Vibration Measurement to Condition-Based Management

Closing in on a Century of Continuous Progress

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Over many decades, dramatic improvements have occurred in the technology, equipment and practice used for vibration measurement, condition monitoring and analysis. From rudimentary instruments that measured overall vibration amplitude to today's high-performance transducers, digitally enhanced hardware and software, the improvement has been striking. The ability to assess condition, detect and diagnose anomalies would be beyond belief to those who formed the basis for today's knowledge and technology. With most of the pioneers no longer with us, it is imperative that those who benefit from their beginning today – recognize and celebrate the names and accomplishments of those who came before. These individuals, who contributed so much, are owed a large debt of gratitude.

A narrative of the advancement of the technology and application of vibration measurement to industrial machinery can be defined in at least six major stages. Each has greatly improved the effectiveness and results gained from vibration as a measure of mechanical condition. From a simple overall amplitude measurement nearly 80 years ago, to the complex dynamic characteristics used today for a detailed picture of condition, vibration monitoring, condition assessment and condition-based maintenance have become essential for safe, reliable and effective operation of today's modern process, production and manufacturing facilities.

The Beginning – Condition Quantified

Vibration Measurement and Severity Assessment. Vibration as an indicator of condition undoubtedly originated with the first machine ever produced. Operators and mechanics must have felt cold fear in the presence of a badly shaking machine.

Most attribute the beginning of the modern era of industrial vibration measurement to T. C. Rathbone. Rathbone, then chief engineer, Turbine and Machinery Division, for the Fidelity and Casualty Company of New York, originated the first guidelines for judging machine condition from vibration measurements in a 1939 paper published by *Power Plant Engineering*. The paper, titled "Vibration Tolerance," provided a guide for condition assessment based on vibration displacement from approximately 60 to 7,200 cpm (1 Hz to 120 Hz).

The Rathbone paper introduced a set of amplitude-versus-frequency severity curves that approximated constant velocity around the rotating frequencies of typical steam turbine generators. The Rathbone severity criteria were based on observations and represent the first known method for equating vibration amplitude with condition, and by implication, risk of failure and service life. It is amazing to recognize that the concepts and severity criteria developed by T. C. Rathbone continue to serve us well today – nearly 80 years later!

Development of Electronic Vibration Measurement. Much of early vibration measurement was accomplished with physical senses and mechanical devices. At some point the electromechanical, moving-coil velocity pickup appeared to provide quantifiable electronic measurement. The velocity pickup was reasonably robust, self-generating and produced an output that could be measured with a voltmeter.

Second Stage – Introduction of Vibration Analysis

As practitioners gained experience, there was a growing recognition that while amplitude was a good measure of condition, frequency and frequency patterns indicated the type of defect present. Full exploitation of this theory was limited by very primitive instrumentation compared with that in use today.

Figure 1. Tuned filter vibration analyzer, 1970

The current era of vibration analysis likely began in 1950, when Art Crawford, then a graduate student who became a universally respected visionary in the industry, accepted a challenge to develop a means to balance high-speed spindles. Based on his results and future potential, he incorporated IRD Mechanalysis in 1952. IRD became the advocate and leader in frequency analysis, condition assessment utilizing external measurements and dynamic balancing for more than 30 years.

Most electronic vibration instruments of the era measured overall velocity amplitude and velocity integrated to displacement. Displacement became a preferred condition measuring variable, perhaps because an analyst had an easier time explaining displacement as a measure of machine condition even though velocity had proven more representative. Later instruments included manually tuned filters, see Figure 1. The latter provided the basis for identifying amplitude and frequency patterns now associated with common problems.

A major milestone occurred in 1968 when John Sohre, a prominent contributor to both machine design and analysis, published "Operating Problems with High-Speed Turbomachinery, Causes and Corrections." The paper introduced the famous "Sohre charts" defining the vibration symptoms of turbomachinery problems along with probable causes. The paper and charts were republished numerous times in several languages and conceptually formed the basis of much of today's detailed diagnostic technology.

By the early 1970s, a number of companies were offering electronic instruments and various forms of methods for measuring and analyzing industrial machinery vibration. The visionary efforts of Don Bently and the Bently Nevada Corporation (now a part of GE Digital Solutions) strongly advocated time domain and orbital analysis from installed shaft displacement sensors. IRD Mechanalysis (later absorbed by Entek and now a part of Rockwell Automation) was certainly a very influential pioneer. IRD promoted velocity-based periodic casing measurements and filtered frequency domain analysis. Ray Data, later merged into Reliance Electric and Vitec also advocated casing vibration measurements. General Radio Corporation and Schenck (now Brüel & Kjær Vibro) were two other companies offering vibration-measuring and analysis instrumentation.

