Machinery Health Monitoring

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VIBRATION - ITS ROLE IN AN AUTOMATED GAS TURBINE SUPERVISORY SYSTEM

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The vibration characteristics generated by operating machinery contain a wealth of information related to the health and performance of the machine and its component parts. In addition to machine protection, these characteristics can be utilized to provide early warning of impending problems, gauge the effectiveness of repairs and form the basis for "on condition" maintenance.

The following paragraphs describe some of the concepts and engineering considerations involved in the design of the mechanical portion of an integrated machinery protection and diagnostic system. It is recognized that mechanical vibration is only a part of an overall health monitoring program which for maximum effectiveness must also include a means by which to monitor aerodynamic performance, flows, pressures and temperatures, routine oil analysis and periodic visual inspections.

Designing an integrated vibration monitoring, protection and diagnostic system requires several discrete steps. First, it is necessary to collect the mechanical vibration characteristics of the machine to be monitored, place them in some usable form and construct a normal or baseline signature to serve as a basis for system design. Next, the characteristics which will be used for machine protection and diagnostics must be selected, appropriate sensors chosen and suitable locations and methods of mounting devised to assure optimum performance and reliability. Third, signal processing electronics and interconnecting cables must be suitable for a harsh industrial environment yet provide ready accessibility for routine maintenance and repair. Finally, the overall system must have a quick response to sudden changes such as might occur during a process upset or ingestion of a foreign object and still retain a capability for detailed in-depth analysis. In most cases, even when computer supervision is utilized, the latter two considerations may conflict with one another and thus require special accommodations.

Depending on a number of factors, including the type of machine, sensor used and method of signal conditioning, vibration characteristics range from simple signatures containing few components to complex signatures such as those generated by gas turbines illustrated in Figure 1. The spectral components found in a gas turbine signature include the very low frequencies originated by ducting and structural responses, rotor running frequencies

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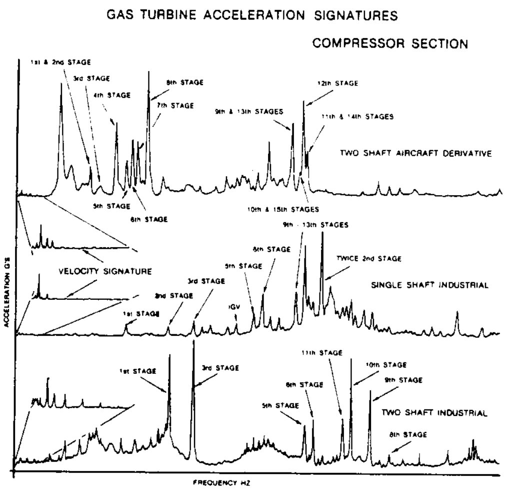

Figure 1

and their multiples, the running frequencies and characteristics of auxiliaries such as pumps and gears and compressor and blade characteristics well above the audio range. Within these frequencies, mechanical conditions such as rotor balance and stability, coupling alignment and the condition of auxiliaries can be assessed with a high degree of accuracy. Blade characteristics, including deposition of foreign material, loss of metal and foreign object damage can be evaluated in a like manner with somewhat greater uncertainties. As more experience is gained in the use of diagnostic techniques, it may be possible to detect problems such as imperfections in anti-friction bearings and seals, fretting in the hot gas path of gas turbines and small developing cracks where the early symptoms are hidden among other stronger characteristics.

The type and location of vibration sensors is based on the specific machine and range of characteristics to be monitored. Gears and bladed machinery such as gas turbines generate a wide range of frequencies and hence require a sensor with a broad dynamic range and frequency response. Since this type of machinery generally has compliant casings, comparatively low casing to rotor weight ratios and relatively flexible supports, a casing mounted accelerometer can collect representative health characteristics at low frequencies as well as high. On the other hand, machinery such as vertically split centrifugal compressors with stiff casings and supports, high casing to rotor weight ratios and little meaningful high frequency activity are generally monitored most effectively with shaft displacement probes. Seismic acceleration sensors are recommended for use on equipment with anti-friction, rolling element bearings. This type of bearing, stiff with very small clearances, limits relative motion between shaft and casing and causes most of the dynamic force developed by the rotor to be transmitted into the structure where it is dissipated as casing motion. Thus, a casing mounted seismic pickup, such as an accelerometer located close to the bearing, collects rotor characteristics much more effectively than a shaft displacement probe limited to measuring relative motion. As an important added advantage, an accelerometer has sufficient range to simultaneously collect the higher frequencies generated within the bearing itself which are indicative of bearing condition.

