A vibro-meter whitepaper

A Practical Guide for Understanding

Gas Turbine Monitoring

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Introduction

For more than 70 years, vibro-meter has been at the forefront of monitoring gas turbines with a broad portfolio of comprehensive product and service offerings to cover the machinery protection and condition monitoring needs of every size and application of these important machines. However, a fundamental aspect of monitoring success is a basic understanding of the underlying machine – providing context for the measurements made and their importance. This whitepaper has been prepared with three types of individuals in mind: the vibration specialist that needs a generalist-level awareness of gas turbines and how they are monitored, the new graduate in an engineering discipline that is entering the maintenance, reliability, condition monitoring, or machinery engineering workforce for the first time and will be working with gas turbines, and the instrumentation professional that needs to better understand the machinery they are instrumenting and controlling when this machinery includes gas turbines. While this document endeavors to provide such an overview, it merely scratches the surface. There are many fine resources on the subject of gas turbines that go into considerably more depth. Some of these are summarized in the "Additional Reading" section at the end of this document.

Gas Turbines

A brief history

Although the first true gas turbine was patented in 1791 by John Barber of Nottinghamshire, England, it would be more than 100 years before a gas turbine able to produce more power than it consumed could be demonstrated and nearly 150 years before one would be put to practical use in power generation service.

Various additional patents were issued during those intervening years, including Elling[1] in 1884, Curtis[2] in 1895, Lemale[3] in 1901, and Whittle[4] in 1930 to name a few.

Early designs entirely separated the compressor, combustor, and turbine from one another into three, free-standing units. Indeed, some even used a reciprocating engine as the gas generator before expanding the hot gas produced thereby through a turbine. Early designs were also fraught with the challenges of finding turbine materials able to withstand the hot gas path temperatures produced by the free-standing combustion chambers, in being even reasonably efficient, and in providing sufficient output power for industrial use. For example, it is reported that when Aurel Stodola – a highly influential figure in the development of the gas turbine – analyzed an early unit built by Armengaud and Lemale, he found it to have an output of only 61 kW and a thermal efficiency of only 3%[5]. For comparison, a steam turbine of the same era was capable of producing 5MW and occupied a relatively small footprint (aside from the boiler) as shown in Figure 2.

The first gas turbine for electric power generation (Figure 3) was placed into service in 1939 and was manufactured by Brown, Boveri & Cie. It produced 4MW, had a turbine inlet temperature of approximately 550° C (1020° F), and was installed in a bomb-proof building at a municipal power station in Neuchâtel, Switzerland where it provided reliable standby (emergency and peaking) power for the next 63 years. Aside from its single, large combustor and separate machine cases for compressor and turbine, it had numerous features still found in industrial gas turbines today. For example, it ran at 3000 rpm to directly drive a 2-pole, 50Hz generator and featured a single-shaft design with compressor, turbine, and generator all mechanically coupled to one another. It also featured an axial-flow compressor, an axial-flow turbine, and a generator coupled to the compressor end of the machine (although it coupled at the compressor outlet or "hot" side rather than the compressor inlet or "cold" side). Stodola himself – at 80 years of age – measured the thermal efficiency of this

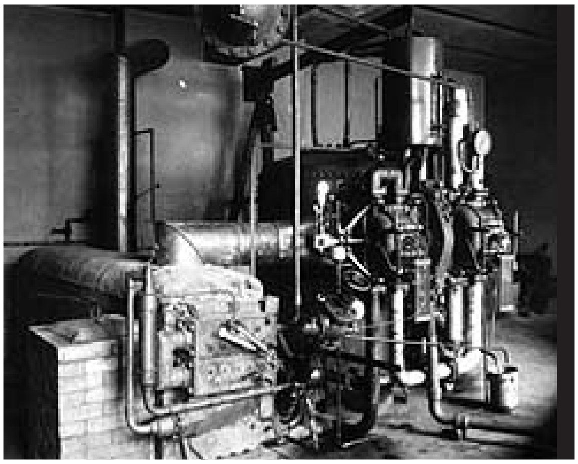


Figure 1: One of Elling's early (circa 1906) gas turbines at a sail cloth factory in Kristiania (now Oslo) Norway.

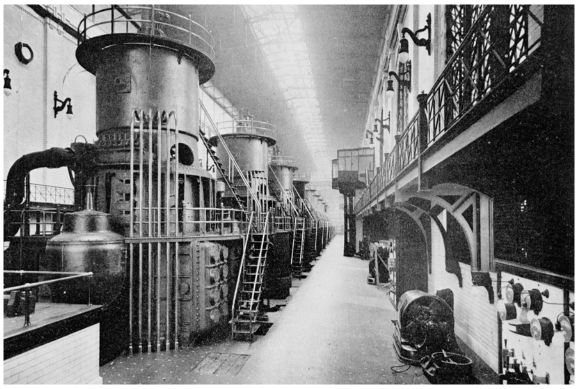


Figure 2: These vertical steam turbines were built by GE and installed at Chicago's Fisk Street Station in 1903. Each one produced 5MW – approximately 100 times more than the gas turbines of the era. It would be 1939 before the first gas turbine for power generation would be installed in the Eastern Hemisphere and 1949 before one was installed in the Western Hemisphere.

machine and found it to be in excess of 17%.[6] While far below the 40%+ efficiencies obtained by modern simple-cycle gas turbines, it represented a six-fold increase in efficiency and a 65-fold increase in output power over Armengaud and Lemale's 1903 machine. The Neuchâtel unit is designated as an ASME Historic Mechanical Engineering Landmark[7]and is today preserved in a special museum on the grounds of the GE (formerly ALSTOM) facility in Birr, Switzerland[8].

During the 1930s and 1940s, interest was increasing in gas turbines as means of aircraft propulsion. Although Sir Frank Whittle's 1930 patent for use of a gas turbine as a jet engine was initially dismissed by the British Royal Air Force as impractical, it would indeed prove itself immensely practical within the next decade – so practical that today gas turbines are used for powering almost all fixed wing and rotary wing aircraft. At the same time, and quite independently, Dr. Hans von Ohain of Germany was conducting similar work. Although Whittle was the first to patent his ideas, it was Ohain's efforts that led to the first jet-powered flight on August 27, 1939 when his own engine – the diesel-fueled HeS 3 – was used to power the Heinkel He 178. Two years later, Whittle would see his design result in a similar milestone: the first jet-powered flight in England[9] on May 15, 1941, using a Whittle W.1 engine integrated into the fuselage of the specially designed Gloster E.28/39. The first jet-powered flight in North America would not occur until Oct 2, 1942, with the Bell X-59 aircraft powered by two GE I-A engines[10].

These advancements in aviation are mentioned because, as will be seen, gas turbines developed originally for industrial use as well as those developed originally for aviation use are both found today in industrial applications. These separate lineages have resulted in important differences in the bearing types used, the maintenance philosophies employed, and the vibration monitoring strategies embraced.

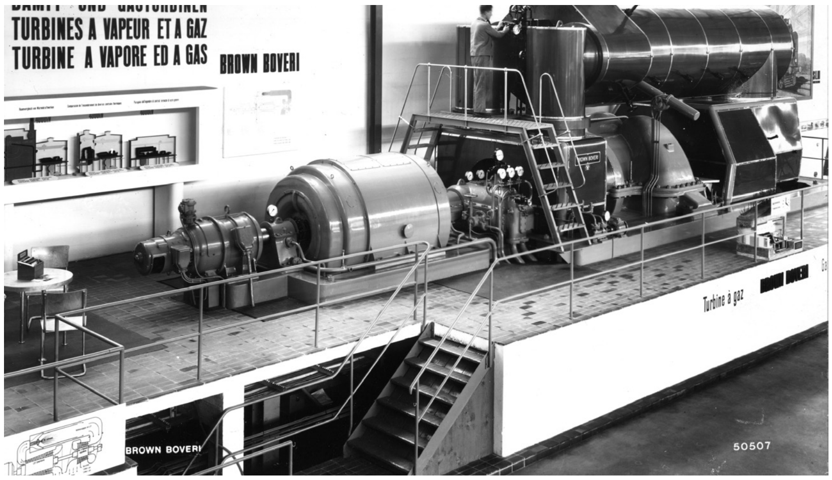


Figure 3: The world's first gas turbine for power generation service was built by Brown, Boveri, & Cie. and placed in service in 1939 at a plant in Neuchatel, Switzerland. Shown here is the actual turbine at a 1939 Swiss tradeshow, prior to its installation at the customer site. Note the size of the man on the platform in proportion to the single, large combustor can situated on top of the unit.

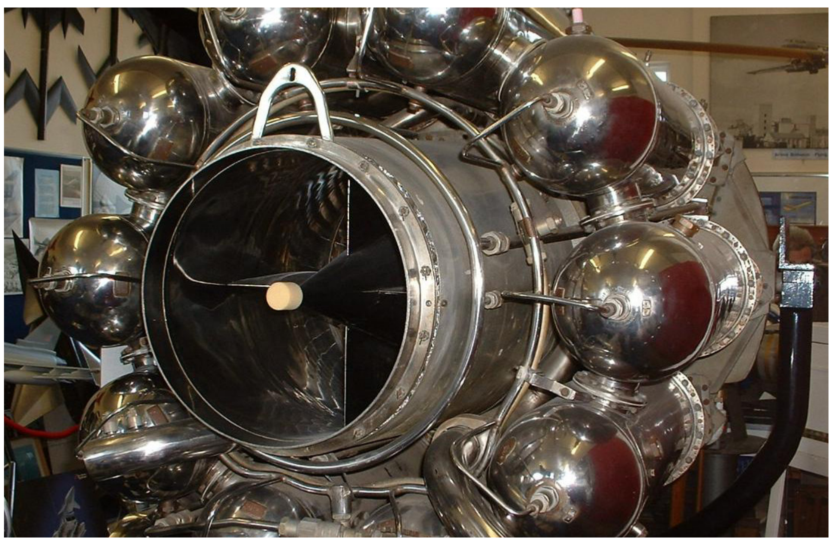


Figure 4: The Whittle W.1 engine was very similar to the W2/700 shown here. While the W.1 was an experimental engine, the W2/700 was mass-produced. Whittle's pioneering work on jet engines was substantially aided during that period by Rolls-Royce, which would later produce the massive RB211 engine (aka Siemens SGT-A35) used on the Boeing 747 as well as in industrial applications.

Gas Turbine Classifications

Gas turbines can be broadly divided into two categories: those designed originally for aviation use – but later adapted for industrial use as well – and those designed solely for industrial use.

As can be easily appreciated, the factors that are important in gas turbines designed for aviation use are different than in those designed purely for industrial use.

We refer to the first category as *aeroderivative gas turbines* because they are derived from aviation designs and adapted for industrial applications such as mechanical drive, power generation, and marine propulsion. For example[11], the Siemens SGT-A35 is an industrial adaptation of the Rolls-Royce RB211 aircraft engine used to power the Boeing 747 as well as the basis of newer Trent engine designs that power the Airbus A330, Boeing 777, and others. Likewise, GE's LM2500[12], LM5000, LM6000, and LMS100 are all industrial adaptations of the CF6 family of engines that power the Airbus A300 and A310 as well as the Boeing 767. As yet a third example, MHI's FT4000 is an industrial adaptation of the Pratt & Whitney PW4000 engine, also used to power aircraft such as the Boeing 777, Airbus A330, and others. To adapt an aviation gas turbine to an aeroderivative – one suitable for industrial use – the core of the aviation engine is generally retained (with perhaps a few modifications) but then a special power turbine is attached to the exhaust end of the machine that extracts power from the hot, high-velocity exhaust gases and converts them into rotative force capable of driving a generator, compressor, pump, blower, or other mechanical load. This is depicted in Figure 5.

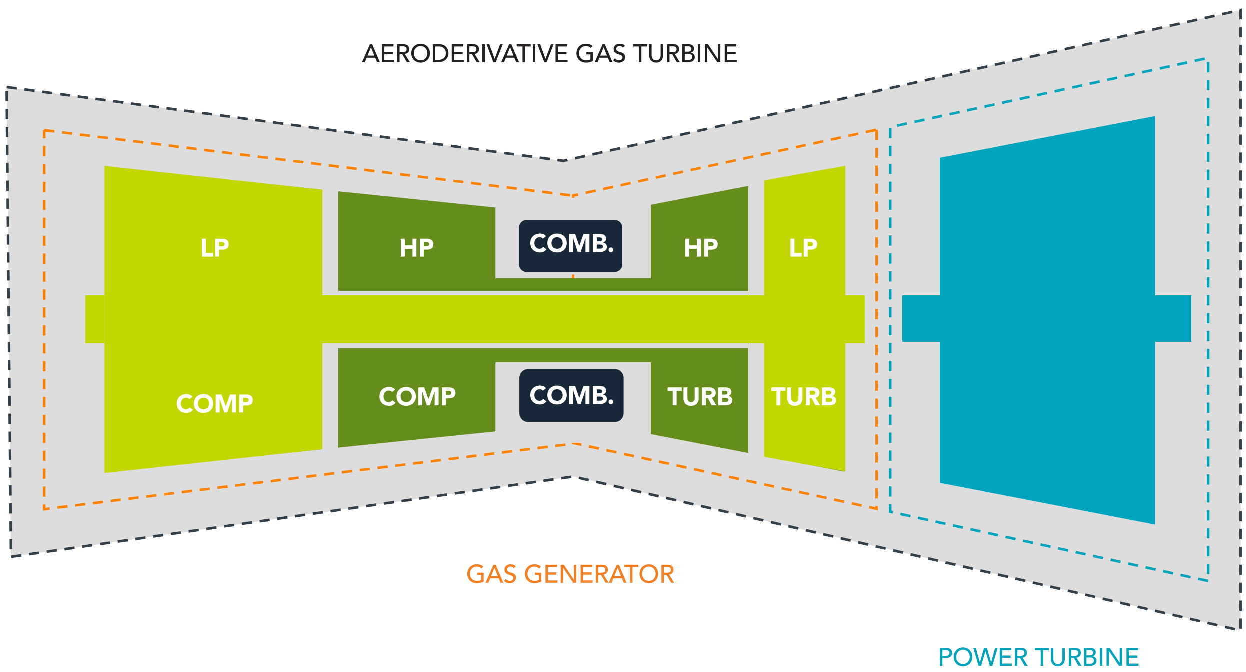


Figure 5: An aeroderivative gas turbine consists of a gas generator and a power turbine. The power turbine (sometimes also called a "free turbine" or "reaction turbine") is not mechanically coupled to the gas generator – it is only aerodynamically coupled – and may employ different bearing types than the gas generator. A two-spool design is depicted here where the gas generator has both a low-pressure spool and a high-pressure spool that are aerodynamically – not mechanically – coupled by means of concentric shafts, allowing the LP shaft to turn freely within the HP shaft.

