TURBOMACHINERY HEALTH MEASUREMENT APPLICATION AND MISAPPLICATION

by

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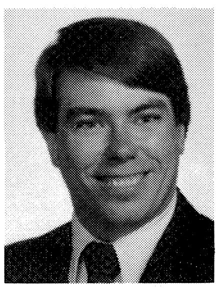

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ABSTRACT

All machinery vibrates, has heat generated internally, and begins to wear as soon as it is put into service. The monitoring process must be customized for each class of equipment. If possible, each machine should be evaluated individually for type and degree of monitoring necessary. In a plant with thousands of pieces of equipment, this degree of scrutiny may be impossible. Computer based monitoring systems are slowly improving the quantity and quality of monitoring and analysis. However, the best computer with the best analysis software is limited by the quality of the available data. This tutorial attempts to guide the user toward choosing the best instrumentation for categories of applications, and the best diagnostic tools for interpretation of the data. A discussion of the most common sensors and instrumentation is presented along with the pitfalls associated with misapplications. Finally, a summary chart is presented that allows the user to quickly identify the proper diagnostic tools for various general classes of turbomachinery.

INTRODUCTION

Measurement of the state of health of turbomachinery should be integral with the design, selection, and installation of that machinery. From then on, after the project is long closed, monitoring is an ongoing process. This process ensures continued reliability, provides data necessary to guide scheduling of routine maintenance, and justifies nonscheduled maintenance or may even initiate design changes. Proper application and interpretation is vital to the success of this process.

Monitoring can range from tactile human sensations to very advanced computer based diagnostic equipment. The ultimate goal of monitoring is to determine what is going on inside a machine without actually shutting it down and opening it up. The reasons for doing this are obvious. For example, a large unspared compressor may be the heart of an entire manufacturing plant. The difference between a planned shutdown for maintenance and a wreck can be millions of dollars. A simple induced draft fan may be applied on a waste treatment boiler; if this machine wrecks, significant amounts of pollutants will be released to the atmosphere. So, whether it is for the corporation or for the general quality of life, knowing what is going on inside of rotating equipment is just as important as knowing what is going on inside process vessels surrounding them.

Questions always arise upon detection of a potential problem. Is this data valid? Is it real? Did you measure the right thing with the right instrument? The answers to these types of questions depend upon how the measurement was made and how the resultant data was interpreted. Thus, proper selection of both the sensor and the readout device is paramount. There is no one right sensor for every job, but there are some wrong choices. There is no one right set of instrumentation for diagnostics, but such instrumentation can be misapplied or misinterpreted unless the user is fully aware of all aspects of the analysis process.

SEISMIC SENSORS

Seismic measurement of vibration is really measuring the *response* of the machine case to the internal forces and *not* the actual internal machine state. It is important to keep this in mind when evaluating seismic data since the machine structure can act as an attenuator, an amplifier (if a casing resonance occurs), or a distorting filter. Thus, different methods of minimizing the distortion have been developed.

The very best method is through familiarity with the machine being measured. If the analyst knows the internal components composition, a better decision can be made as to how and where to apply the proper sensor. Due to the wide variety of structures being measured, consistency in measurement location is as important as the vibration limits applied to a given machine. As long as the data is consistent, a data base of information is compiled for a specific machine, and subsequent readings can isolate changes and lead to a more precise analysis of the machine's internal state.

Velocity Measurement

There are several different types of velocity transducers, and a cutaway drawing of a typical one is shown in Figure 1. A permanent magnet is suspended between springs, usually surrounded by some type of damping fluid. Forced by external vibration, the magnet oscillates, generating a signal in the surrounding wire coil. Since this sensor is a spring-mass-damper system, it has its own mounted natural frequency, typically in the 5 to 20 Hertz (Hz) range. The sensor design is such that this resonance is *critically* damped and no amplification of the signal occurs. How-

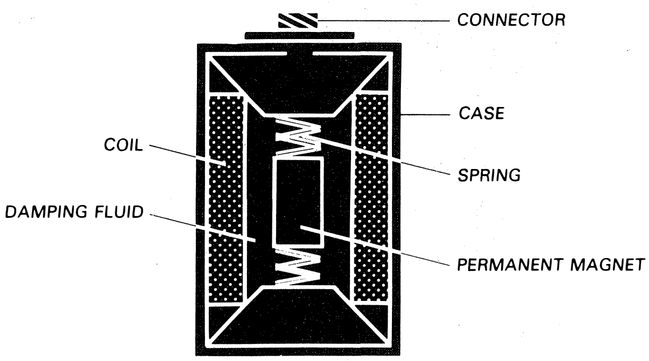


Figure 1. Cutaway View of Typical Velocity Transducer (courtesy Hewlett-Packard Co.).

ever, at low frequencies, there is usually a phase *shift* that might be confusing while balancing low speed machinery. Some manufacturers partially compensate for this phase shift electronically.

Advantages

Velocity transducers are self powered, permanent magnet generators and are ideal for portable measurement. The signal is powerful and can be transmitted many hundred feet without significant attenuation. Output levels range from 500 millivolts/in/sec up to over one volt/in/sec. Commercial velocity pickups are robust in construction and stand up well to daily use and abuse such as being dropped. Mounting arrangements are easily adaptive for use with a magnetic base, permanent stud mounting (usually with a thin layer of epoxy or ceramic cement), or hand held directly to the case with or without an extension rod. Special "fishtail" riders can be used to read shaft vibration directly. Some of these mounting arrangements are illustrated in Figure 2. The output, in velocity units, is independent of frequency and, thus, allows easier setting of vibration limits. The output of a velocity transducer is easily converted to displacement.

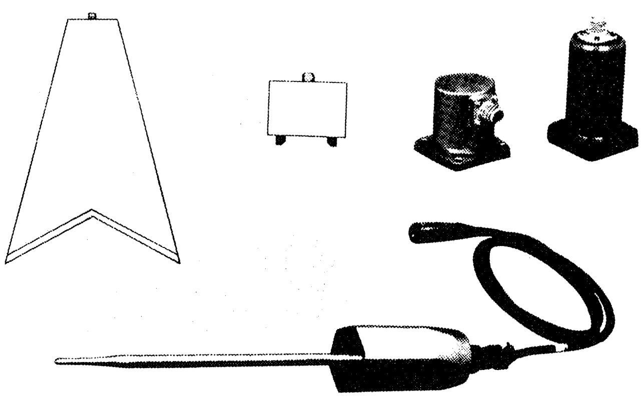


Figure 2. Several Mounting Arrangements for Velocity Transducers.

Disadvantages

Due to their rugged construction, velocity transducers are heavy, and when a magnetic base is added, the sensor can weigh 15 to 30 oz. On very light machinery, this alone could rule out this type of sensor. Frequency response drops off rapidly below 10 Hz and, while electronic means are used to compensate for this, care must be exercised at these low frequencies. The upper limit on the frequency response is approximately 5,000 Hz (300,000 cpm), which makes this sensor unsuitable for many gearbox applications. For best results, this author prefers to limit velocity transducers to situations where the maximum expected frequency is 1,000 Hertz (60,000 cpm). The reason for this is the mounting arrangement. Magnetic mounting usually means attachment to an irregular, often painted surface and experience has shown that this severely limits the high frequency response. Hand holding the probe also results in less than optimum frequency response.

Stud mounting with cement implies permanent mounting. This gives the best frequency response, but introduces another problem with velocity transducers: old age. Since they are a mechanical device, these sensors are subject to wear, loss of damping fluid, and physical abuse during routine maintenance of the target machinery. The real problem is that, barring an electrical failure, the velocity sensor signal often grows weaker and weaker over time, until the magnet stops oscillating at all. This is an extremely difficult failure mode to detect. Regular testing is the only way to avoid this problem. While some testing services will perform this task, there is at least one simple testing method. A fractional horsepower motor with a phase reference marker and an unbalanced wheel attached is mounted to a bench. A steel plate on the motor serves as the test point. Sensors in normal use are compared to test sensors for amplitude and phase output. While this is a single frequency test, it will easily detect the most common flaws and failure modes in seismic transducers.

