# From Vibration Measurements to Condition Based Maintenance Seventy Years of Continuous Progress

John S. Mitchell, San Juan Capistrano, California



John S. Mitchell conducts Asset Management/Optimization workshops, provides coaching, advice and support for organizations committed to improving the productivity, utilization and effectiveness of physical plant and equipment assets.

Positions held include: Site Manager in a large petrochemical complex leading the implementation of a comprehensive, site-wide asset productivity improvement and maintenance process transformation initiative: Vice President Mainte-

nance Operations and Engineering with ABB, Inc; founder and

Over the last seventy or so years, dramatic improvements have occurred in the technology, equipment and practice used for machinery vibration measurement, condition monitoring and analysis. From mechanical instruments that might capture a simple, low frequency vibration waveform to today's high performance digital instrumentation, detailed fluid chemistry and oil debris analysis, motor current and circuit analysis, ultrasonics and thermography, the change has been striking - especially over the past twenty years. Adoption of the microprocessor field data collector/analyzer, the PC for automated monitoring, diagnostics and information management combined with major improvements in electronics and signal processing technology have greatly advanced the ability to assess condition, detect and diagnose anomalies. It is almost beyond belief that today's portable data collectors have greater functionality and performance than an entire truckload of laboratory analysis instrumentation less than twenty-five years ago! Today, the earliest stages of most flaws can be recognized in ample time to minimize the impact on production and avoid outright failure. Condition Monitoring and Condition Based Maintenance (CBM) have indeed come a long way! The path taken and how we arrived is an interesting story - the individuals who contributed so much are owed an enormous debt of gratitude.

A narrative of the progressive advancement of the technology and application of vibration measurements to industrial machinery can be defined by at least five major developments, Figure 1. Each has accelerated the use, effectiveness and results gained from vibration as a measure of mechanical condition. From a simple overall amplitude measurement seventy years ago to the complex dynamic signatures utilized today for a detailed picture of condition; machinery vibration monitoring and condition assessment have become an essential element for the safe operation and effectiveness of today's modern process, production and manufacturing facilities.

### The First Great Development

**Condition Quantified Vibration Measurement and Severity Assessment** – Vibration as an indicator of condition undoubtedly originated with the first rotating machine. Although quantitative measurements may have been far in the future, the first operators president of MIMOSA, the Machinery Information Management Open Systems Alliance; Manager, Condition Monitoring Systems, Brüel & Kjær, A/S; and President and CEO, Palomar Technology International.

During his more than 35 years of professional experience, Mitchell has been a strong, visible advocate for the development and implementation of business, technical, and operating strategies for optimizing the lifetime performance and utilization of industrial plant, equipment and infrastructure assets. He has authored over 100 technical papers and articles and delivered numerous presentations and workshops throughout the world detailing the technological, financial, and business benefits of Asset Optimization, Profit-Centered Maintenance, vibration analysis, condition assessment and condition based maintenance. Mitchell is the author of two books: *Physical Asset Management Handbook*, Fourth Edition published in 2006 and *An Introduction to Machinery Analysis and Monitoring*. He is a graduate of the U.S. Naval Academy, Annapolis, MD.

and mechanics must have felt cold fear in the presence of a badly shaking machine. High vibration is not a comforting sensation that would lead anyone to a conclusion of well being – personally or for the 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 paper published in 1939. The paper, titled "Vibration Tolerance" and published in *Power Plant Engineering*, provided a guide for condition assessment based on vibration displacement from approximately 60 cpm (1 Hz) to 7,200 cpm (120 Hz).

The Rathbone paper introduced a number of profound ideas including 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, service life and risk of failure. It is amazing to recognize that the concepts and severity criteria developed by T. C. Rathbone continue to serve us well today; sixty seven years later!

**Development of Electronic Vibration Measurement** – Much of the early vibration measurement was accomplished with mechanical devices; the trusty, highly calibrated index finger, screwdrivers, a coin stood an edge were all used well into the age of electronic measurement. At some point the electro-mechanical, moving coil velocity pickup appeared (IRD introduced the Model 544 in 1952-53) to introduce quantifiable electronic measurement. The velocity pickup was reasonably robust and, most important, was self-generating with a low impedance output that was easy to handle with standard connectors and cabling. With the electro-mechanical velocity pickup, vibration amplitude could be measured with a voltmeter.

# The Second Great Development

Introduction of Vibration (Frequency) Analysis – As practitioners gained experience, there was a growing recognition that while amplitude was a good, intuitive measure of severity (the harder it shakes the worse it is!), frequency and frequency patterns indicated the type of defect present. Full exploitation of this theory was lim-



Figure 1. Major developments in the progression of vibration measurement, monitoring and condition assessment.



Figure 2. Hand vibrograph.

ited by vibration analysis instrumentation that were very primitive by today's standards. The earliest signal analyzer, the mechanical Hand Vibrograph shown in Figure 2, traced a time-domain vibration displacement waveform on pressure sensitive waxed paper. A skilled user with an abundance of imagination could tell if the prime excitation was at rotating frequency, if other frequencies were present – and little more.

The current era of vibration analysis likely began in 1950 when Art Crawford, then a graduate student, today a universally respected giant in the industry, accepted a challenge to figure out a means to reliably balance high speed spindles. The ultimate result, IRD (International Research & Development), was incorporated in 1952 and became the advocate and leader in dynamic balancing, frequency analysis and condition assessment for over thirty years.

Most electronic vibration instruments of the era measured overall displacement and velocity amplitudes, Figure 3. Unfortunately, displacement became a preferred condition measuring variable; perhaps because a budding analyst had an easier time explaining displacement to a boss who had difficulty connecting how fast he drove to work with machine condition. Other instruments had manually tuned filters, Figure 4. The latter provided the basis for the amplitude and frequency patterns we now associate with common problems such as unbalance, misalignment and looseness. Laboratory instruments with greater capability for both measuring and displaying vibration signals were bulky and cumbersome to use, Figure 5, with a fraction of the capability taken for granted in today's hand-held data collectors.

A major milestone occurred in 1968 when John Sohre, a major contributor to both machine design and analysis, published "Operating Problems with High Speed Turbomachinery, Causes and Corrections" at the ASME Petroleum Mechanical Engineering Conference. The paper included the soon to be famous "Sohre charts" describing the vibration symptoms of turbomachinery problems along with the probable causes in exhaustive detail. The paper and charts were republished numerous times in several languages and conceptually form the basis of much of today's detailed diagnostic technology.