Early Efforts at Periodic Condition Monitoring. Beginning in the late 1960s, many facilities initiated programs of periodic manual condition measurement. One or two people would use a velocity sensor and vibration meter to record vibration amplitude on external bearing caps. Measurements were typically overall levels in an ordered sequence at strategic points on plant machinery. Vibration amplitudes were recorded numerically on log sheets and trended manually. Those engaged spent about 80% of their time manually logging and trending data. For the most part these programs were abandoned because of the high proportion of time required for data collection contrasted with the time remaining that could be devoted to obtaining results by value-added defect identification and analysis.

Frequency analysis, accomplished with a manually tuned filter, was a tedious and time-consuming process that was only justified when high overall amplitude indicated a problem. The velocity pickup itself simplified the task by inherent force and frequency limitations that limited the sensor output. Manual frequency analysis did not provide much detail beyond the strongest few components in a relatively simple vibration signal so was not of much value as early warning of deteriorating condition. Real gains in early-warning machinery analysis using the extended frequency range of accelerometers had to await the introduction of real-time FFT frequency analyzers into the industrial world beginning in the early 1970s.

Third Stage – Shaft Monitoring and Protection

Non-Contact Proximity Measurement, Continuous Monitoring and Protection. In the mid to late 1960s the noncontact, eddy-current, proximity probe was applied to measure shaft motion relative to its bearing housing. Two individuals participated in the birth of this concept: Don Wilhelm (Helm Instrument Co.) and Don Bently. Bently rightfully deserves most of the credit for his vision and great perseverance to develop and refine shaft-monitoring technology for rotating machinery, advocate the necessity and benefits. He essentially initiated and drove the modern era of installed machinery monitoring, protection and analysis.

By the mid 1970s, noncontact, proximity measurement and continuous shaft displacement monitoring from X-Y shaft displacement sensors mounted 90° apart had gained near universal acceptance as the preferred method for monitoring the mechanical condition of large turbomachines with fluid-film bearings. Today, shaft displacement monitoring and alarming systems are considered an essential part of the protective instrumentation for all mission-critical machinery equipped with fluid-film bearings.

Time domain and orbital analysis, pioneered by Bently Nevada consisted of viewing phase-referenced X-Y signals directly on an oscilloscope. This method provided direct insight into shaft motion relative to its bearing. The technology and companion diagnostic analysis provided the basis for understanding and solving the greatest problem encountered by turbomachinery in the 10 or so years from 1965 to 1975 – subsynchronous instability.

Subsynchronous Instability. Serious rotor dynamics problems arose during the late 1960s and early '70s as machine manufacturers doubled, and in some cases even tripled, the size and rotating speed of existing designs to meet requirements for greater production output. Designs and design calculations existing at the time were inadequate for the new size and rotating speed regime. A few machines were unable to successfully traverse the first critical speed due to excessive vibration. Some machines that had been operating successfully for years suddenly developed high vibration that required immediate shutdown or worse, resulting in catastrophic failure. Solution often took weeks of trying this and that until something succeeded.

These were very eventful times in the field of rotor dynamics as well as vibration monitoring and diagnostic analysis. Shaft displacement measuring systems allowed rotor stability problems to be observed, dissected and analyzed in time segments. Improved designs were in turn validated by the same measurements. The history of solving subsynchronous instability is far too long to address here; however, the impact on continuous vibration monitoring must be noted.

A large portion of the credit for developing the science of rotor-bearing analysis and stability goes to researchers at Mechanical Technology Incorporated (MTI) founded by a group of engineers from General Electric, notably Jørgen Lund, one of the greatest practical researchers in the field of rotor dynamics.

In addition to pioneering the measurement technology, Don Bently and The Bently Nevada Corporation made a major contribution to rotor dynamics analysis for identifying and solving bearing instability. Technology leaders such as Ed Gunter and his colleagues at the University of Virginia used shaft-displacement measurements to develop and advance the theory of rotor dynamics as well as computer programs that contributed significantly to stable bearing designs and dynamic balancing. Developing modifications to assure the stability of the space shuttle propulsion pumps is an illustrative example.

Neville Reiger (Rochester Institute of Technology and MTI and later founder of STI) made a major contribution to the knowledge of rotor dynamics and balancing flexible rotors. Mike Adams at Case Western University extended bearing stability analysis with nonlinear rotor dynamic analyses of large turbine generators that solved many problems.

