, which resulted in catastrophic failures.

Fig. 2. Engine bearing failure.

Early warning of abnormal bearing acoustics opens the possibility of early corrective actions. Typical conditions when starting an engine may be events such as reduced clearances between blade tips and shrouds due to incorrect temperature stabilization, seal rubs, etc.

Some operating conditions can lead to fretting of the blade root, which can eventually lead to a fatigue failure (→ **fig. 3**). Detecting fatigue cracking on a blade, which can lead to failure, remains the job of non-destructive testing (NDT) as part of the preventative maintenance routine. Cracks in, for example, blade roots, do not produce any vibration signals. However, vibration "events" that are the symptoms of a primary cause of fatigue, for example, rubs, can be detected.

To prevent damage to the engine, it is important to log such events in order to change operating parameters or to change operational routines for the installation. Again, the trending of blade-pass signals opens the possibility of early corrective actions.

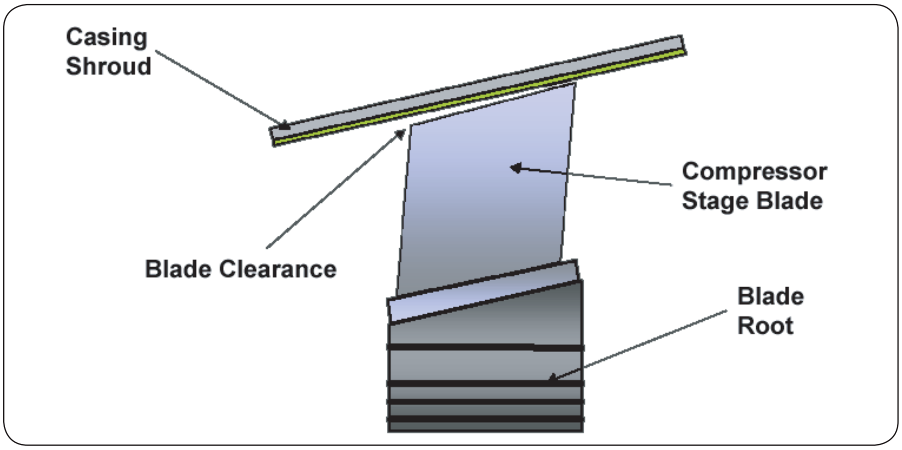

Fig. 3. The compressor blade.

Vibration characteristics

Traditional vibration protection systems measure for a running speed (1x) between 75 to 250 Hz (4 500 to 15 000 r/min). With harmonics up to 10x, a total frequency range of only 2,5 kHz is usually only considered.

Blade pass frequency is defined as running speed (1x) multiplied by the number of blades on any rotor, and in an aeroderivative gas turbine a typical rotor stage may have over 50 blades. Hence to detect primary damage manifested by a blade pass frequency, a much higher frequency, up to the 15 to 20 kHz range, needs to be considered. Other factors to consider when measuring vibration on aeroderivative gas turbines:

- **Gas stream noise** – The bearings are at the heart of the machine, supporting each spool. Between the bearings and the outside world lies the gas stream. With its continuous flow of high pressure and temperature gas, it presents a large obstacle to bearing and blade vibration signal transmission.
- **Lightweight casings** – The design of the aeroderivative is based around minimum weight owing to its aerospace origins. The mass of the spool/rotor assembly is much larger than its surrounding casing. This produces high levels of casing vibration, with overall velocity levels in excess of 12,5 mm/sec (0.5 ips) being considered quite normal.
- **Transient data** – As with larger turbo-machinery, a wealth of diagnostic information can be obtained during transient conditions when the machine is in run up or coast down. However, with aeroderivatives, transient conditions are of a short duration, measured in seconds.
- **Steady state data** – Gradually developing problems can be detected in steady state. Owing to gas stream noise, extracting bearing and blade vibrations from the background presents a challenge, with very small changes in amplitude to be detected.
- **Strict engineering** – The high value of these machines means OEMs keep strict control of what can and cannot be fitted to the engines in terms of vibration sensors.
- **Documentation** – Tracking of all data, to provide a reference with which to compare the above-mentioned small changes, is critical.
- **Remote locations** – With a predominance of off-shore applications, access of acquired data remotely is a significant requirement.

