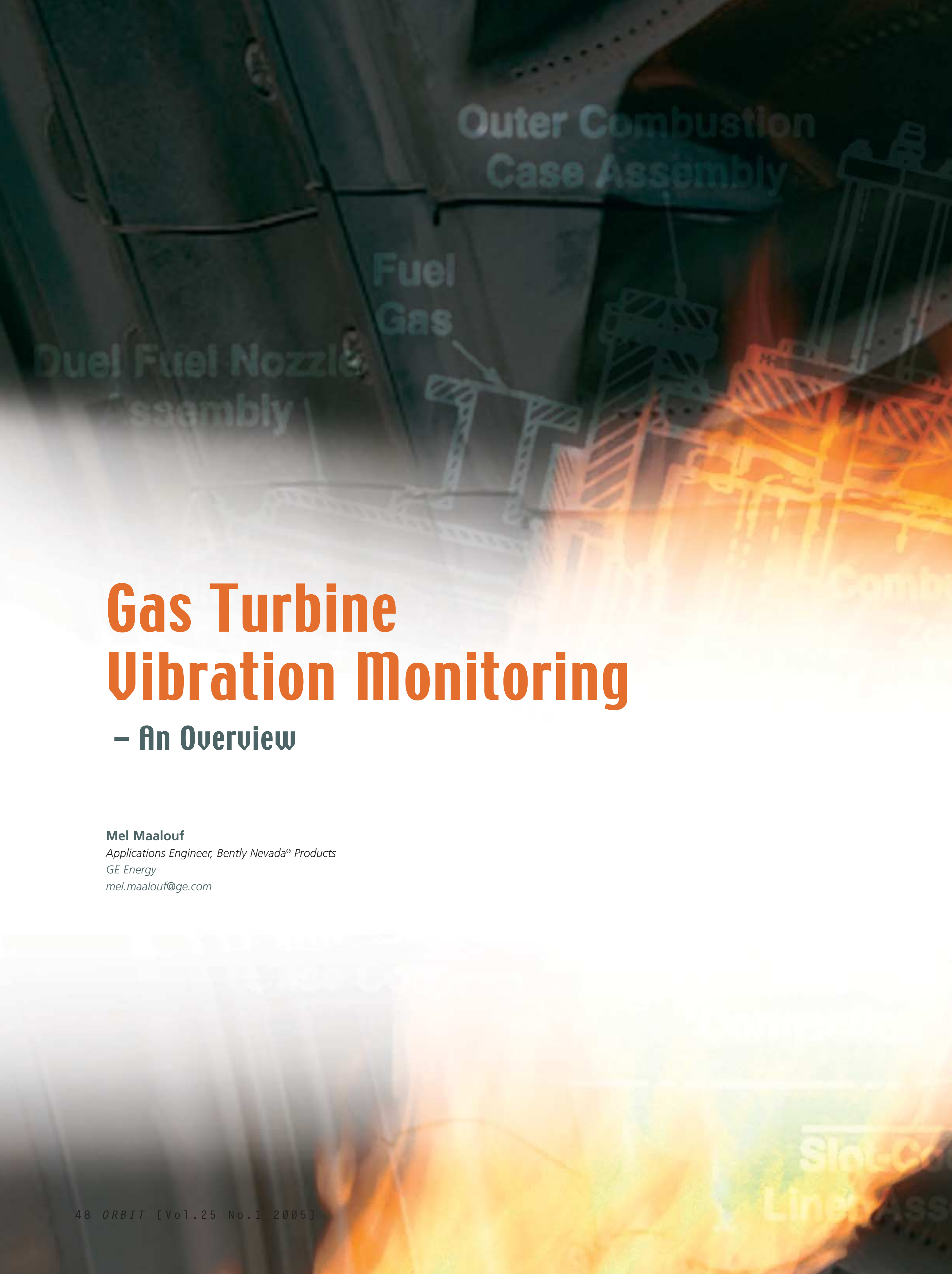

Gas Turbine Vibration Monitoring

– An Overview

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Introduction

For well over 30 years, the Bently Nevada® product line has been used by gas turbine manufacturers and end-users to monitor these important machines. More than perhaps any other type of turbomachinery, gas turbines have undergone the most dramatic evolution in the past several decades, with increased firing temperatures, usage of advanced – even exotic – composite and alloyed materials; extremely sophisticated cooling mechanisms for components such as blades, nozzles, and transition pieces; innovative methods to reduce emissions; and significant increases in overall thermal efficiencies. Not surprisingly, these technological innovations have made gas turbines the prime mover of choice for many power generation and mechanical drive applications. Today, there is an extremely large installed base of these machines around the world.

However, while gas turbines have unquestionably evolved in sophistication, the basic approach to vibration monitoring on these machines has remained largely unchanged. What has changed over the last several years is the additional measurements available today that complement Bently Nevada vibration monitoring products, such as combustion instability monitoring, hazardous gas detection, flame detection, exhaust gas temperature diagnostics, thermodynamic performance monitoring, and overspeed detection.

This article reviews the basics of monitoring vibration on gas turbines, providing recommendations, and discussing some of the new measurements now available. It begins with a review of the two broad classifications of gas turbines: aeroderivative and industrial.

Aeroderivative Gas Turbines

Aeroderivative gas turbines (sometimes called aeroderivative *engines* – the terms are used interchangeably in this article) are derived from aircraft applications. To meet the needs of the aerospace industry, aeroderivative gas turbines have primary emphasis on power-to-size/weight ratios, since smaller, lighter engines reduce the weight of the aircraft, and therefore fuel consumption. With few exceptions, aeroderivatives use rolling element, rather than fluid-film, bearings. Some also employ concentric shafts, allowing the various compressor and turbine stages to run at different speeds, and making them better able to produce the large pressure ratios required in certain engine designs.