We refer to the second category as *industrial gas turbines* because they are neither designed for nor used in aviation applications. We can further divide industrial gas turbines into so-called "heavy-industrial" and "light-industrial" machines as shown in Figure 6.

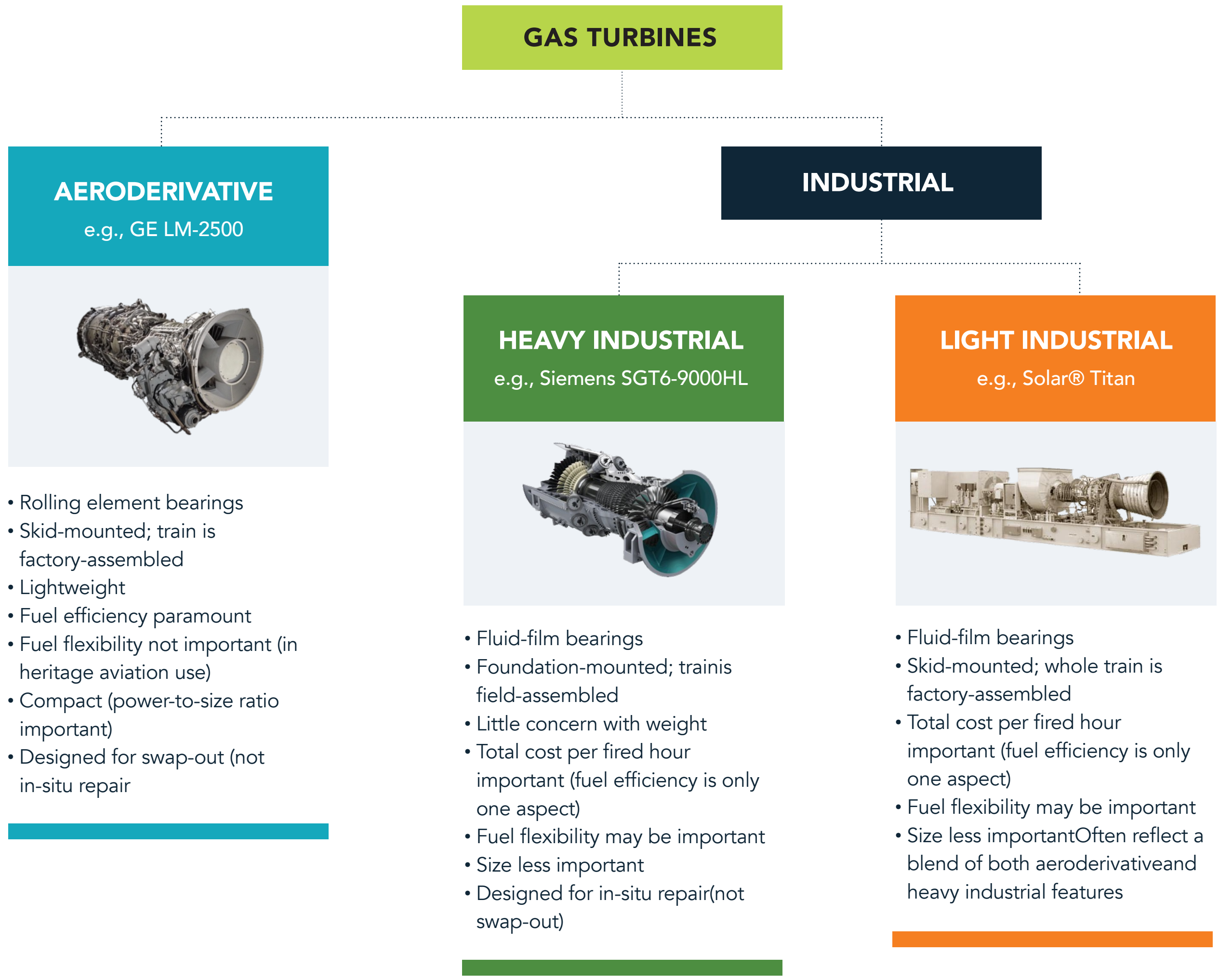


Figure 6: When used for mechanical drive, power generation, and marine propulsion, gas turbines can be broadly classified into the three categories shown here. The high-level attributes listed convey some of the key distinctions that help distinguish each category.

A major difference between industrial machines and aeroderivative machines is in the bearing types used. All aeroderivative gas turbines use rolling element bearings while almost all industrial gas turbines use fluid-film bearings. This governs the types of sensors used, where and how the sensors are placed, and the type of information that is of primary importance to the user. Another major difference is in the respective market forces and regulatory factors that led to particular maintenance philosophies for aeroderivative versus industrial machines. We examine the heritages of these different gas turbine types next, and how this has influenced the type of monitoring systems generally applied.

Aeroderivative Gas Turbines

We first consider gas turbines with an aviation heritage. In their original embodiment as aircraft propulsion, they must be concerned with fuel consumption, weight, and a compact design that does not require extensive auxiliary systems such as large lube oil reservoirs and delivery systems.

For this reason, as was noted, these engines were designed at the outset to use rolling element bearings and their much smaller accompanying lube oil systems. In addition, an aircraft engine is not expected to operate for thousands of hours at a time without intervening inspections or maintenance. They are instead generally inspected at very frequent intervals based on running hours rather than extensively measured mechanical condition via online vibration instrumentation. The engines are designed to be swapped out easily rather than to facilitate extensive in-situ maintenance on individual components such as blades or combustors. In a very real sense, a gas turbine engine on most aircraft is treated as a replaceable component – much as one would replace a spent ink cartridge on a printer and then recycle it for refilling and refurbishment. This is not to say that one replaces an aircraft engine with the same ease, but merely to say that the same basic philosophy is at play: replacement rather than in-situ refurbishment and repair. An aircraft engine in need of anything more extensive than simple, externally accessible service is typically removed from its nacelle, sent to a repair facility for maintenance and refurbishment, and a replacement engine inserted in its place. An engine may thus rotate among numerous aircraft as it undergoes maintenance and inspection cycles.

It is also important to note that the primary impetus for aircraft engine maintenance is safety-related because an engine failure could mean loss of lives. The aviation industry around the globe is thus highly regulated through oversight by the relevant government agencies of their respective countries – such as the FAA in the United States and the EASA in Europe. These agencies, among other things, mandate intervals for safety inspections of aircraft and their constituent assemblies such as engines. Combined, these factors mean that aviation engines are primarily monitored for only extreme failures – such as loss of blades through, for example, ingestion of a foreign object – and the resulting gross rotor imbalance that can be easily measured. This is in stark contrast to failures that typically progress more slowly and subtly such as rolling element bearing degradation and require very sophisticated monitoring strategies and signal processing. Thus, in aviation engines, rather than taking great pains to monitor individual bearings and other components, there are mandated manual inspection intervals that are generally much shorter than the expected life of the subject components.

All of these factors have led to a relatively small number of vibration sensors on aeroderivative gas turbines and a particular set of parameters that are monitored, which differ from the parameters used on non-aeroderivative gas turbines. Namely, the approaches for aeroderivatives arise from an inspection-based, safety-driven maintenance heritage where only the most catastrophic failures need to be detected in-flight: loss of blades or other catastrophic failures.

This can be readily observed by inspection of Figure 7 and considering its implications.

One of the first things to notice about Figure 7 is that although there are eight bearings, the accelerometers are mounted nowhere close to the bearings and are instead mounted on the engine casing. There are several reasons for this. First, there is no room on the inside of the machine to mount accelerometers at each bearing. Additionally, the temperatures inside the engine are appreciable and not readily conducive to sensors or cabling. Although one could arguably "make a way" to install internal sensors on each bearing if sufficiently motivated, this cuts to the heart of the issue: there is not sufficient motivation. On an aircraft, only the most severe vibration would warrant removing the engine from service. Even the longest flight rarely exceeds 17 hours[13] so even if a bearing fault were detected at the moment of takeoff, it would be unlikely that it was so pronounced that the bearing would fail entirely within the flight duration. In contrast, if a bird or other foreign object were to hit the engine and remove a section of blades, this would be relatively easy to detect via gross casing vibration amplitudes, alert cockpit personnel, and shut the engine down. And indeed, this is precisely the monitoring strategy used. Most commercial aircraft are built today with two engines, but are designed to safely sustain the loss of one engine. Rather than continuing to fly with an engine that has sustained serious damage, and risk a fire or additional catastrophic results, it is far safer to shut the engine down and finish the flight on the remaining engine(s), even if that means rerouting to a closer destination and landing prematurely (but safely).

In practice, each aeroderivative manufacturer monitors for this gross imbalance (and overall amplitude indicative of other major problems) in a slightly different way. However, this is largely a difference not in philosophy but method. The overall philosophy of monitoring only for gross imbalance and other gross changes rather than subtle changes and bearing condition is uniform and consistent across manufacturers.

It should also be noted at this point that we are thus far examining only the monitoring for the gas generator – not that of the attached power turbine or the load it drives (such as a generator). Monitoring for those will be discussed in later portions of this document.

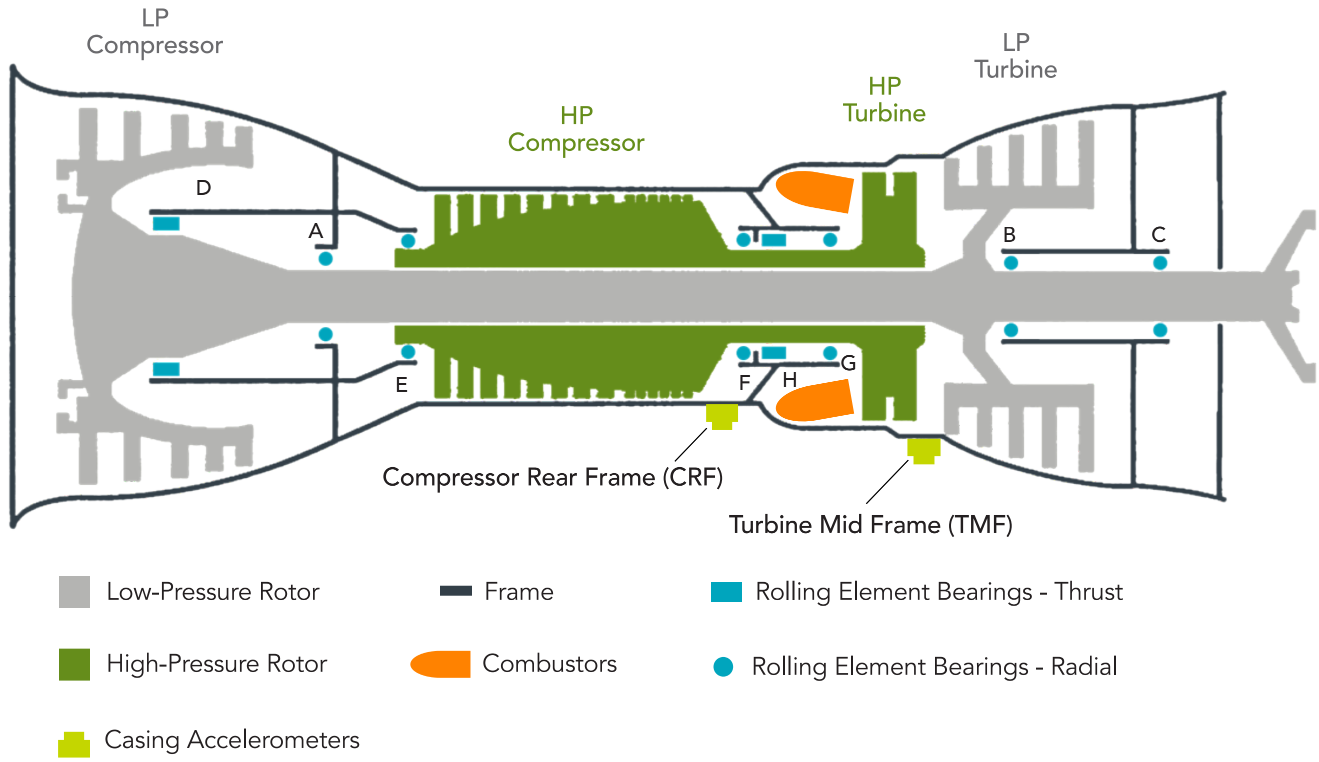


Figure 7: The GE LM6000 gas generator has eight rolling element bearings. Three (A-C) are used to provide radial support for the LP rotor, three (E-G) are used to provide radial support for the HP rotor, one (D) is used to constrain thrust forces on the LP rotor, and one (H) is used to constrain thrust forces on the HP rotor. Notice that there are only two accelerometers – one on the rear frame of the compressor and one on the mid frame of the turbine. Notice also that this is a two-spool machine, allowing independent rotative speeds of each spool to give optimal performance to the respective compression and expansion sections. Such multi-spool designs are found in most aeroderivatives.