Requirements

Measurement targets:

- 1x, 2x, 3x, 4x, overall level and phase angle changes
- Sub-synchronous vibration
- Bearing cage, rolling element, inner and outer race signals
- Blade pass signals from each stage in the compressor and turbine
- Special regions of interest (ROI)

Continuous streaming

In order to capture the brief duration events witnessed under transient conditions in a gas turbine, a continuous streaming system is required. Many on-line machinery monitoring systems concentrate on a multiplex operation. That is, digital data is sampled in series by a single microprocessor routed through a multiplexer (MUX). This approach minimizes the cost per channel of the vibration data acquisition hardware, at the expense of the time resolution of the data acquired. In on-line predictive maintenance applications there are often large channel counts; for example, a paper machine may have up to 500 critical bearings. In this case, the MUX design is very successful.

On a gas turbine the channel count is lower and parallel data acquisition for each channel becomes more cost effective. Parallel data acquisition can either be achieved by individual A/D converters/samplers per channel or a MUX unit so fast that acquisition of the input channels is effectively continuous. In the case of the SKF M950N system, the latter approach is employed to reduce costs, but the A/D sample rate is 200 kHz. Over 16 channels the data is thus sampled a 12,5 kHz, that is, 12 500 digital samples per second ***on each channel.***

With a 200 kHz A/D rate, enough digital samples are acquired on each channel to produce a vibration spectrum in milliseconds. For example, in a 10 second transient period, sufficient data is captured to calculate approximately 120 spectra per channel. This resolution of data provides ample data to diagnose problems in the short transients of a gas turbine start-up.

Another key feature is a rolling buffer, where time data is stored continuously on either side of a trigger event. If the trigger event represents a sudden problem on the machine, e.g., a surge condition, then transient vibration data both before and after the trigger is captured.

Clearly, if all data is streamed to disk in the manner of a digital tape recorder, then a finite memory/storage capacity will be filled eventually with a large quantity of unwanted data. Thus it is critical to only store data on a valid trigger condition, which tags data as either valuable or not valuable. Thus the system continually scans six triggers.

- **Speed change (Delta r/min)** is checked to determine a run up or coast down condition
- **External triggers** are checked to determine a manual “start capture” instruction
- **3 × ROI (regions of interest)** amplitudes are checked to capture “upset” conditions
- **A timeout buffer (Delta time)** is checked to collect an appropriate amount of data in steady state running

Valuable data is stored to disk for calculation of FFT data. Non-valuable data is discarded.

Vibration signal processing

For the purposes of condition monitoring in this application, the vibration spectrum can be divided into three main ROI, which dictates which filters need to be applied to the incoming vibration signal.

- **Low Frequency (10 to 1 000 Hz)** – To consider unbalance and other synchronous harmonics
- **Mid-Frequency (100 to 4 000 Hz)** – To consider bearing defect frequencies
- **High Frequency (3000 to 15 000 Hz)** – To consider blade pass frequencies

Furthermore, to further assist the extraction of the very small amplitude bearing frequencies from the background noise, the ***acceleration enveloping*** method has proved a very useful signal conditioning method, both for diagnostics of rolling element bearings and extraction of blade pass events. In brief terms, the principles of the acceleration enveloping (signal demodulation) technique are:

- **Synchronous vibration is filtered out** in order to reduce background noise. The choice of this filter is critical for aeroderivatives and in a much higher range to that employed in other machinery.
- **Enveloping** – The “rectified” time domain signal is approximately squared and only the repetitive signals, systematized as integers, are presented in a Fast Fourier Transform (FFT) spectrum.

The following sensor criteria must be taken into consideration when configuring a diagnostic system:

- Accelerometers must be used
- Accelerometers must be strategically positioned
- Accelerometers must have resonance frequency above the chosen filter ranges, and it is recommended that they be of a well known and proven type

Sensors

Typically, field vibration signal input comes from the engine-approved accelerometers already fitted to the machine by the OEM. These are typically charge output type accelerometers (to withstand the high temperatures) with a charge amplifier and galvanic isolation circuit. Typical sensitivities are only 5 mV/g.