For a number of years, MTI had a very successful field service group led by Don Wilson that applied the latest rotor dynamic technology to solve industrial machinery vibration problems. The group may have been the first to apply advanced rotor dynamics to field problems. Others, included Southwest Research Institute (SWRI), Engineering Dynamics, Inc (EDI), founded by Buddy Wachel and several individuals including Bernie Herbage, Dana Salamone; John Nicholas, Rotating Machinery Technology, Inc.; and Malcolm Leader, Applied Machinery Dynamics Co. Many of them were educated at the University of Virginia under Ed Gunter and provided vital services to solve bearing design and rotor dynamics problems.

Continuous noncontact shaft displacement monitoring systems had been totally accepted as essential protection for large, turbomachines by the mid to late 1970s. The cost justification process that had been the subject of many papers heated conference discussions and emotional internal arguments were no longer necessary. Leaders such as John Sohre and Brian Erskine (ICI) refined criteria for judging the severity of relative shaft vibration.

Fourth Stage – Condition Monitoring Expands

In early 1979, Charlie Jackson (Monsanto), a giant presence, terrific humorist and great personality to whom all in the field owe enormously, published a pacesetting book: *The Practical Vibration Primer* – the first effort to document the great expansion of vibration practices and interpretation that had occurred during the 1970s. It provided a solid knowledge base on which analysts could learn and build. Since Jackson's primer, a number of excellent books have been published on vibration analysis by industry notables such as Ronald Eshleman and Robert Eisenmann.

Technology Advances – Accelerometers and Tape Recording. Beginning in the early 1960s, the aerospace testing community began driving a new generation of standardized instrumentation for missile testing. Highly accurate multichannel FM (frequency modulated) magnetic tape recorders (lower left Figure 2) and acceleration sensors developed for missile testing were adopted by the machinery analysis community in the early 1970s.

The accelerometer has a much broader frequency range compared to a velocity sensor. It opened a new window into predictive analysis for equipment such as bladed turbines, gears and machines equipped with rolling-element bearings.

Initial accelerometers used for machine analysis were taken directly from testing catalogs. Charge-conversion electronics were required prior to input to a display, recording or analysis instrument. Introducing internal conversion electronics by innovators

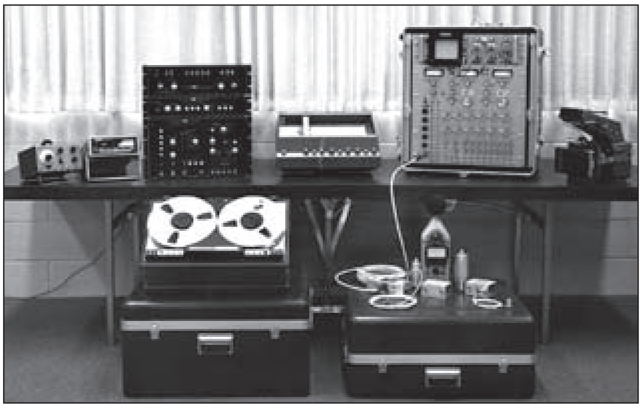

Figure 2. 1970s' data acquisition and analysis system; real-time analyzer table on left, multi channel tape recorder below.

Figure 3. Analysis van – inside view of instrumentation; note the real-time frequency analyzer and plotter similar to those shown in Figure 2.

such as Kistler and PCB Piezotronics largely eliminated the problems and made acceleration sensors practical for use in industrial environments. Today, virtually all acceleration sensors used in industrial applications are of this basic design. Some include internal integration to produce a velocity output.

Vibration collected with portable tape recorders provided the basis for most predictive monitoring programs through the mid 1980s. In a tape-recorder-based condition monitoring program, vibration sensors were connected to the tape recorder, typically through pre-amplifiers, and the signals recorded for a short time. The signal was later reproduced in an analysis lab, passed through a spectrum analyzer and plotted. The results were manually examined for anomalies and compared to prior spectra to identify trends.

Instrumentation tape recorders manufactured by Ampex, Hewlett Packard, Lockheed Electronics, Sangamo, Honeywell and later Teac with both direct and FM channels were adopted to gain the frequency response needed for detailed analysis. FM recording had the advantage of a linear response to below-shaft rotating frequencies. Multichannel tape recorders permitted capturing transient vibration characteristics and instantaneous shaft position simultaneously from multiple locations for detailed analysis. Combined with the noncontact shaft displacement pickup multichannel FM tape recording provided the data, insight, and later validation for solving the bearing stability problems mentioned earlier.

Note that the early instruments for recording vibration signals were physically large, heavy and cumbersome. Some visionary facilities mounted the bulky equipment necessary for detailed condition monitoring and analysis in a van or trailer to minimize the set up required (see Figure 3).