Examples of Aeroderivative Monitoring

Vibro-meter monitoring systems have been specifically designed with sufficient flexibility to implement the monitoring requirements of all major aeroderivative manufacturers.

However, no attempt is made in this document to discuss every make and model of aeroderivative, every variant thereof, and every driven machine.[14] The three examples provided next are simply to illustrate the general observations pertaining to all aeroderivatives. Namely, that aeroderivatives gas generators are monitored using a relatively small number of high-temperature accelerometers mounted on the casing, that the monitoring strategy is primarily to detect catastrophic issues such as loss-of-blade events rather than subtle changes in bearings or other components, and that filtering is used to isolate the frequencies associated with these catastrophic malfunctions – where the filters may be wideband, narrowband, or notch, and where the filter center frequency may be fixed or tracking.

In this document, we have studiously avoided conveying the specifics of these filters such as center frequencies and roll-off because some OEMs consider such details to be proprietary while others are more open. Similar remarks pertain to the monitoring of combustion dynamics. Regardless, you can consult the gas turbine OEM or packager to obtain such details. For example, GE provides these details for each of its aeroderivatives in a document known as the Installation & Design Manual (IDM). This document is available upon request to GE customers and to monitoring providers such as vibro-meter. Other OEMs provide similar documentation.

Example A:

GE Aeroderivative Monitoring Strategy for GE Aeroderivative Engines

It should come as no surprise that GE's monitoring strategy for the LM6000 is based on the monitoring strategy for its flying counterpart (the GE CF6) and that all aeroderivative engines – regardless of manufacturer – use essentially the same basic formula: monitor for catastrophic damage (generally imbalance), alert the operator, shut the machine down, and replace the machine in its entirety with a spare.
For example, GE uses tracking filters on its engines so that each accelerometer is filtered to each spool speed, allowing the 1X (i.e., rotative speed) vibration component to be ascertained for each spool, even under changing speed conditions. In the case of the LM6000, for example, four 1X measurements are returned as summarized in Table 1.

Table 1 – Filtered vibration measurements for LM6000 aeroderivative gas turbines

Speed	TMF Sensor	CRF Sensor
N1 (LP spool)	#1 – 1X from TMF @ LP speed	#2 – 1X from CRF @ LP speed
N2 (HP spool)	#3 – 1X from TMF @ HP speed	#4 – 1X from CRF @ HP speed

GE specifies its monitoring strategy in their IDM (Installation Design Manual) for each engine type. In general, and as summarized in Table 2, it specifies a monitoring approach that is consistent across GE aeroderivative engine types[15] including the LM1600, LM2500, LM5000, and LM6000. Using the basic information in Table 2 and referring again to Figure 7 showing the LM6000's two accelerometers (CRF and TMF), Figure 8 depicts the specific IDM-compliant monitoring implementation for the LM6000.

Detect Loss-of-Blade Events	Detect blade loss on any stage of any spool via isolation of the 1X component from each accelerometer signal, for each spool speed. If there are two spools and two accelerometers, this corresponds to 4 measurements. If there is a single spool and two accelerometers this corresponds to 2 measurements, etc. For most GE machines, the 1X component is measured in velocity units and is isolated by means of a narrowband tracking filter that adjusts itself automatically with speed.
Detect Other Engine Problems	Detect "other" engine problems by monitoring and alarming on the overall velocity amplitude within a wider band of frequencies (the "Detection Band") encompassing several hundred Hz[16].
Provide Easy Signal Access for Supplementary Diagnostics	Provide access to the unfiltered acceleration signals for connection to portable diagnostic systems.
Use alarm delays to prevent false alarms	Because high 1X can be reliably detected with GE's tracking filters, short alarm delays (1 sec or less) are used to quickly take action. To prevent spurious alarms from the wide-band signals, sustained violations of the setpoint (typically 10 sec or more) are required.

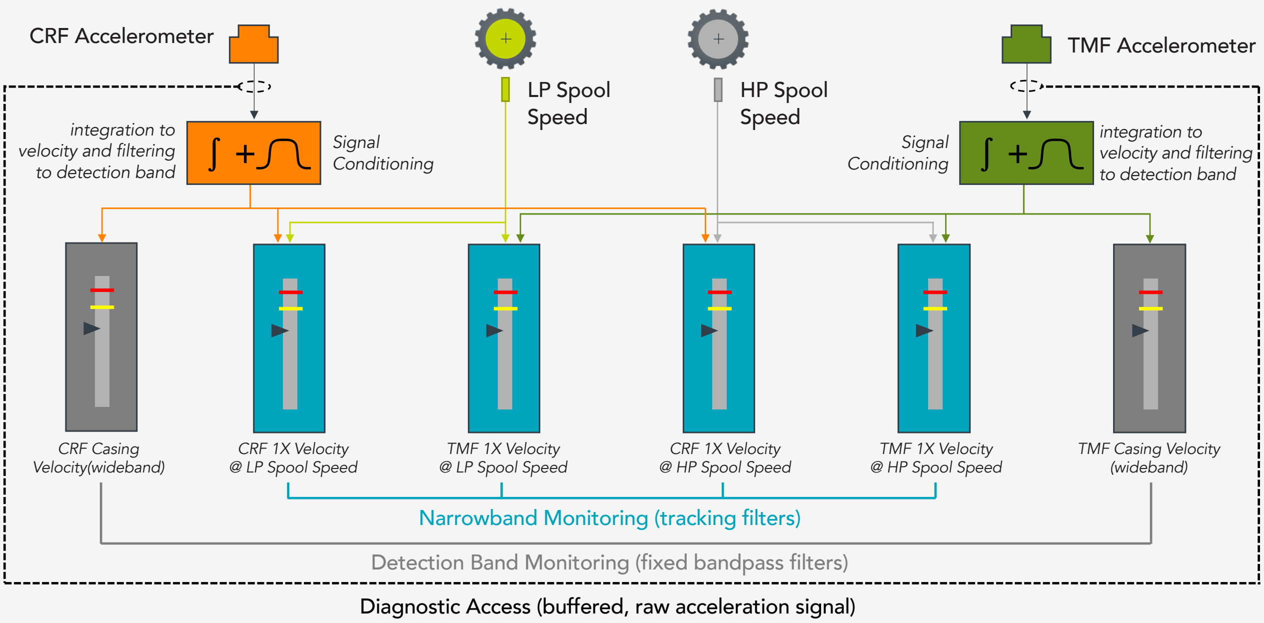


Figure 8: Monitoring channels and signal processing for an LM6000 gas generator complying with the GE IDM. Note that the monitoring for the power turbine, for the driven machine (such as a generator), or for the combustion dynamics is not shown.

Example B:

Monitoring Strategy for Rolls-Royce Aeroderivative Engines

Siemens has acquired the gas turbine divisions of numerous other gas turbine manufacturers over the years, such as Westinghouse, Rolls-Royce, EGT (aka Ruston), Allison, and others. Here, we examine Siemens engines with a Rolls-Royce heritage, such as the Avon and RB211. In general, the monitoring philosophy is to use passband monitoring with a fixed center frequency rather than the tracking filter approach used by GE and is summarized in Table 3.

Table 3 – Basic Rolls-Royce Aeroderivative Monitoring Strategy

Detect Loss-of-Blade Events	Detect blade loss on any stage of any spool via gross changes in overall velocity amplitude within a passband (the "Detection Band") of several hundred Hz. To reject frequencies outside this band, filters with very steep roll offs are used.
Detect Otwher Engine Problems	Detect "other" engine problems by monitoring and alarming within the same Detection Band as for loss-of-blade events.
Provide Easy Signal Access for Supplementary Diagnostics	Provide access to the unfiltered acceleration signals and the high-pass velocity signals for connection to portable diagnostic systems.
Use alarm delays to prevent false alarms	To prevent spurious alarms from the Detection Band signals, sustained violations of the setpoint (typically 1 sec or more) are required.

While the Avon engine has only two accelerometers and thus two monitored locations for casing vibration, the RB211 has three as shown in Figure 9.

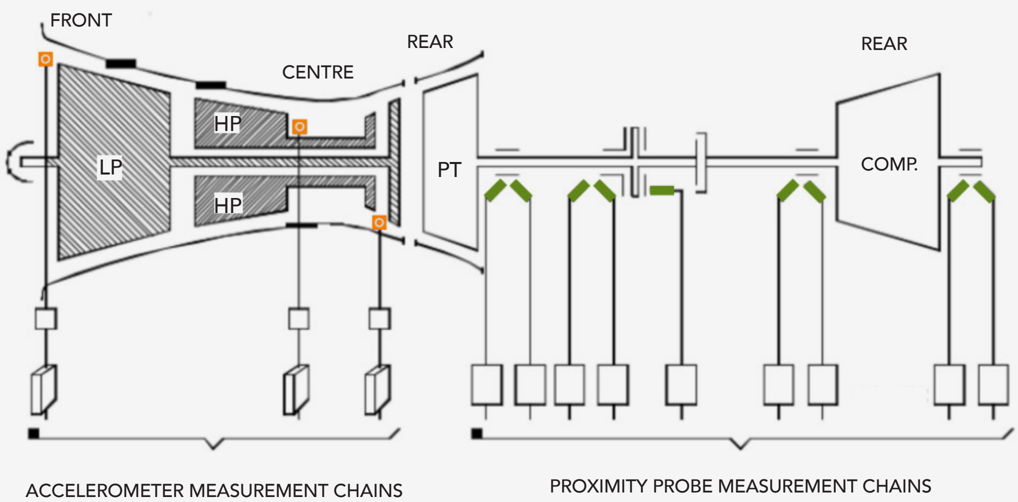


Figure 9: Excerpt from 1999 vibro-meter application note for RB211 monitoring. The gas generator is monitored with three accelerometers while the power turbine and driven machine (pipeline booster compressor) have fluid-film bearings and are monitored with proximity probes. Note the overhung design of the power turbine, which is typical regardless of bearing type used.

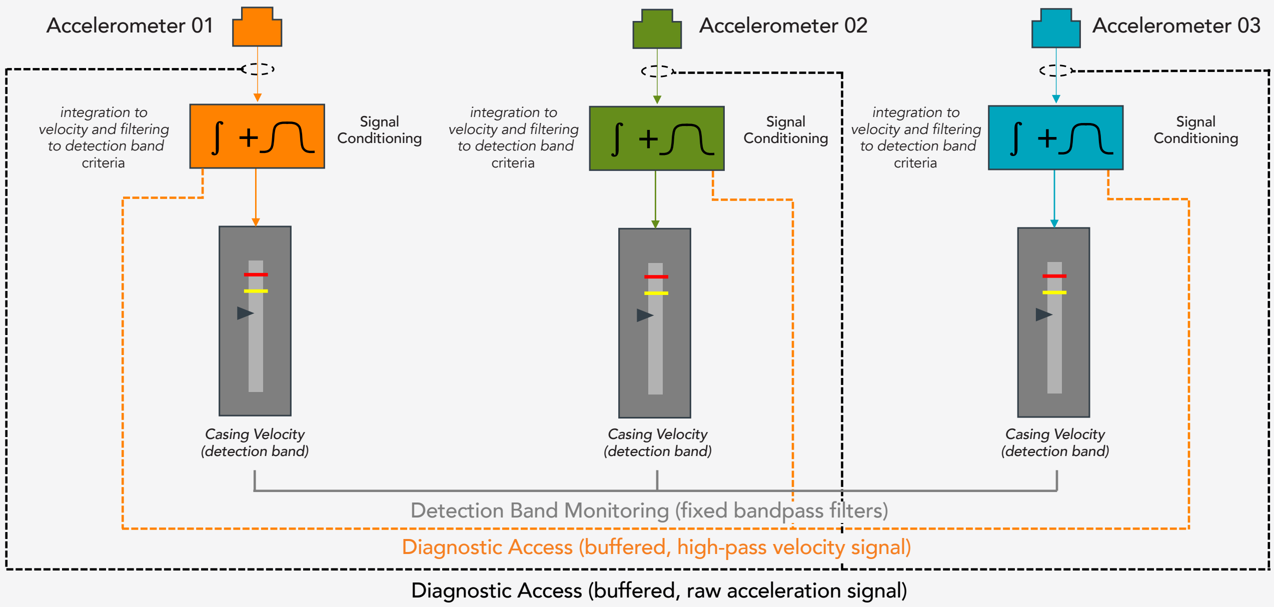


Figure 10: Monitoring channels and signal processing for an RB211 gas generator. Note that the monitoring for the power turbine, for the driven machine (such as a gas pipeline compressor), or for the combustion dynamics is not shown.

At this juncture, it is appropriate to note that we have shown here only the basic OEM recommendations for monitoring the gas generator. In reality, the ability to provide enhanced monitoring of aeroderivatives by supplementing OEM recommendations is often recommended. For example, the RB211 engines in use by a leading North American gas pipeline operator supplement the basic monitoring described here with tracking filters to better isolate the 1X and 2X vibration components and notch filters (so-called "NOT 1X") to better isolate the amplitudes other than 1X.

Similar observations can be made for other aeroderivatives where it is frequently beneficial to augment the basic OEM recommendations with additional measurements – but often without the need to add additional sensors. For example, Figure 11 shows the supplemental measurements added by vibro-meter on the RB211 engines used by the aforementioned North American customer.