Typical Applications and Misapplications

The ideal use for velocity transducers is in the routine monitoring of general spared equipment such as motors, pumps, blowers and low speed gears that are surveyed on a scheduled basis. The signal can be easily integrated to mils, if that is preferred. Common troubles such as unbalance, misalignment, bearing failures, and centrifugal pump blade-pass vibration are easily detected. Misapplications include high speed gears, very low speed machinery, extremely light machines such as a high speed spindle, and machines with a large casing-to-rotor weight ratio such as a typical barrel compressor.

Because velocity probes contain permanent magnets, they can be excited by external magnetic fields. This is a common problem when measuring electric motors. This author has seen indicated levels of 0.75 ips on a 2,000 horsepower (hp) two-pole induction motor, when the actual casing vibration was 0.15 ips. Two solutions are to shield the pickup with a magnetically impermeable material, or use an accelerometer. To see this phenomena, place a velocity pickup very near, but not touching, a large two-pole induction motor. Or, try measuring the apparent "vibration" on a large transformer sometime.

Acceleration Measurement

There are many types of accelerometers which differ primarily in their internal construction. This discussion is limited to the type shown in Figure 3, which utilizes a mass held in compression against a piezoelectric crystal stack. Motion of the sensor causes inertial forces on the piezoelectric crystal which, in turn, emits a voltage charge proportional to the acceleration. This charge is very small and must be electronically amplified to be useful. As a reference, API 678 specifies the requirements for a seismic based vibration monitoring system. Since a very stiff spring-mass system exists, sensor system resonance occurs at very high frequencies, often greater than 20,000 Hz. A typical machinery based accelerometer frequency response plot is shown in Figure 4. This resonance can be used advantageously for detection of very weak signals in this frequency range. Minute flaws such as pits on a ball bearing race can be detected in this manner. A piezoelectric crystal device can also be used to detect other dynamic forces as in a pressure sensor or load cell.

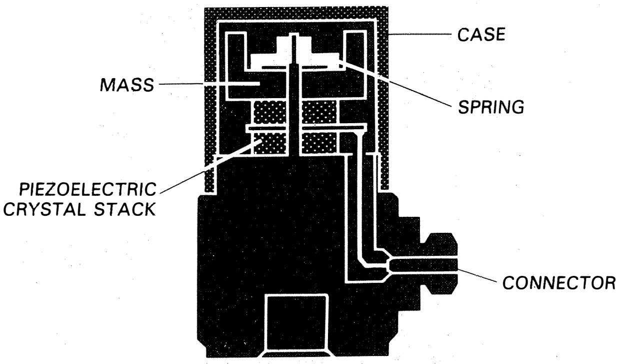


Figure 3. Cutaway View of Typical Piezoelectric Accelerometer (courtesy Hewlett- Packard Co.).

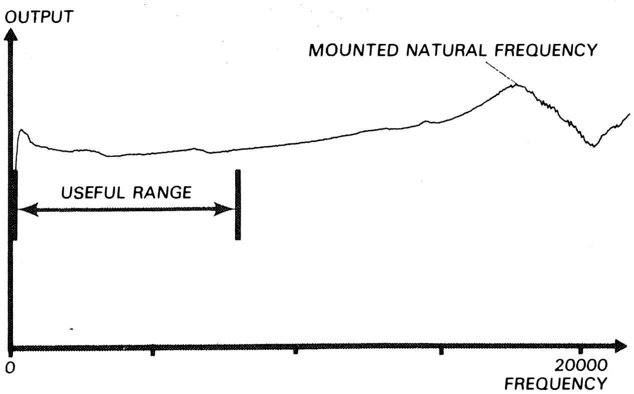


Figure 4. Frequency Response Plot for Machine-based Accelerometer (courtesy Hewlett-Packard Co.).

Advantages

Accelerometers can be made virtually any size. The smaller the transducer, the higher the frequency response, and the less obtrusive the sensor is to the system being measured. For example, blade resonances can often be measured with accelerometers where a larger sensor would mass modify the system producing false results. The standard usable frequency response is approximately 2.0 to 20,000 Hz with lower and higher limits obtainable. Acceleration signals are easily integrated to velocity readings. Special sensors are available which internally integrate the signal, effectively transforming the accelerometer into a velocity transducer. *Double integration* to displacement is not good general practice, since it will often lead to distorted and false readings at low frequencies and data hidden in the background noise at high frequencies. After all, what does a displacement reading of gearmesh frequency mean? For high temperature applications, it is important to follow the guidelines provided by the manufacturer, but accelerometers that can withstand 1,200°F are available. Since there are no moving parts in an accelerometer, it does not wear out in normal use.

Disadvantages

Mounting integrity is crucial to attain the full frequency response from an accelerometer. The API 678 recommended mounting method is shown in Figure 5. Machined flat surfaces, properly torqued mounting studs, and a thin coating of ceramic cement will provide the best results. In temporary applications, a very thin coating of wax or a magnet may be used for holding. These mounting methods reduce the mounted natural system resonance frequency, and thus, diminish the useable frequency response range.

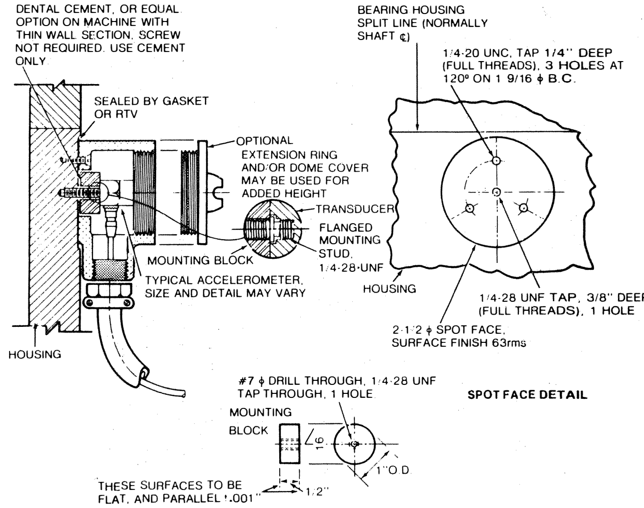


Figure 5. API 678 Recommended Methods of Accelerometer Mounting (courtesy American Petroleum Institute).

Since the charge output is induced by the degree of strain on the piezoelectric crystal, external forces not intended to be measured may affect this sensor. Mounting must be strain-free from the hardware and wiring, and proper torque on the mounting stud is also important. Transverse dynamic loads are greatly attenuated but must be considered.

The piezoelectric crystal is particularly sensitive to thermal stresses which can be significant. Often called "breeze disease" by users, this phenomenon occurs when the accelerometer is mounted on a hot machine and a cool wind causes thermal stresses in the sensor casing. This can cause significant output voltage from the crystal where no real vibratory forces exists. This problem has been greatly reduced in some current accelerometer designs and shielding methods also exist.

Most of the accelerometers available today contain "on board" electronics that amplify and condition the charge signal from the crystal. A direct current source is needed to power this circuitry and thus limits the portability and intrinsic safety in hazardous environments. Low voltage batteries are often used for the current source. Applications of accelerometers without built in circuitry can be a nightmare of matching impedances and system capacitance with the proper cables, amplifiers, and signal conditioners. In high temperature situations, the on board electronics may not survive, and a "bare" accelerometer must be applied. On the other hand, the built-in amplifier can be a liability in the event the transducer is dropped. This author has seen an accelerometers ruined after a fall from less than three feet—and these sensors are not repairable.