Developments in the US Navy. Beginning in the late 1960s and early '70s, the US Navy began developing condition monitoring technology to improve the reliability and predictability of shipboard machinery. The most advanced submarines were equipped with 1/8th- and 1/10th-octave-band analyzer systems from General Radio Corp. (GRC). Its strip chart recorders were installed with the systems to provide a permanent record of readings for comparison analysis.

Ray Misialek at the Naval Ship Engineering Support Center at the Philadelphia Navy Yard may have been one of the first to evaluate aerospace accelerometers for the task of monitoring industrial machinery. Using acceleration sensors, the Navy surface fleet adopted octave-band analysis and a system of "Chapman Numbers" consisting of logarithmic condition levels expressed in dB acceleration, velocity and displacement. The methods were designed to provide an optimum indication of condition from relatively simple and easily interpreted numerical measurements.

Gas Turbine Engines. Over the years, the necessity for monitoring both the mechanical condition and aerodynamic performance of gas turbines has been recognized and accepted. With the advent of wide-body commercial aircraft, the engine vibration-monitoring system became an integral part of the onboard flight instrumentation. Aero engine monitoring systems pioneered by Endevco and Vibro-Meter used high-temperature accelerometers and tracking filters. Filtered amplitude at rotating frequency was displayed on cockpit indicators. The same system was essentially applied to monitoring systems installed on aero-derivative gas turbines in stationary and shipboard applications.

With time, users of large industrial gas turbines who recognized the advantages of shaft displacement monitoring on machines equipped with fluid-film bearings, began to demand non-contact shaft displacement probes and continuous monitoring systems. Bently Nevada developed the application, and the noncontact shaft displacement monitoring system is essentially standard today on large industrial gas turbines equipped with fluid-film bearings.

Many users of gas turbines found that aerothermal performance was a better measure of condition than vibration, since combustion path anomalies are more prevalent on a typical gas turbine than mechanical defects. Hamilton Standard led the development and installation of gas turbine performance-monitoring systems focused primarily on thermodynamic analysis and operating efficiency.

Concurrent Advances in Monitoring and Analysis Technology. Many individuals, including Jack Frarey, then at MTI and later Shaker Research, Ralph James at Exxon and Bruce Baird at Boeing developed methods for early recognition of rolling-element bearing defects using high-frequency vibration enveloping and other techniques. The work accomplished by these and other pioneers forms much of the basis for current success in this area.

Ralph Buscarello, another major presence in the industrial vibration field, contributed greatly to the body of knowledge and practice of vibration analysis and condition assessment. Concentrating on measurements and methods that could be easily used by field practitioners, Ralph added significantly to the body of diagnostic knowledge with methods of diagnosing common problems from amplitude and phase information.

A description of analysis methods would not be complete without mentioning the work of three individuals who contributed significantly to the body of knowledge in gear and bearing analysis. James I. Taylor developed methods for bearing and gear analysis using spectrum shapes and time-domain analysis. Robert Randall at Brüel & Kjær refined cepstrum analysis, essentially a spectrum of a spectrum, for gear analysis. He authored two excellent articles describing the technology of machinery monitoring in the March and May 2004 issues of *Sound &Vibration*. Jim Berry advanced analysis technology with a series of comprehensive and highly practical diagnostic charts.

Parallel Developments of Condition Assessment in the Soviet Union. Alexei Barkov of VAST, Inc., St. Petersburg, Russia, contributed the following description of the development of Russian methods to detect rolling-element bearing defects (for a full description see "Condition Assessment and Life Prediction of Rolling Element Bearings" in the June and September, 1995 issues of *Sound &Vibration*):

In about 1971, the Soviet Navy gained information that the shock-pulse method was very efficient for rolling-element bearing diagnostics and flaw detection. In 1976, our laboratory became aware of the Boeing success in detecting rolling-element bearing defects. We applied our techniques and published results including the algorithm for calculating modulation index from the envelope spectrum.

Beginning in 1980, a standard of the Soviet shipbuilding industry was prepared by our team. The standard covered the condition diagnostics of rolling-element bearings utilizing high-frequency envelope spectrum analysis. We published the first open paper devoted to these methods in 1986 in the Shipbuilding Journal.

Condition Assessment Standards. During the 1960s, Michael Blake, then with Monsanto Chemical Company, published a refinement of the Rathbone severity chart. The full Blake chart is reproduced in the book by Ronald Eshleman, *Basic Machinery Vibrations*, VI Press Inc., Clarendon Hills, IL - ISBN 0-9669500-0-3.