From the foregoing, it can be seen that a typical monitoring and diagnostic system will most likely contain a mixture of casing and shaft displacement sensors, each chosen for maximum effectiveness in a specific application.

In order to use the wide frequency response of an accelerometer, particular attention must be directed toward the method of mounting. A bolted attachment to a flat ground on the surface of the machine casing is preferred. However, mounting blocks similar to that shown in Figure 2, secured by a long bolt at either a horizontal or vertical casing joint, have been used with success where ground flats were not available. Plate or angle brackets should not be used unless they have been tested to ensure a flat response, free from resonances, within the frequency range of interest. Magnetic or glued attachments are not recommended at all for use in permanent protection systems.

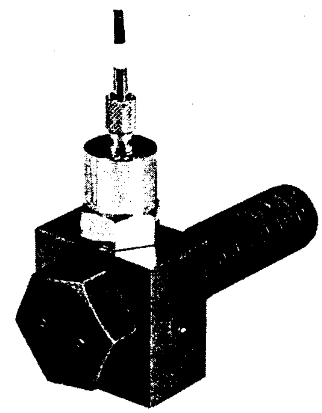

Figure 2

Shaft displacement probes should be located as close to the bearings as possible and observing a smooth surface with a total runout of less than .1 mil as measured by the probe itself. In general, casing sensors should be located at the bearings to assess rotor and shaft related characteristics and at the mid span of compressor and turbine sections to collect aerodynamically coupled blade characteristics. Where a group of identical units are to be monitored, it is important to utilize the same sensor locations on each unit so the data collected will be comparable.

One disadvantage of accelerometers is their high impedance output which necessitates care in the selection and attachment of cabling and connectors to minimize the effects of noise and stray currents. Although electronics can be implanted within the accelerometer to convert the high impedance charge signal to a low impedance voltage output, this limits the accelerometer to a maximum operating temperature of approximately 250°F. Since the surface temperatures found in both the compressor and turbine sections of most gas turbines are usually well above 250°F, accelerometers with integral electronics are usually not applicable.

Locating charge conversion electronics in a relatively cool area as close to the transducer as possible appears the best compromise. This minimizes the length of expensive low noise cable and only two sensitive, high impedance connectors are required; one at the accelerometer and one at the charge converter. Although the low impedance output from the charge converter is capable of being transmitted over long distances using shielded, twisted pair cable and standard connectors, it may be desirable to include amplification within the converter to enhance the signal to noise ratio.

The complex signal must next be processed to extract the principal health related characteristics. Although there are a number of methods to accomplish this task, a two level system continuously monitoring the low frequencies for machine protection and periodically scanning all frequencies for trend detection and diagnostics will be examined in detail. The need for two levels, one devoted strictly to protection, will become more apparent later in the discussion.

An acceleration channel in a typical system containing both continuous protection and diagnostics is shown in Figure 3. Following the sensor and charge converter or line driver are five principal components: Signal conditioning, an analog monitor and alarm system, multiplexer, FFT or real time analyzer and a computer supervisory and diagnostic system.

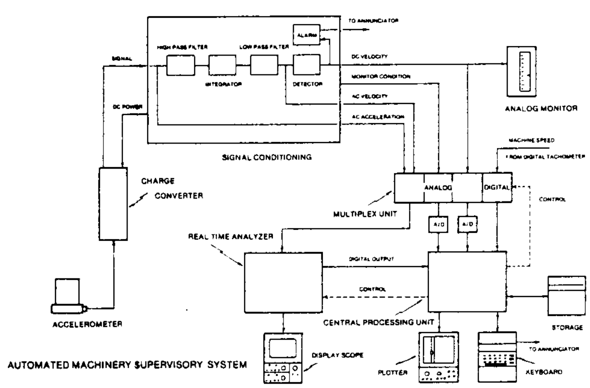

Figure 3

Signal conditioning, generally in interchangeable modular form as shown in Figure 4, receives a vibration signal from the charge converter and performs the manipulations required for compatibility with other parts of the system.

The analog monitor and alarm system provide an easy means to access the system for additional diagnostics or troubleshooting and serves as a back up protective system in the event of a computer outage.