A separate topic, applicable here is the issue of signal cables. You *will* have cable and connector failures, and they will occur more often than sensor or read out device failure. Buy the very best connectors and cables available with strain reliefs. Coiled cables are a fine convenience, but tend to have a higher failure rate that straight cable. Accelerometers come with "micro" connectors and very thin cables. This weak cable should be tied down, if possible, and routed directly to the electronics. From there, the amplified signal can be diverted to more rugged cable for long distance transmission.

Typical Applications and Misapplications

Accelerometers can be applied as general vibration sensors provided the necessary external power is available. They are ideal for monitoring high speed gears, detecting vane pass frequencies, and mounting on very light structures. Another use for accelerometers is in measuring angular acceleration rates and torsional oscillations. Mounted 180 degrees apart, in pairs, to cancel out centrifugal effects, either slip rings or radio frequency telemetry is used to monitor the angular acceleration.

Inappropriate applications would include low speed (less than 120 rpm) machinery or on non-geared machinery with a casing-to-rotor weight ratio over five. Because of their small size, the mount is usually by a very small stud, or by cement. Someone looking for a foothold can easily break the sensor off the machine, so applications without a protective cover over the sensor should be avoided. A typical protective cover arrangement is shown in Figure 6.

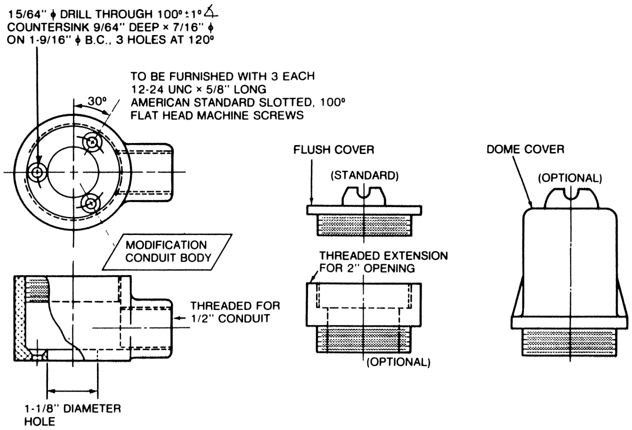


Figure 6. Protective Cover Arrangement for Accelerometers (courtesy American Petroleum Institute).

NON-CONTACTING DISPLACEMENT SENSORS

There are several ways to measure distance without contact. Sound, air pressure, light, inductance, and capacitance have all been applied to this task. This discussion will be limited to the eddy current probe, commonly called the proximity probe, marketed by many vendors today for vibration detection and thrust position sensing. A typical probe arrangement is shown in Figure 7 as specified by API standard 670. This type of probe requires a radio frequency signal applied to a flat coil. This coil generates a field that is readily absorbed by a nearby conducting metal. The amount of the field that is absorbed is linearly (within limits) related to the distance between the probe and the adjacent surface. The distance corresponds to a demodulated direct current (DC) voltage. All that a proximity probe "knows" is gap voltage. Since a changing DC voltage is an alternating current (AC) voltage, as a shaft vibrates, the gap changes, giving a signal proportional to the relative motion between the shaft and the proximity probe.

Advantages

Proximity probes have extremely good frequency response from *zero* cpm to over 500,000 cpm. The zero frequency response condition is used for thrust or other static gap measurements. The output of the excitation module (called an oscillator-demodulator) can be sent up to 1,000 ft with no degradation to the signal. Extremely small displacements (approximately 0.1 mil) can be detected accurately. These probes are very stable, nearly drift free and can be made very small and can be adapted to a wide variety of applications. Normally mounted near the bearings of a journal bearing machine, they can ascertain the location of the shaft in the bearing (attitude angle and eccentricity) and the relative vibratory motion at the same time. Unaffected by most lubricating oils, many process gases and temperatures up to 350°F, these sensors are the closest thing to X-ray vision that the analyst has. No matter how isolated the rotor, its motion relative to the proximity probe can be measured. With enough effort, rotor motion at any location can be observed and actual rotor modeshapes can be determined.

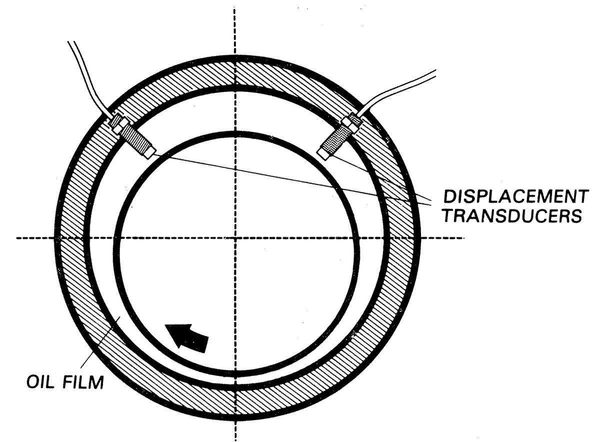


Figure 7. Typical Displacement Probe Arrangement (courtesy Hewlett-Packard Co.).

The exact same probes can measure rotor thrust, lateral vibration, and provide a phase reference on a given machine. API standard 670 delineates the specifications for these probes and their associated systems and is recommended as the final guide in applying these sensors. Used in conjunction with an integrated velocity case reading from the same location, *true* absolute shaft motion can be determined. The integrated velocity signal is vectorially added to the displacement signal to achieve this result. This is a bulky package and, in most applications, is needed only if the case motion is substantial enough to make direct relative measurements erroneous.

Disadvantages

As mentioned before, the proximity probe only knows gap. This means that if the probe holder is moving as well as the shaft, the read out will be the *vector difference* between the two motions. If the casing to which the probe is mounted is resonating or is less than five times the rotor weight, this can be significant. If the rotor is mounted in antifriction bearings, the relative shaft-to-housing motion near the bearings will be negligible. If the probe mount is not stout enough, or is perhaps resonant, false readings will exist. A common probe mounting arrangement is shown in Figure 8.

A typical calibration curve for a proximity probe is depicted in Figure 9. The slope of the linear portion of this curve is the sensitivity (usually 200 mv/mil) and is dependent on the sensed metal and the sensing electronics. This shows that to achieve maximum accuracy and range, the calibration curve for each sensor should be known. If the initial DC gap is at one end on the curve, the linear range of a sensor could be severely limited. To guard against this, monitors usually incorporate a sensing circuit to warn the user if operation outside the linear portion of the curve occurs. All machines in fluid film bearings have a shift of shaft position from static to running condition. In many machines, this is one-third to one-half of the diametral bearing clearance. In gear sets, it can be 75 percent of the clearance and in any direction depending on the gear loads. Once this shift is known, the DC gap should be set for the center of the linear range to be attained at operating conditions.