In 1972, Michael Blake formed the Vibration Institute to advance the technology and application of vibration measurement and diagnostic technology. Through the superb efforts of Ron Eshleman, the Vibration Institute has become a focal point for condition assessment technology, diagnostic knowledge and technical certification. As an added note, the Mechanical Failures Prevention Group (MFPG) was formed about the same time as the Vibration Institute to provide a forum and facilitate reliability improvement within government agencies and the military. The MFPG and Vibration Institute connected at the top levels in 1990 and it became a division of the Institute. Success of the MFPG, later changed to the Society for Machinery Failure Prevention Technology (MFPT) from 1990 to 2006 was largely due to the efforts of Henry Pusey and his wife Sallie. Later, Treble-One of Dayton, Ohio, under Chris Pomfret, successfully managed MFPT.

In 1964, IRD published a copyrighted vibration severity chart to serve as a guide for assessing machinery condition. The IRD chart was based on filtered vibration levels measured externally on a machine casing with a velocity pickup in nine categories of constant velocity condition ranging from extremely smooth to very rough.

While the IRD casing criteria worked well for most equipment of the time, it could be misleading when applied to some machines, particularly the high-speed turbomachines then entering service. Generalized severity criteria based on casing velocity were essentially useless when applied to high-pressure compressors with heavy, stiff casings, light rotors (high-casing-to-rotor weight ratio) and fluid-film bearings. As noted earlier, shaft relative motion, measured with noncontact displacement probes, was the only way to accurately assess condition.

Absolute shaft vibration was recognized as a necessity to assess condition on large, slower speed machines; typically turbo generators operating at synchronous or half-synchronous speed. These machines have significant variations in stiffness between bearings and typically were equipped with permanently installed, spring-loaded, shaft-riding (contacting) velocity transducers for continuous monitoring and protection. Shaft riders were prone to lifting from the shaft at high amplitudes and therefore often did not represent true motion and condition. Shaft riders were replaced with a dual-sensor combination of noncontact shaft displacement probe and casing sensor with the outputs combined electronically.

Additional standards were introduced in the 1970s. Dresser Clark published a widely used standard for shaft displacement that included the now-familiar decline in allowable displacement amplitude with frequency for a given condition.

In 1972, the American Gear Manufacturers Association (AGMA) released a standard for gear acceptance that included constant acceleration above 1,000 Hz similar to Blake. During the same period, the American Petroleum Institute (API), led by visionaries including Charlie Jackson, Murray Rost (Mobil) and Dick Dubner (Chevron) developed a series of specifications for machine design, minimum margins to critical speeds, vibration acceptance, balance quality and sensitivity to rotor unbalance (stability). All were based on the hard-learned lessons to achieve rotor bearing stability and proved highly successful to improving machine design and operating reliability.

In 1974, the International Standards Organization (ISO) published several vibration standards that included vibration severity. The contribution of Ed Noonan of the David Taylor Model Basin, Paul Maedel and Stewart Maxwell, the founder of the Canadian Machinery Vibration Association, must be noted.

American Petroleum Institute Standard 670, "Vibration, and Axial-Position Monitoring Systems," is another key standard that shaped condition monitoring technology and practice. Originally conceived by a group of highly visionary users led by V. Ray Dodd of Chevron and Charlie Jackson, API 670 was developed as a definitive standard for shaft displacement monitoring systems to assure reliability and standardization. Currently in its fifth edition, the principles that emerged have been refined and enhanced over the years to define continuous condition monitoring and protection systems for mechanical equipment.

In the early 1990s, General Motors published a highly detailed standard for vibration acceptance based on external measurements. This standard was the product of a task force ably led by Jim Pyne. The standard specifies vibration amplitude criteria in frequency bands for several classes of equipment ranging from precision machine tools to general-purpose motors and fans. It is by far the most detailed standard for casing vibration acceptance criteria and has been modified and adopted by many companies outside the automobile industry.

Fifth Stage – Real-Time/FFT Frequency Analyzer

Shaft displacement and casing velocity measurements provided great insight into common problems; however, both were limited in frequency response. Shaft displacement by the force needed to produce a measurable displacement at high frequencies and the amplitude roll off above approximately 1,500 Hz of most velocity transducers. By the late 1960s, there was growing awareness that higher frequencies held a great deal of information that provided early identification of anomalies that could lead to failure.

Medium frequencies included pump vane-passing frequency, symptoms of cavitation and components related to specific defects on rolling-element bearings. Still higher were gear mesh and blade-passing frequencies related to the performance and long-term health of these components. Higher yet were frequencies generated by impacts from defects in rolling-element bearings.

Accelerometers provided the window into medium- and high-frequency condition characteristics; however, most analysis methods available at the time weren't able to differentiate individual frequencies within complex signals. Early efforts to mechanize the filter process were largely unsuccessful. Enter the real-time analyzer (RTA).