Figure 3. Early fixed filter vibration meter.



Figure 4. Tuned filter vibration meter, 1970.

By the early 1970s a number of companies were offering electronic instruments for measuring and analyzing vibration on industrial machinery. The visionary, user-focused efforts of Don Bently and the Bently Nevada Corporation (now GE Energy Optimization & Control) strongly advocated installed shaft displacement monitoring, time domain and orbital analysis (detailed in a later section). Another very influential pioneer mentioned earlier, IRD Mechanalysis (later absorbed by Entek who in turn was purchased by Rockwell Automation) promoted velocity based periodic casing measurements and filtered frequency domain analysis. Ray Data, (later Reliance Electric) and Vitec likewise advocated casing measurements. General Radio and Schenck Trebel were also offering vibration-measuring and analysis instrumentation.

**Early Efforts at Periodic Condition Monitoring** – Beginning in the late 1960s many companies initiated programs of periodic manual condition measurement. One or two people would utilize a vibration meter similar to the unit shown in Figure 3 and a



Figure 5. Late 1960s laboratory vibration measurement instruments.

velocity sensor to record external bearing cap vibration. Measurements were typically overall levels made in an ordered sequence at strategic points on plant machinery. Vibration levels were recorded numerically on paper log sheets and trended manually. The task was difficult, and time consuming, especially for one person who had to hold a measuring instrument, sensor, log sheet on a clipboard and a writing instrument using only two hands. Typically the measuring instrument was hung from a neck strap, the sensor held in one hand, the log in another with the pencil clenched between the teeth! Those engaged estimated that they spent 80% of their time manually logging and trending data. Only about 20% was available for identifying and analyzing problems! 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 value-added problem recognition and analysis.

During this period and through the mid 1970s, the velocity pickup was the prime seismic vibration sensor. Frequency analysis was accomplished with a manually tuned filter, Figure 4. At best this was a tedious and time-consuming process that did not provide much detail beyond the strongest few components in a relatively simple vibration signal. The velocity pickup itself made the task simpler by inherent force and frequency limitations that simplified the sensor output. Real gains in machinery analysis from the extended frequency range of accelerometers had to await the introduction of real-time/FFT analyzers.

Today's practitioners have no comprehension of the time and difficulty involved with gaining insight into the frequency content of a complex vibration signal when the best, and only, tool at the time was a manually tuned filter. It was not unusual to spend an hour cramped in a highly awkward position within a very hot and noisy environment to determine vibration frequency content to only 4 or 5 orders of rotating frequency at one location on a machine! High frequency vibration, separating closely spaced components and the ability to view sidebands – all current necessities to evaluate the condition of gears, motors and rolling element bearings – were far beyond the state-of-the-art or even the imagination. Shortcuts such as comparing filtered to unfiltered amplitudes and displacement filtered to rotating frequency versus measured and calculated velocity, were developed to gain a quick appreciation of the primary frequency in a vibration signal, and hence the source of a problem.

As time passed there was growing awareness that frequencies could be divided by diagnostic interpretation. Lower frequencies, shaft rotating frequency and a few harmonics, were indicative of problems such as unbalance, misalignment and looseness. Medium frequencies contained 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. Although this early knowledge was not yet matched by capability, it led to various schemes for utilizing segments of a vibration signal for diagnostic monitoring. The U.S. Navy settled on octave band separation; Brüel & Kjær advocated constant percentage bandwidth filtering. SPM and later IRD utilized the mechanical resonance of an accelerometer to magnify and identify high frequency impacts (Spike Energy) as a measure of rolling element bearing condition. Dual path, spectral band monitoring (described later) and enveloping/demodulation are all improvements to the initial concept made possible by advances in instrumentation and signal processing.

#### The Third Great Development

Shaft Displacement Monitoring and Protection, Non-Contact **Proximity Measurement, Continuous Monitoring and Protection** - In the mid to late 1960s the non-contact, eddy-current, proximity probe was applied to measure shaft motion relative to the bearing housing, Figure 6. Two individuals share credit for the birth of this concept: Don Bently and Don Wilhelm (Helm Instrument Co.). To Don Bently, the giant of the monitoring industry, goes total credit for the vision and perseverance to develop the technology for rotating machinery; refine its application; promote the necessity and benefits and initiate and drive the modern era of installed machinery monitoring, protection and analysis. By the mid 1970s, non-contact, proximity measurement and continuous shaft displacement monitoring had gained near universal acceptance as the preferred method for monitoring the mechanical condition of large turbomachines with fluid film bearings, Figure 7. Today, shaft displacement monitoring and alarming systems, Figure 8, are considered an essential part of the protective instrumentation for all critical machinery equipped with fluid film bearings.

Time domain and orbital analysis, pioneered by Bently Nevada were based on viewing the signals from X-Y shaft displacement sensors mounted 90° apart directly on an oscilloscope, Figure 9. This method provided excellent insight into shaft motion relative to its bearing. As we shall see in the next section, the technology and companion diagnostic interpretation provided the basis for understanding and solving the greatest problem encountered by turbomachinery in the ten or so years from 1965 to 1975 – subsynchronous instability.

# Although the waterfall plot looked somewhat benign, the noise and panicked shouts to "shut her down" from people present left no doubt of the total catastrophe that occurred!

**Solving Subsynchronous Instability** – Serious rotor dynamics problems arose during the late 1960s early 1970s as machine manufacturers doubled, and in some cases even tripled, the size of existing designs to meet requirements for greater production output. As shaft rotating speed increased, high speed, light rotor turbocompressors equipped with fluid film bearings were especially susceptible to bearing instability. A few machines were unable to successfully traverse the first critical at commissioning due to excessive vibration. Large turbine generators experienced bearing instability as well as several unique problems of their own. The infamous 1,000 MW "Big Allis" commissioned by Consolidated Edison in New York City in 1965 is certainly a part of this history!

Before the problems were understood and solutions developed, subsynchronous instability was considered by many as something



Figure 6. Non-contact shaft displacement sensors and oscillator demodulator, 1976, courtesy General Electric.



Figure 7. Typical high pressure turbocompressor requiring non-contact shaft sensors and continuous monitoring.