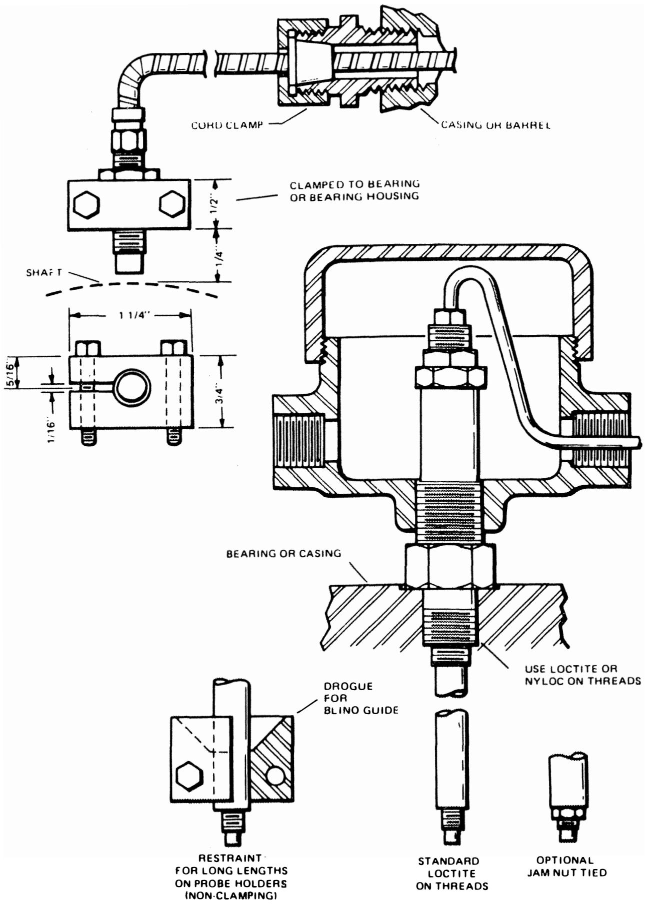
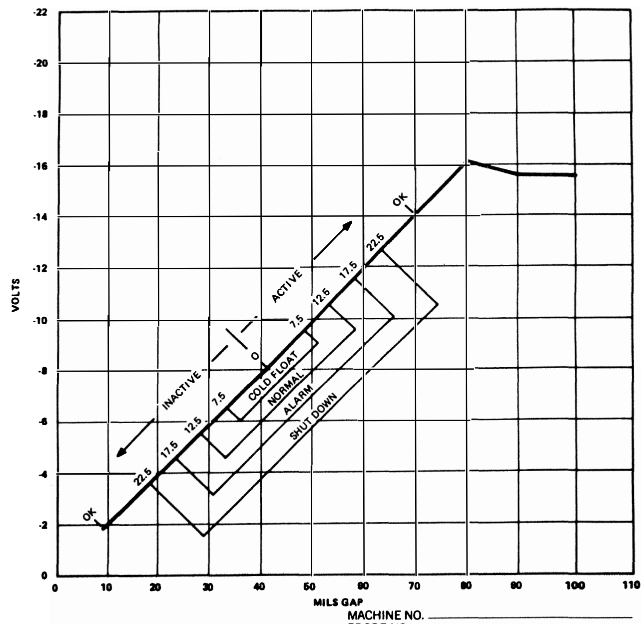


Figure 8. Recommended Mounting Methods for Displacement Probes (courtesy American Petroleum Institute).



CALIBRATION MILS/GAP	VOLTS	METER
10	-2.0	+30
20	-3.9	+20.5
30	-5.9	+10.5
40	-7.8	+1.0
50	-9.8	-9.0
60	-11.9	-19.5
70	-14.0	-29.5
80	-16.1	
90	-15.6	
100	-15.6	

Figure 9. Displacement Probe Calibration Curve-200 mv/mil (courtesy American Petroleum Institute).

Anomalies in the shaft itself such as runout will be detected exactly the same as a true vibration signal. Scratches, dents and conductivity irregularities in the shaft material will all be "seen" as vibration by the proximity probe. Manufacturing operations such as grinding or magnetic particle inspection can have a drastic effect on the electromagnetic properties of the metal and on what the eddy current probe senses. Chrome and other coatings must be carefully avoided in probe sensing areas or, with great difficulty, allowed for. Electronic shaft runout techniques are available, but are not a good solution, compared to properly preparing the shaft surface initially. Even if the manufacturer delivers a shaft with very low surface defects and runout, the first overhaul might have a highly burnished probe area damaged by dragging a sleeve over it or a tool banging into the surface. It is both a tribute and a drawback that the eddy current probe has such tremendous resolution.

Typical Applications

Proximity probes are easily applied to a wide range of turbomachinery. For lateral vibration detection, the most common applications are on large, unspared equipment such as turbines, motors, and compressors running in fluid-film bearings. Ideally, two probes are mounted orthogonally to produce true centerline shaft orbits and measure shaft position as well as vibration. In new machinery, the standard approach is to mount two probes, 45 degrees on either side of true vertical, as close to the bearing as possible. When retrofitting machinery, *any* location for two probes 90 degrees apart is acceptable, given the alternative of not having the probes. Documentation of these probe locations is extremely valuable and a good example is shown in Figure 10.

Since there is no lower end to the frequency response, these probes can accurately measure very slow speed shafts such as mixers or extruders. Also, vane tip or cutter tip clearances can be easily monitored while in operation, and sometimes operating clearances can be adjusted "on the run" to optimize process performance. Other applications include measurement of casing growth for hot alignment studies and permanently mounted casing growth sensors.

Perhaps the most protective role for proximity probes is their use as thrust monitors. All turbines, compressors, pumps, single helical gears, and other machinery generate axial thrust loads which must be controlled by a thrust bearing. A proximity probe can accurately gage the rotor's location and be incorporated into alert and shutdown circuits. Thrust bearing failures sometimes

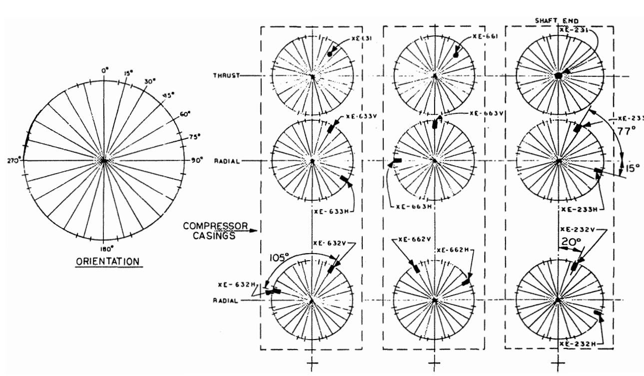


Figure 10. Example of Well Documented Probe Locations.

occur slowly as in the case of electric-static discharge babbitt removal. However, historically, when a thrust bearing fails, it often deteriorates very rapidly. There is no time for a "management" decision. For this reason, many applications have the thrust probes set to automatically shutdown a machine before major damage occurs. To reduce false shutdowns, two probes are applied in a "dual voting" arrangement where *both* probes must detect the danger point before an actual trip occurs. This arrangement is shown from the API 670 specification in Figure 11. There is a great deal of controversy concerning automatic shutdown from thrust probes. Only the final end user can judge the consequences of losing a machine to the shutdown circuitry compared to losing a machine to a catastrophic thrust bearing failure. Trending of thrust position, particularly when load and process conditions are correlated to thrust position, can be a very powerful diagnostic tool.

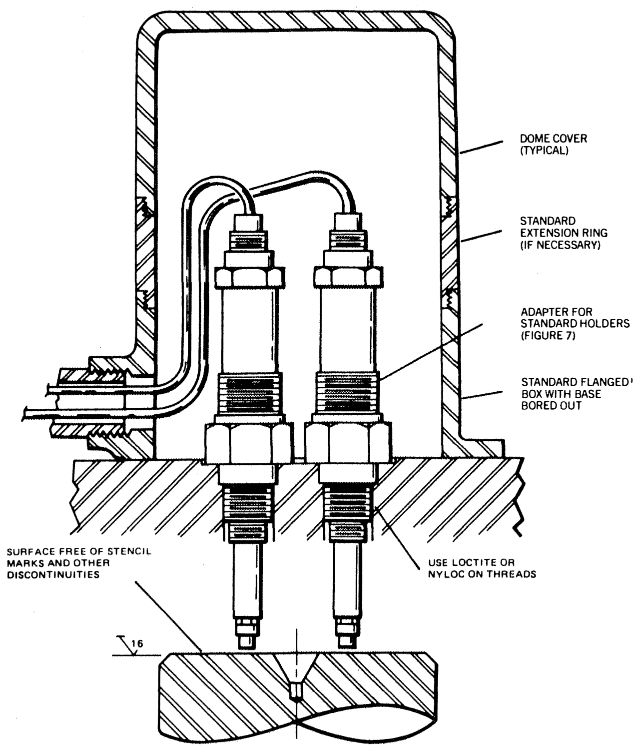


Figure 11. API 670 Dual Thrust Probe Mounting Arrangement (courtesy American Petroleum Institute).