Real-Time Analyzer. Federal Scientific was the first to offer a time compression RTA in the mid 1960s. The concept of time-compression analysis originated from speeding up a tape loop to reduce the time necessary to measure amplitude at lower frequencies set by the period of the lowest frequency of interest. At that time, digital shift registers became available to implement a storage loop from which a segment of a stored waveform could be read out nondestructively at an accelerated rate.

The Federal Scientific team, led by Henry Bickel, deserves full credit for designing and implementing the initial RTA. They had the courage to be among the first to implement using leading-edge integrated circuits (ICs) that had no history at the time.

Referring back to Figure 2, RTAs like that at the upper left were capable of transforming complex vibration signals into amplitude versus frequency spectrum in essentially real time. For the first time, complex vibration signals from accelerometers could be decomposed into individual components, "signatures" in the frequency domain for quantitative comparison, identification of mechanical defects and trending. The RTA opened an entire new window of machinery analysis to detailed assessment.

By providing dramatic new insight into the behavior of high-frequency dynamic vibration signals, the RTA provided a first look at the complexity and variations that form the basis of much of today's rolling-element bearing, gear and electro mechanical condition assessment. RTAs contributed significantly to the understanding of lower-frequency dynamic problems by allowing the frequency response of equipment to be viewed in real time during transients such as startup and coast-down.

Some of the early work with real-time frequency analysis was accomplished by David Mellen and Larry Mitchell, then with DuPont. Mitchell, later at Virginia Tech. Spectral Dynamics Corporation published a number of application notes that described real-time analysis for machinery, especially gear diagnostics. Richard Burchill at MTI was performing field analysis with this technology in the late 1960s, early '70s. One of the first papers describing spectrum analysis for machinery condition monitoring directed at a user audience was delivered at the Texas A&M First Annual Turbomachinery Conference in 1972: "Applications of Spectrum Analysis To Onstream Condition Monitoring and Malfunction Diagnosis of Process Machinery."

Application to Condition Analysis. With this new technology, many companies initiated extensive programs of detailed time and frequency analysis on critical machinery. Since critical machines were, for the most part, monitored continuously with noncontact shaft displacement systems located in the control room and the monitors had external outputs, access to the shaft displacement signals was relatively easy.

Most companies that embarked on detailed periodic analysis programs supplemented measurements from installed sensors with additional measurements recorded from temporarily installed casing sensors. This led to a great deal of insight into the varying response characteristics of shaft-relative and casing-seismic measurements and the presence of failure precursors in the casing signal that were barely or not at all visible in the shaft vibration characteristics and vice versa. There were cases of machines being allowed to operate despite significantly increased noise levels or obviously severe external vibration because shaft vibration had only increased a little. In several cases, broken gear teeth and even shaft fractures caused enormous damage. The reverse occurred as well. Severe shaft vibration appearing on an installed monitoring system was dismissed as an instrument problem and the machine allowed to continue operation because no one could feel excessive external vibration, and casing vibration measurements were inconclusive!

Leading companies such as Exxon, Shell, Amoco (now part of BP) and Chevron quickly extended detailed vibration condition analysis to general-purpose equipment. The process typically included two people and a van or trailer. The van was outfitted with sensors, a long multiconductor extension cable, amplifiers, one or more tape recorders, a real-time analyzer and plotter. To perform a condition analysis, the van or trailer was parked alongside a process unit. One person positioned sensors on equipment in a standard route or sequence. In many cases, the cable connecting sensors and van included two-way communications so that the field person could inform the analyst inside the van of the equipment number and sensor location. The person in the van recorded the signals, performed preliminary analysis and plotted the results on a frequency vs. amplitude chart.

The best vans, exemplified by one constructed by Uri Sela of Exxon, Figure 3, were in reality mechanical measurement facilities that found use well beyond condition monitoring and assessment. Although technically successful, these programs were very labor intensive and most eventually collapsed due to the resources and cost necessary for operation. However, the stage was set for introduction of the portable data collector.

At about this point in time, the mid to late '70s, the term predictive maintenance appeared. Predictive maintenance defined maintenance performed on actual conditions obtained from externally accessible characteristics that could be measured without affecting operation – primarily vibration and lubricating oil. Jim Badders, then with Dow Industrial Service, is the likely originator of the name originated during work in South Africa. Whoever was responsible, the name stuck and is used to this day.

Technical Evolution – the FFT Analyzer. By the late 1970s, time compression analyzers had been replaced by digital fast-Fourier transform (FFT) analyzers. These instruments were based on technology introduced by Tukey and Cooley in a 1965 paper. Although initial units were large and heavy, they benefited from rapid developments in digital hardware and firmware that quickly reduced size and weight compared to time compression RTAs. FFT analyzers rapidly evolved from single-channel to multi-input instruments that typically incorporated a fully featured display, averaging and order tracking in one instrument. Later evolutions provided cross-channel functions including transfer function and coherence.