Obviously, the primary function of a gas turbine when used on jet aircraft is to generate the thrust necessary for propulsion. This is accomplished by channeling the hot gases through a nozzle and, sometimes, by also turning the large fan in the engine (turbo-fan or high-bypass engine). When adapted for industrial applications, however, the thrust must be converted into mechanical torque, able to drive a generator, process compressor, blower, pump, propeller (when used in marine propulsion), or other driven machine. Channeling the hot gases into an aerodynamically coupled power turbine, rather than a nozzle, accomplishes this. The hot gases spin the power turbine which is coupled mechanically to the driven equipment.

The nomenclature used when referring to aeroderivative gas turbines is shown in the simplified diagram of Figure 1. It illustrates that most aeroderivative gas turbines consist of two fundamental components – the gas generator and the power (sometimes called 'reaction') turbine. Collectively, these are referred to as the "gas turbine." While the gas generator does have an integral turbine section, it serves only to extract enough energy to drive the compressor section of the engine. The rest of the energy produced by the gas generator is in the form of hot, high-pressure, high-velocity gas, which drives the power turbine. As shown in Figure 1, the power turbine is not mechanically coupled to the gas generator – there is no shaft linking the two components.* They run at different rotational speeds and are coupled aerodynamically by the hot gas produced in the gas generator.

**While this is true for most aeroderivatives, there are some exceptions. For example, the GE LM6000 has a power turbine that is an integral, direct-coupled part of the engine rather than a separate aerodynamically coupled element.*

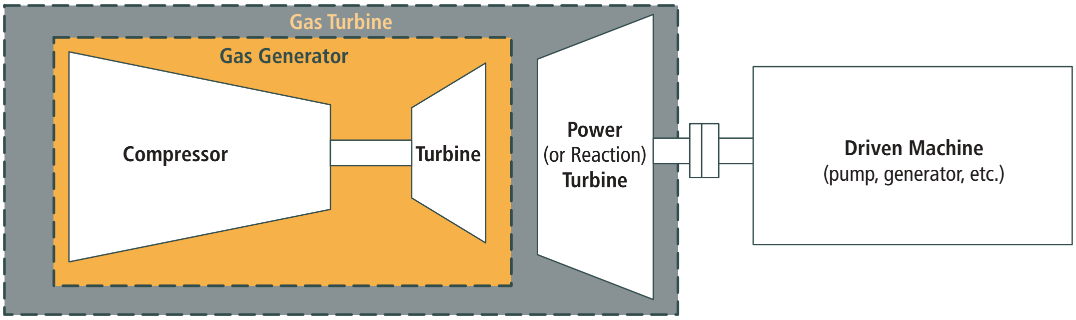


FIG. 1 | NOMENCLATURE USED FOR MANY AERODERIVATIVE GAS TURBINES

Industrial Gas Turbines

Unlike aeroderivative gas turbines, industrial gas turbines are not derived from a design with a different primary purpose. Instead, they are intended only for industrial applications, and they employ design features that reflect industrial needs, rather than the needs of aircraft. They use fluid-film bearings for both radial and axial shaft support. They generally employ conventional lube oil and seal oil auxiliary systems, and they feature heavier construction, since the intense weight-driven concerns that govern aeroderivative designs are not present. And, unlike the concept of a gas generator section and a separate reaction turbine present in most aeroderivatives, many industrial gas turbines have a direct-coupled, integral power turbine that extracts all the energy needed to both drive the compressor section of the turbine and transmit torque to the driven equipment through an output shaft.

While these are obviously not the only differences between industrials and aeroderivatives, they do highlight some of the fundamental differences. As will be shown, the approaches to vibration monitoring used for these machines stem largely from the type of bearings employed, causing distinctly different systems to be used for aeroderivatives than for industrials in most cases.

Variations

Categorizing gas turbines into one of two families, aeroderivative or industrial, does not fully reflect some of the nuances of design within the industrial family. Clearly, referring to a particular gas turbine as an “aeroderivative” is quite straightforward – it was either originally intended for use on aircraft (and has simply been adapted for industrial applications), or it was not. However, it is also typical for industrial gas turbines to be further subcategorized into “packaged” and “heavy” classifications, and we will use this nomenclature when a distinction is necessary in this article.

By “packaged” industrial gas turbines, this article is referring to those with power outputs generally less than about 20MW which are available as a completely packaged system on a single, movable skid – the gas turbine, auxiliaries, driven machine (often generator, compressor, or pump), and sometimes even the controls. Although not derived from an aircraft design, this allows packaged industrials to enjoy one of the main advantages of aeroderivatives – namely, the ability to rapidly “swap out” the entire gas turbine when major maintenance is required. In contrast, larger gas turbines (sometimes called “heavy” or “heavy-duty”) are not packaged in this single-skid fashion. Consequently, it is more common to see maintenance performed in-situ on these units, or with individual components or engine sections sent to a repair facility. The “engine swap” method is not generally a viable option for these machines.

Hybrids

It is also worth mentioning several new gas turbines that have emerged over the last few years, blending design features that were traditionally the exclusive domain of either aeroderivatives or industrials, but not both. Although these ‘hybrid’ designs incorporate selected elements of both categories to a greater or lesser extent, they tend to align as either industrials or aeroderivatives in terms of the way they are monitored, generally a function of the types of bearings used.

Maintenance

Because aeroderivative gas turbines derive from engines originally designed for aircraft, it is useful to consider the difference in maintenance practices that have historically been employed in the aerospace industry, compared with the practices used in the power generation and hydrocarbon processing industries where industrial gas turbines are primarily focused.

Since aerospace applications of gas turbines, whether military or civilian, involve transportation of human beings, both as passengers and as pilots, safety is of paramount concern. An engine failure in an aircraft has a much higher likelihood of jeopardizing human life than a gas turbine failure in most industrial settings. Not surprisingly, aerospace maintenance practices are primarily driven by safety concerns. Failures simply cannot be tolerated because they impact much more than just business interruption. Governing agencies mandate that engines be maintained and inspected at specified running-hour intervals.