Typical Misapplications

The most often misuse of proximity probes is attempting to detect very high frequencies such as gear mesh. The displacements associated with gear mesh vibration are extremely small even on a "rough" gear set, and may be below the noise floor of the instrumentation.

It is important to know the rotor modeshape both at critical speeds and at operating speeds. A probe near a node point will yield attenuated amplitudes. For example, as shown in figure 12, the first critical speed modeshape of a typical centrifugal compressor will have two node points outside of the bearings. Knowing the location of the nodes in relation to the probe locations allows better understanding of the data from those probes. Typical modeshapes are shown for various classes of equipment on the summary chart (Figure 13).

Adjusting thrust probe gaps without knowing exactly where the rotor is in its thrust float zone will lead to uncertainty, misinformation and, worst case, to disaster. At no time should on-the-run gap adjustments be made without extremely careful consideration. The best way to avoid these problems is to coordinate mechanical thrust position measurement with instrument calibration during maintenance. The confidence level of absolute rotor position is directly related to the installation practice and maintenance upkeep of the instruments.

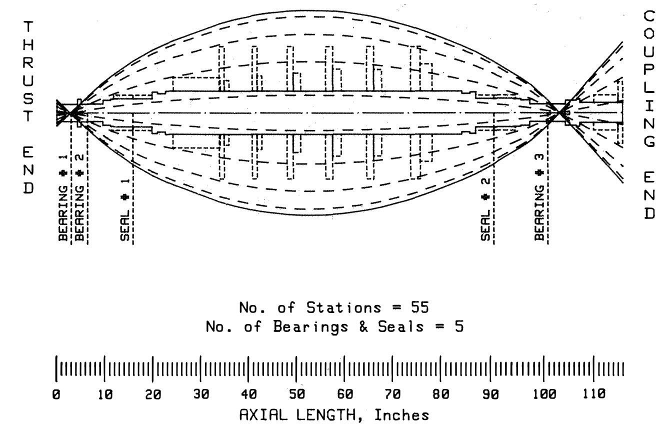


Figure 12. Typical Centrifugal Compressor First Critical Speed Mode Shape.

GENERAL MACHINE CLASSIFICATION	EXAMPLE OF THIS CLASS	VIBRATION CHARACTERISTICS	RECOMMENDED TRANSDUCERS AND LOCATIONS	RECOMMENDED ANALYZERS
Large, Slow speed, Anti-friction bearings	Mixers Some Fans Rotary Kiln Mill Rolls	Large shaft displacements at running speed transmit well to support structure. Bearing defects - acoustic	Special low frequency seismic transducers and accelerometers to detect ball bearing failure	Local panel for low frequencies Portable acoustic emission
Large, Medium speed, Sleeve bearings	I.D. Fans Some Pumps Centrifuges Generators	Usually rigid body - high transmisability to support structure. Blade pass frequencies common.	Regular accelerometers or velocity transducers Permanent mounting only if accelerometer.	Local panel Remote alarm in control room Oscilloscope
Small, spared equipment, medium speeds anti-friction bearings	Process Pumps Motors up to 500 HP Some Blowers Sm. Turbines	Running speed and higher multiples including vane passage. Line frequencies and multiples in motors. Usually rigid body motion.	Permanent mount usually not justified. Periodic montioring with portable seismic based system. Accelerometers prefered.	Spectrum record and time-base record are a must. Acoustic emission ok.
Large, high speed, usually unspared with sleeve bearings high horespower	Compressors Turbines Large Motors Some Pumps Gas Expanders	Running speed and higher multiples. Possible subharmonics. Possible vane passage. Axial vibration important.	Permanent mount accelerometers not as good as displacement probes in or near bearings. Thrust monitoring paramount.	Permanent panel local or remote Oscilloscopes Spectrums, keep trend records.
High speed, light rotor, sleeve or anti-friction bearings	Cryogenic expanders Thread winder Spindles	Running speed and higher multiples. Possible subharmonics. Possible vane passage. Acoustic emission detection important.	Permanent mount accelerometers OK - Best choice displacement probes in or near bearings. Thrust monitoring paramount.	Permanent panel local or remote Oscilloscopes Spectrums, keep trend records.
Geared machines of all types Usually sleeve bearings	Speed reducer and increaser Auxillary pump drives Governor drives	Gear mesh frequencies and sidebands most important. Running speeds of each shaft and higher multiples of each shaft also present	Accelerometers a must to monitor gear mesh. Running speeds are best monitored with permanent mount displacement probes Thrust monitoring a must	Permanent panel local or remote Oscilloscopes Spectrums, keep trend records.

Figure 13. Summary Chart for Selection of Instrumentation and Analysis Equipment for Many Classes of Turbomachinery.

UNITS AND VIBRATION LIMITS

No discussion of vibration sensors and analysis equipment can avoid the controversial subjects of units and vibration limits. Specific sensors produce specific outputs which *may* be electronically modified (e.g., integrated) to produce the desired final output. It is up to the analyst to visually assess this output and determine the condition of the machine.

The problem with units is one of becoming *comfortable* with what they relate to physically. One can easily visualize measured distances and relate this to shaft motion, so peak-to-peak mils is clearly the most widely understood vibration measure. Mils RMS, sometimes seen displayed, is a carryover from the electronics world and should not be used in discussing machinery vibration. Velocity, in inches-per-second (ips), is also quite easy to visualize, since it is like the maximum speed attained in stop-and-go traffic. What concerns us here is the peak velocity reached between the stops. Quite often, velocity is integrated to mils for those who find displacement more acceptable. Acceleration is the least understood unit of measure, mainly because it is the intuitive inverse of displacement. Note that acceleration in units of gravity, or Gs, is *not* the same as inches per second squared. One G is 386 in/sec^2.

Returning to the stop-and-go traffic analogy, think of starting out at a stop sign and then accelerating to a peak speed, then braking to stop for the next stop sign. Then, instead of going forward, reverse direction and return to the preceding stop sign. The distance traveled is two blocks sign-to-sign. The peak velocity reached is the posted speed limit and that limit is reached halfway between the stop signs (this driver is very smooth). The peak acceleration rate and peak deceleration rate are achieved at the beginning and end of each start and stop. The frequency is analogous to the length of the block. A long block means large displacements. To traverse the long block, the driver accelerates at a lower rate, reaches the *same* top speed and coasts gently to a stop. As the blocks become shorter and shorter, the driver has less and less displacement, the *same* top speed, but greater and greater acceleration rates. This relationship is shown in Figure 14 which is simply the mathematical relationship between the three units of measure. Thus, on slow speed equipment, such as a 25 rpm mixer, large displacements, say 20 mils peak-to-peak, might be normal. On a 10,000 rpm gearbox, this same displacement would be unthinkable. If the "speed limit" is set at 0.3 ips then (within limits) it doesn't matter whether a 1,150 rpm motor or a 6,000 rpm pump is being measured. Acceleration measurement on the low speed mixer at 20 mils, would show only 0.0002 Gs while the gearbox would show 28.4 Gs for the synchronous vibration component.