Sixth Stage – The Portable Data Collector

By the early 1980s, it was clear that packaging a microprocessor capable of FFT analysis with on-board memory in a handheld machinery analysis instrument was an inevitable development. Gerry Mueller with Esso Research and Engineering promoted the concept in about 1980 in a widely distributed paper. The first commercial instrument was the AVM-1, introduced by Tecalamet Electronics in the UK in about 1982. The AVM-1 used an acceleration sensor, recorded vibration levels in octave bands and stored the results in on-board memory, which could be transferred to a computer for trending.

A bit later, Brian Long, Dave Schu and Brian Howes at Beta Monitors and Controls in Calgary Canada introduced the Data Trap. About the same time Brian Long pioneered reciprocating machinery analysis via the pressure volume relationship.

Soon after, Vitec introduced an instrument similar to the Data Trap. Both recorded an instantaneous-time waveform that was converted to an overall level and frequency spectrum in a host microcomputer. The host accomplished automatic trending and notification whenever a monitored value exceeded a preset threshold. The Beta and Vitec instruments were simple to operate and had minimal field displays. The two units gained passionate supporters and were widely used despite the lack of averaging considered essential by most experienced users of FFT analyzers.

In 1983, Technology for Energy Corporation (TEC) introduced the "Smart Meter." The Smart Meter added an internal FFT, amplitude monitoring in six frequency bands, a small FFT display, capabilities for downloading a prearranged "route" of measurements for collection in a logical geographic sequence, on-board storage and PC host software to manage and display the measurements.

IRD Mechanalysis introduced a very similar instrument also in 1983. IRD was awarded a U.S. patent in 1986 for the concept of a route-capable portable data collector.

During this same time, John Hawkins at PPG Industries in Lake Charles, Louisiana, constructed a home-built computerized vibration data collector using standard components and self-developed software. An example of what innovative people can accomplish when expectations are developing faster than commercial technology.

In 1984, Palomar Technology International introduced the first portable data collector with a high-resolution internal FFT analyzer, averaging and a large-screen FFT display. "Micrologʺ was about the same size and shape as today's iPad, although a bit thicker, a bit heavier and with a smaller screen due to battery and display technology at the time. The display was quickly upgraded to include a moveable cursor, frequency and amplitude indication at the cursor position and eventually all of the features of a laboratory FFT analyzer, including zoom and waveform display. This is the basic design that has been constantly extended and substantially improved by Computational Systems, Inc. (CSI), now a part of Emerson Process Management; Diagnostic Instruments of West Lothian Scotland (now a part of SKF), SKF Condition Monitoring, DLI Engineering Corp., (Azima DLI Corporation) and others over the past 25 years.

Combined with PC condition monitoring software, the portable data collector opened a totally new era of machinery condition assessment. For the first time, complex vibration characteristics could be collected easily, subjected to detailed analysis and comparison while minimizing the manual efforts that had doomed prior periodic monitoring programs. The 80-20% collection analysis split mentioned earlier was reversed, with 80% of the total time expended now available for highest-value problem identification and analysis. The ready availability of detailed machinery characteristics, automatic comparison, trending and notification when a measurement went out of limits led to a virtual elimination of unexpected failures by enlightened operating companies who recognized the compelling value of detailed condition assessment programs.

Of equal importance, the analysis and display capability of the portable data collector allowed virtually all analysis to be conducted at the machine. If the operator of the data collector observed an anomaly during collection, the data collector could be used to view, study and record additional characteristics for a greater understanding of the situation. By the late 1980s, computerized data collectors had largely replaced tape recorders for routine monitoring. Multichannel digital data acquisition systems essentially eliminated the last bastion of tape recorders within machinery monitoring and condition assessment by the mid 1990s.

Time Marches On – Progress Continues

Computerized Diagnostic Monitoring Becomes a Reality. As periodic diagnostic vibration monitoring gained success and acceptance, it became apparent that some vital equipment and components that could benefit from condition assessment were not safely accessible for collecting measurements during normal operation. Paper machine bearings, cooling tower fan reduction gears, underwater pumps and many bearings on machine tools fall in this category. The first logical idea was to permanently install sensors, typically accelerometers, and lead the cables to a safely accessible location where they could be periodically monitored with a portable data collector. Terminating the sensor cables at a rotary selector switch greatly facilitated data collection. PCB Piezotronics, IMI, Vibra-Metrics, Wilcoxon Research and others were quick to supply the selector boxes.

