The PDM-QC Connection: A Proactive Approach to Quality with Predictive Maintenance Technology

Robert E. Gladd, ASQC Section 1105

Computational Systems, Inc.
Knoxville TN • Houston TX • Brussels Belgium EC

Industrial Statistical Process Control (SPC) methods focus principally on diagnostic monitoring of process output variability for indications of conditions adverse to quality. In a manufacturing environment, SPC analyses are typically performed by sampling the process outputs according to an established sampling plan, calculating the appropriate QC statistical parameter estimates which reveal the extent and nature of process variability, and using the empirically derived SPC indices to set warning and control limits with which to define the "in control" and "out-of-control" status of production output.

The most widely used SPC techniques involve the construction of any of the variants of the "Shewhart Control Chart." The example in figure 1 is that of an "XBAR" chart, in which the means, or arithmetic averages, of repeated output sample sets are plotted over time. The Upper and Lower Warning and Control Limits (± 2 and 3, respectively) are defined as 2x and 3x multiples of the Standard Error of the Mean ("SE"). Processes said to be "in statistical control" exhibit a control chart scatter more or less randomly dispersed in symmetrically decreasing proportions about the "grand mean" line (XBAR, denoting the average of all of the sampling means), with few if any points lying outside the warning limits. Points located outside the "± 3-SE" Control Limits (e.g. fig. 2) usually precipitate an investigation to uncover assignable causes of the excessive or skewed dispersion.

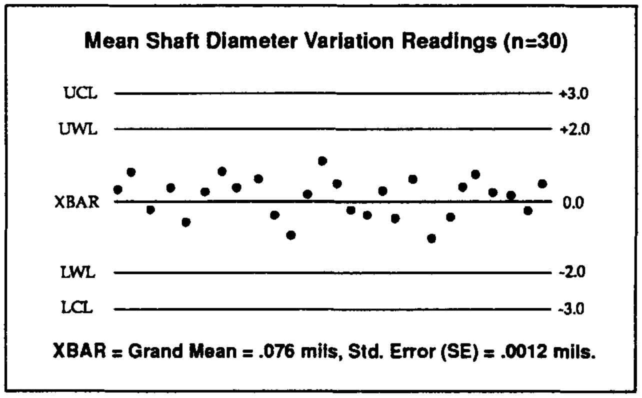

Figure 1. SPC Means Chart: Process "In Control"

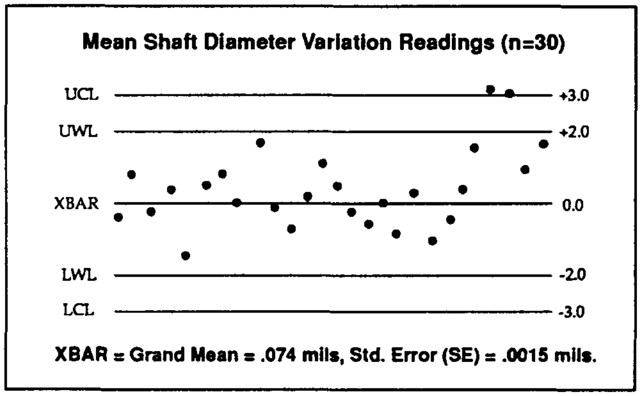

Figure 2. SPC Means Chart w/"Out-of-Control" points

SPC charts may be constructed to analyze a variety of numerical measurements of the physical characteristics of process output such as length, volume, weight, thickness, temperature, "mean-time-to-failure," and so forth. Control charts are also often constructed for nominally "qualitative" output attributes such as "fraction defective." The Control Chart, whatever its particular format, provides the QC analyst with a useful diagnostic tool for monitoring process fluctuations. As data accrue over time, changes in the variation patterns become readily apparent; trends away from the process norms may be confirmed by slope testing methods, and systematic process biases are easily detected.

While traditional SPC practices are indisputably valuable techniques for monitoring and evaluating process variability and product quality, they are often used in an essentially "reactive" fashion, in that the QC analyst becomes aware of production problems only as indicated by the product "going out of spec," either gradually (through an emergent trend) or suddenly (typically owing to some process failure). Only when output specimen data indicate actual or looming production problems does the search for assignable causes normally begin.