Figure 8. Typical late 1970s shaft displacement monitoring system, Bently Nevada 7200, courtesy General Electric.

akin to witchcraft. Machines that were operating successfully suddenly developed horrible vibration that required immediate shutdown. Very expensive catastrophic failures occurred without warning; some on restart following overhaul and years of successful operation. Others took weeks of trying this and that until something succeeded (no one knew quite what) and the machine sort of conceded to run temporarily at tolerable levels of vibration. At times factory service representatives were observed carving up bearings with 'precision' instruments such as a file and Dremel hand-held grinder until they finally coaxed operation!

Figure 10 is a waterfall spectrum recorded during an instability induced catastrophic failure suffered in 1972 on the compressor train shown in Figure 7. In the lower plot 10a, the compressor train is operating normally. A trace of subsynchronous instability at approximately 48% of rotating speed is present in the frequency spectrum. In the middle plot, 10b, the compressors are surging with an accompanying variation in rotating speed due to the inability of the driving turbine governor to keep up with the variations in load.



Figure 9. Time domain waveform and shaft orbit from X-Y shaft displacement probes.



Figure 10. Shaft displacement waterfall recorded during a catastrophic compressor failure. a) Compressor operating normally, slight trace of subsynchronous instability at approximately 48% of rotating frequency. b) Compressor begins surging causing rotating speed to vary; aerodynamic shock and speed variations increase excitation of subsynchronous instability at the compressor first critical speed. c) Subsynchronous amplitude increases to bearing and seal destruction; compressor is tripped and coasts down; subsynchronous instability remains locked to first critical frequency until shaft rotating speed decreases significantly.

Note the major increase in subsynchronous amplitude as well as the constant frequency indicating that the aerodynamic shock and speed variations are exciting the first natural frequency (critical speed) of the compressor rotor. The condition persists for a minute or so until the unit is tripped and begins coasting down; middle of Figure 10c. By this time the compressor radial bearings, external and internal seals are all destroyed. Note that during the coastdown the subsynchronous frequency remains essentially constant along with its harmonics. Note also the presence of sum and difference frequencies generated by interactions between subsynchronous and rotating frequencies. Although the waterfall may look somewhat benign, the audio and panicked shouts to "shut her down" from people present leave no doubt of the total catastrophe that occurred! (*Has anyone ever thought why temperamental machines are always female?*)

With problems like the one just described, the late 1960s through the mid 1970s were very exciting times in the field of rotor dynamics as well as vibration monitoring and diagnostic analysis. The massive rotor stability problems were surmounted by the creative development of bearing and shaft designs that were confirmed using information gained from non-contact shaft displacement measurements. Although the history of solving subsynchronous instability is far too long to address here, the effect on vibration, especially shaft relative displacement measurement, should certainly be noted.

Charlie Jackson , a giant presence, terrific humorist and great personality to whom so many owe so much, published *The Practical Vibration Primer*. This outstanding book was the first effort to document the great expansion of vibration practices and interpretation that had occurred during the 1970s.

Whether rotor dynamics problems drove the development and acceptance of installed shaft displacement monitoring and protection systems on large, critical turbomachines, or the technology provided the key to unlocking the problem and confirming the solution, the two are inextricably intertwined and the end result is the same. Casing vibration measurements were clearly inadequate unless all one wanted was to document the final stages of a wreck! Today, shaft displacement monitoring is considered essential protection for large, production critical machines equipped with fluid film bearings.

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; especially Jørgen Lund. Dr. Lund, a founder of MTI and one of the greatest practical researchers in the field, later joined The Technical University of Denmark, continuing his work with MTI during the summer.

Dr. Jørgen Lund is credited with the development of numerous bearing analysis design programs. He was the first to understand the importance of the whirl frequency ratio for fluid film bearings and to begin evaluating the stability performance of fixed geometry bearings using these parameters. He also developed what has become the industry standard for calculation of damped critical speeds of flexible rotor bearing systems. Dr. Lund and his associates at MTI were the first to develop bearing design guides and design charts for both liquid and gas, hydrodynamic and hydrostatic bearing designs. His analytical methods and programs remain the basic foundation for the design of industry-standard tilting pad bearings and are still being applied today. (Extracted from the *Journal of Vibration and Acoustics*, October, 2003, Vol. 125.)

Don Bently and Bently Nevada pioneered the measurement technology and made a major contribution to the supporting rotor dynamics analysis for identifying and solving bearing instability. Technology leaders such as Dr. Ed Gunter and his colleagues at the University of Virginia utilized shaft displacement measurements to develop and advance the theory of rotor dynamics as well as computer programs that contributed significantly to stable bearing designs.

Dr. Neville Reiger (at Rochester Institute of Technology and MTI; later founder of STI) made a major contribution to the knowledge of rotor dynamics and balancing flexible rotors. He wrote an extensive monograph for SVIC. Mike Adams at Case Western Reserve University extended bearing stability analysis with non-linear rotor dynamic analyses of large turbine generators that solved many problems.

In addition to the major contribution to the science of rotor dynamics, MTI developed methods for balancing flexible rotors using influence coefficients that led to greatly improved results and standards. Moore in England developed the modal method of balancing.

For many years MTI had a very successful field service group under Don Wilson that applied the latest rotor dynamics technology to solve industrial machinery vibration problems. The group may have been the first to apply advanced rotor dynamics to field vibration problems. Others, including 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 whom were educated at the University of Virginia under Ed Gunter; provided and continue to provide services to solve bearing design and rotor dynamics problems.

#### **Condition Monitoring and Analysis Expands**

As stated in the previous section, continuous non-contact shaft displacement monitoring systems had been totally accepted as essential protection for large, critical turbomachines by the mid to late 1970s. The cost justification process that had been the subject of many papers, heated conference discussions (expenditure for a monitoring system typically determined by the cost of one or two days lost production) and emotional internal arguments ("You want to spend how much for a few probes and meters?") was no longer necessary. Leaders such as John Sohre and Brian Erskine (ICI) developed and refined criteria for judging the severity of relative shaft vibration. Instruments such as ADRE from Bently Nevada, Figure 11, probably one of the most popular instruments ever from a single supplier, had been introduced and were in widespread use extending the knowledge of machine dynamics.

In early 1979, Charlie Jackson (Monsanto), a giant presence, terrific humorist and great personality to whom so many owe so much, published *The Practical Vibration Primer*. The outstanding Vibration Primer was the first effort to document the great expansion of vibration practices and interpretation that had occurred during the 1970s and provides a solid knowledge base on which future analysts can build. Since Charlie Jackson's Vibration Primer, a number of excellent books have been published on vibration analysis by industry notables such as Ron Eshleman and Bob Eisemann.