In addition, an aircraft is not in the sky 100% of the time, running continuously. Thus, the ability to perform inspections and maintenance during these relatively frequent windows of “down time” is more practical than with industrial machines, which generally run continuously. Consequently, gas turbine maintenance in the aerospace industry employs the practice of “swapping out” an engine or major sub-assemblies in need of inspection and repair with a fresh engine or sub-assembly, much as one might take a faulty starter out of an automobile, replace it with a refurbished unit, and send the old starter in for repair and refurbishment. The aerospace industry has become quite proficient at rapid change-out of parts and even entire engines. This practice allows aircraft to remain in service as much as possible, but without jeopardizing safety.

In contrast, industrial gas turbines are often involved in continuous service that does not have frequent “normal” machine downtime of sufficient duration to perform maintenance and inspections. Instead, maintenance outages must be scheduled, often only once per year or even less frequently. While industrial gas turbines rely in part upon set intervals for determining when maintenance is required, such as a fixed number of operating hours for a set of blades, they also rely heavily upon continuous condition-based information for determining maintenance. Industrial gas turbines (with notable exception of some packaged units as mentioned earlier) are generally not removed from service and replaced with a refurbished unit, as is often the case for aeroderivatives. This is partly due to the historical maintenance practices in the process industries versus the aerospace industry, but it is also due to the design of the machines themselves. Heavy industrial gas turbines are simply not designed to be lifted out of place as a single unit and replaced with a new unit. In contrast, aeroderivatives (and some packaged industrials) are almost always designed to facilitate such a “drop in” replacement approach.

The aerospace heritage of aeroderivatives helps explain why the industrial usage of aircraft-derived gas turbines has resulted in maintenance practices and contractual scenarios that are often closer to those of the aerospace sector than the industrial sector. Many aeroderivative users will even contract with an Original Equipment Manufacturer (OEM) to have entire spare engines on-hand, or will purchase spare engines and keep them in their own warehouse for rapid change-outs should a failure occur. In some instances, a crew can change out an entire engine in as little as eight hours.

Before turning to a discussion of condition monitoring differences between these two types of gas turbines, it is important to note that differences in maintenance philosophies should not be construed as being inferior or superior to one another, or that the aerospace industry is “safe” while others are not. Aircraft engines simply function under very different operating and business conditions than do gas turbines in an industrial setting. The maintenance practices and philosophies that have evolved to address these machines reflect those differences.

Condition Monitoring and Machinery Protection

Understanding the background behind the two basic categories of gas turbines – aeroderivative and industrial – is helpful because it provides a framework for better understanding why two approaches to condition monitoring for gas turbines have arisen over the years. Basically, aeroderivatives use one approach while industrials use a different approach, as discussed next.

GAS TURBINE MAINTENANCE IN THE AEROSPACE INDUSTRY EMPLOYS THE PRACTICE OF “SWAPPING OUT” AN ENGINE OR MAJOR SUB-ASSEMBLIES.

Industrial Gas Turbines

Vibration monitoring for industrial gas turbines is much the same as most other types of high-speed turbomachinery that employ fluid-film bearings. This is summarized in Table 1. Similar recommendations occur in widely used industry standards pertaining to gas turbines .

Almost every manufacturer of industrial gas turbines will provide provisions (i.e., holes drilled and tapped) for the radial vibration, axial position, and Keyphasor® probes noted in the first three entries of Table 1. Often, these transducers are used as part of acceptance testing and commissioning. For the oil and gas industries, this requirement is typically driven by American Petroleum

TABLE 1 | RECOMMENDED VIBRATION MONITORING FOR INDUSTRIAL GAS TURBINES

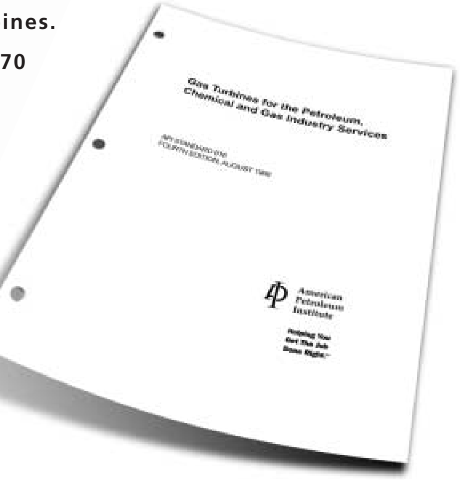
MEASUREMENT	DESCRIPTION
RECOMMENDED FOR ALL DESIGNS	
Radial Bearings	Two proximity probes should be mounted in an X-Y (i.e., orthogonal) configuration at or near each bearing, directly observing the relative motion between bearing and shaft. Recommended as a shutdown parameter.
Thrust Bearings	Two proximity probes should be used, observing the axial position of the shaft within the thrust bearing clearance, and voting[1] these two probes. Recommended as a shutdown parameter.
Shaft Speed / Phase Reference	A Keyphasor® transducer should be supplied on each independent (non-mechanically coupled) shaft to provide a once-per-turn reference signal for determining vibration phase and shaft rotative speed. It is generally recommended that the Keyphasor transducer be installed on the driver in a machine train, so that if the unit is run uncoupled, a phase reference signal will still be available. This is not possible when a Keyphasor transducer is only installed on the driven machine.
SUPPLEMENTAL MEASUREMENTS RECOMMENDED FOR SELECTED LARGE-FRAME MACHINES	
Casing Vibration[2,3]	For machines that are extremely compliant (i.e., exhibit significant motion between the bearing housing and free space), seismic vibration transducers should be mounted on the machine's casing (typically, the radial bearing housings), and these signals should be used along with the radial bearing proximity probes for assessing machinery malfunctions and for use as shutdown protection when vibration becomes excessive. If a gas turbine does not exhibit significant compliance in its casing or mounting structures, these measurements may be considered optional, as the radial proximity probes will generally provide superior machinery protection and diagnostic capabilities.
Eccentricity	Gravity sag causing extremely massive rotors to bow from their own weight after sitting idle for an extended period of time is a well-known phenomenon on large steam turbines. This can also affect many of today's largest gas turbines. Allowing a machine to reach speed when too much bow is present can cause extensive damage and a direct or indirect measurement of shaft bow is often used as a control system permissive, ensuring the machine is not started when residual bow is outside of permissible limits. An eccentricity monitor is designed to measure this residual shaft bow during the slow speeds encountered as part of start-up and while on turning gear. It is measured using a single radial proximity probe. On gas turbines, the most accessible location for this measurement will often be near a coupling, several shaft diameters away from the nearest bearing. This ensures the probes are not located too near a nodal point.