Compass, introduced by Brüel & Kjær in 1992 and based on an earlier system developed for a North Sea oil production platform, was one of the first if not *the* first installed monitoring systems to include both protective (fast response) and predictive diagnostic (detailed analytical) monitoring in a single integrated system. In addition to both protective and predictive monitoring from connected sensors and full integration with data recorded with a portable data collector; the Compass system included an ability to define separate monitoring strategies by machine state – an innovative method of data compression developed by Eric Tomassen of B&K – and network transmission.

With Internet capability, detailed condition assessment information from machines and machine components are instantly available anywhere in the world. It's no longer necessary to be physically at the equipment to perform a full diagnostic analysis.

Additional Condition Measurement Technology. By the mid 1990s, it was becoming apparent that vibration condition measurement technology was much more effective when combined with complementary additions. These included lubricating oil debris and chemical analysis, motor current analysis, thermography, flux analysis, ultrasonics, operating performance and efficiency.

Lubricating oil chemical analysis had been available since the 1950s. Ferrographic debris monitoring, originally developed by the Foxboro Corporation, had been available since the mid 1970s. Both had been treated as separate technologies and seldom combined with vibration to form a more complete picture of condition. Beginning in the late 1990s, condition monitoring software systems began to incorporate vibration, fluid analysis and other condition defining data.

Motor current analysis, initially developed by William Thompson of the Robert Gordon Institute in Aberdeen, Scotland, utilized a current sensor and zoom FFT to monitor the amplitude of slip-frequency sidebands around line excitation frequency. The ratio of sideband-to-line frequency amplitude, measured in dB, proved to be a good measure of the electro magnetic condition of an induction motor rotor. The method has been refined and continues in use.

Today's best predictive monitoring programs integrate all technologies and measurements from on- and off-line sources. These technologies have been significantly improved over the past 25 years, and their use has greatly expanded among industry-best companies. Many credit broad use and integration of condition assessment and performance monitoring technologies within a value-driven reliability program as primary factors to their overall success.

The Missing Element – Clear Financial Justification

No article describing condition assessment and condition-based maintenance would be complete without a statement regarding the necessity of financial justification. Despite well over 50 years of demonstrated success and benefits, condition assessment programs are still not fully accepted within an industrial operating culture as a permanent, essential business activity. Many tremendously successful programs are reduced or terminated altogether as a "cost-saving" measure, because the program has been successful and failures are scarce. With primary interest in analysis and details such as determining that a bearing is failing due to a defect on the outer race, many successful practitioners fail to recognize the importance of demonstrating the business value they and their condition assessment program contribute to their companies.

At a recent vibration conference, participants were asked how many thought their efforts were recognized and appreciated by their companies for value produced. One individual in the group of about 150 raised his hand! In a survey, people were asked how they justified their condition monitoring programs. One replied, "We don't do money." Perhaps there is a connection between not doing money and lack of full appreciation for value added by condition assessment programs!

It should go without saying that if the work and results developed over the last 80 or so years by the giants who contributed so much to the field of condition assessment are to be continued and extended, current practitioners and those who follow will have to do a great deal more to promote and demonstrate the essential results and value of the practice and technologies.

The key to success is no longer about technology, but awareness and promotion of value delivered to the enterprise!

Acknowledgments

Thanks to Max Wishaw, of Wishaw Engineering Services, Perth, Australia, for recognizing that 1999 marked the 60th anniversary of the first paper published on condition monitoring and suggesting that it would be most fitting to celebrate with a historical perspective of our progress. He began the process with a paper delivered in Perth in 1998 from which this grew. Thanks to the friends of many years who were willing to read and comment on various drafts: James Berry (Technical Associates of Charlotte) for his comments on the initial version published in the November 1999 issue of *Sound & Vibration*; Heinz Bloch, the late Jack Frarey, John Hawkins and Uri Sela for their comments. Special thanks to Ronald Eshleman (Vibration Institute), a major contributor to the success of this industry and a terrific friend over the years, for his excellent comments on the 1999 version and major contribution to the 2007 version on which this is based. Special thanks also to Art Crawford, a pioneer and truly admirable person in every way, for his reminiscences on the beginnings of IRD and frequency analysis.

As a final note, the narrative sequence generally follows topics and may be out of chronological order in some places. For skipping around in the narrative and any discrepancies from fact, notable developments and participants who might have been inadvertently omitted (such as participants and discussions at the wonderfully enlightening Engineering Foundation Conferences held during the 1970s that gathered people from multi disciplines working with similar technology) or not given full credit for their contribution, the author takes sole responsibility and apologizes. SV

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