**Technology Advances: Accelerometers and Tape Recording** – Beginning in the early 1960s the aerospace testing community began driving a new generation of standardized instrumentation made necessary by requirements for missile testing. Highly accurate multi-channel FM (Frequency Modulated) magnetic tape recorders constructed to the IRIG (Inter Range Instrumentation Group) standard and the 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 with force considerations emphasizing the higher frequencies. Thus, the accelerometer opened a new window into predictive analysis for equipment such as bladed turbines, gears, rotary positive displacement compressors and machines equipped with rolling element bearings.

Initial accelerometers were taken directly from testing catalogs. They were far too fragile for routine use by people with big fingers proficient with slugging wrenches, had a high impedance charge output, employed laboratory cables and Microdot miniature connectors. The output was sensitive to connector, cable (length and movement) and temperature ("breeze disease") variations. Expensive conversion electronics were required prior to input to



Figure 11. A popular time domain analyzer; ADRE from Bently Nevada, courtesy General Electric.

a display, recording or analysis instrument. Introduction of internal conversion electronics by innovators such as PCB Piezotronics largely eliminated the problems and made acceleration sensors practical for use in industrial environments. The low impedance output from an integral electronic accelerometer eliminated the

expensive, fragile and noise sensitive connectors and cable. Today, virtually all acceleration sensors used in industrial applications are of this basic design. Many include internal integration to produce a velocity output.

Early integral electronic accelerometers experienced a "ski slope" problem that must be mentioned as part of the learning process. Although most integral electronic accelerometers performed well in early machine monitoring applications there were a few that produced unrealistically high amplitudes at low frequencies when integrated to velocity. Based on the output, the accelerometer appeared to be operating well within its performance (dynamic range) limits. The problem continued, so discrediting in some cases that it required replacing accelerometers with velocity sensors. It gradually became apparent that the problem accelerometers all shared one characteristic - installation on a gear, turbine or failing rolling element bearing that was generating very high amplitudes at high frequencies. Substituting lower sensitivity charge mode accelerometers clarified the problem. It turned out that the combination of 24 volt excitation and 100 mv/g sensitivity - specified, unwisely in retrospect, for industrial accelerometers - caused an integral electronic accelerometer to clip internally at high frequencies when subjected to high crest factor vibration (peak/rms ratio) that often occurred on gears and rolling element bearings with a developing failure. With integral electronics hiding the piezoelectric crystal output from external examination, the source of clipping couldn't be observed. But, the result was that the low frequency distortion was greatly amplified when the output was integrated to velocity. Awareness and solution of this problem cleared the way for accelerometers to become the seismic sensor of choice today.

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, often through pre-amplifiers, and the signals recorded for a minute or so. Later, the signal was reproduced through a spectrum analyzer and plotted in an analysis lab. The results were manually compared to prior spectra and examined for anomalies. Many experienced practitioners found that 'listening' to the recorded signal on speakers or a headset often provided highly valuable additional information.

The portable, two channel direct (AM) tape recorder manufactured by Kudelski in Switzerland, Figure 12, was one of first used in a condition monitoring application. Its name 'Nagra' means "[it] will record" in Polish, the native language of the founder of the company. Larger instrumentation tape recorders manufactured by Hewlett Packard, Lockheed Electronics and Honeywell with both direct and frequency modulated (FM) channels were adopted to gain a greater frequency response needed for detailed analysis. FM recording had the advantage of a linear response to very low frequencies, even DC when necessary. The larger multi-channel tape recorders permitted capturing transient vibration characteristics and instantaneous shaft position simultaneously from multiple locations for later detailed analysis. Combined with the non-contact shaft displacement pickup, multi-channel FM tape recording provided the data, insight, and later validation, for solving the bearing instability problems mentioned earlier.

It must be noted that the early instruments for recording vibration signals were physically large, heavy and cumbersome. With one exception, the seven-channel magnetic tape recorder manufactured by Lockheed Electronics, multi-channel recorders similar to that illustrated in Figure 13 (a 1 inch, 14 channel magnetic tape recorder)



Figure 12. Nagra two channel magnetic tape recorder used in early predictive maintenance programs (in carrying case).



Figure 13. 1970s 'portable' data acquisition and analysis system.

weighed 50 pounds or more. Most required external amplification (the large box on the right in Figure 13) when used with vibration sensors. Although many traveled with the 'portable' instrumentation illustrated in Figure 13 and gained excellent results, the combination was difficult to transport, complex and time consuming to set up, required calibration for each channel and was often in error if amplifier gain settings were incorrectly recorded (very easy to do). And that doesn't include the acute embarrassment when a 70 lb box of electronics smashed a little old lady's carpet bag on an airline baggage carousel! It will be shown in a later section how plants mounted the bulky equipment necessary for detailed condition monitoring and analysis in a van or trailer to minimize the set up required.

Deviations from normal amplitude and phase transient behavior on runup and coastdown, captured with a multi-channel tape recorder, were employed very successfully by the Central Electricity Generating Board (CEGB) in the UK to identify and assess the risk of potentially catastrophic shaft cracks that had occurred on large turbine generators. In this case, the presence of a crack or cracks was detected as a shift in the frequency and change in the amplitude amplification at the shaft's critical speed. The defect was displayed as amplitude and phase vs. shaft speed in either polar or rectangular coordinates. The concept was eventually standardized and installed permanently on most of the large steam turbine generators in service in the CEGB.

### **Developments in the US Navy**

Beginning in the late 1960s and early 1970s, the U.S. 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 Corporation (GRC). GRC strip chart recorders were installed with the systems to provide a permanent record for readings for comparison analysis.

Ray Misialek at the Naval Ship Engineering Support Center in the Philadelphia Navy Yard may have been one of the first to evaluate aerospace accelerometers for the task of monitoring industrial type machinery (shipboard in his case). Ray did a fair amount of testing and evaluation to prove the concept that led to interest in an industrial sensor among the accelerometer suppliers. 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 basically designed to provide an optimum indication of condition from relatively simple and easily interpreted numerical measurements. Unfortunately for all, there was little dialog between the Navy and industrial users as the developments progressed. As a result, the technology, measurements themselves and diagnostic interpretations were incompatible. The opportunity to combine Naval research and development with the rapid learning that was occurring within industry to the mutual benefit of both parties was not exploited.