In contrast, the Predictive Maintenance technology (PDM) pioneered for industry by Computational Systems, Inc. (CSI) at once aids in improving product quality, dramatically reduces catastrophic process failures, and lowers the cost of equipment maintenance by applying the diagnostic capabilities of technologically advanced yet affordable and simple-to-use digital vibration analysis instruments to the manufacturing equipment itself during normal plant operations—without disturbing production—rather than awaiting the arrival of unacceptable (and thereby wasted) product samples to trigger QC investigations.

What is Vibration Analysis?

Vibration analysis is the art and science of assessing the operational condition of mechanical and electrical equipment by monitoring the oscillating energy patterns emanating from the machinery during routine production activities. Wasteful and destructive machine conditions may be detected by careful analysis of the vibration signature characteristics (see Figures 3 and 4) of components such as bearings, shafts, pumps, pulleys, belts, fans, gears, electrical rotors, structural housings, and the like. Of all the diagnostic parameters that can be measured in industry today, the one containing the most analytically useful information is the vibration signature.

Machinery vibration is the inevitable result of the economic limits of accuracy and precision in the building of industrial equipment. Perfectly balanced, coupled, and aligned machines exist only in design engineers' drawings. The reality of the production workplace is one of parts that work loose or drift out of alignment, rotors or shafts with off-center heavy spots, bearings that wear, electrical windings that short, and gears that fail to mesh properly.

Vibration energy is energy lost from the production system, transformed to excess heat and noise. A perfectly constructed machine would silently and smoothly transfer nearly all of its input energy to the output product or process. The best we can hope for, however, is to construct machines with sufficiently well-matched and balanced components as to minimize the destructive effects of vibration.

The Empirical Basis of PDM

Engineers who have studied machine vibration phenomena closely for decades have found that the vibration signatures exhibited by common machine components during routine operation follow well-defined patterns enabling the trained observer to diagnose the sources of potentially damaging vibrations without having to stop and disassemble the equipment. The entire science of Predictive Maintenance is grounded firmly in this empirical principle, and PDM methods represent a significant improvement over "run-to-failure" practices and the more traditional techniques of routine Preventive Maintenance (PM) employed by most industries. The costly and potentially dangerous shortcomings of a "run-to-failure" philosophy are patently obvious. The inadequacies of routine preventive maintenance methods are less overt, however, and routine preventive maintenance procedures have historically been regarded as the best available techniques for assuring plant safety and machine quality.

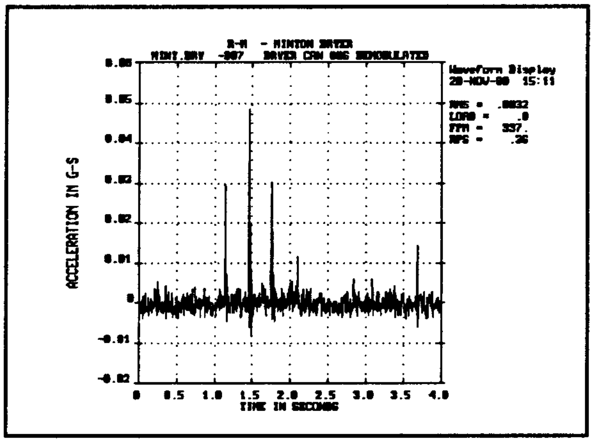

Figure 3: Vibration Time Waveform of a dryer roll bearing assembly revealing large energy peaks caused by bearing defects.

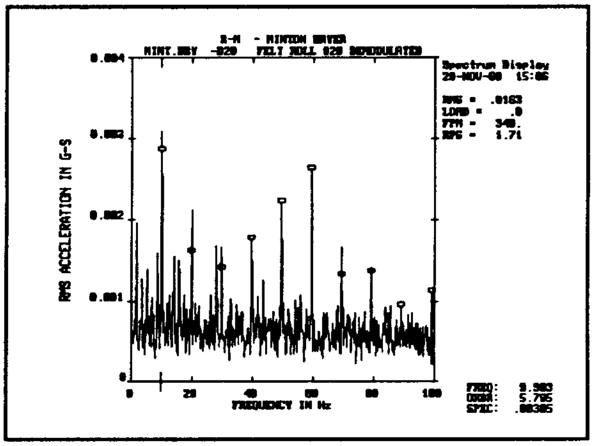

Figure 4: FFT Spectrum Plot of the Time Waveform for the dryer roll bearing assembly, with cursors set on peak frequencies.