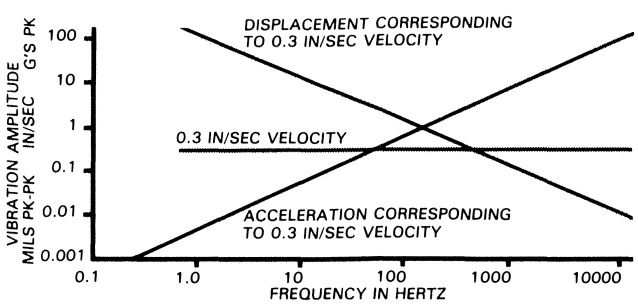


Figure 14. Frequency Relation Between Displacement, Velocity and Acceleration (courtesy Hewlett Packard Co.).

Many charts have been published showing "good-fair-rough" type guidelines and Figure 15 is one such example. Note that the constant velocity lines are also constant condition evaluation lines. One of the most important ideas to remember here is that these guides can *only* be used for filtered readings. Moreover, these types of charts are best applied to synchronous vibration only. Overall measurements in any units cannot be accurately evaluated unless their frequency content is known. What simple addition of sine waves can do to the overall reading is clearly demonstrated in Figure 16. It all depends upon the phase relationship between the signal components. This situation is further acerbated with displacement probes when a scratch or surface deformation occurs. An example of this is shown in Figure 17. Here, the panel meter would read 1.6 mils, while the true synchronous vibration was only one mil. An oscilloscope will quickly aid in the diagnosis of this error. Any type of nonsynchronous vibration such as oil whirl or 60 Hz beating in a motor will result in unsteady overall vibration readings. An example is shown in Figure 18 for a 60 Hz "beat" in a two-pole induction

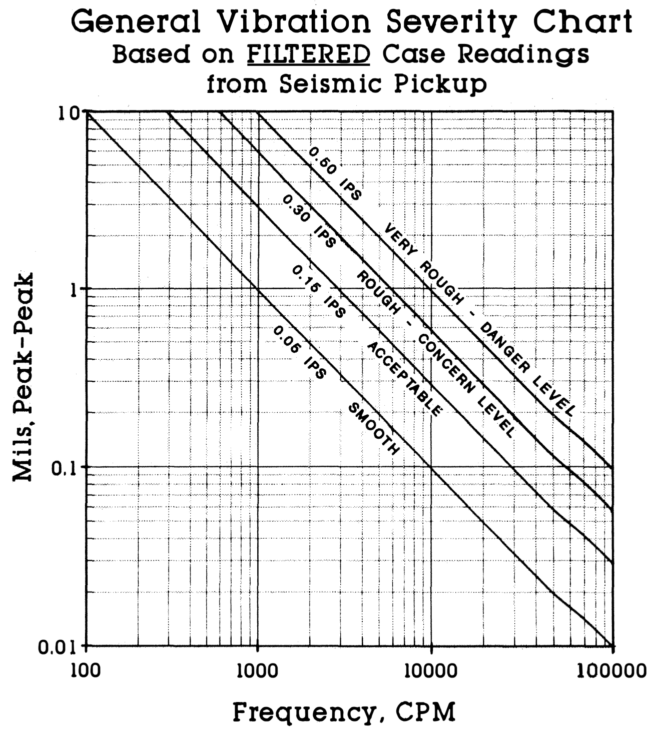


Figure 15. Recommended Filtered Vibration Limit Guidelines.

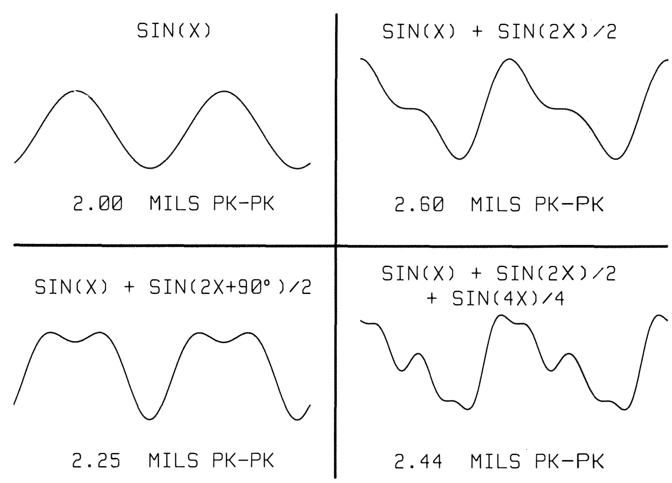


Figure 16. Various Combinations of Simple Sine Waves Show Different Readings.

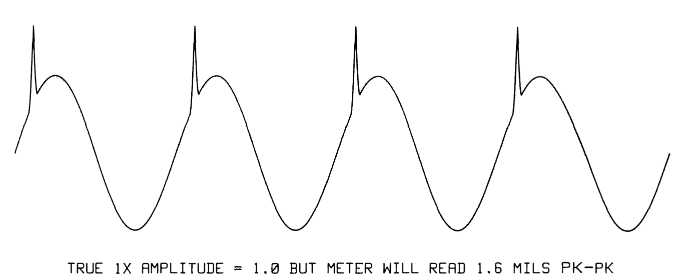


Figure 17. Surface Deformation Can Cause False Meter Reading.

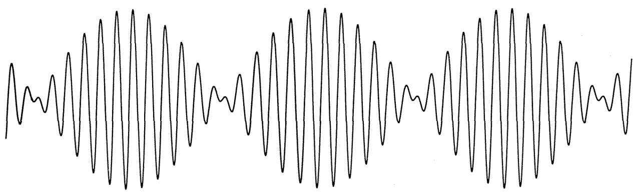


Figure 18. 60 Hertz "Beating" in a Two-pole Electric Induction Motor.

motor. What is the overall vibration here: the peak level or the average or something else?

Vibration limits, such as the ever popular 0.3 ips used to distinguish acceptable *vs* not acceptable vibration must be tempered by several factors. First, the nature of the machine being measured and the user's experience with it are most important. Even though velocity is a frequency independent measure, it should not be blindly applied as a go-no go evaluation. For example, the casing transmissibility must be considered. Housing resonances may occur that result in high velocity readings with no actual internally damaging forces. Vane-passage vibration in pumps is a good example where a knowledge base must be built to determine if 0.3 ips is damaging or not. On the other hand, ball bearing induced vibration (ball pass, race defects) will indicate damage at 0.1 to 0.15 ips. It would be nice if firm boundaries could be drawn, but there are always going to be broad gray areas in setting vibration limits.

The truth is that any discussion of vibration levels and limits must include a precise knowledge of the type of measurement being made, what sensors are employed and also both the time domain and the frequency domain of the signal in question.

INSTRUMENTATION

Once the proper sensor is selected, the next task is to select the analysis equipment or read out device. The two types of devices discussed here are permanently installed monitors and mobile, multiple use equipment that can be applied to many different machines.

The human ear and sense of touch are sophisticated, but uncalibrated, vibration measuring devices. Within certain frequency ranges, the human senses can analyze the health of rotating machinery quite accurately. This is art, not science and is only as good as the *experience* of humans interpreting their sensory inputs. It is likely that a person with considerable experience can listen to and touch a machine and accurately say whether the machine is "healthy" or in need of repair. However, the ultimate goal is to promote this process beyond "art" and turn it into a useful and well-understood science.

Instrumentation that receives signals from all types of sensors is a means of quantifying the vibration levels and frequencies emanating from a vibrating piece of machinery. For the correct diagnosis to be made, the instrument used must be suited to the task and the human interpreting the output of the instrument must have the *experience* and training to properly analyze the data.

Permanent Monitors

Permanently installed monitors are usually applied only to critical, unspared equipment or on equipment that has historically proven to be troublesome. Economically, permanent monitoring of other classes of machinery is difficult to justify. There are examples of plants that have monitored virtually every piece of machinery they have. These instances are rare, and this discussion is limited to the more common forms of permanent monitoring.