The use of casing mounted accelerometers is critical for detection of rolling element bearing defects. There has been debate regarding use of high sensitivity displacement ("proximity") probes – targeted on the bearing outer raceway to make a direct measurement. The drawbacks of this approach far outweigh any benefits:

- The displacement probe has inadequate maximum frequency response.
- The mounting of the probe is intrusive. The bearing is at the heart of each spool, and any internally mounted probes pose significant problems with regard to installation.
- There is evidence that mounting holes in the bearing housing load zone provide a stress concentration point that can lead to premature bearing failure.
- Any condition monitoring sensor system that places a question mark against mechanical integrity of the machine is unacceptable.
- The use of casing mounted accelerometers has been accepted on this type of machine for decades.

There can be up to four accelerometers per engine. Each accelerometer can have 3x acceleration enveloping ROI, which require inputs of 12 channels on the M950.

The entire machine train, aeroderivative gas turbine (including power turbine) gearbox and compressor/generator can be accommodated with 16, 32 or 48 channel DADs.

In the case of the generator and compressor, the bearings are most commonly fluid film (journal) bearings, and the most appropriate transducer in this case will be the displacement ("proximity" or "eddy current") probe. The CMMA950N handles both types of sensor input. Multiple M950 systems can be networked.

SKF high speed data acquisition device – M950N

The M950N high speed data acquisition device, formerly known as the advanced monitoring system (AMS), provides the next stage. It digitizes the signal with the continuous streaming process and stores to disk according to trigger conditions.

The M950N is designed for a 19" rack mount format, with dual redundant power supplies, redundant fan cooling and as many standard PC components as possible to ease upgrade and maintenance.

Fig. 4. SKF M950N high speed data acquisition device.

CMSS 672-ENV mechanical condition monitor (MCM)

The CMSS 672-ENV mechanical condition monitor (MCM) provides the first line of signal conditioning, providing filtering and acceleration enveloping of the incoming acceleration signal from the transducers installed on the engine. Three MCM's are used per sensor signal, low, mid and high frequency.

Fig. 5. CMSS 672-ENV mechanical condition monitor (MCM).

SKF VEWS system

The hardware components are assembled in a free-standing cabinet assembly for mounting in a instrument room. A Windows NT based file server, keyboard and screen act as a local network gateway and analysis station. A UPS power supply ensures continued operation of the system to collect run down operation in the event of a power outage. The necessary interfaces on-site are comprised of:

- Speed signals
- Control system signals (optional)
- Power supply
- Telephone lines and/or network connection for remote access to a diagnostic center

Hard-wired signal outputs consist of alarm annunciation relays to illuminate warning lights displayed on the cabinet for:

- Unbalance
- Bearings
- Blades

Operator interface

Another challenge is to configure display graphics and information so that the system can be operated by turbine operation personnel without the assistance of vibration specialists. This can be achieved by the combination of an operator training program and development of logical display graphics (→ **fig. 6**).

The vibration level of the selected components and systems are continuously monitored. When a vibration signal reaches the level of a preset value, the system alerts the event and starts the signal transmittal to the local operator station and/or to a remote diagnostic station.

The system is capable of detecting and trending vibration changes at an early stage of development and can prevent consequential damages, such as that illustrated in **fig. 2**, showing a gas turbine roller element bearing that broke down without any pre-warning.

A diagnostic center can, via telecommunications, connect on-line to the installation in question and assist and guide in diagnostics work and corrective action recommendations.