There are several major objections to a total reliance on PM methods, however. First, overall industry data reveal that up to 10% of machinery replacement parts are defective when installed; routine exchange of parts therefore sometimes introduces problems into machines where none existed before! Additionally, even if a replacement part is defect-free, improper installation also risks introducing a new problem in a machine. Furthermore, mechanical failure patterns are typically randomly distributed, limiting the efficacy of scheduled maintenance. Such realities undercut a principal assumption of preventive maintenance: that of erring on the side of caution.

An additional shortcoming of the PM approach concerns waste; routine replacements mean that perfectly serviceable equipment components are inevitably discarded, driving up costs.

Fundamentals of Vibration Analysis

Figures 3 and 4 are examples of typical computer graphic displays of a vibration monitoring location, in this case a roller element bearing assembly for a large, continuous paper roll dryer. The vibration energies revealed by these plots point toward a defective inner bearing race, one emitting a sharp acceleration energy spike in the time waveform each time a bearing passes through the "load zone" of the race assembly. The FFT, or Fast Fourier Transform algorithm, decomposes a complex time waveform signal into its frequency domain harmonic components. The plot depicted in Figure 4 is an FFT frequency plot of the time domain waveform shown in figure 3. Vibration analysts use the data provided by the FFT spectrum to isolate the often obscure sources of machine problems. Various types of equipment dysfunction exhibit predictable FFT spectral patterns enabling the analyst to quickly determine the sources of problems and predict (and thereby prevent) impending failures or unacceptable product runs.

Vibration signals are collected during routine operations through probes, or transducers, which are placed at strategic sampling locations. Vibration signals are converted to DC voltage energy which is then digitized by an analog-to-digital (ADC) converter and stored in the computer for subsequent analysis. Once digitized, the vibration data are easily manipulated for display and analysis in a variety of formats such as instantaneous, average, or RMS (Root-Mean-Square) velocity or acceleration, or mechanical Peak-to-Peak displacement (in mils or microns). Vibration data are typically recorded and observed over time for trend analysis. Frequency band-specific alarm thresholds may be set to warn the analyst of excessive vibration levels, a concept similar to the SPC control limits common to QC work, and the alarm frequency band threshold values may even be set up to shift as a function of machine speed to provide flexibility in monitoring variable-speed, variable load equipment. For example, figure 5 is an depicts an FFT spectrum plot of a gearbox containing a selective frequency band alarming envelope. Notice the cursor set at the fundamental frequency of 15 Hz (equivalent to the running speed of 900 RPM). This example reveals RMS acceleration peaks exceeding the alarm limits at several frequency regions, and would likely precipitate an investigation into the sources of the excessive vibration. The analyst would take particular note of the fact that the energy peaks are distinctly related as integer harmonic multiples of the 15 Hz running speed. The high acceleration peak at the fundamental frequency ("1 x RPM") would tend to indicate an unbalance condition. The presence of a substantial 2nd order peak (2 x RPM) would merit a check for looseness or shaft misalignment. The absence of any elevated non-synchronous spectral components tends to eliminate the possibility of vibration contributions from other sources (e.g., poor gear mesh, or energy contribution from a nearby motor not coupled to this component).

Vibration measurement location data are typically stored in a database, and may be instantly recalled for multi-spectrum plotting to reveal vibration trends. This "trending" analysis is particularly important for identifying and correcting mechanical problems before they result in equipment failure or defective product. Figure 6 is an FFT overlay plot of actual vibration data taken near a bearing housing in a large industrial continuous roll paper machine. The inner bearing race suffered an increasingly severe spawl, and this damage was reflected in the vibration signatures recorded and displayed by the PDM crew. The manufacturer estimated the savings at approximately $100,000 by avoiding a run to failure. This impending failure may well have been detected by QC inspection of the process output, but at a possibly substantial cost in wasted product, and potentially leaving little time to spare in scheduling shutdown and repair. Clearly, the vibration analysis program earned its keep in this example.

Vibration Analysis of Transient Events

Programs are available to display the vibration signatures of transient vibration phenomena such as those encountered under machine startup or coastdown conditions. Such a capability is useful for verification of proper operating condition of new equipment, repairs to existing machines, and assessment of variable-speed/variable-load equipment. For example, figure 7 illustrates a set of vibration spectra derived from a 300 horsepower industrial electric motor. The slanted axis represents RPM increase over time (the "z-axis" on this array of FFT plots). This type of "cascade" plot reveals, among other characteristics, the resonant frequencies of a machine (i.e., the RPM at which the natural vibrational damping of the machine is at a minimum, resulting in maximum system vibration). Cascade plots help determine optimal operating speeds and aid in verification of corrective damping adjustments. The motor depicted here suffered from loose and broken rotor bars. A post-repair cascade plot revealed a marked decrease in the amplitudes of the upper harmonic "noise" visible in figure 7.