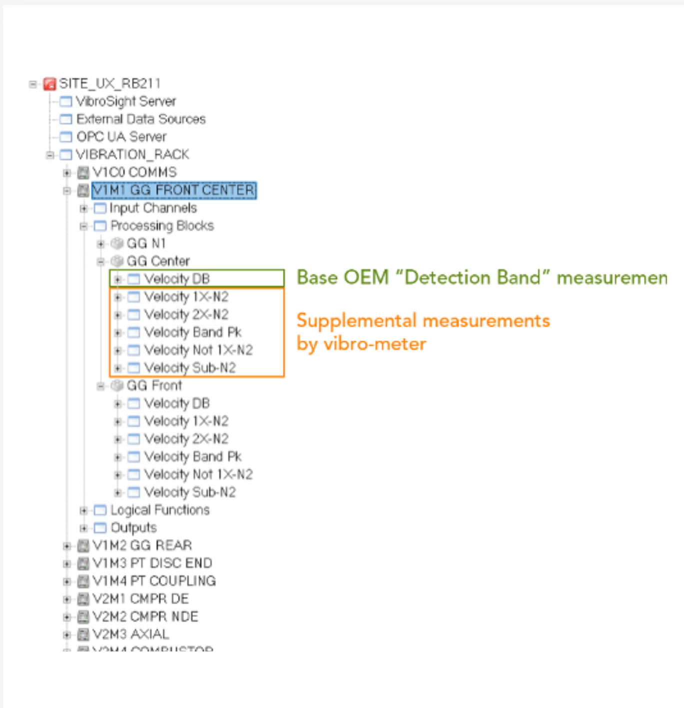


Figure 11: Screen capture of configuration for RB211 engine showing base OEM monitoring parameter (i.e., "velocity band") and supplemental measurements made without need of any additional sensors.

Vibro-meter is deeply experienced in understanding both these basic OEM recommendations and these supplemental measurements that can result in easier isolation of problems and more timely maintenance intervention. At the aforementioned North American pipeline, for example, our solutions are used to monitor both vibration and combustion for the following engine types:

- Rolls-Royce RB211 and Avon
- GE LM1600 and LM2500
- Allison 501KC

Example C:

GE Aeroderivative Monitoring Strategy for Pratt & Whitney Aeroderivative Engines

The Pratt & Whitney FT4 and FT8 aeroderivatives were adapted from the JT4 and JT8 engines respectively. The FT prefix stands for "Free Turbine" (see Figure 5) and denotes engines used for industrial applications while the JT prefix stands for "Jet Turbine" and denotes engines used for aviation jet propulsion. Mitsubishi acquired Pratt & Whitney Power Systems in 2013, encompassing their aeroderivative engines used for power generation service.

The overall monitoring philosophy used on Pratt & Whitney aeroderivatives is again consistent with those of other manufacturers; namely, to monitor only for gross changes and catastrophic events such as blade loss. However, to deal with large vibration amplitudes arising from water injection and from the power turbine, the gas generator monitoring is a bit more sophisticated as summarized in Table 4

Table 4 – Basic Pratt & Whitney Aeroderivative Monitoring Strategy

Detect Loss-of-Blade Events	Detect blade loss on any stage of any spool via gross changes in overall velocity amplitude within a passband (the "Detection Band") of several hundred Hz. To reject frequencies outside this band, filters with very steep roll offs are used. Where necessary, notch filters are used to suppress high-amplitude vibration frequencies from one component from influencing the measurements of other components.
Detect Other Engine Problems	Detect "other" engine problems by monitoring and alarming within the same Detection Band as for loss-of-blade events.
Provide Easy Signal Access for Supplementary Diagnostics	Provide access to the unfiltered acceleration signals and the high-pass velocity signals for connection to portable diagnostic systems.
Use alarm delays to prevent false alarms	To prevent spurious alarms from the Detection Band signals, sustained violations of the setpoint (typically 1 sec or more) are required.

A typical FT8 (Figure 12) will have accelerometers mounted at the A Flange (engine inlet), K Flange (mid-engine, near combustors), and S Flange (power turbine exhaust). Some engines will also have an accelerometer at the R Flange (power turbine inlet). Unlike our discussion of the LM6000 and RB211, we are here mentioning the measurements on the power turbine (R and S Flanges) and not just the gas generator (A and K Flanges). A more complete discussion of power (reaction) turbine monitoring is found in section 5.

- Issues with the exhaust collector box would be monitored using the accelerometer closest to that component: the S Flange (power turbine exhaust).
- Issues with water injection would be monitored using the accelerometer closest to the combustors: the K Flange (mid-engine).
- Engine issues related to the low-pressure shaft would be monitored using the accelerometer at the engine inlet (where the low-pressure compressor is located): the A Flange
- Engine issues related to the high-pressure shaft would be monitored using the accelerometer closest to the high-pressure components: the K Flange (mid-engine).

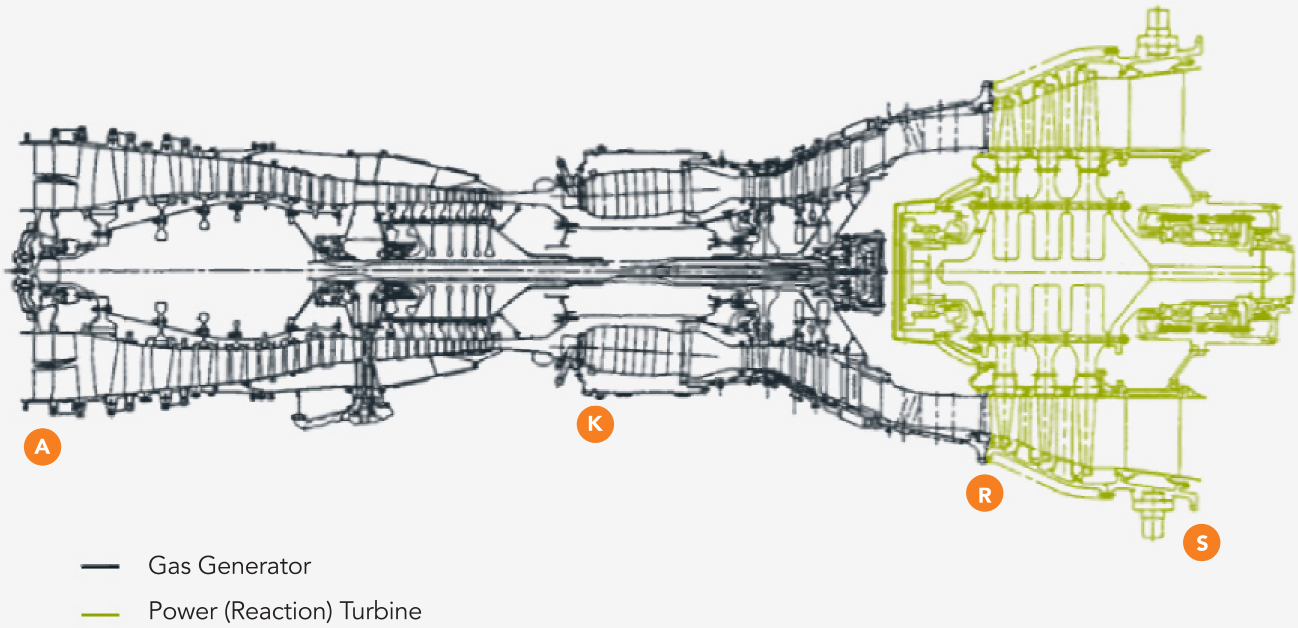


Figure 12: An FT8 aeroderivative gas turbine showing the gas generator, the power (reaction) turbine, and the four locations (Flanges A, K, R, and S) where casing accelerometers are typically affixed.

Aeroderivative Power (Reaction) Turbines

Up to this point, we have focused on the gas generator section of aeroderivatives. However, the gas generator is designed to extract only enough power (through its turbine stages) to drive its compressor stages.

The rest of the energy produced occurs in the form of hot, high-velocity exhaust gases that must then be converted to rotative force. This is done by means of a power (reaction) turbine as shown in Figures 5, 9, and 12. Because the power turbine is only aerodynamically coupled to the gas generator, it is not constrained to rotate at the same speeds as any of the gas generator spools. It is becoming increasing common for power turbines to be designed specifically for the speed and type of machinery they will drive, eliminating the need for a gearbox. This is shown in Figure 13 for an FT8, but similar approaches are used on aeroderivatives from other manufacturers as well.

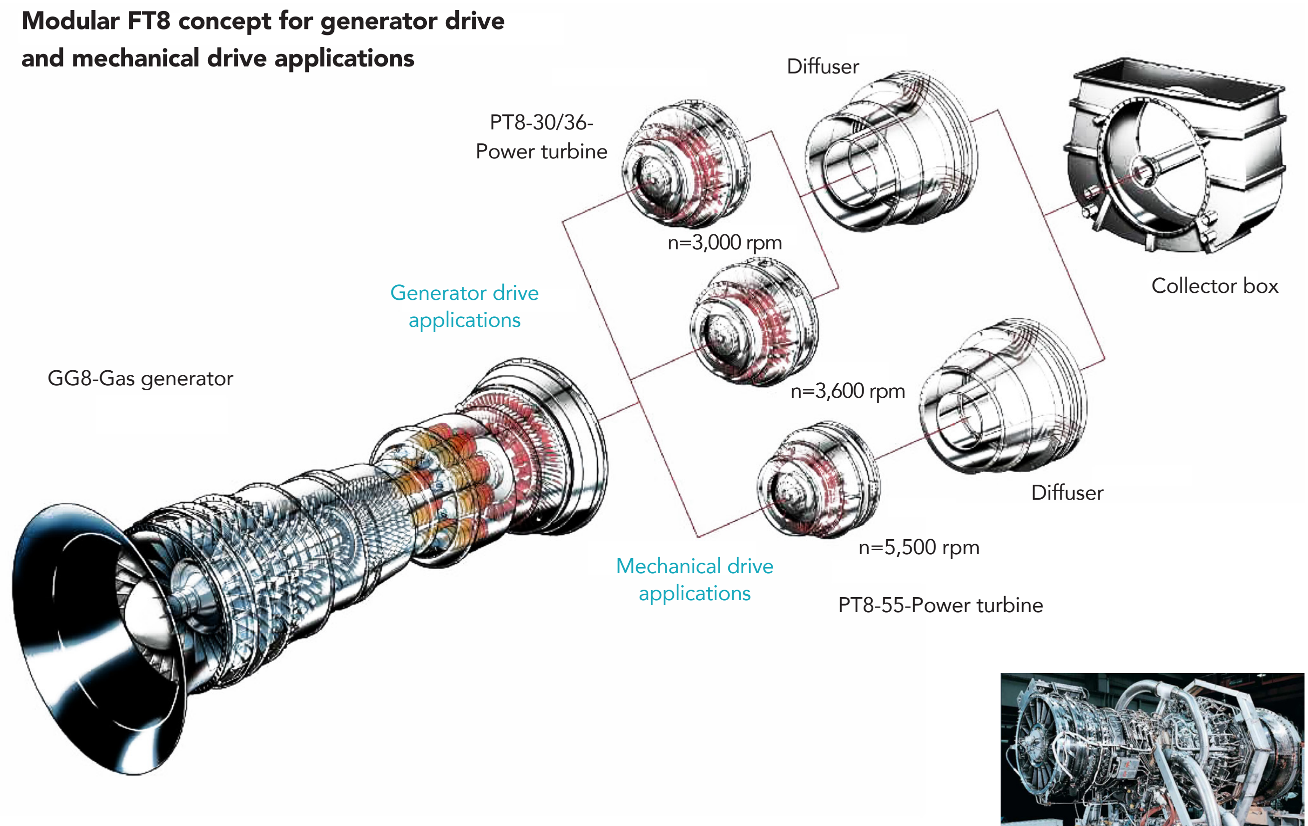


Figure 13: Excerpt from a 2008 MAN Turbo brochure for the FT8 aeroderivative gas turbine showing the gas generator (GG8) and three corresponding types of power turbines: one for 3000 rpm (50 Hz) generator drive service, one for 3600 rpm (60 Hz) generator drive service, and one for 5500 rpm mechanical drive service.The exhaust collector box is also shown along with the two different types of exhaust diffusers.

While gearboxes were used extensively in the past to adapt the output speed of a gas turbine to that needed by a generator, or to another driven piece of equipment, they are becoming less commonplace today. This is not to say that gearboxes are no longer found on machine trains with aeroderivative prime movers. It is merely to say that they are not as prevalent as in the past. There are several compelling reasons why a power turbine that can directly drive its load is preferable. First, it eliminates a component (the gearbox) in the train, its corresponding cost, its corresponding energy losses, and its corresponding maintenance requirements. It also has the advantage of reducing the physical footprint of the machine train, allowing smaller enclosures and associated space-related costs.