#### **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. Early on, Curtiss Wright developed and promoted a near field sound measuring system to assess the mechanical condition of jet engines. The effort was not successful although cabin sound recorded in flight and analyzed disclosed a great deal of interesting engine related detail.

Early industrial and aero derivative gas turbines were typically monitored by high temperature velocity transducers and filtered overall levels. These systems provided very basic protection in the event of a catastrophic failure but weren't much use for predictive monitoring beyond trending overall levels. More detailed analyses of these engines accomplished with add-on sensors in the mid 1970s revealed a great deal more predictive information including auxiliary drive, blade and combustor problems that were invisible on the installed system.

With the advent of wide body commercial aircraft, the engine vibration monitoring system became an integral part of airborne instrumentation. Airborne engine monitoring systems pioneered by Endevco and Vibro-Meter used high temperature accelerometers and tracking filters steered by a tachometer signal to limit the signal and cockpit amplitude indication to frequencies around the rotating speeds of the compressor (often two rotors) turbine and fan. The same system was essentially applied to monitoring systems installed on aero derivative gas turbines in stationary and shipboard applications.

Hamilton Standard developed and installed a number of gas turbine performance monitoring systems (Trends). Primarily focused on thermodynamic analysis and operating efficiency, some were still in operation and performing satisfactorily as late as 1990. Today, many gas turbine users state that aerothermal performance is a better measure of condition than vibration since a typical turbine experiences more variations in performance than mechanical condition over its lifetime.

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 probes and shaft displacement monitoring systems. Although there were challenges, particularly in routing cables outside the turbine, Bently Nevada developed solutions and the non-contact shaft displacement monitoring system is essentially standard today on large frame industrial gas turbines equipped with fluid film bearings.

#### **Concurrent Advances in Technology**

Many individuals, including Jack Frarey, then at MTI, 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, and the experience gained, forms much of the basis for current success in this area.

Ralph Buscarello, another major presence in the field, contributed mightily to the body of knowledge and practice of vibration analysis and condition assessment. By concentrating on measurements and methods that could be easily used in the field, Ralph added significantly to the body of diagnostic knowledge by developing and promoting highly practical 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 utilizing spectrum shapes and time domain analysis. Robert Randall at Brüel & Kjær refined cepstrum analysis, essentially a spectrum of a spectrum, for gear analysis. As a matter of note, Bob Randall authored two excellent articles describing the technology of machinery monitoring in the March and May 2004 issues of *Sound and Vibration*. Jim Berry advanced analysis technology with a series of highly practical and very comprehensive diagnostic charts. They were so valuable that they replaced the ubiquitous Rigid Tool Company calendars (which featured scantily-clad female models) as the center of attraction in most vibration analysis offices.

### **Condition Assessment in the Soviet Union**

Dr. 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 and 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. Several research institutes engaged in developing instruments were ordered to apply this method. At least 4 laboratories were involved in this work from 1972 through 1974:

- Central vibration laboratory of the shipbuilding industry
- Central laboratory of the Navy
- Machinery design institute of the Academy of Science
- Our laboratory that was dealing with vibration issues in the electrotechnical industry of the Navy

The final reports (dated 1974) of at least two laboratories recommended use of the high frequency vibration envelope. One, our laboratory, suggested a spectrum analysis of the envelope.

Results of high frequency vibration envelope spectrum analysis were first reported in 1972. This followed a comparison of results gained by two methods of high frequency vibration spectra analysis. The first method was to shift the high frequency vibration to the low frequency domain by the use of a heterodyne process. In this case, no harmonic components were found in the resulting spectrum. The second method viewed the spectrum after demodulation. In this latter case, bearing defect harmonics were definitely present. It became evident that we were dealing with the process of modulation of vibration power. In 1973 we developed mathematical methods to determine the modulation index.

In 1976 our laboratory became aware of the results of Boeing research in detecting rolling element-bearing defects (patent dated 1974). We applied our techniques in civil industry and published results (USSR Patent dated 1979) 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. Our team 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 chart. He identified five grades/regions of condition from AA Danger to D No Fault separated by multiples of 10 dB (linear multiple or ratio of 3.2) and based on vibration levels from 5 Hz to 10,000 Hz in terms of displacement, velocity and acceleration. (It should be noted that judging changes in severity by a constant multiple can lead to some exciting times at higher levels of vibration where absolute level must be considered in addition to change.) Service Factors were specified to qualify condition grades for various machine types. The "Blake Chart" was based on constant velocity criteria from approximately 20 Hz to 1,000 Hz and reduced the allowed velocity for a given severity grade at both the low and high frequency extremes. This is carried through in condition grades for both acceleration and displacement and confirms Rathbone's conclusion that force considerations shift emphasis to displacement as frequency is reduced and to acceleration as frequency increases. By offering constant velocity in terms of displacement amplitude versus frequency, Blake satisfied the Dilbert boss who couldn't wrap his mind around velocity as a primary measure of condition. The force, frequency relationship and the concept of service factors are extremely important principles that form the basis for much of today's success in vibration based condition assessment. The full Blake chart is reproduced in the book written 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 Dr. Ron Eshleman the Vibration Institute has become the focal point for condition assessment technology and diagnostic knowledge to the present day.

In 1964, IRD published and copyrighted a 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. IRD utilized constant velocity criteria from 100 to 100,000 cpm expressed as peak displacement versus frequency. Constant velocity lines separated nine categories of condition from Extremely Smooth to Very Rough. For some reason lost to antiquity, velocity criteria was expressed to three significant Figures in multiples of 2 above and below 0.1  $\pi$  (0.314 in. per sec) contrasted to the multiple of 3 used by Blake. Three significant digits implied that severity assessment was far more exacting than was actually the case.

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. The interior would resemble the scrap from a lathe before external vibration exceeded the "slightly rough" category. As stated earlier, shaft relative motion, measured with non-contact displacement probes, was the only way to accurately assess condition, Figure 14.

Although both the Blake and IRD charts specified peak vibration as the condition defining abscissa, external seismic measurements made with vibration meters in common use at the time in the U.S. actually measured average amplitude multiplied by 1.57 with the measurement labeled peak. This discrepancy between terminology and actual measurement proved very disruptive and will be addressed in more detail later.