NOTES:

1. A discussion of voting logic and philosophies is beyond the scope of this article, but suffice to say that a thrust bearing failure, unlike high vibration at a radial bearing, can actually cause a probe to go beyond its linear range and can be indistinguishable from an instrument failure under some circumstances. To assist in preventing false shutdowns, two probes are used in redundant fashion and the signals are voted. Only when both probes show excessive axial movement is a high thrust excursion annunciated. For additional information, refer to the article "Voting Thrust Measurements with Other Parameters" in the First Quarter 2001 issue of ORBIT, pp. 51-54.

2. For additional information on this measurement, refer to the article "Vibration Characteristics of Industrial Gas Turbines" in the Third Quarter 2000 issue of ORBIT, pp. 18-21.

3. Occasionally, some manufacturers will include only seismic transducers on smaller industrial gas turbines. While these afford a degree of machinery protection capabilities, proximity probes will generally also be available from the OEM as a standard option. We recommend the installation of these additional proximity transducers because they allow superior machinery diagnostic information – particularly important when the machine will be in unstaffed or inaccessible locations such as offshore platforms. They also allow a greater degree of machinery protection because they are sensitive to machinery problems that originate at the rotor (such as bearing preloads, bearing wear, and other conditions) that may not transmit faithfully to the machine's casing and/or be observable with casing-mounted seismic transducers.



Gas Turbines for the Petroleum, Chemical and Gas Industry Services

American Petroleum Institute

API 616 is one of the most widely used standards for industrial gas turbines. It references API 670 for vibration monitoring.

Institute (API) Standard 616, covering industrial gas turbines, and calls for not only the use of proximity probes during acceptance testing of the machine, but also their inclusion as part of a permanent machinery protection (monitoring) system. The details of this permanent monitoring system are covered in a separate standard, API 670. It is common for end users to use this standard in industries beyond just petroleum, such as power generation. Thus, gas turbines used across many different industries will often be supplied with transducers and monitoring systems in accordance with API 670.

Regardless of whether API 670 is specified or not, in many cases the manufacturer's standard offering for machinery protection will include a Bently Nevada monitoring system, such as 3500, 3300, or 1701, connected to the transducers noted in Table 1 and interconnected to the turbine control system for alarming and auto-shutdown. In other cases, the manufacturer will leave the transducers on the machine, but they will not be connected to a permanent monitoring system unless specified by the end-user, in which case the manufacturer generally provides a standard option for a Bently Nevada monitoring system. In still other cases, the manufacturer will not provide either the transducers or the monitoring system, unless the customer specifies otherwise. However, holes will generally be drilled and tapped to allow for the installation of transducers for connection to a monitoring system at a later time. It is strongly recommended that end users ensure that all machines they purchase are at least supplied with provisions for proximity probes, as this is generally far less expensive and invasive than a project to drill and tap holes in a machine in the field as part of a later transducer retrofit.

It is important to note that considerable engineering often must be applied to accommodate vibration transducers, particularly when they are embedded in the machine, as is frequently the case with proximity probes. Gas turbines can present special challenges, such as routing cables through areas with high temperatures and/or areas in direct contact with lubricating oil. Machinery OEMs have often worked collaboratively with us to develop special solutions to such issues. For example, one well-known manufacturer routes the cables for certain bearings on its industrial gas turbines through oil return lines, ensuring that the cables remain well below their upper temperature ratings, but presenting special challenges for sealing against oil leakage. Bently Nevada high-pressure feed-through cable assemblies are available in special lengths to prevent pressurized oil migration on the outside of the cable, as well as the incorporation of FluidLoc® technology in many of our newest transducer cables that prevents oil migration through the inside of the cable. Other manufacturers have worked with us to develop special probe configurations, unique to their machines, that address tight or difficult-to-access mounting locations.

Obviously, we advocate not just installation of the transducers noted in Table 1, but also their connection to a permanent monitoring system. And, the vast majority of gas turbine manufacturers go beyond just making 'provisions for' these transducers and instead provide both permanently installed transducers and monitoring systems as standard. They, and their customers, understand the valuable role a monitoring system provides in protecting the gas turbine and in helping to diagnose problems that may arise during the machine's service. Indeed, the emergence of long-term service contracts have helped OEMs partner more closely with their customers, allowing the OEM to play a more

GAS TURBINES USED ACROSS MANY **DIFFERENT INDUSTRIES** WILL OFTEN **BE SUPPLIED** WITH **TRANSDUCERS** AND **MONITORING SYSTEMS** IN ACCORDANCE WITH API 670.

active role in operating and maintenance decisions over the life of the machine. This has led to more prevalent utilization of not just transducers and permanent monitoring systems, but also the diagnostic and condition monitoring software connected to such systems, allowing end users and OEMs alike to more easily incorporate detailed condition information into their asset management decisions.

These are just a few examples, intended to underscore the importance of working with the OEM when specifying vibration monitoring for new or retrofit applications. We are very proud of the working relationships that have been established with virtually every gas turbine manufacturer worldwide. These relationships allow us to supply pre-engineered monitoring solutions that have been approved by the OEM for use on their machines, and which reflect both the needs of the OEM and the end user. Because of the familiarity they have with our quality solutions, you can confidently work with your machinery OEM and ask for Bently Nevada products and services by name.