Power turbines are almost always overhung. They can use rolling element bearings (like the gas generator to which they are connected) or they can use fluid-film bearings (like the driven machine to which they are connected). When fluid-film bearings are used, there are two radial bearings and a single thrust bearing. When rolling element bearings are used, there may be separate radial bearings and a thrust bearing, or there may be one radial bearing and one tapered element bearing that carries both radial and thrust loads. See Figure 14

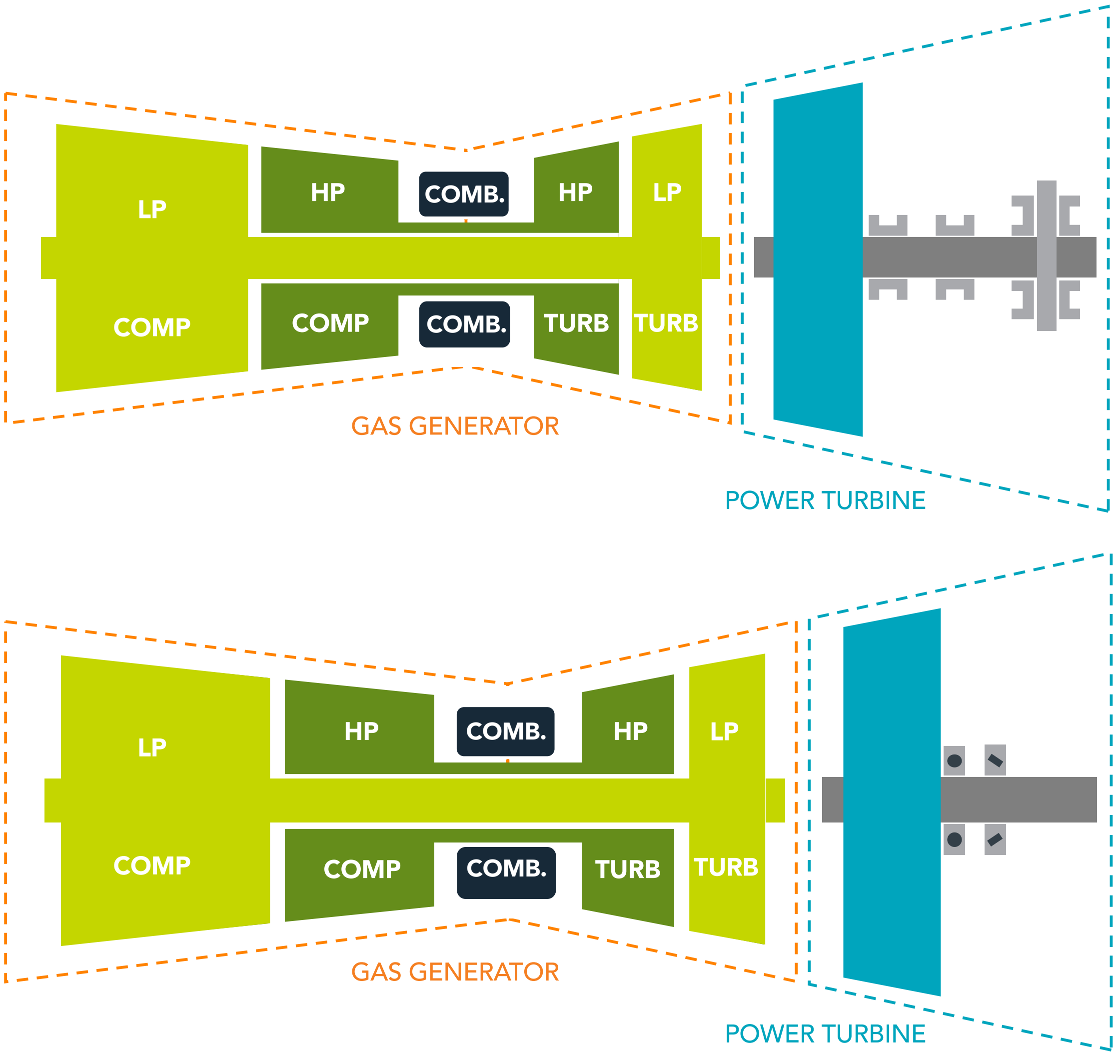


Figure 14: Power turbines used with aeroderivative gas generators are usually overhung and may use fluid-film bearings or rolling element bearings. The top configuration has fluid-film radial and thrust bearings; such a configuration is often encountered in mechanical drive applications. The bottom configuration has rolling element bearings where one carries radial loads and the other carries both radial and axial loads; such a configuration is often encountered in power generation applications.

Referring again to Figure 14, the top configuration uses fluid-film bearings and is thus monitored by means of a conventional complement of proximity probes; namely:

- X-Y probes at each of the two radial bearings
- A phase reference probe on the free-spinning power turbine shaft
- Dual-voting axial probes monitoring a thrust bearing (if present).
  An example of this is depicted in Figure 9 (minus the phase reference probe and minus the redundant axial probe).

In contrast, the bottom configuration would use casing-mounted accelerometers, but these are rarely mounted directly on the rolling element bearings. The FT8 in Figures 12 and 13 is a typical example and as was described, the monitoring consists of at least one accelerometer mounted at the S Flange (PT exhaust) and sometimes also another accelerometer mounted at the R Flange (PT inlet). Other manufacturer's power turbines using rolling element bearings are instrumented similarly – typically with one or two casing-mounted accelerometers and a monitoring philosophy similar to that of the gas generator. Namely, to look primarily for gross changes in overall vibration levels indicative of catastrophic malfunctions rather than trying to detect bearing-related defects. This is because the power turbine is often itself a module that can be changed out in a manner similar to the gas generator. It should thus not be surprising that they are monitored similarly.

Fluid-film bearings are most commonly encountered in mechanical drive applications such as for pipeline booster compression. In contrast, rolling element bearings are most commonly encountered in power generation applications.

"Fluid-film bearings are most commonly encountered in mechanical drive applications such as for pipeline booster compression."

However, designs with rolling element bearings are increasing in popularity for both applications. Designs with fluid-film bearings are sometimes called "industrial" power turbines to acknowledge that they are more like the conventional industrial machine(s) to which they are attached. Designs with rolling element bearings are sometimes called "aeroderivative" power turbines to acknowledge that they are more like the gas generator to which they are attached.

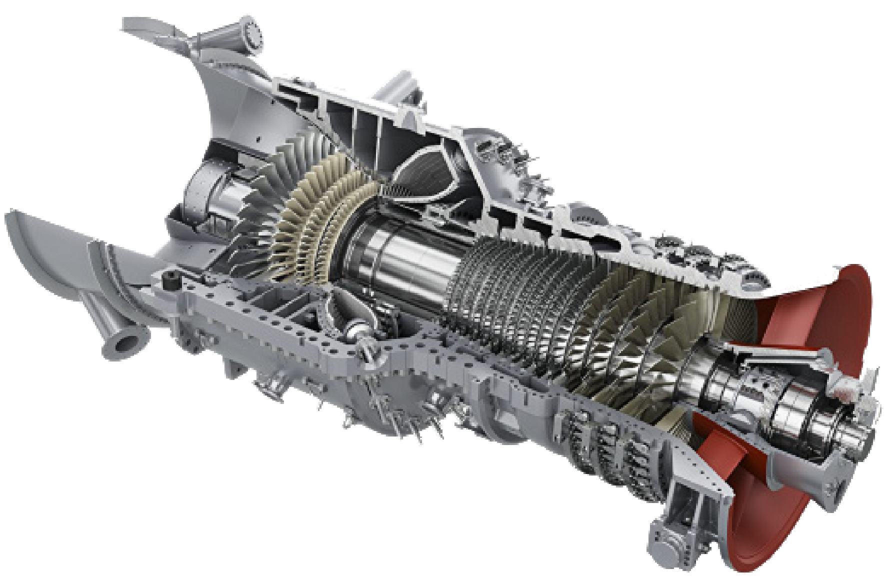


Photo Credit: Siemens Energy

Industrial Gas Turbines

While aeroderivative gas turbines tend to have OEM-specific recommendations for monitoring that entail very specific types of filtering, specific signal processing, specific mounting locations for casing accelerometers, and even specific radial orientations for the accelerometers, there tends to be far less variation in the monitoring approach to industrial gas turbines, whether heavy or light. This is simply because industrial machines – unlike aeroderivatives – use fluid-film bearings and the methodology for monitoring such machines has evolved over the last 60 years to reflect far less variation.

Proximity Probes

In machinery with fluid-film bearings, proximity probes are used, allowing us to put sensors directly "where the action is" – inside the machine, directly observing the shaft. It becomes far less necessary to infer what is happening inside the machine by making measurements on the case because we can, in fact, literally go inside the machine to closely observe the vibration at the rotor, where it originates.

One of the reasons we can instrument the bearings directly is because they are accessible. Another reason is that the temperatures involved are automatically constrained by virtue of the bearing materials used – specifically the babbitt metallurgy. Most fluid-film bearings are not designed to operate above 130° C (265° F)[17] and babbitt temperature is often the limiting factor when designing a bearing and selecting babbitt material[18]. This means that the temperatures encountered on fluid-film bearings are within the allowable operating temperatures of proximity probes and that the cabling to exit the machine can be routed in a manner that also keeps it within temperature constraints. Consequently, both heavy and light industrial gas turbines are (or can be) monitored with a conventional complement of X-Y and axial position proximity probes as shown in Figures 15 and 16.
At this juncture, it is useful to also consider the maintenance heritage of industrial gas turbines. Unlike aeroderivative designs, industrial gas turbines (particularly heavy industrial) were never designed to be removed from site to conduct maintenance. Instead, they assume in-situ maintenance. Also, the primary impetus for conducting maintenance on most industrial gas turbines is not safety-related but instead economic-related, such as loss of

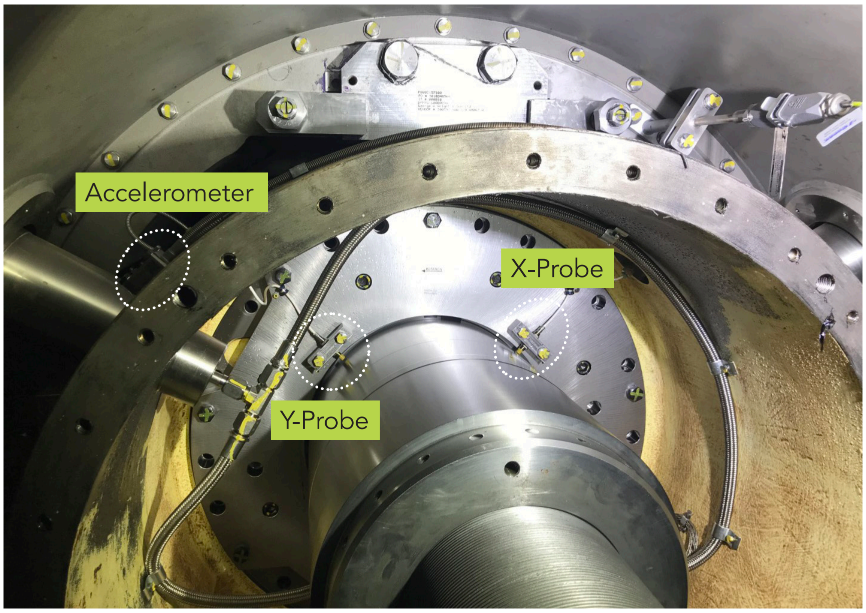
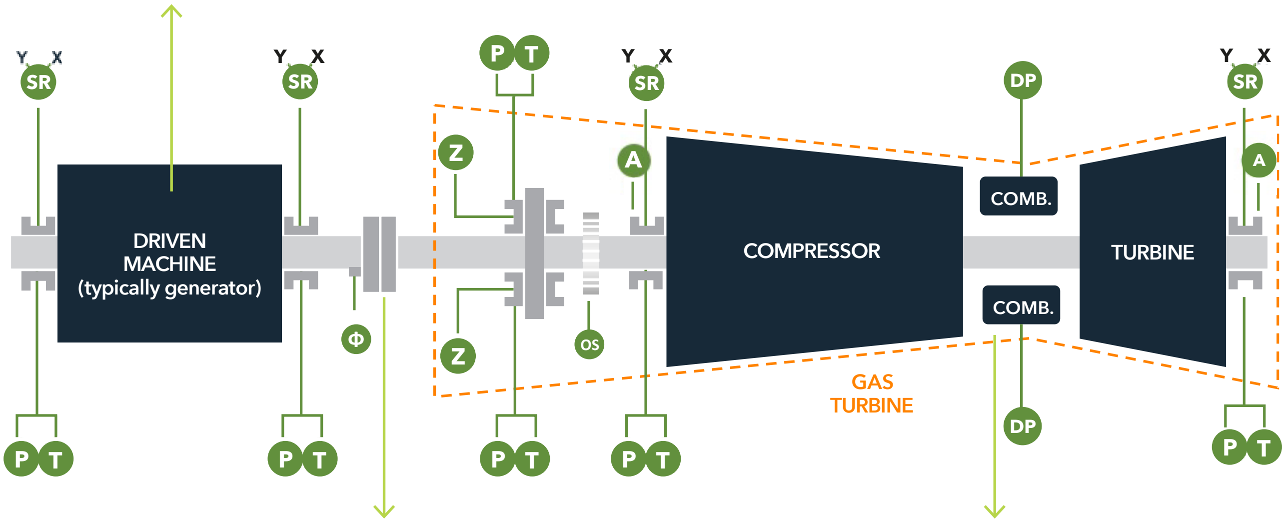


Figure 15: X-Y proximity probes mounted to the face of a radial bearing on the exhaust end of an industrial gas turbine. Note also the location of the accelerometer to measure casing vibration.