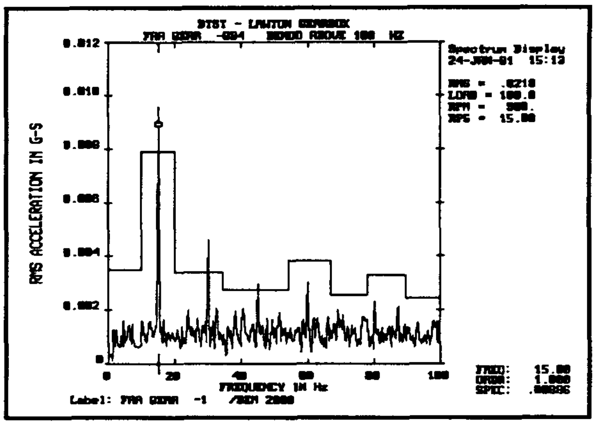

Figure 5: An FFT spectrum with frequency alarm band overlay.The alarm amplitudes may be programmed to shift as a function of RPM.

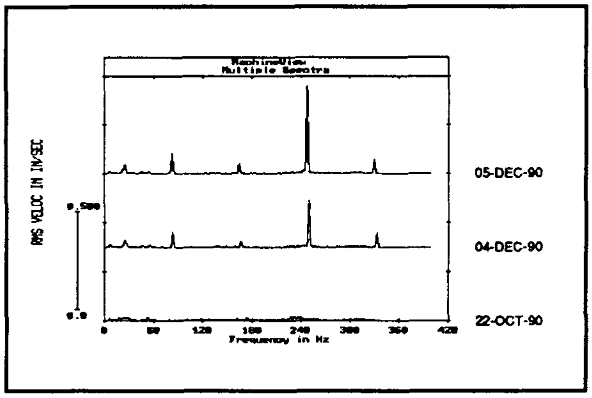

Figure 6: Multiple FFT frequency domain spectra revealing impending bearing failure in a paper machine press roll.

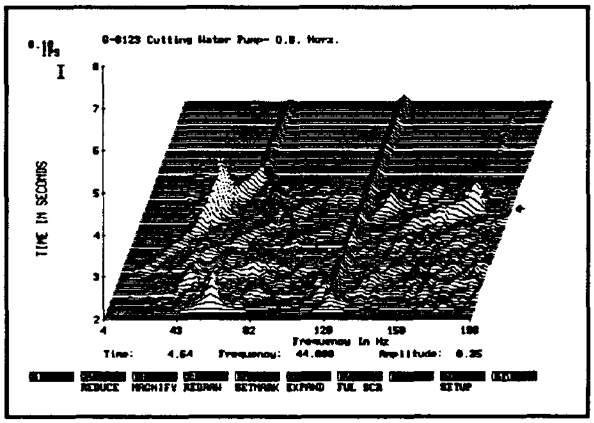

Figure 7: A Transient Plot of the vibration characteristics of a machine at startup. Note the changes in the signature at various RPM.

Related PDM Techniques

While vibration analysis is the predominant method employed in PDM systems, a variety of diagnostic tools exist for monitoring machinery condition. Thermal techniques, using infrared probes, provide for analysis of heat emanations from pressurized steam energy systems. Oil analysis is used to assess the internal condition of engines by analyzing the wear particle, viscosity, and contaminant levels of lubricants. Acoustic analysis is a close cousin of mechanical vibration analysis used in a variety of diagnostic applications. These technologies, long recognized for their utility by progressive maintenance departments, are equally useful to the QC function.

PDM: A Quality Control Technology

Maintenance departments and quality control departments ultimately work toward the same end: increased profitability through quality processes and products. An ailing manufacturing system inevitably degrades sufficiently to be revealed through unacceptable product. Traditional SPC programs attempt to minimize production losses by pinpointing the sources of excessive variability as expressed in the attributes of the products themselves. Predictive Maintenance technologies, on the other hand, facilitate the identification of the causes of excessive variability even before they surface in poor quality output, providing Maintenance and QC functions with powerful and cost-effective tools for assuring quality product output while reducing operating costs. ❐