Aeroderivative Gas Turbines

As has already been discussed, aeroderivative engines differ from their industrial counterparts in at least three very important respects pertaining to condition monitoring:

- They were originally designed for use as aircraft propulsion, and are usually adapted for industrial applications by the use of an aerodynamically coupled power turbine which converts engine thrust into mechanical torque;
- They use rolling element, rather than fluid-film, bearings (with exception of the aerodynamically coupled power turbine section, which sometimes uses fluid-film bearings);
- The maintenance practices surrounding aeroderivatives rely predominantly on changing the engine out in its entirety, rather than performing in-situ repairs.

Next, the implications of each of these differences are examined.

Aircraft Heritage

An aircraft engine does not run continuously. While it must be extremely dependable in flight, once the aircraft is on the ground a failure may be inconvenient – and perhaps expensive – but it is not life threatening. Conversely, when the engine is running during a flight, one is not likely to stop it unless it sustains truly catastrophic damage (such as foreign object damage), which keeps it from operating. Although modern commercial aircraft are designed to be able to operate safely even with the loss of one engine, an engine is not turned off in-flight unless warranted by the most extreme circumstances.

With this in mind, it is easy to understand that as aircraft engines evolved and vibration monitoring was introduced, the purpose of vibration monitoring was not so much to provide detailed mechanical diagnostics as it was to provide very basic protective functions for failures that might be encountered during a flight – namely, foreign object damage as mentioned above. Such damage tends to result in loss of blades and gross imbalance, which generally can be detected by examining the vibration amplitude of frequencies primarily centered about the running speed (1X) of the engine. Consequently, the vibration monitoring for in-flight engines is generally designed to filter out everything except the basic shaft rotational speeds. On some engines, this is accomplished by processing the vibration signal through a narrow band-pass filter that attenuates everything except a very narrow band of frequencies centered about the running speed of the engine. The center frequency of the filter automatically "tracks" up and down as the engine changes speed by use of a speed signal from the engine shaft. On other engines, the filter does not track; it simply uses a broad enough pass-band to encompass the 1X vibration component for the envisioned range of running speeds. Also, many aeroderivatives use concentric shafts which permit compressor and turbine sections to operate at different speeds, so there are often multiple shaft speeds that must be monitored.

Regardless of whether a tracking filter or fixed-band filter is used, by looking at only the 1X aspects of the vibration signal, the pilot is alerted to catastrophic engine damage, but certainly not subtle changes in the turbine such as bearing wear. This is by design. There is no point concerning a pilot with such information when what is needed is merely a go/no-go type of signal that indicates whether the engine has sustained damage that is too serious to allow continued operation.

As aircraft engines began to be adapted for industrial applications, this approach to monitoring that had evolved for use on "flying" engines remained largely unchanged. Hence, the monitoring systems on most aeroderivatives today suppress most aspects of the vibration signal with the exception of 1X by using band-pass filtering as described above. While monitoring these frequencies is useful for detecting gross problems such as loss of blades and severe imbalance, it is not really capable of permitting advanced condition monitoring to the extent possible on industrial gas turbines. This is partly due to the signal processing performed on the raw vibration signal, which suppresses many frequency components as just explained. However, it is also due to the types of transducers and mounting locations, as discussed next.

Rolling Element Bearings

Because aeroderivative engines use rolling element bearings, bearing vibration cannot be addressed with conventional proximity probes – the rotor is essentially rigidly fixed to the bearing providing no relative vibratory movement between bearing and shaft. Thus, mounting a conventional proximity probe to observe the shaft vibration relative to the bearing (as is done with industrial gas turbines) is not an option. One approach that we pioneered is to install special high-gain proximity probes in aeroderivatives that observe the outer ring of the bearing. As the elements of the bearing pass over a fixed location on the outer ring, tiny deflections occur. These deflections are observable by the probe and provide both rotor-related and bearing-related information; however, this practice is not yet widespread.

*[**Editor's Note:** For additional information on this monitoring method, refer to the article "Aeroderivative Internal Transducer Design" in the Second Quarter 2001 issue of ORBIT]*

A WORD ABOUT POWER TURBINES…

Aeroderivative gas turbines, as previously discussed, often incorporate an aerodynamically coupled power turbine, which in turn drives a load such as a generator or pipeline compressor. Often, the power turbine, since it is used only in industrial applications, will use fluid-film bearings rather than the rolling element bearings typical of aeroderivative gas generators. In this case, it is recommended that the power turbine be monitored with conventional radial proximity probes in the familiar X-Y configuration. In other cases, the power turbine uses rolling element bearings, in which case it is monitored with casing-mounted transducers, just as the gas generator portion of the machine. Internally mounted bearing housing accelerometers, as discussed above, are also a viable option for these designs.

Bently Nevada does not recommend the exclusive reliance upon casing-mounted seismic transducers for power turbines that employ fluid-film bearings. Fluid-film bearings serve to dampen rotor-related vibrations and simply do not allow sufficient transmission of these vibrations to the machine casing in many instances.

Another approach that is gaining interest among users is to mount accelerometers on the bearing housings, inside the machine. This approach does not require significant modifications to the bearing support structure and puts the transducer much closer to the source of vibration. Unlike fluid-film bearings, a rolling element bearing very stiffly couples shaft and bearing vibration to the bearing support structure. Thus, seismic transducers can be a good choice for these machines, provided they are mounted in a location to which shaft, bearing, and other vibration is faithfully transmitted. Because the transducers are "closer to the action" when mounted internally in this fashion, they are better able to observe bearing degradation and rotor-related problems (such as imbalance and misalignment) than transducers mounted on the outside of the engine. Also, the temperatures near the bearings – although inside the machine – are, ironically, less extreme than when transducers are mounted on the outside of the machine. OEMs and end users are encouraged to contact us if they would like to participate in this approach. This technique is presently being tested at several locations and has received support during dialogs with customers at several industry conferences.