Forked shaft sticks, generally made of lubricant soaked wood and attached to a velocity pickup were used on occasion for the purpose of measuring shaft absolute vibration. Absolute shaft vibration was recognized as a necessity to assess condition on large machines, typically turbo generators, characterized by significant variations in stiffness between bearings. This led to permanently installed, spring-loaded shaft riding (contacting) probes for continuous monitoring and protection, Figure 15. Shaft riders were widely applied to large steam turbine generators and some gas turbine generators. Although some of these systems still exist today, shaft riders were prone to lifting from the shaft at high amplitudes and therefore often did not represent true motion and condition. (The author fondly recalls crawling into the space around the exhaust duct of a large gas turbine on startup to determine if excessive vibration measured on a shaft displacement system was real or not real as indicated by the shaft riders. (It was very real!) Most shaft riders have been replaced with a dual sensor combination of non-contact shaft displacement probe and casing sensor, Figure 16. Shaft absolute motion is derived by combining the two signals electronically.

During this same period the US Navy Bureau of Ships developed Mil-STD 167 specifying limits for external bearing cap as well as shaft vibration. Since this standard was to be used on submarines



Figure 14. A Bently Nevada shaft displacement probe installation on a high pressure centrifugal compressor, 1975.



Figure 15. A spring loaded shaft riding seismic vibration pickup.



Figure 16. Dual, non-contact and casing seismic pickups installed on a steam turbine generating unit.

where vibration and the resulting noise were catnip to anyone lurking about in the deep listening for prey, the limits were considerably lower than what was acceptable in a commercial environment.

Additional standards were introduced in the 1970s. Dresser Clark published a widely used standard for shaft displacement, Figure 17, that included the now familiar decline in allowed 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), 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 of rotor dynamics and stability discussed earlier. They proved highly successful toward improving design and operating reliability and are



Figure 17. Dresser Clark shaft displacement severity chart.

likely the greatest legacy of these eminent individuals.

In 1974, the International Standards Organization (ISO) published standards:

- ISO 2372, Mechanical Vibration of Machines with Operating Speeds from 10 to 200 rps – Basis for Specifying Evaluation Standards (based on the German VDI 2056)
- ISO 3945, The Measurement and Evaluation of Vibration Severity of Large Rotating Machines in Situ, Operating Speeds from 10 to 200 rps.

ISO 2372 has since been greatly expanded into ISO 10816, Mechanical Vibration - Evaluation of Machine Vibration by Measurements on Non-Rotating Parts (about 8 parts). These standards established constant velocity as the ISO measure of severity assessment from casing vibration measurements. The standards specified both the method for calculating rms and bandwidth (10 to 1,000 Hz). They also established four machine classes with different severity criteria applied to each class. From the U.S. perspective Ed Noonan of the David Taylor Model Basin was the driver who led the efforts to establish ISO 2372, 3945 and 7919, Mechanical Vibration of Non-Reciprocating Machines - Part 2, Measurement and Evaluation of Shaft Vibration of Large Turbine/Generator Sets (six or seven more parts). The major contributions of Paul Maedel and Stewart Maxwell, the founder of the Canadian Machinery Vibration Association, to the development of ISO 7919 and ISO 10816 should also be noted.

As mentioned earlier, the use of rms in the ISO Standards for external casing vibration measurements was a major departure from the practice of U.S. based instrument manufacturers who had been using peak vibration calculated from average  $\times$  1.57. Although measurements of rms amplitude and average amplitude times a constant are more or less equivalent in terms of their response to defects, the difference in terminology and variation in amplitude for a given severity level led to confusion and a major discrepancy in measurements that isn't fully resolved to this day.

Overall, unfiltered velocity measurements will be identical on a machine vibrating primarily at rotating frequency, true peak will be much higher than rms times a constant on machines generating high frequency (high crest factor) excitation such as gears and rolling element bearings with defects present. Tests conducted by Jack Frarey at the Electric Power Research Institute (EPRI) Eddystone, PA M&D Center disclosed that early digital instruments utilizing rms detection for high frequency acceleration were not nearly as sensitive to bearing defects compared to instruments using true peak detection even though the difference was opaque to the user.

The story is quite interesting and caused major confusion during the shift to digital instrumentation. It was discussed in detail in an article published by the Vibration Institute in the December 1987 issue of *Vibrations* (Vol. 3 Numbers 3/4).

API 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 progressive 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. The standard specified strict requirements for shaft displacement monitoring including system reliability features such as first out alarm indication and dual voting logic and performance. The standard included dimensions and minutiae such as terminal strip size, meter orientation, full scale range and graduations. Although there were many arguments regarding the wisdom embodied in the standard (e.g., true peak-to-peak measurement compared to rms conversion) and a certain amount of finger pointing due to the individuals and companies involved, the principles that emerged and were refined over the years basically define shaft monitoring and protection to this day. In 1975 Dymac, now a part of SKF Condition Monitoring, introduced the first monitoring system fully compatible with API 670. Endevco introduced an API 670 compliant system a year or so later. By the late 1970s virtually all monitoring system manufacturers were API 670 compliant.

About six years after the issue of API 670 a companion specification, API 678, "Accelerometer-Based Vibration Monitoring System," was published to cover casing vibration. The standard ratified "dual path" monitoring first introduced by Endevco in a paper published in 1976. Dual path monitoring provided a method of simultaneously providing protection and prediction from signals obtained from accelerometers. Dual path monitoring utilized fixed filters to separate low frequencies commonly used for protective monitoring from high frequency predictive characteristics. The low frequency band, typically integrated to velocity, was used in accordance with conventional practice for assessing conditions such as unbalance and misalignment. The high frequency band, generally monitored in acceleration, was set to identify anomalies on components and equipment such as rolling element bearings and speed changing gears that are primarily predictive of long term problems. This concept, introduced in an earlier section, evolved into the multiple frequency band monitoring used today by digital instruments.

As stated, API 670 was highly successful and became the guiding principle for shaft displacement monitoring in virtually every industry. API 678 was not as successful. In November 1993 a third edition API 670, "Vibration, Axial Position, and Bearing Temperature Monitoring Systems" was released. The third edition merged the casing vibration monitoring provisions of API 678 into a comprehensive monitoring standard focused primarily on performance and reliability rather than specific implementation. Performance characteristics deemed essential for reliable digital implementation were specified. Most of the strict "how to" requirements of earlier editions were eliminated. A fourth edition published in early 2000 extended requirements for monitoring system reliability while allowing more flexible implementation and greater integration with process control systems. Functions could be distributed so long as reliability and response met requirements. Today, API 670 is widely accepted by instrument manufacturers and users alike as the governing standard for machine protection systems.