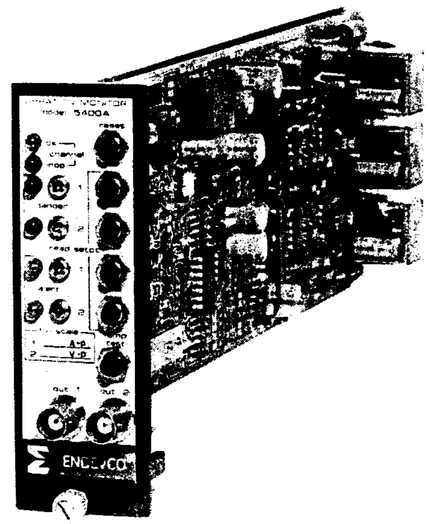

Figure 4

The multiplexer section provides the computer with direct and rapid access to a signal representative of health for machinery protection as well as control of and access to the analyzer for on line diagnostics.

Before proceeding further, it is well to distinguish between the requirements of a system designed for machinery protection and one designed for diagnostics. In a machine protective system, the prime consideration must be rapid response to changes in mechanical condition. On the other hand, instant response is not as important in a diagnostic system as its ability to recognize small trends and deviations in performance.

In order to recognize small variations in performance and determine if they represent a potentially harmful trend, a diagnostic system must perform a detailed discrete analysis. This generally involves transforming the complex wide frequency range vibration signal into a usable form such as a frequency versus amplitude spectrum, averaging the spectrum or signature over some time period in order to obtain statistical accuracy, then comparing the averaged signature to a previously established norm or baseline. The time required to complete this process depends mainly on the amount of averaging required to produce a representative signature and is generally on the order of several seconds. As a rule, a casing acceleration signal obtained from light, flexible equipment such as gas turbines and gears will require more averaging time compared to the shaft displacement signature of stiff, heavy equipment such as high pressure centrifugal compressors.

It can be seen from the preceding that several minutes may elapse between successive diagnostic examinations of a given location, especially on large systems with hundreds of monitored points. Since this is totally incompatible with the requirement of a protective system to respond instantly to a sudden unexpected change such as might occur on ingesting a foreign object, a two level system is required: One level scanned at millisecond intervals to serve as protection against sudden changes and the other scanned at much longer intervals for a detailed analysis directed toward early recognition of slowly developing trends.

The signal conditioner is thus required to supply vibration signals intended for two different purposes, protection and diagnostics. Since significant machinery problems ultimately produce an increase in amplitude in the frequencies around running speed, the portion of the spectrum from approximately 30% running frequency to 4 or 5 times running frequency may be used as a coarse indicator of mechanical condition and a final warning for machine protection.

As illustrated in Figure 1, the relative size of the low frequency components in a broadband acceleration spectrum makes them very difficult to identify and use effectively without additional processing. Electronic integration to velocity is one convenient, widely used method to enhance the low frequencies contained in a complex acceleration signature. Prior to the integration step, however, it is usually necessary to pass the signal through a high pass filter in order to attenuate the low frequencies generated by foundations and ducting and not related to machinery health before amplification in the integration process. A low pass filter is often inserted after the integrator to eliminate unwanted high frequency components not sufficiently attenuated by the integrator. The exact roll off points of both high and low pass filters should be selected to enclose characteristics of the unit to which the transducer is attached while eliminating, where possible, the characteristics of adjacent equipment.

The filtered dynamic vibration signal should be readily accessible at a front panel connection for additional diagnostics and troubleshooting after which it is directed to an AC to DC converter within the signal conditioning unit. In the system depicted in Figure 3, the detected DC signal is used to actuate the back up alarm system, may be displayed on a local analog meter and is transmitted to a solid state multiplex switch for rapid scanning by the computer.

Wideband acceleration and velocity or displacement signals for use in the diagnostic system are generally passed through the signal conditioning system with modifications such as amplification or attenuation only when necessary for compatibility with the input range of the multiplex unit.

As shown in Figure 3, the multiplex unit actually consists of one digital and three analog multiplex switches. The first analog switch scans the detected signals for machine protection, the second scans a DC signal or contact closure from the conditioner which indicates the monitor system itself is functioning properly while the third selects a wide band dynamic signal for transmission to the diagnostic system. Since the first two analog signals are DC and the last is scanned at a relatively slow rate dictated by averaging time, the multiplexing task is not difficult. The digital multiplex switch transmits tachometer signals to the computer for use in the diagnostic system.