While internally mounted transducers show potential for providing superior machinery condition information and machinery protection capabilities, most aeroderivatives are not currently monitored with internal vibration transducers. Instead, these machines have historically been monitored by mounting casing accelerometers on the outside of the engine. The transducer mounting locations are generally chosen by the OEM to coincide with engine frame points that represent the most direct bearing-to-structure load path that is externally accessible.

The signal processing applied to these transducers generally incorporates band-pass filtering, designed to capture little more than the 1X amplitude. In addition to the reasons already noted for such filtering, another practical reason is to ensure that the large amplitudes in the acceleration signals do not "swamp" the smaller rotor-related signals that are present. Most often, these high-frequency, high-amplitude signals are generated by blade/nozzle pass, by acoustic airflow through the gas generator and power turbine sections, and by combustor noise. Although the amplitudes can be high, the actual energy and destructive capabilities may be small.

Even though acceleration units are the intrinsic output of an accelerometer, most aeroderivatives do not use acceleration units for monitoring. Instead, it is customary to integrate or double-integrate the signal, in addition to the band-pass filtering mentioned above, resulting in either velocity units (integrated acceleration) or displacement units (double-integrated acceleration). Although some OEMs recommend that both velocity and displacement units be used as part of a "dual path" monitoring scheme with alarm levels established for both, it is more typical to see machines that use velocity or displacement units, rather than both.

Depending on aeroderivative engine size, make, and model, anywhere from one to three casing-mounted seismic transducers are typically supplied on the gas generator. As examples of this variation in the number of sensors and the signal conditioning applied to each, one popular two-spool machine (concentric shafts) uses two casing accelerometers, with tracking filters, to provide the 1X amplitude at both shaft speeds. Another manufacturer supplies one of its larger engines with three accelerometers with a fixed band-pass filter in each accelerometer circuit. The filters pass frequencies between 40 Hz and 350 Hz to the vibration monitor. Still another popular engine has historically been supplied with a single seismic transducer and a filter that suppresses all frequencies below 110 Hz. Thus, although the general approach is to use casing-mounted transducers exclusively and some form of signal conditioning that intentionally limits the frequency content seen by the monitoring system to a rather narrow band, there are very few other generalizations that can be made regarding the monitoring systems used on aeroderivative engines. The sensor scale factor, the sensor mounting footprint, the sensor mounting locations, the filter roll-offs and band-pass ranges, integration or double-integration – all tend to differ from one manufacturer and one engine to the next, and are normally detailed in a monitoring specification generated by the OEM. Bently Nevada monitoring systems are available to address these OEM specifications.

Another aspect of monitoring aeroderivatives relates to the frequent requirement for a setpoint multiplier (often called "trip multiply") capability in the monitoring system. This is a feature of the monitoring system whereby the alarm setpoints are temporarily elevated during start-up to allow the machine to pass through its first, and sometimes second, balance resonance(s) without generating spurious vibration alarms. Because aeroderivatives employ rolling element bearings, they exhibit considerably less damping than machines using fluid-film bearings or squeeze-film dampers. This results in higher synchronous amplification factors (i.e., the ratio of vibration amplitude as the machine passes through a resonance to the vibration amplitude when operating well away from a resonance is quite large). Although the use of setpoint multiplier functionality is not strictly limited to aeroderivative turbines, its use is more predominant on these machines due to the rotordynamic response characteristics just discussed. Also, some OEMs use an inhibit function that bypasses alarms altogether, rather than setpoint multiplication. However, when feasible, it is advisable to use setpoint multiplication rather than complete bypass, as this ensures that the machine will always have some type of vibration alarms enabled, regardless of its operating state.

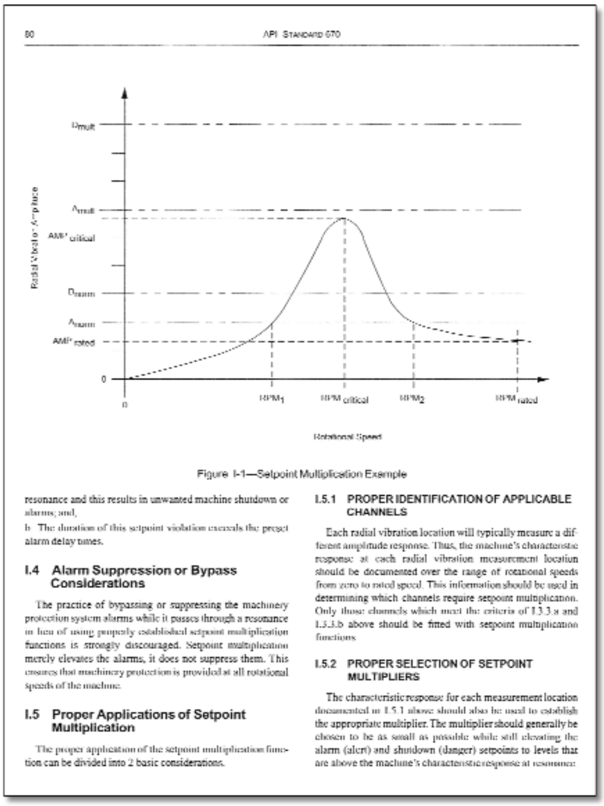


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Figure I-1—Setpoint Multiplication Example

resonance and this results in unwanted machine shutdown or alarms; and,

b. The duration of this setpoint violation exceeds the preset alarm delay times.

I.4 Alarm Suppression or Bypass Considerations

The practice of bypassing or suppressing the machinery protection system alarms while it passes through a resonance in lieu of using properly established setpoint multiplication functions is strongly discouraged. Setpoint multiplication merely elevates the alarms, it does not suppress them. This ensures that machinery protection is provided at all rotational speeds of the machine.

I.5 Proper Applications of Setpoint Multiplication

The proper application of the setpoint multiplication function can be divided into 2 basic considerations.