In closing this discussion of standards it must be mentioned that General Motors Corporation published a highly detailed *Vibration Standard for Machinery and Equipment* in 1997. This standard, currently in a second edition, 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 available today and has been modified and adopted by many companies outside the automobile industry.

#### The Fourth Great Development

Adoption of the Real Time/FFT Analyzer – Shaft displacement and casing velocity measurements provided great insight into common problems; however, both were limited in frequency response. Shaft displacement measurements were limited by the force needed to produce a measurable displacement at high frequencies (something would break first). Velocity measurements were limited by the



Figure 18. Machine vibration signal recorded from an accelerometer.

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.

Accelerometers provided the window into these highly valuable condition characteristics, however, most analysis methods available at the time couldn't make rhyme or reason out of the complex signals. Signals looked like a series of somewhat repetitive scratches in the time domain, Figure 18, and no one had the patience (or lifetime) to search for high frequency components with a manually tuned filter. Early efforts to mechanize the swept filter process produced some now ridiculous solutions including a motorized signal generator and analyzer connected with a bicycle chain! Enter the real-time analyzer. Early real-time analyzers, the large black box to the left of center in Figure 13, were initially based on time compression and rapid swept filter technology (see the article by Joe Deery in this issue for greater detail). They were capable of transforming complex vibration signals into an amplitude versus frequency spectrum in essentially real time. For the first time, complex vibration signals from accelerometers could be easily decomposed into individual components, 'signatures' in the frequency domain for quantitative comparison, identification of mechanical defects and interpretation in real time. An entirely new window of machinery analysis opened up to detailed assessment.

By providing dramatic new insight into the behavior of high frequency dynamic vibration signals, the real time analyzer 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. They 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 coastdown as illustrated in Figure 10.

Some of the early work with real time frequency analysis was accomplished by Dave Mellon and Larry Mitchell, then with Du-Pont; Dr. Mitchell later at Virginia Polytechnic Institute. 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 1970s. 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."

Early real time analyzers were large and heavy. Time compression units manufactured by Federal Scientific (holder of the technology patent), Spectral Dynamics, shown in Figure 13, and Saicor (later purchased by Honeywell) all weighed in at about 50 lbs, just squeezing in under the airline baggage maximum when packed in a protective case. Display, order tracking and even averaging were, for the most part, add-on units. The author fondly remembers field consulting in the mid 1970s where it was necessary to schlep close to 1,000 lbs of instruments including packing cases that filled a full size station wagon to the roof. This was necessary to assure sufficient information to identify and provide recommendations



Figure 19. Analysis van – from outside showing reeled extension cable for connection to remote sensors.



Figure 20. Analysis van – inside view of instrumentation; note the real time frequency analyzer and plotter similar to those shown in Figure 13.

for solving a complex, potentially operation limiting problem prior to site departure. Today, with the exception of simultaneous multi channel recording, far more capability can be carried in a large briefcase that will fit in under the seat in front of you!

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 non-contact shaft displacement systems located in the control room and the monitors had buffered 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. There were cases of continuing to operate machines in spite of significantly increased noise levels or obviously severe external vibration (cracked grout and oil lines, broken pressure gauges!) because shaft vibration had only increased a little. In several cases fractured 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 in operation because no one could feel excessive external vibration (the calibrated index finger failed) and casing vibration measurements were inconclusive!

Leading companies such as Exxon, Shell, Amoco (now a 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 similar to that shown in Figures 19 and 20 created by Uri Sela at Exxon. The van was outfitted with sensors, a long multi-conductor extension cable (typically on a reel as shown in Figure 19), amplifiers (by Encore Electronics in the center right of Figure 20), 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 residing in air conditioned splendor 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. Sequential vibration signatures at a given point on a machine were typically plotted one above the other on a single sheet to facilitate comparison over time.

In one case, spectra plotted one above the other appeared as essentially straight lines with no visible detail except for a small bump at rotating speed. When queried, operators stated that they wanted to get an entire year's worth of readings on one 8.5 by 11 in. sheet of graph paper that required an amplitude scale of 1 in. vertical equals 0.5 in./sec velocity!

The best vans, exemplified by Uri Sela's shown in Figures 19 and 20, were in reality mechanical measurement facilities that found use well beyond condition monitoring and assessment; tracking process condition changes as one example. Although technically successful, these programs were very labor intensive and most eventually collapsed due to the resource requirements and costs of operation. However, the stage was set for introduction of the portable data collector.

At about this point in time, the mid to late 1970s, the term Predictive Maintenance originated. Predictive Maintenance described a new methodology of performing maintenance based on actual condition 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 coined during work in South Africa. Whoever was responsible, the name stuck and is used to this day.

**Further Evolution: the FFT Analyzer** – By the late 1970s time compression analyzers had been replaced by fast Fourier transform (FFT) analyzers. These instruments were based on technology introduced by Tukey and Cooley in a 1965 paper. They were much reduced in size and weight compared to the time compression real time analyzers and performed the transformation from time to frequency domain digitally, in firmware. The FFT analyzers included a fully featured display, averaging and order tracking, all in one instrument.

Minicomputers: The First Step to Installed, Automated Diagnostic Monitoring – During the mid to late 1970s several large turbomachines equipped with continuous shaft displacement monitoring systems suffered sudden, very costly, catastrophic failures. In each case the monitoring system responded but too late to prevent the failure and the extensive damage that occurred. Post failure analysis indicated the possibility of failure precursors such as a change in sound or vibration pattern that, although insufficient to trigger alarm setpoints of the installed monitoring system, might have provided additional warning sufficient to avoid most of the damage.

One logical step was to automate the detailed diagnostic monitoring that had proven successful for periodic condition assessment and thereby enable performing the analysis automatically at greatly reduced intervals. This led to the development of a minicomputer controlled, multi-channel, multiplexed monitoring system centered on a FFT analyzer. The system automatically stepped through installed sensors (primarily shaft displacement) in a fixed sequence, performing detailed diagnostic analysis and spectrum comparison on each.