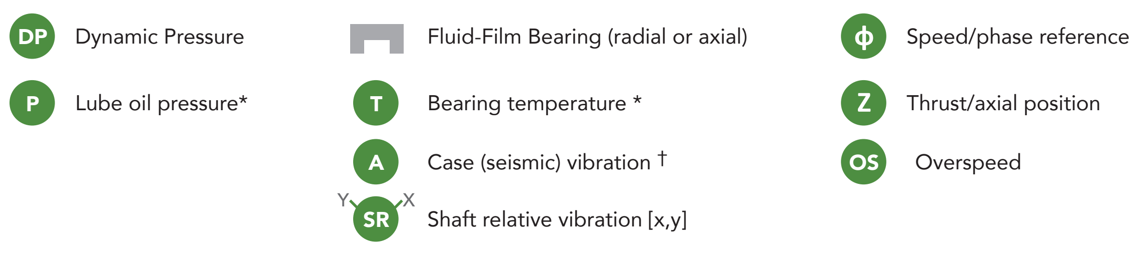
production, and thus inspection intervals are not mandated by regulatory agencies. Indeed, the economic losses can often be quantified quite accurately based on lost generating capacity and the current price of electricity or loss of production and the current price of the product sold. Many industrial gas turbines were also designed to be in continuous service where they run for week, months, or even years at a time between outages and inspections[19]. Under such circumstances, there is significant motivation to monitor the machine more extensively than for machines that can be easily swapped out for a spare as is the case with aeroderivatives. It should not be surprising, then, that the maintenance philosophy surrounding industrial gas turbines has been largely condition-based rather than inspection-based, and that the appetite to more heavily instrument these machines exists.

When the driven machine is a generator or pump, a thrust bearing will ot be present. When the driven machine is a compressor, a thrust bearing (not shown) will be present, instrumented similar to that shown on the gas turbine.



A direct-drive train is depicted here. When a gearbox is present between the turbine and its driven machine(s), the gearbox will normally have 4 radial bearings and 2 thrust bearings. They will be monitored identically to each radial and thrust bearing shown here. In addition, there will be generally be two casing accelerometers (one for the low-speed shaft and one for the high-speed shaft) to monitor gear-related issues. Lastly, there will be a speed/phase reference sensor on the output shaft of the gearbox in addition to the one already shown on the gas turbine.

Only 2 combustors are shown here for simplicity but there are typically 6-12, and they are typically arranged annularly around the turbine case; each combustor will typically have its own dynamic pressure sensor.



* Although Meggitt vibro-meter® does not provide temperature and static pressure sensors, our protection and condition monitoring systems can integrate these readings.

† These sensors can also be used in conjunction with shaft relative vibration sensors to obtain shaft absolute measurements if oriented to coincide with shaft relative measurement planes.

Figure 16: An industrial gas turbine and its driven machine showing the complement of proximity probes used to monitor all radial and thrust bearings. Casing (seismic) vibration is also generally included and measured by means of velocity or acceleration sensors on or near the bearing housings.

Casing Measurements

While proximity probes can be used on almost all makes and models of industrial gas turbines – and indeed most OEMs install these sensors at the factory (or at least drill and tap holes to make provisions for these probes) – many manufacturers also use casing measurements. Whether these casing measurements are used for machinery protection – or merely to provide supplemental diagnostic information – varies not only by the particular OEM, but also by the particular model of turbine. Often these variations within a single OEM's portfolio are the result of acquisitions they have made over the years, resulting in gas turbine offerings that reflects numerous lineages. As of this writing, for example, the Siemens portfolio of industrial (non-aero) machines consists of heritage Ruston/EGT gas turbines, heritage KWU (so-called V-series[20]) gas turbines , heritage Westinghouse gas turbines, heritage ABB Stal gas turbines, and others, but all go to market under the Siemens name and nomenclature.[21] Not surprisingly, these machines reflect not only differing design philosophies, but slightly different monitoring philosophies. However, the differences are less than one might think as – with only a few exceptions – industrial gas turbines are generally protected based on casing-mounted seismic vibration measurements rather than proximity. This does not mean the proximity probes are not valuable or do not play a major role in determining the machine's health. It simply means that for purposes of automatic trip based on high vibration as part of the OEM's protection scheme, it is generally seismic casing vibration rather than shaft-relative vibration from proximity probes. It should go without saying, however, that protection against thrust bearing failure is always proximity-based given the nature of the measurement.

With exception of aeroderivatives, Siemens gas turbines are all fitted with both[22] casing-mounted seismic sensors and with proximity probes. Those with a Westinghouse heritage, such as the 5000F, use proximity probe measurements as the basis of protection. Those with a European heritage, such as the 4000F, 8000H, and 9000HL, use seismic casing velocity as the basis of protection.

GE's industrial gas turbines are also fitted with both proximity probe and casing seismic vibration sensors; however, only seismic measurements are used as the basis for machinery protection. The proximity probes (with exception of thrust probes and the driven machine – usually a generator) are used only for diagnostics and monitoring – not protection. The seismic sensors that GE has standardized on are special moving-coil designs. However, because these devices are subject to a very aggressive environment, and because they have moving parts that wear out, GE generally recommends replacement intervals for the sensors of approximately 3 years. Also, they install these sensors

> **"With exception of aeroderivatives, Siemens gas turbines are all fitted with both casing-mounted seismic sensors and with proximity probes."**

in redundant pairs on each bearing cap, allowing the two measurements to be compared and contrasted to help detect when one sensor is failing – and to allow protection even when one sensor has failed. It is also important to note that many moving-coil velocity sensors are designed to sustain vibration in one axis but not a perpendicular axis (so-called "cross-axis" vibration). When mounted in an environment with high levels of sustained cross-axis vibration, the springs and support mechanisms can wear out prematurely. Lastly, many designs are axis-dependent, meaning they cannot be mounted in any orientation due to the effects of gravity. For example, some moving-coil devices are designed to be mounted in a pure vertical direction, others in a pure horizontal direction, others within ±45° of vertical, others within ±45° of horizontal, and still others that can tolerate any orientation.

"End users, however, may wish to augment the seismic-based protection with proximity-based protection and the OEM can (and should) be consulted in such circumstances."

Generally, the more tolerant the sensor is of broad mounting orientations, the more limited its frequency response will be due to the different support mechanism.

GE has been quite resistant to moving away from moving-coil designs for their industrial gas turbines[23], even though piezo-electric sensors afford many advantages. Historical insistence on moving-coil technology was because the turbine control system had no facility to power a piezo-electric accelerometer and a self-generating sensor was required. In addition, the moving-coil device required no special additional signal processing such as filtering and integration and GE's control system was designed to accept such sensors directly rather than to use a separate, stand-alone monitoring system.

However, as was previously noted, vibro-meter generally recommends the use of piezo-electric accelerometers rather than moving-coil devices where possible, due to their absence of moving parts and propensity for wear.

The situation described above – namely, that seismic measurements rather than proximity are used for radial vibration protection – comes as a surprise to many users, particularly because the machines are fitted with both proximity probes and seismic sensors. The reasons for this are rooted in many factors, not the least of which is historical data for seismic measurements and corresponding recommendations for alarm and trip setpoints. End users, however, may wish to augment the seismic-based protection with proximity-based protection and the OEM can (and should) be consulted in such circumstances. At minimum, however, proximity-based measurements can provide very valuable condition monitoring information and the alarms can be used to alert operators to developing conditions well before they manifest as increases in seismic bearing cap readings.

Solar® gas turbines are typical of the so-called "light industrial" category. Those destined for mechanical drive applications (particularly in the oil & gas sector) will typically be fitted with both proximity probes and seismic sensors, with primary reliance upon proximity-based measurements for machinery protection. As a general rule, oil & gas customers demand the most sophisticated vibration monitoring packages while those outside this segment may be less demanding. For example, if a package will be used for emergency power generation in an industry where vibration monitoring sophistication is not typically present, the package may ship with only basic monitoring and protection rather than a more comprehensive complement of sensors. Regardless, proximity-based measurements are generally used for protection on Solar machines, augmented with seismic sensors on the gearbox (if present) and sometimes high-temperature versions – similar to the moving-coil designs used by GE – on the gas turbine itself.

Our purpose here is not to catalog the approach used by each and every OEM for each and every model of gas turbine. It is simply to convey that some will use seismic measurements as the primary basis of protection while others will use proximity, even though the machines are most often fitted with both seismic and proximity probes.

While vibro-meter does not advocate instrumenting industrial gas turbines with only casing seismic measurements as a best practice, it is important to understand that some OEMs rely exclusively on these casing measurements as the basis for protection. Our general recommendation is to specify a full complement of transducers when the machine is ordered and to use these additional sensors for at least condition monitoring if not protection. Also, the protection for the driven machinery (and an intervening gearbox if required) will generally rely on proximity and the inclusion of similar measurements from the gas turbine itself will generally not present technical difficulties.

Seismic Sensors

As can be appreciated, the surface temperatures on the casing of a gas turbine are appreciable – particularly at locations close to the combustion chamber(s).

The sensors must be extremely robust, able to withstand very high temperatures and sustained vibration levels of many g's – often 10 or more. Meggitt is particularly proficient at building such sensors and is relied on not just for industrial applications of gas turbines, but also aviation applications where the sensors are used on flying engines. Consequently, although the vibro-meter product line devotes itself to industrial machinery applications, it draws upon and contributes to the core competencies across the Meggitt portfolio for extreme environment sensing. Vibro-meter sensors are thus standard and preferred by many of the world's leading gas turbine manufacturers.

Three broad product lines exist within vibro-meter for casing seismic measurements. The first consists of our CE accelerometers. These accelerometers can be used in environments up to 350° C (662° F) and feature integrated signal conditioning electronics. For example, the CE 134 is used extensively on Rolls-Royce engines such as the Avon and RB211.

Figure 17: The CE134 has integral electronics and is rated for use in environments up to 350° C (662° F).

The second product line consists of our CA accelerometers. These accelerometers are specially designed to handle more extreme temperatures by separating the base sensor from its signal conditioning electronics (charge converter). In this manner, the sensor itself can be located in environments up to 700° C (1292° F) while the signal conditioning electronics can be mounted off the engine where temperatures are greatly reduced. The sensor and signal conditioner are connected by appropriate mineral insulated cable, also able to withstand the extreme temperatures incurred on the engine.

Figure 18: The CA901 has separate electronics and is rated for use in environments up to 700° C (1292° F).

The third product line consists of our CV moving-coil velocity sensors. These are available for environments up to 204° C (400° F). Because these are moving-coil devices, they do not require external power, but – as was noted earlier – the presence of moving parts means that these sensors typically have a shorter lifespan when used on gas turbines than when piezo-electric accelerometers are used. The lower temperature range than our accelerometers means that they are restricted to use only on gas turbines with lower surface temperatures. Regardless, vibro-meter generally recommends the use of a piezo-electric accelerometer instead of a moving-coil device because it has no moving parts that can wear out. The acceleration signal is simply integrated to velocity units using a separate signal conditioner such as our IPC707.

Figure 19: The CV213 is a moving-coil velocity sensor and is rated for use in environments up to 204° C (400° F).

wIn instances where the monitoring system must interface to the OEM's standard moving-coil device (such as those used by GE), vibro-meter monitoring systems can be so configured to accommodate these sensors.

Lastly, it is also worth noting that there are a few gas turbines, such as the GT11N2[24], that benefit from so-called shaft absolute measurements due to the characteristics of the bearing pedestals. In such turbines, the amount of seismic vibration at the pedestals will normally be even higher than the shaft-relative vibration levels, and measuring both shaft relative and shaft absolute vibration is beneficial. A shaft absolute measurement vectorially subtracts the shaft relative measurement from a casing absolute measurement made in the same plane, resulting in the shaft motion relative to free space (rather than relative to the bearing housing). Vibro-meter monitoring systems are able to provide such measurements when a suitable complement of transducers exists. We are also able to provide the sensors when they are not pre-installed on the machine.

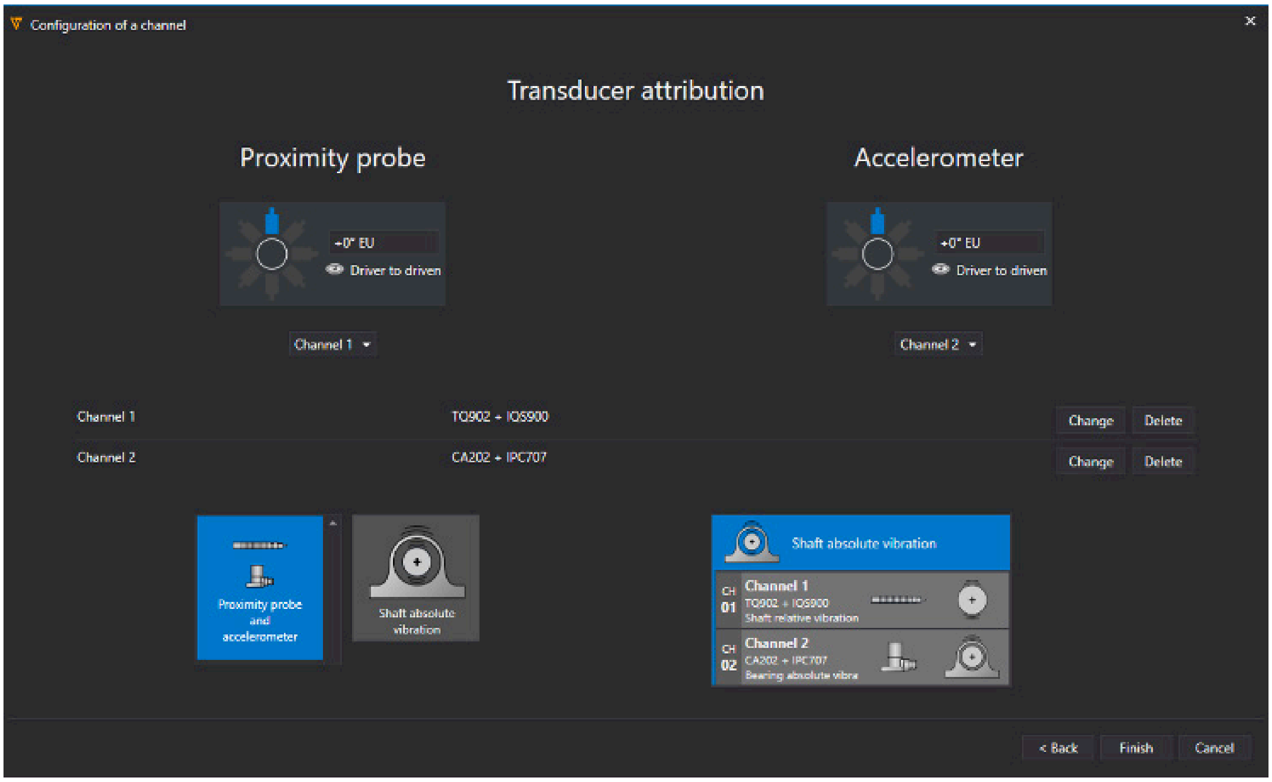


Figure 20: Screen capture from VibroSight Protect software, used for configuring a shaft absolute measurement in our VM600^{Mk2} protection and condition monitoring platform. Such measurements can be useful on selected types of industrial gas turbines where the bearing pedestals exhibit vibration levels approaching or even exceeding the shaft-relative vibration levels.