I.5.1 PROPER IDENTIFICATION OF APPLICABLE CHANNELS

Each radial vibration location will typically measure a different amplitude response. Thus, the machine's characteristic response at each radial vibration measurement location should be documented over the range of rotational speeds from zero to rated speed. This information should be used in determining which channels require setpoint multiplication. Only those channels which meet the criteria of I.5.3.a and I.5.3.b above should be fitted with setpoint multiplication functions.

I.5.2 PROPER SELECTION OF SETPOINT MULTIPLIERS

The characteristic response for each measurement location documented in I.5.1 above should also be used to establish the appropriate multiplier. The multiplier should generally be chosen to be as small as possible while still elevating the alarm (alert) and shutdown (danger) setpoints to levels that are above the machine's characteristic response at resonance.

THE SETPOINT MULTIPLIER FUNCTIONALITY OF A MONITORING SYSTEM, AND THE REASONS FOR ITS USE, ARE DISCUSSED IN MUCH GREATER DETAIL IN API 670, APPENDIX I.

Aeroderivative Maintenance Practices

The third difference between aeroderivatives and industrial gas turbines with respect to how they are monitored lies in the way that they are maintained. As has already been discussed, aeroderivatives rely more on maintenance practices that simply "swap out" an engine, rather than attempt in-situ repairs. The tendency for industrial units to incorporate more comprehensive condition monitoring is due, in part, to the inability to easily swap out the gas turbine. While this is feasible on aeroderivatives, and many industrial "packaged" units, it is not possible on so-called heavy industrial units. Hence, the need to diagnose the machine in-situ drives a greater reliance on condition monitoring achievable from vibration data. This is not to say that aeroderivatives and packaged industrials cannot benefit from more capable condition monitoring. It is merely to point out that the time to swap out an engine is often measured in hours, rather than days, and the relative speed with which an engine can simply be replaced when there are problems allow aeroderivative (and some packaged industrial) users the luxury of maintenance options that are not practical for heavy industrial units.

ANOTHER ASPECT OF MONITORING AERODERIVATIVES RELATES TO THE FREQUENT REQUIREMENT FOR A SETPOINT MULTIPLIER (OFTEN CALLED "TRIP MULTIPLY") CAPABILITY IN THE MONITORING SYSTEM.

Recommendations for Vibration Monitoring on Aeroderivatives

The vibration monitoring supplied with most aeroderivative packages is designed to provide a measure of basic machinery protection, but does not generally deliver the same level of diagnostic information for in-depth condition assessment that can be achieved on industrial gas turbines fitted with proximity probes. This is not to say that condition monitoring on aeroderivatives is impossible, or does not provide value. It is merely to point out that aeroderivatives, compared with their industrial counterparts, present a different and more challenging set of constraints to the diagnostician. There are several things that can be done to improve the condition monitoring capabilities on aeroderivatives. The first, and often the simplest, is to bring not only the band-pass filtered vibration signal into the monitoring system (which is used for machinery protection purposes), but to also bring the unfiltered acceleration or velocity signal into the monitoring system. By doing this, the “raw” signal can be used by condition monitoring software to look at the full frequency content, providing additional useful signal content rather than merely the 1X amplitude which is generally all that is available within the band-pass filtered signal. Although the broadband acceleration signals are often difficult to interpret due to the issues previously discussed, improved methods are being developed to extract meaningful condition monitoring information from these signals. Another strategy for improvement, as previously discussed, is to mount seismic transducers internally, on or near the embedded bearings, close to the source of vibration.

Regardless of whether a user seeks to increase the condition monitoring capabilities on their turbines or merely ensure that the existing instrumentation continues to operate trouble-free, the importance of observing proper seismic transducer installation practices on aeroderivatives cannot be over-emphasized, as discussed next.

Seismic Transducers

The seismic transducers used on aeroderivatives (and industrial gas turbines) are specially engineered to withstand the extreme temperatures and g-forces encountered. While the high surface temperatures of gas turbines are readily apparent and are rarely overlooked, many users are not similarly aware of the high g-forces encountered on these machines, requiring special installation considerations for sensors, cables, and connectors. It is very typical for aeroderivatives to have steady-state vibration of 20 g’s or more, with peaks of up to 100 g’s regularly occurring. This introduces a number of mechanical fatigue concerns in the instrumentation system which have been responsible for more than their fair share of false alarms and trips. Fortunately, these can generally be overcome by careful installation practices, summarized in the five recommendations below:

1. Use a solid-state transducer without moving parts. Velocity transducers using moving-coil technology are sometimes used for gas turbine seismic measurements. Due to the very aggressive g-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, we advocate the use of 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 at very high g-levels is particularly damaging to moving-coil sensors, accelerating their fatigue. While industrial gas turbines will sometimes employ moving coil sensors with better results, this is largely because such turbines use fluid-film bearings which tend to dampen the vibration seen at the machine casing. Aeroderivatives do not have the “benefit” of this damping, so the use of moving coil transducers on these machines is strongly discouraged because they will generally fatigue much too rapidly.

2. Where possible, use a transducer with an 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 g-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. In fact, this is the single most common problem encountered with aeroderivative gas turbine vibration instrumentation systems. 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.

3. Anchor the cable securely. Regardless of whether an integral cable is used, it is extremely important to anchor the cable securely. This is particularly true for so-called "hardline" cable that is quite stiff. 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 a number of problems, the most common being 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, be certain to use clamp inserts that will not degrade and can sustain the surface temperatures encountered. Otherwise, the clamp inserts will deteriorate, allowing metal-to-metal contact and the reintroduction of high-cycle fatigue and chafing problems. Another reason for anchoring the cable is that many aeroderivative accelerometers are charge-coupled devices and cable movement can result in a triboelectric effect, generating noise that interferes with the actual vibration signal.

4. Be sure that brackets are properly designed. As is true for any transducer installation, 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. The resonance of the bracket must be well above the vibration response of the transducer, and the bracket must be rigidly affixed. A bracket that may seem "stiff" may in fact 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. In addition, a bracket that may be tight today may not be tight tomorrow due to the high g-forces previously discussed. Be sure to make certain that any bolted connections are tight – and stay tight. 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.