The most widely applied monitors are for lateral shaft vibration and thrust displacement detection. Along with the displacement monitors, velocity and acceleration monitors are often permanently installed as well as rotational speed and temperature readouts. Ideally, the outputs from these instruments are polled by computer on a regular basis for later analysis. However, their main function is to alert the operating personnel to changes in the equipment condition before any damage has occurred. Many operations manually log the monitor output values on data sheets. To them, the absolute numbers are not as important as changing numbers and the alert and danger set points. Automatic shutdown may also be enabled by these instruments as discussed earlier for the thrust monitor. A typical instrumentation rack in a control room is shown in Figure 19.

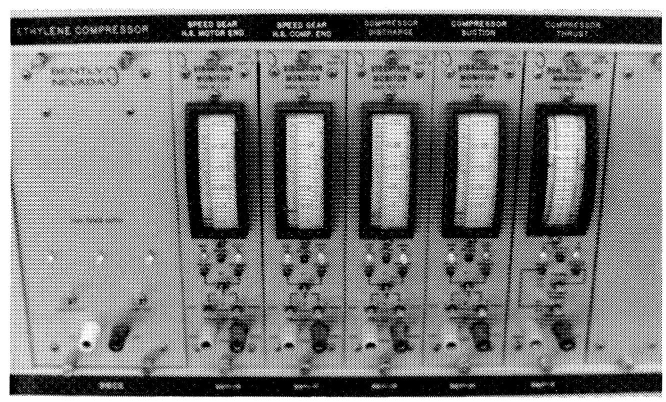


Figure 19. Typical Instrument Panel in a Plant Control Room.

Some monitors may serve as crude analyzers. For example, with the addition of appropriate filters, a monitor can be set to only sense gear mesh or vane pass frequencies. The analog meter is, however, an averaging device and intermittent peaks and transient vibration are difficult to detect with these devices. Digital devices may blink numbers faster than the eye can read them.

No instrumentation is completely stable as time passes. Given their main function as warning and shutdown devices, it is most important to maintain the correct calibration of monitors at scheduled intervals. Simulating alert and shutdown conditions during periods when the machines are not operating is excellent confirmation that they will function as intended when called upon to perform these tasks on line. It is best to actively stimulate the actual installed sensor and calibrate the entire system simultaneously.

Vibration Analysis Instrumentation

Vibration analysis has become more elaborate in the past decade as electronic data processing capabilities have increased in speed and resolution and decreased in physical size. The storage of data on magnetic media has reduced data management complexity. Instead of piles of paper, now there are piles of floppy disks. The problem of translating the raw data into meaningful interpretation remains. The root of this problem is based on lack of correlation between signal analysis and fault diagnosis.

Often, too much reliance is placed on the "analyzer" to do the actual diagnosis. The instrument that resolves the time base vibration signal into its Fourier frequency components only performs a mathematical operation on the time based amplitude signal. No additional information is "created"—this process simply allows the same data to be viewed in a different format. The *analyzer* is the person who views the waveform or the spectrum and decides what it means.

Time Based Signal Analysis

The primary instrument employed in analyzing the amplitude *vs* time signal is the oscilloscope. This instrument is only able to display amplitude versus time or an "X *vs* Y" display. Some oscilloscopes can add and subtract signals. The very nature of the simplicity on this instrument makes it a very powerful analyzer. Connected to a sensor or monitor it will be immediately obvious whether the signal is overloaded, masked by noise, steady or intermittent, contains transients, or is something unexpected. With very little work, amplitude and frequency measurements can be made by counting peaks and divisions on the screen and doing some simple math. More false readings have been made and more incorrect diagnoses have been made because the analyst did not first look at the time waveform. For example, as shown in Figure 20, a clipped sine wave from an overloaded amplifier will create harmonics in the spectrum that do not exist. A ball bearing failure is shown much more clearly in Figure 21 than the spectrum would.

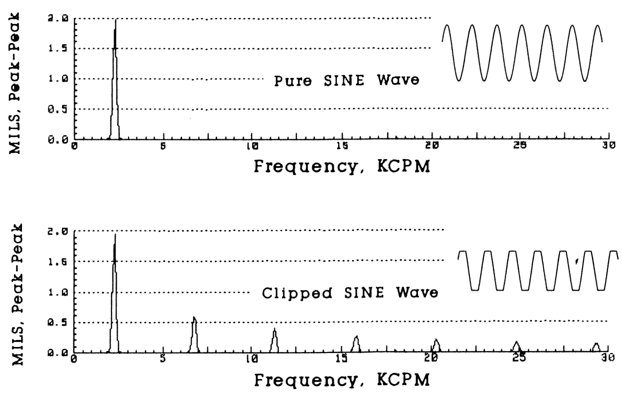


Figure 20. Clipped Sine Wave Produces False Harmonics in Spectrum.

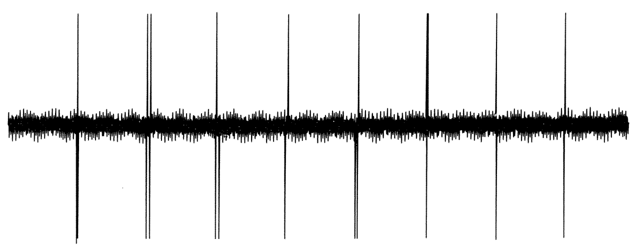


Figure 21. Time Wave Clearly Showing Early Ball Bearing Failure.

Orbit analysis, which displays the output of two orthogonal sensors is a powerful diagnostic tool. Light rubs will show a "banana" shaped orbit and a heavy rub will show a figure "8" orbit. Adding the timing mark output to the external intensity input on the oscilloscope allows accurate phase measurements for balancing. A typical orbit is shown in Figure 22, as sensed by proximity probes. A subsynchronous instability will show a steady orbit but an unsteady timing mark.

Frequency Spectrum Analysis

As good as the oscilloscope is, its usefulness becomes limited as signals become more complicated. Thus, the next instrument employed is known by several names. It is called a spectrum analyzer, a dynamic signal analyzer, a "real time" analyzer, or sometimes, a Fast Fourier Transform (FFT) analyzer. Its basic function is a mathematical transformation of the time-base signal into the frequency domain. The FFT is the mathematical method employed to do this. The relationship between these two domains is shown in Figure 23. This transformation sorts the components of the time wave and displays the amplitude content of each frequency.

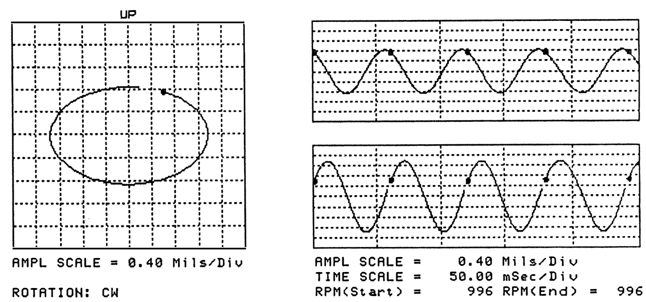


Figure 22. Typical Shaft Centerline Orbit from Proximity Probes.

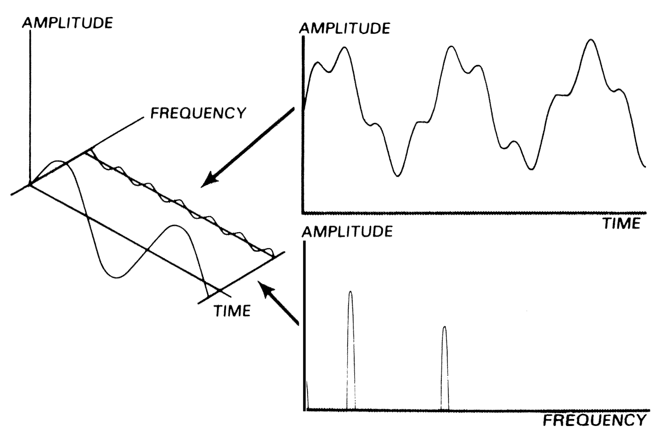


Figure 23. Relationship between Time and Frequency Domains (courtesy Hewlett-Packard Co.).