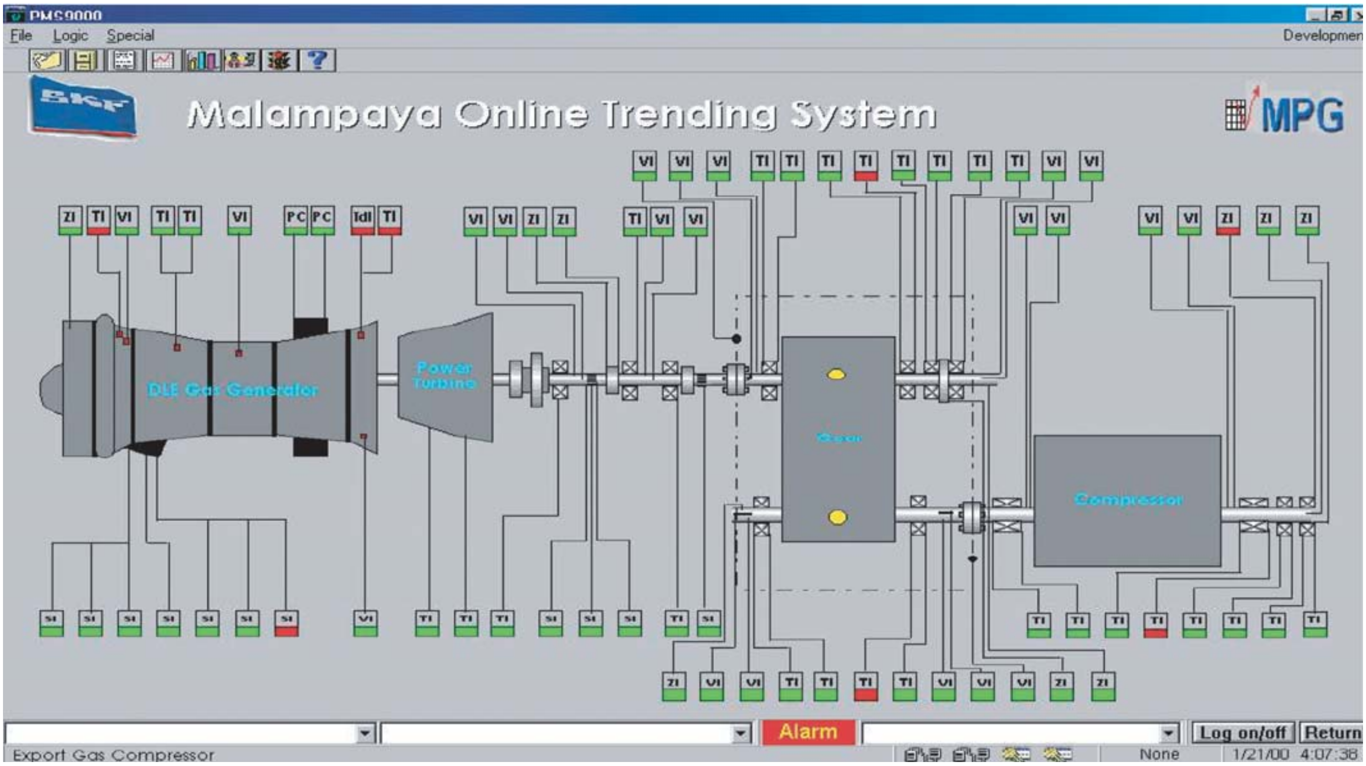

Fig. 6. Operator interface.