Combustion Monitoring

In the quest for higher efficiencies, manufacturers of gas turbines have increasingly raised the firing temperatures for more complete combustion of the fuel.

However, this increased efficiency comes at the expense of higher emissions such as NOx – not to mention the necessity of more exotic materials in the hot gas path, such as single-crystal turbine blades, composite materials, and ceramic coatings, better able to withstand the extreme temperatures. To reduce these emissions, water or steam injection (see Table 4) using "diffusion combustor" designs was adopted and used for several decades. It worked by lowering combustion temperatures (and therefore NOx emissions), but the approach has largely been displaced today in favor of so-called Dry Low Emissions (DLE) technology. DLE technology basically operates the combustion as close to flame-out as possible (i.e., as lean as possible), but without so little fuel as to actually extinguish the flame. This is known as metastable combustion because without extensive feedback control, the flame is only partially stable and will not sustain itself. Unfortunately, while operation in this regime does indeed lower NOx to single-digit parts per million levels, it can lead to damaging pressure pulsations. These can be particularly destructive when the pulsation frequencies coincide with a resonance and can literally destroy the combustor in short order if left unchecked. Nor does such destruction confine itself merely to the combustor; fragments will be ingested into the hot gas path where extensive additional damage can occur to blades and buckets. When one considers that a single row of gas turbine blading can cost upwards of $3M USD, the need to avoid such scenarios is abundantly clear.

Initially, the industry dealt with these issues by periodically tuning[25] the combustion control system at regular intervals – typically every six months. However, even this did not prove to be entirely reliable in preventing damaging pulsations and the attendant premature combustor degradation or catastrophic failure. As a result, online approaches[26] to continuously monitor combustion dynamics began to appear in the early 2000s as a preferable and more reliable method compared to periodic, manual tuning alone. Vibro-meter participated heavily in these pioneering efforts by adapting our monitoring systems to the unique needs of such measurements and by developing dynamic pressure sensors able to withstand the extreme conditions inside the gas turbine, on or near the combustor apparatus. Today, we are a recognized leader in this field both for our sensors and for our combustion dynamics monitoring systems.

The concept behind online combustion dynamics monitoring is quite simple: detect damaging pressure pulsations – either directly or indirectly – in real time using appropriate sensors and adjust the combustion properties to move the combustor out of damaging regimes. It is thus a closed-loop control activity as shown in Figure 21.

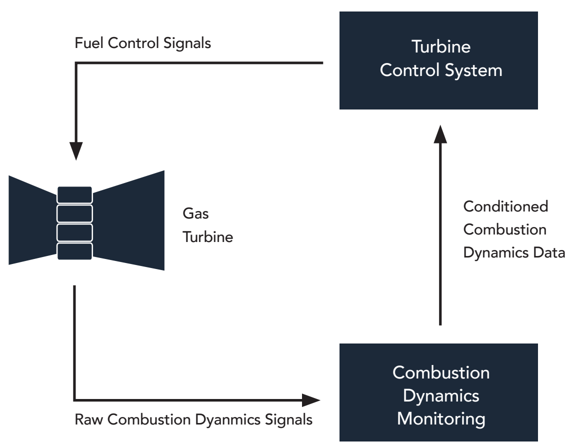


Figure 21: Combustion dynamics monitoring forms a closed control loop between the turbine's combustion control system and the gas turbine combustors. When damaging pressure pulsations are detected, the combustion is altered by the control system to exit the damaging combustion regime.

Dynamic pressure is measured either by means of dynamic pressure sensors mounted on or near the combustors, conventional high-temperature accelerometers mounted near the combustors, or both. The type, number, and location of sensors will vary based on the design of the combustion system, which can range from conventional combustion cans arranged annularly around the turbine periphery, to single or dual silo-type cans, to a fully annular combustion chamber that merely has individual burners rather than individual combustors, to hybrid so-called "cannular" designs. Regardless, the basic mechanism is the same: detect damaging pulsations in real time, provide feedback to the combustion control algorithm in the turbine control system, and use this feedback to alter the combustion particulars until the damaging pulsations stop.

Dynamic combustion is detected by filtering the raw pressure or acceleration signal into bands that are known to be characteristic of each OEM's combustor type and combustion process. As can be appreciated, these details are highly proprietary and are unique to each OEM. Consequently, we do not disclose the details of any particular turbine in this document and you should instead approach your OEM(s) directly if you wish to know more about the specifics of the detection scheme for a particular make and model.

Referring to Figure 22, notice that the particular gas turbine in this example has two sensors (Probe A and Probe B) and the signal from each one is processed into three different bands: J, K, and L. Figure 22 also shows that not only is the pressure in each individual band is monitored, but also the aggregate pressure in certain combinations of bands (e.g., J+K), and total pressure. The exact frequencies corresponding to each band and the way in which particular values within these bands affect the fuel control signals are – as mentioned above – proprietary. However, the general approach does not vary markedly from one turbine to the next – only the particulars such as number of bands, upper and lower frequencies that define a band, and how the values within a band (or group of bands) are interpreted by the turbine control system to indicate damaging pulsations.

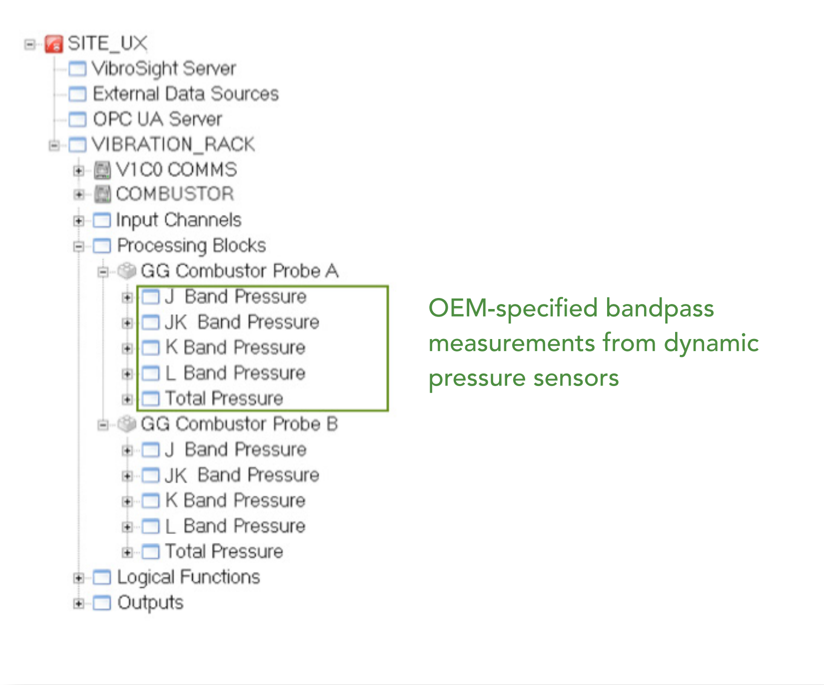


Figure 22: Monitoring configuration screen from a gas turbine with combustion dynamics monitoring.

As can be appreciated, the signal conditioning technology to digitize and process a dynamic pressure signal along particular frequency bands is very similar to the technology needed to do this for dynamic vibration signals. It is thus logical that the same system used for vibration monitoring could also be used for combustion dynamics monitoring. The box labeled "combustion dynamics monitoring" in Figure 21 is thus not a stand-alone device but is instead an integrated system that handles both vibration monitoring and combustion dynamics monitoring. Both of vibro-meter's continuous monitoring platforms are capable of such integrated vibration and combustion dynamics monitoring: our centralized VM600^{Mk2} platform and our distributed VibroSmart platform. Indeed, the RB211 discussed in section 4.2 as well as all of the other machines mentioned at the end of that section are monitored by means of our VibroSmart platform deployed in an integrated fashion that monitors both vibration and combustion dynamics.

Before we leave this topic, it is worth mentioning an important difference between vibration monitoring and combustion dynamics monitoring: one (vibration) is used for protection and the other (combustion dynamics) is used for control. By protection, we mean that an excessive level results in an automatic shutdown (trip) of the machine – not an attempt to reduce the vibration by modulating the operating parameters of the machine. In contrast, combustion dynamics monitoring is used to *control* the machine – not *trip* the machine. When damaging pressure conditions are sensed, this is communicated digitally to the turbine control system which then adjusts the combustion particulars until the pressure conditions have been returned to acceptable levels.

Combustion Sensors

Dynamic pressure sensors are very similar to high-temperature accelerometers, but they measure pressure instead of acceleration. Vibro-meter's CP product line is devoted to such measurements, and models are available that can sustain temperatures of up to 650° C (1200° F). These sensors are specifically designed for high-temperature, dynamic pressure measurements in gas turbine combustion systems. The same remarks can be made here as were made on page 23; namely, that Meggitt has extensive experience in designing sensors for extreme environments and that those within the vibro-meter product portfolio are specifically intended for industrial applications.

While dynamic pressure sensors today rely on many of the same technologies as our piezo-electric acceleration sensors, this presents limitations and gas turbine OEMs can benefit from sensors that provide even more reliable detection of combustor problems. To this end, we are engaged in substantial R&D efforts surrounding the use of advanced, optical technologies for combustion dynamics sensors. We anticipate being able to launch commercial versions of this technology to the marketplace shortly, and invite you to connect with us if you would like to remain updated on our progress.

Figure 23: The CP211 is an example of vibro-meter's extensive dynamic pressure sensor offerings, designed specifically for monitoring combustion dynamics in gas turbines. This particular model can survive temperatures of up to 650° C (1200° F).

"By protection, we mean that an excessive level results in an automatic shutdown (trip) of the machine – not an attempt to reduce the vibration by modulating the operating parameters of the machine."

Monitoring Solutions

Thus far, we have addressed the basic approaches to monitoring gas turbines and how these approaches differ based on whether the gas turbine is an aeroderivative type or an industrial type.

Figure 24: The VM600^{Mk2} platform is vibro-meter's centralized monitoring architecture. It is particularly suitable for machines where the wiring already exists and has been pulled to a central location, such as a control room.

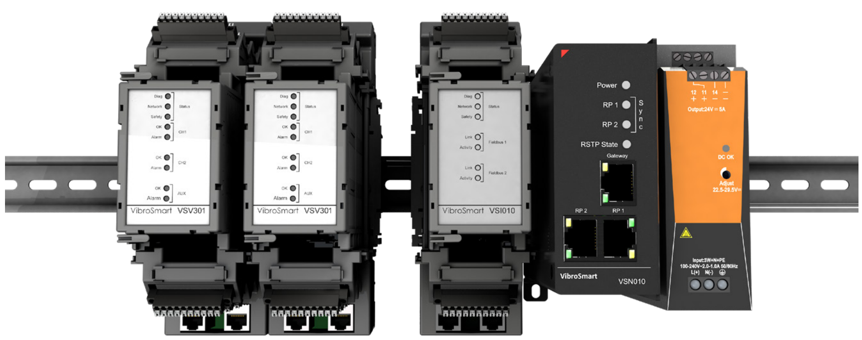


Figure 25: The VibroSmart platform is vibro-meter's distributed monitoring architecture. It is particularly suitable for packaged gas turbines where the controls are co-located with the machine.

We have studiously avoided extensive discussions of particular hardware platforms for three reasons:

1) The focus of this whitepaper is on the monitoring methodologies used – not the specific equipment.

2) Vibro-meter's two primary monitoring platforms (VM600^{Mk2} and VibroSmart) are extensively discussed in other publications. It is thus not necessary to repeat that information in this document versus simply referring the reader to those other documents.

3) Vibro-meter platforms are intentionally designed to be somewhat agnostic to the types of measurements needed and thus both provide similar features. The differences are not so much in channel types and signal processing as in the form factors. One platform (VM600^{Mk2}) is designed for centralized wiring architectures where the monitor is located some distance from the machine – such as in a control room – and the wiring usually already exists. The other platform (VibroSmart) is designed for distributed wiring architectures where the monitoring is located close to (or on) the machine as a means of reducing wiring costs and then using network communications to route information from the monitoring system to various destinations such as the DCS and historians.

Customers thus choose based on the desired architecture – not the desired measurements. Both platforms also offer integrated vibration and combustion monitoring, and machinery protection with integrated condition monitoring rather than the need for separate boxes.

In general, however, machine trains that can be addressed with 20 channels or less are often well-served by our VibroSmart platform. This is particularly true when it is a new machine train and wiring does not already exist, allowing the potential for savings in reduction of field wiring. For larger channel counts, and when field wiring has already been pulled to a central location, our VM600^{Mk2} often represents the best fit.