Modern spectrum analyzers range in complexity from simple single channel tuneable filters, which read amplitude and frequency on analog meters, to intricate multi-channel digital devices which can manipulate and process signals in many ways. This tutorial only covers the most basic aspects of these functions. References are given that list some publications which cover more advanced aspects of spectrum analysis.

The resolving power of a spectrum analyzer is its major strength. All of the Fourier components of a very complex waveform are easily determined. Logarithmic amplitude scaling can be used to view extremely small components of the vibration signal. In the opinion of this author, this practice should be exceptional rather than general practice. Logarithmic scaling enhances insignificant signal components and makes extraneous noise components seem much more important than they are. This type of scaling is not intuitive and the physical relationship between peaks is lost. Only when special emphasis is needed to examine known frequencies, such as gearmesh side bands, has the author found logarithmic scaling necessary.

Perhaps the most common mistake in applying spectrum analysis is choosing the wrong frequency range. Too low a range will have the important peaks out of the displayed range. Too high a range will have all the data compressed in the left hand side of spectrum plot with most of the display a flat line. Examples of these two faults are shown in Figure 24 which shows two spectrums taken on a typical multistage pump. Naturally, proper input sensitivity and amplitude scaling must also be selected; some analyzers have automatic scaling capabilities. Many analyzers also have overload lights or onscreen warnings in the event the sensitivity is improperly set.

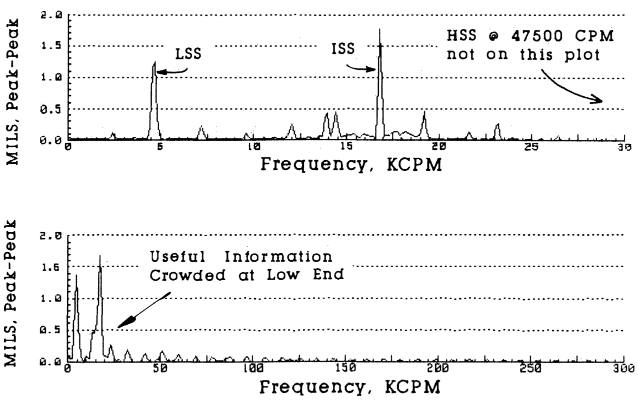


Figure 24. Examples of Improper Frequency Scaling on FFT Spectrums.

Since most modern spectrum analyzers use digital sampling, it is necessary to discuss aliasing. This phenomena occurs when the sampling rate is not sufficient to adequately resolve the incoming time base signal. A time honored concept, called the Nyquist Criterion, suggests that the sample rate should be greater than twice the highest expected frequency. This is often not adequate enough. This author recently had to explain why an expander running at 67,000 rpm showed a *triangular* orbit on the portable data collector. The reason was that the collector was taking *three* samples per revolution. Four samples per revolution would have generated *square* orbits.

To understand the principal of aliasing, think of watching a baseball batter warming up, swinging the bat. An observer is blinking their eyes at the same rate as the batter swings—so the observer sees a motionless batter. The same thing happens to sampling rates of signals and the connection to spectrum analysis is shown in Figure 25. To avoid this problem, *most* spectrum analyzers employ anti-aliasing filters. These filters cut off any high frequencies which might falsely show up in the spectrum. The filter cut off frequency changes automatically as the selected frequency range changes.

In this author's experience, about ninety percent of all analysis jobs are satisfied by single channel spectrum analysis. Dual or more channel analysis has a definite niche and is an extremely powerful tool. However, with added power comes added complexity. Multiple channel analysis allows transfer function analysis, cross correlation between signals, coherence analysis, and even advanced modal property analysis. These and other topics are far too specialized to be adequately covered here. If the user needs the power to perform these analyses, they should have it, but for routine spectrum analysis, a simpler single channel signal analyzer will be easier to use and provide the vast majority of the necessary output data.

As they have evolved, spectrum analyzers have become more and more complex with more and more functions. This is fine

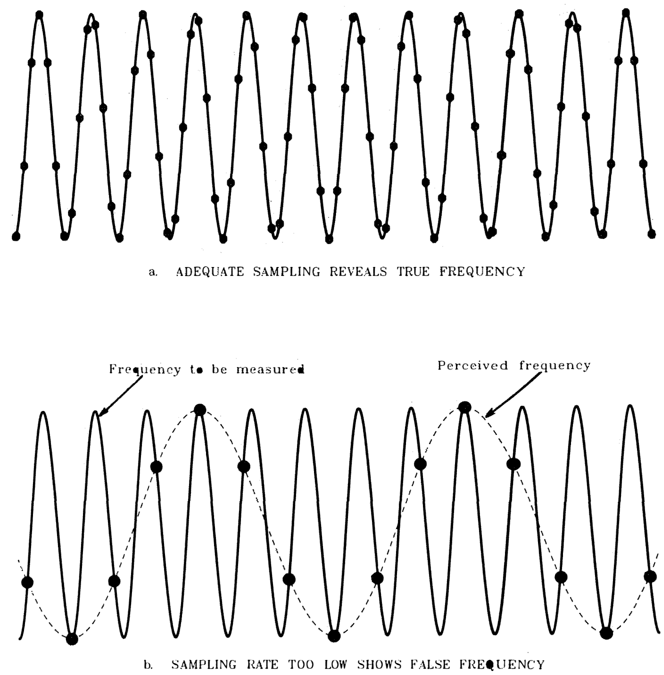


Figure 25. Aliasing May Produce False Frequencies in Spectrum Analysis.

for the person who constantly uses the instrument. The real difference between instruments is *not* whether one unit has such-and-such a specification, but rather how well the manufacturer has done the human engineering aspects making the analyzer logical and easy to use. Some units have dozens of buttons, *all the same size, shape and color*. Other units match purpose with shape or color that clearly delineate control functions. The newest analyzers have built-in software with menu functions that are arranged in logical "trees" allowing fast access to even the most complicated functions. The very best units also incorporate operator error detection and readily available *guidance* to the operator should an improper function selection be made. It is strongly recommended that, without sales pressure, the user "test drive" any analyzer before purchase. Note the times that the instructions must be consulted, that the instrument seems puzzling and the ease with which the desired reports are accessed.

CONCLUSIONS

The degree of scrutiny to which rotating machinery is subjected is mandated by how crucial the service of that machine is to the process involved. The choice of monitoring methods is dictated by the concern for reliability and safety. This means that the user must choose the suitable sensors and instruments to meet the monitoring requirements. To properly monitor and diagnose the health and condition of machinery, careful thought must be given to the sensor selection, its mounting method and mounting point, and to the manipulation of the data from the sensor.

There are many combinations of instruments and data manipulation techniques that can reveal a wealth of information about the monitored machinery while it is in operation. There are also combinations which are inappropriate, misleading or even useless. The interpretation of the outputs from these sensors is a formidable task. Some systems now use computers to screen the routine data and alert maintenance personnel to possible malfunctions. However, outside of very common malfunctions, such as unbalance, misalignment, or known system frequencies, these systems are limited. The human senses and correlation abilities are the final arbiter, based on experience. This author knows of no better way to speed the process of building experience than time and training.

Currently there are no "expert systems" known to this author which can compete with the hard earned human experience gained from correlating signal analysis with machine health. Perhaps in the future there will be such a system, but in the mean time we will all have to rely on human interpretation of proper application and analysis techniques.