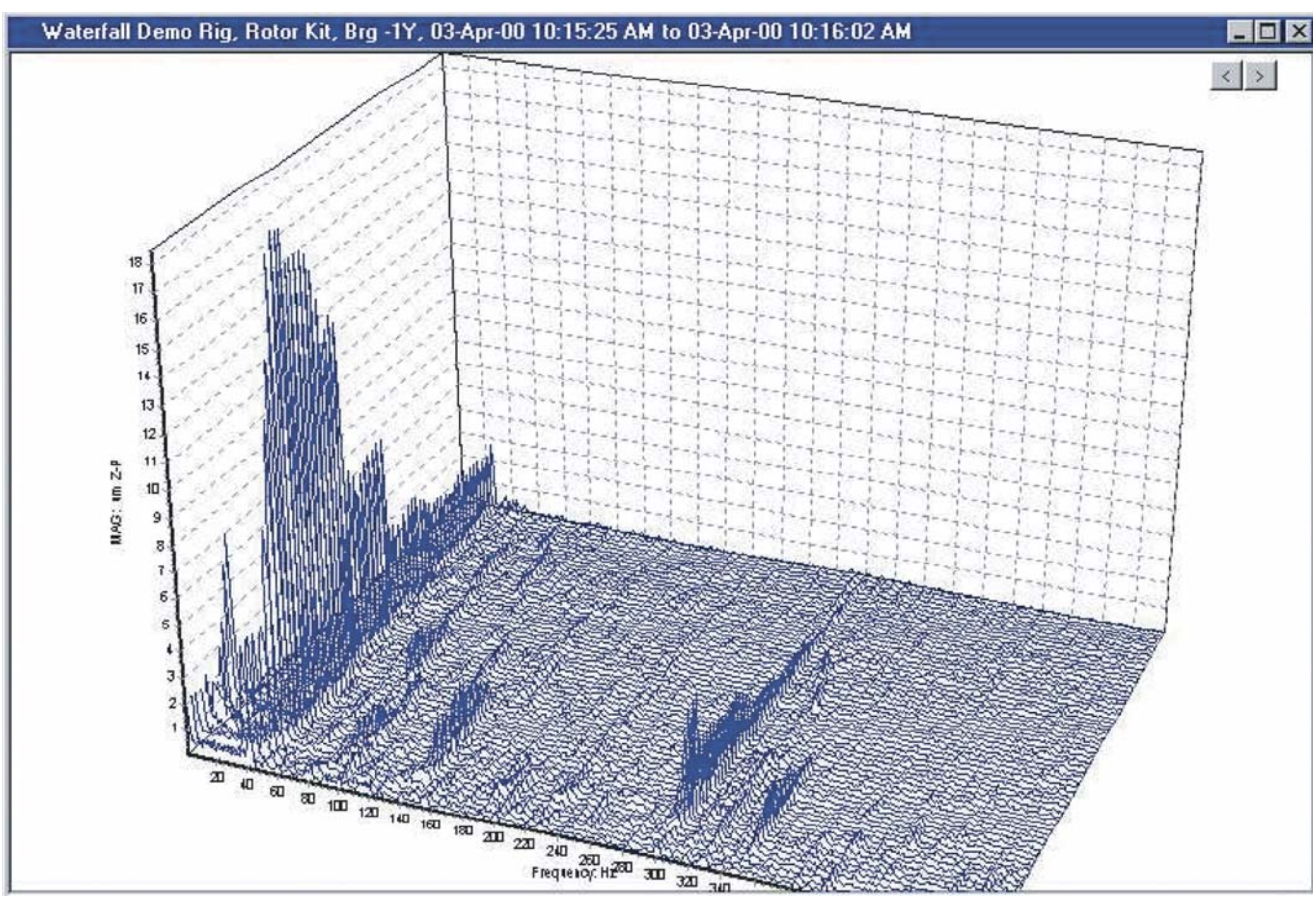

Fig. 7. Cascade/Waterfall.

Software

The SKF M960NT software of the VEWS system provides the FFT processing and display functions of the data captured by each DAD. The system operates on a Windows NT based platform, with 32-bit processing and an open database, which greatly simplifies data networking. A comprehensive set of analysis displays for the vibration analyst are provided:

Software – display functions

- Time signal
- Overall trend
- Acceptance region
- Single spectrum
- Shaft centerline
- Cascade/Waterfall
- Tabular plot
- X-Y plot
- Mimic
- Bode plot
- Orbit
- Polar plot

Diagnostics

To accurately perform vibration diagnostics, essential components must be identified and the monitoring system must be configured to trace the component signal signature. Diagnostic experience is normally built up gradually, and it is important to systematize and store all data individually for each machine. Historical files can be used as general diagnostic background information.

System designed and tested 1996-1998

Europe

- North Sea – Statoil
- Scandinavia – Power plant

Asia Pacific

- Sarawak Field – Shell exploration and production
- Philippines – Shell exploration and production

Engine types

- GE LM-2500/LM 6000
- Under development – Pratt and Whitney, Borsig GHH, Rolls Royce

Operational feedback

Vibration events in steady state must be relayed in an understandable way to provide operations staff with feedback in order to alter operational conditions that might be causing adverse (and avoidable) vibrations. In addition, the vibration warning levels must be implemented so that they will not give spurious warnings or alarms.