5. Mount interface modules in a vibration-free environment. Some acceleration sensors (such as the new High-Temperature Velocity Acceleration Sensor – see page 76) integrate the charge amplifier and other signal conditioning electronics as part of the sensor and cable assembly. In these cases, the sensor, cable, and signal conditioning electronics are designed to sustain the vibration normally encountered in their mounting locations. However, sensors using external charge amplifiers and/or integration and band-pass filtering electronics must take care to mount any external signal conditioning (often called an Interface Module) in an environment with little or no vibration. If these practices are not observed, internal components and the field wiring connections at the Interface Module can vibrate loose over time, causing intermittent problems and possibly even false alarms.

Additional Solutions

Today, a much larger selection of measurements for protecting and managing gas turbines is available, complementing the vibration monitoring traditionally supplied. Many of these can be integrated into a Bently Nevada® 3500 Series Machinery Protection System. Others act as independent systems that can be integrated within System 1® optimization and diagnostic software.

Overspeed Detection

One particularly important aspect of machinery protection for gas turbines is overspeed detection. The 3500 Series is a very capable platform for providing this important measurement. There are very strong economic and safety incentives to replace the mechanical overspeed bolt, and upgrading to an electronic overspeed detection system can often pay for itself immediately by eliminating the process interruptions that normally occur as part of testing an overspeed bolt.

*[**Editor's Note:** You can read more about overspeed in the feature-length article on page 16.]*

Combustion Monitoring

Today's lean-burning gas turbines must operate on the verge of flame-out in order to achieve the extremely low emissions that are being demanded. Combustion instabilities are a consequence of this lean-burn operation, resulting in pressure pulsations in the combustors. If left unchecked, these pulsations can quickly damage components, and the ability to detect incipient and actual combustion instabilities are thus important. The 3500 Series can be used not only for vibration monitoring and overspeed detection, but also for monitoring pressure pulsations in gas turbine combustors. The 3500/64M Dynamic Pressure Monitor provides this capability and is designed to be used with a variety of industry-standard dynamic pressure transducers. It is already widely used on several aeroderivative and industrial gas turbines and is designed for inclusion by OEMs on new units and for retrofit to field units by end users or OEMs.

Flame Sensing

GE Energy's Flame Tracker™ sensor is an innovative solution for monitoring the presence of a flame, as needed for permissives during start up, and to ensure that fuel does not continue to flow and build up to potentially explosive levels if a flame-out occurs during start-up or steady-state operation. The inability to reliably detect a flame manifests itself in either falsely detecting the presence of a flame when one is not present (a safety hazard), or the failure to detect a flame when one is actually present (entailing an expensive process interruption and restart with subsequent impact on hot gas path component life). The Flame Tracker sensor uses Silicon Carbide (SiC) technology to provide a reliable and robust measurement that is ten times more sensitive than Geiger-Mueller sensors and much less susceptible to the conditions (such as steam injection) that often cause flame sensors to give false readings. A retrofit of these sensors often has a very rapid payback by eliminating false flame-out indications.

*[**Editor's Note:** You can read more about Flame Tracker sensors in the feature-length article beginning on page 77 in this issue.]*

Exhaust Gas Temperature (EGT) profiles

System 1® optimization and diagnostic software now features the ability to monitor this important parameter, indicative of hot gas path component life and proper combustion. Temperature deviations, differentials, and a variety of OEM- and user-defined variables can be calculated, allowing advanced monitoring of the hot gas path.

*[**Editor's Note:** You can read more about this new plot type beginning on page 88.]*

Performance Monitoring

Thermodynamic performance information is particularly relevant to gas turbines, providing insight into efficiency degradation and allowing optimal maintenance planning, such as identifying the ideal time to conduct a compressor wash. Because gas turbines are often used as part of a larger thermodynamic system, such as combined cycle or cogeneration plants, end-to-end heat balance monitoring of all parts of the plant (not just the gas turbine) are important as well.

*[**Editor's Note:** The article on page 64 discusses our online software solutions for both single machine train performance monitoring as well as plant-wide heat balance monitoring.]*

Hazardous Gas Detection

It is very common to find control panels for gas turbines (particularly those in the oil & gas sector such as pipeline compressor stations) fitted with both vibration monitors and hazardous gas detection monitors. Combustible gases are often used as the fuel for gas turbines and/or in the processes for which gas turbines drive pumps or compressors. Leaks of such gases must be detected to prevent the buildup of explosive levels, particularly in enclosed spaces, and dedicated monitoring systems are used for this important measurement. Today, the 3500 Series can make this measurement by way of the 3500/63 Gas Detection Monitor. The ability to achieve hazardous gas detection by using only a single slot in a 3500 rack can result in substantial installation savings, and also allows easier integration to plant control and automation systems.

*[**Editor's Note:** You can read more about the 3500/63 in the article in the Second Quarter 2004 issue of ORBIT, page 28.]*

Summary

Aeroderivative and industrial gas turbines come from very different backgrounds and design criteria, resulting in different bearings, different maintenance practices, and different construction. In turn, this has led to distinctly different vibration monitoring practices. This article has explored some of these differences, along with some of the most common approaches to monitoring both types of gas turbines. In today's competitive climate, a well-instrumented gas turbine should include more than just rudimentary vibration monitoring for basic machinery protection; it should also include the capabilities for more advanced condition monitoring, thermodynamic performance monitoring, flame detection, overspeed detection, combustor instability monitoring, EGT profiling, and (in some applications) hazardous gas detection. O

Additional Reading

API Standard 616 – Gas Turbines for the Petroleum, Chemical and Gas Industry Services, Fourth Edition, August 1998, American Petroleum Institute, Washington, D.C.

API Standard 670 – Machinery Protection Systems, Fourth Edition, December 2000, American Petroleum Institute, Washington, D.C.