It is worth noting, however, that the monitoring needs of gas turbines go beyond just the machinery protection and closed-loop combustion dynamics monitoring functionality of our hardware platforms. Machinery condition monitoring is also a concern, and both of our hardware platforms offer integrated condition monitoring along with complete connectivity to our VibroSight condition monitoring software.

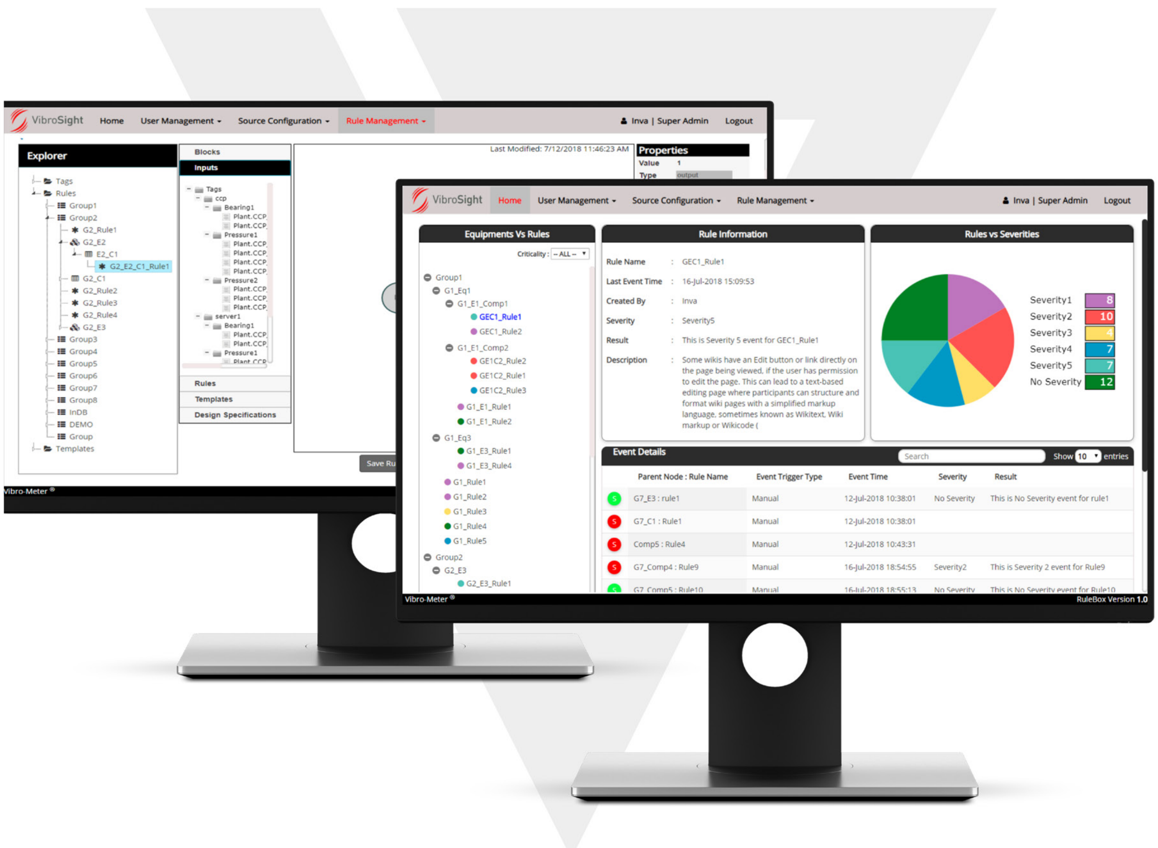


Figure 26: The VibroSight software suite provides condition monitoring and other functionality for the VM600^{Mk2} and the VibroSmart platforms, creating a unified machinery management environment.

Summary

In this whitepaper, we have endeavored to provide you with a basic foundation on how and why gas turbines are monitored as they are. As was shown, gas turbines evolved along two parallel paths: those intended for aviation propulsion and those intended purely for industrial use.

The influences on aviation-related gas turbines – so-called "aeroderivatives" – meant that the engines were designed for easy replacement, light weight, and compact size. These influences also meant that the monitoring systems were focused primarily on catastrophic failures – such as loss-of-blade events – and that an inspection-based maintenance philosophy has been dominant, precisely because aviation is a highly regulated industry where safety concerns are paramount. We further saw that rolling element bearings are used exclusively on these machines and that the monitoring relies on casing-mounted accelerometers and OEM-specific filtering schemes designed to detect mostly 1X vibration at the different spool speeds, indicative of catastrophic damage such as unbalance through ingestion of a foreign object and subsequent loss of blading on a flying engine.

In contrast, the influences on industrial gas turbines were considerably different, with maintenance practices being primarily driven by process downtime economics rather than safety-related concerns. In addition, we saw that industrial gas turbines use fluid-film bearings and are thus monitored more like conventional turbomachinery with X-Y proximity probes at each radial bearing and redundant axial probes at each thrust bearing.

We intentionally avoided discussion of monitoring for the equipment driven by gas turbines – not because it is not important, but because we have confined the scope of this whitepaper to the gas turbines themselves and not the extensive ensuing discussions that would be required to do justice to gearbox monitoring, pump monitoring, generator monitoring, compressor monitoring, and the monitoring of any other type of equipment driven by gas turbine prime movers. However, just because this whitepaper has not addressed those machines, vibro-meter has extensive application expertise on the entire machine train and can be consulted regardless of whether the application is in the power generation sector, the oil & gas sector, or any other industrial sector where gas turbines can be found.

We lastly addressed the topic of combustion dynamics monitoring, showing that vibro-meter has extensive experience in this domain and that its platforms have been designed to monitor both vibration and combustion dynamics in an integrated package.

It is out hope that this whitepaper has succeeded in its mission: providing a basic foundation that allows you to better understand how gas turbines are monitored. For an even deeper understanding of gas turbines, any of the resources in the "Additional Reading" section will prove helpful. And, for a deeper understanding of monitoring than has been provided in this introductory guide, you are encouraged to contact your nearest vibro-meter office for further assistance.

Additional Reading

Gas Turbines: A Handbook of Air, Land, and Sea Applications, 1st Edition
Soares, C., 2007, ISBN 978-0750679695

The Gas Turbine Handbook, 4th Edition
Boyce, M., 2011, ISBN 978-0123838421

Combustion, 4th Edition
Glassman, I., 2014. ISBN 978-0124054356

Gas Turbines for Electric Power Generation 1st Edition
Gülen, S.C., 2019. ISBN 978-1108416658

Basic Gas Turbine Engine Technology
ASME Online Training, Course EL540,
https://www.asme.org/learning-development/find-course/basic-gas-turbine-engine-technology/online

What is an Aero-Derivative Engine? PW4000™ to FT4000®
Mitsubishi Power Aero, LLC https://youtu.be/vq6a18seW8A

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Figure 1: Public domain (Wikimedia Commons).

Figure 2: Division of Work and Industry, National Museum of American History, Smithsonian Institution. Used by permission.

Figure 3: Historical Archive ABB Switzerland, N.1.1.50507. Used by permission.

Figure 4: Public domain (Wikimedia Commons).

Endnotes

[1] Bakken, L.E., et. al., "Centenary of the First Gas Turbine to Give Net Power Output: A Tribute to Ægidius Elling." Proceedings of the ASME Turbo Expo 2004: Power for Land, Sea, and Air. Volume 2: Turbo Expo 2004. Vienna, Austria. June 14–17, 2004. pp. 83-88. ASME.

[2] Curtis, C. G., "*Apparatus for Generating Mechanical Power*" US Patent 635,919 (filed Jun 24, 1895)

[3] Lemale, C., *"Turbo-moteur à combustion continue intérieure"* French Patent FR179E (filed Feb 8, 1901)

[4] Whittle, F. "*Improvements relating to the propulsion of aircraft and other vehicles*" UK patent GB347206A (filed Jan 16, 1930).

[5] From "Gas Turbine History" at www.turbomachine.com.

[6] Langston, L. S. (April 1, 2010). "Visiting the Museum of the World's First Gas Turbine Powerplant." ASME. Mechanical Engineering. April 2010; 132(04): 51. https://doi.org/10.1115/1.2010-Apr-7

[7] "The World's First Industrial Gas Turbine Set at Neuchâtel (1939)" ALSTOM publication PSE/BGENE/WFDGTN07/eng/PSER3/06.07/CH/6245 (June 2007).

[8] "World's First Gas Turbine Plant in Birr Receives International Award" ALSTOM Press Release, Jun 4, 2007.

[9] Although this was indeed the first jet-powered flight in England, it was the world's fourth jet-powered aircraft overall after Germany's Heinkel He 178 (1939), Italy's Caproni Campini N.1 (1940), and Germany's Heinkel He 280 (1941).

[10] Kellner, T. "The Story of the 1st US Jet Engine: The Hush-Hush Boys Wanted to Win the War but Ended Up Shrinking the World". Mar 21, 2021.

[11] Additional notable examples include the GE LM1600 (F404), LM1500 (J79), and LM500 (CF34); the Siemens SGT-A02 (Rolls-Royce Avon 200); and, the Siemens SGT-A05 (Allison 501-K).

[12] GE's LM nomenclature stands for "Land and Marine" and conveys the intended uses outside of aviation.

[13] As of this writing, the longest available commercial flight is 17.5 hours between Singapore and New York City.

[14] For detailed guidance on monitoring specific models of aeroderivative gas generators, specific types of attached power turbines, specific types of driven equipment (whether generators, pumps, or compressors – and whether with or without an intervening gearbox), and specific types of industries whether power generation, LNG, pipeline compressor, or other, contact your nearest vibro-meter sales office.

[15] The LMS100 is purposely omitted from this list because it is somewhat unique in the industry and represents a blend of aeroderivative and heavy-industrial technologies in a single machine. Its monitoring is thus a blend, too. The core of the LMS100 is essentially GE's LM6000 where LM denotes "Land and Marine" (see endnote 12). The low-pressure compressor is essentially from GE's MS6001 FA heavy-duty gas turbine where MS denotes "Mechanical Shaft". The LMS prefix is an intentional blending of the LM and MS prefixes because the resulting machine is likewise a blend of its two constituent machines: aeroderivative and heavy industrial.

[16] The frequencies corresponding to the detection band differ according to each OEM and generally each engine model. Thus, the detection band for GE engines may differ slightly between the LM1600, LM2500, LM5000, and LM6000. And, the detection band(s) used on Roll-Royce engines will differ from those used by GE or those used by Pratt & Whitney.

[17] "*How to Estimate Bearing Babbitt Temperature*" www.kingsbury.com

[18] "*A General Guide to The Principles, Operation and Troubleshooting of Hydrodynamic Bearings*" pp. 13, 18, 22. March, 2015. Kingsbury, Inc. Philadelphia, PA.

[19] 15,000 – 20,000 hours is typical (2.25 years of continuous service).

[20] Diakunchak, I. McQuiggan, G., Kiesow, H.J., "*The History of the Siemens Gas Turbine*" Proceedings of the ASME Turbo Expo 2008: Power for Land, Sea, and Air. Berlin, Germany. June 9–13, 2008. ASME. https://doi.org/10.1115/GT2008-50507.

[21] Siemens nomenclature today is as follows: SGT#-XNNNNKK where
- SGT = Siemens Gas Turbine
- # = 5 (50 Hz) or 6 (60 Hz) and is used only on models larger than the SGT-800 and thus intended solely for power generation instead of mechanical drive
- X = A for aeroderivative but is omitted for non-aero models
- NNNN = 2- to 4-digit number reflecting size, with lower numbers reflecting smaller units and larger numbers reflecting larger units (e.g., SGT-50 is a 2MW unit while SGT6-9000 is a 440 MW unit; SGT-A05 is 5MW aeroderivative while SGT-A35 is 35MW aeroderivative)
- KK = 1- or 2- character code indicating the generation of technology and used only on machines numbering 1000 series or higher (e.g., the SGT5-2000E designates E-class technology, the SGT5-4000F designates newer F-class technology, and the SGT6-8000H designates even newer H-class technology).

[22] The generator itself may or may not have seismic sensors in addition to proximity probes. Machines with a North American heritage, such as Westinghouse and GE, instrument the generator with only proximity probes and thus protect that part of the train with only proximity measurements. Those with a European heritage protect the entire train (turbine and generator) based on seismic velocity measurements and thus place seismic sensors on the generator bearings in addition to proximity probes.

[23] GE does not use moving-coil seismic sensors on their aeroderivative gas turbines. Piezo-electric accelerometers are used instead, such as our CA3XX series models.

[24] Florjancic, S., Franklin, W., Lievely, N. "*Vibration Measurement Techniques on an Industrial Gas Turbine Rotor Train*" Proceedings of the ASME 1998 International Gas Turbine and Aeroengine Congress and Exhibition. Stockholm, Sweden. June 2–5, 1998. V005T14A018. ASME. https://doi.org/10.1115/98-GT-297.

[25] Angello, LC, & Castaldini, C. "*Combustion Tuning Guidelines: Understanding and Mitigating Dynamic Instabilities in Modern Gas Turbine Combustors.*" Proceedings of the ASME Turbo Expo 2004: Power for Land, Sea, and Air. Vienna, Austria. June 14–17, 2004. ASME. https://doi.org/10.1115/GT2004-54081

[26] Swanekamp, R. "*Gas Turbines – On-Line Monitoring Systems Help Silence Combustor Humming*" Power Engineering Magazine, Vol 108, Issue 5, May 2004.

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