The main requirements for establishing a proper feedback from the vibration analysis system are that the system is configured by personnel with thorough knowledge of the gas turbine and available analysis techniques.

Performance monitoring

The performance of major machinery directly influences its operating costs and efficiency. Modern control systems provide a large amount of raw process data, which is difficult to interpret.

To assess the condition and performance of a critical machine, key performance indicators (KPI) such as thermal efficiency and specific gas consumption are often calculated from test data prior to a return to service from a turn-around. The calculations required are complex and require many process measurements including flow rate and power output.

A Performance Monitoring module is available that can be added to the VEWS application. The first function of the Performance Monitoring module is to interrogate the distributed control system (DCS) database to gather raw process data that is relevant to condition monitoring.

This data is then displayed as a "measured variable" on graphics that have a "machinery look" instead of a "process look". This alone can assist a machinery analyst in diagnosing a problem. A good example is where the measurements of the thermocouple array located at the turbine outlet are displayed to show the distribution of temperature around the circumference. An uneven distribution can warn of fouling or firing problems. The raw data is then used to calculate derived variables or KPI. Industry accepted calculations are used to calculate the KPI. The next task is then to simply trend KPI over time.

A more sophisticated option is to calculate and display the complete performance characteristic. That is, an "aerothermal map" of measured and calculated KPI versus theoretical optimum is derived (→ **fig. 8**).

Live data can be calculated and warning alarms generated. Alarm envelopes are placed around performance characteristics to warn of any drift away from the optimum. To display this in an easily understandable way, the software is designed within WonderWare Intouch, a world leading HMI package.

Finally, an automated diagnostics function can be incorporated to assist operations in solving potentially costly problems.

The commercial benefits of monitoring the KPI on-line are great; they allow constant watch to be kept on a machine's performance.

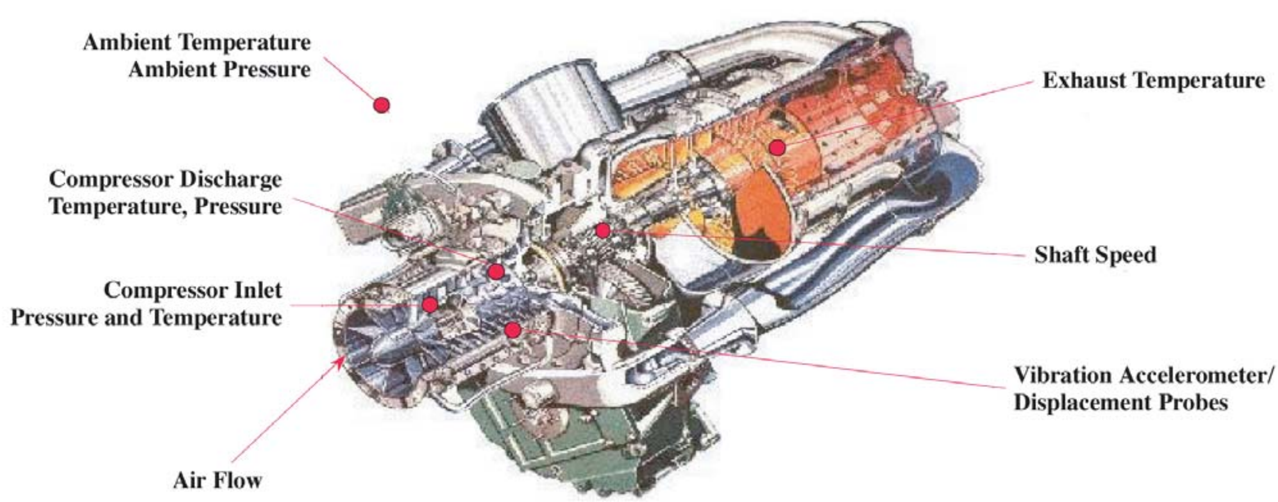

Fig. 8. Aerothermal map parameters.

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