The protective scheme can be simple or complex depending on specific requirements. From the multiplex unit, the detected DC signal proportional to velocity is converted to digital form for input to the computer. The computer can be programmed to alarm and shutdown on preset limits which in themselves can be weighted by other parameters such as temperature or power or varied by the computer in response to changes in speed. The latter becomes especially useful when passing through a critical speed. Limits can be based on an expected or predetermined amplitude response and continuously varied as a function of speed to warn of abnormal performance long before the machine reaches operating speed. As mentioned in a previous paragraph, a broadband acceleration signature is broken down into two segments with the division occurring at approximately 1500 Hz. The low frequencies, integrated to velocity, provide the means to assess changes in rotor balance and alignment while the high frequency portion of the spectrum contains characteristics related to the long term mechanical health and performance of components such as blading and gears. Both segments must be subjected to a detailed component by component analysis in order to detect the small changes indicative of future problems. A diagnostic system performs this task in two steps: Reduction of the complex signal into some usable form after which the reduced signal is compared to a norm or baseline. At the present time, a frequency versus amplitude spectrum or signature appears to be the most useful presentation for comparison. Transforming the complex acceleration signal into this format can be accomplished in several ways using equipment such as an FFT processor, a real time analyzer, or an FFT software routine.

Of the three alternates, a computer supervised and controlled real time analyzer appears to offer several advantages. It costs much less than either a hardware FFT processor or a computer based FFT system, and does not require a great deal of computer storage or processing time even when a large amount of averaging is required. This conclusion may change as micro processors, designed for a specific task such as FFT, become available.

In the diagnostic system presented schematically in Figure 3, the real time analyzer is connected to the dynamic vibration channels via an analog multiplex switch. The computer selects the channel to be analyzed and accordingly aligns the multiplex switch. Next, it sets the frequency range and input attenuation of the real time analyzer and then commands it to begin averaging for a preselected time period. Since averaging is accomplished within the RTA, the computer is free to perform other tasks during the several seconds required to complete the average. Upon completion, the RTA supplies the computer with a series of digital words representing component amplitudes along the frequency spectrum. The computer then recalls the appropriate baseline from storage, compares the two, reports significant changes and accomplishes additional routines for trend detection.

Diagnostic routines may be initiated by several actions of which three appear the most useful. First, the central processing unit is programmed to perform detailed diagnostics at a fixed time interval for trend detection. Next, a diagnostic analysis can be ordered manually at the keyboard. Finally, the diagnostic routine is initiated automatically together with an estimate of severity, whenever a parameter exceeds limits. In the latter situation, the processing unit also shifts to a rapid data acquisition and storage mode so the sequence of events can be accurately recreated for a detailed analysis of what happened.

Establishing the norm or baseline may be accomplished in several ways. If a number of identical machines are available, such as is often the case with gas turbines, the vibration characteristics of several different units may be statistically averaged to obtain a median signature. The use of this procedure to obtain a low frequency baseline signature is illustrated in Figure 5. To calculate the baseline amplitudes shown in the bottom plot, vibration signatures, such as those shown above the baseline, were collected from approximately 11 identical units. The amplitudes of each prominent component within the signature was tabulated and a statistical median, represented by the horizontal line within each shaded block, calculated. The extent of the shaded area represents the range of amplitudes observed in the sample group and may be used to set limits. In this manner, limits are based on actual operating characteristics rather than general rules which are often not entirely applicable to a specific type of machine.

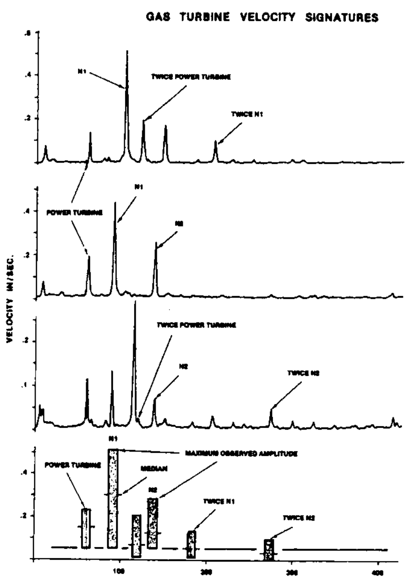

Figure 5

Norms and limits for high frequency characteristics can be established in the same fashion although the task is far more complex. Added complexity is introduced by the necessity to account for normal changes in amplitude with flow, power and speed, particularly the latter at high frequencies due to wide variations in mechanical impedance. This problem can be surmounted by requiring diagnostic routines to be accomplished within a narrow band of speed and power by calculating and programming additional baselines or by selecting average characteristics over a range of speed and power. While the second is undoubtedly more accurate, a vast amount of time is consumed collecting and reducing the data, calculating medians and programming the computer. The actual method should be the simplest possible for the particular application.