Zonic Corporation was the pioneer and leader in this new area. While the concepts were very innovative, hardware and software technology available at the time could not match requirements and expectations. The early minicomputer systems were expensive, slow and incapable of accommodating rapidly changing conditions. There were reports of minicomputer systems analyzing measurements on one machine while an unrecorded failure occurred on another connected machine. However, the die was cast. The concept of using a computer for machinery monitoring and analysis was firmly established. All that remained to complete the puzzle was a faster and less expensive platform.

# The Fifth Great Development

**Introduction of 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 portable machinery analysis instrument was an inevitable development. Jerry Muller with Exxon Research and Engineering promoted the concept in a widely distributed paper. The first commercial instrument in this direction was the AVM-1, introduced by Tecalamet Electronics in the UK in about 1982. The AVM-1 utilized 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, Dave Schu, Brian Long and Brian Howes at Beta Monitors and Controls in Calgary, Canada introduced the Data Trap. Vitec introduced a similar instrument shortly after Beta. Both instruments recorded an instantaneous time waveform that was converted to an overall level and FFT in a host micro computer. 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. Dymac licensed the Beta technology to reinforce their installed monitoring systems.

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 display, capabilities for downloading a prearranged 'route' of measurements for collection in a logical geographic sequence, on-board storage and a PC host to manage and display the measurements. TEC was awarded a US patent for the band-monitoring concept.

IRD Mechanalysis introduced a very similar instrument, also in 1983. IRD, in a stroke of genius, applied for a generic U.S. patent for the concept of a route capable portable data collector. The patent was awarded in 1986.

Somewhere during this time John Hawkins at PPG Industries in Lake Charles, LA constructed a home built computerized vibration data collector using standard components and self developed software. This illustrates what innovative people can accomplish faced with requirements that are developing faster than commercial technology.

In 1984 Palomar Technology International introduced the first portable data collector with a high resolution internal FFT, analyzer style selectable windowing and averaging, and a large screen FFT display, Figure 21. 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 (SKF Condition Monitoring), Entek IRD (Rockwell Automation), DLI Engineering Corp., SKF Condition Monitoring and others over the past fifteen years.



Figure 21. Portable data collector, 1985.



Figure 22. Typical computerized data analysis system used with a portable data collector.

Although it is difficult to believe today, the early data collectors were viewed with a great deal of skepticism. Many who were experienced with a tape recorder, FFT analyzer data acquisition system couldn't believe that such a small device could duplicate the performance they were accustomed to with the much larger instruments. A few concluded there was some sort of trickery involved; perhaps a highly trained and very energetic hamster.

The transition between an older analog instrument used for monitoring to a digital data collector was often an experience that seems quite humorous today. In many cases, the incumbent instrument was used as the calibration standard even though it may have been resident in the back of a pickup truck since purchase many years before. If the measurement from the brand new, presumably calibrated, data collector differed from the analog instrument, the data collector supplier had to explain why and modify the data collector to match the earlier analog instrument. A typical question: "If the analog and digital data collector read the same on a balance machine why are the measurements inconsistently different in the field?" Differences in filter characteristics, rms and true peak detection caused numerous questions in these early days of the portable data collector. The wife of one independent consultant was so disturbed that he paid so much for such a little box that she took a claw hammer to the keyboard. When that didn't do any major damage she drove her car across the data collector until the housing finally collapsed! The still functioning data collector was replaced under warranty by the supplier. Hammer and tread marks on the front panel were used to illustrate the ruggedness of the instrument in something a bit more harsh than the typical industrial environment!

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 spectra 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 the portable data collector, only 20% of the time was spent collecting data on hot noisy machines while 80% could be devoted to analyzing and solving problems in a quiet, climate controlled room; note the smile in Figure 22. 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 monitoring programs.

Of equal importance, the analysis and display capability of the portable data collector allowed virtually all analyses to be conducted at the machine if necessary and without any extraordinary setup. If the operator of the data collector observed an anomaly during collection (difficult with a tape recorder system) the data collector could be used to collect, view and study additional characteristics for a greater understanding of the problem. Many consider this type of local analysis superior to laboratory analysis. By the late 1980s, computerized data collectors had largely replaced tape recorders for routine monitoring. By the early 1990s, data collector technology had advanced to the point where they had virtually replaced the laboratory FFT in all but the most complex machinery analysis tasks. Multi channel computerized 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

Variations on Installed Condition Assessment/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 into 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 the data collection. PCB Piezotronics, IMI; Vibra-Metrics; Wilcoxon Research and others were quick to supply the selector boxes. Vibra-Metrics went a step further by providing a means to transmit the vibration signals over a network to a central location.

From here, moving to an automated system, similar in architecture to the minicomputer system described earlier, was a very short and logical step. In this system, an inexpensive microcomputer controls an input multiplexer connected to multiple sensors. By the late 1980s, the broad use, rapid improvement and low cost of PC derived components made the architecture both practical and cost effective. The microcomputer performs diagnostic analysis on the signal from each connected sensor. Outputs, including detailed spectra, overall and spectral alarms, are transmitted to a central location – typically a host PC, over a digital network. One of the initial systems manufactured by Palomar Technology used a portable data collector, permanently powered, housed in a waterproof enclosure and connected to a multiplexer to perform the local control, analysis and transmission tasks.

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 monitoring system 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 and an innovative method of data compression and network transmission. Within Compass, the only real difference between protective and predictive monitoring was the interval at which vibration signals were examined.

Periodic, detailed, diagnostic monitoring from installed, permanently connected sensors has proven its value and is currently available as complementary technology within most continuous protection systems. It is well accepted as a primary method of monitoring equipment on which failures typically develop slowly and are long preceded by well known defect symptoms that require detailed analysis for earliest detection. With internet capability, detailed condition assessment information from machines and machinery components are instantly available anywhere in the world. It's no longer necessary to "trudge out on a cold wet night, loaded down with heavy, awkward instrumentation to decide if some warm machine will last 'til' dawn" as expressed in the preface of one text on vibration analysis!

Additional Condition Measurement Technology – By the mid 1990s, it was becoming apparent that condition measurement technology, which had been considered primarily vibration by all but die hards in the lube oil community, 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 never combined with vibration to form a more complete picture of condition. Beginning in the late 1990s, condition monitoring software systems began to incorporate both vibration and oil analysis data. This combination provides the analyst with a more complete picture of machine operating condition.

Motor current analysis, initially developed by Dr. 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 all integrate vibration and lubricating oil analysis, with motor current, thermography, ultrasonics, operating performance and other condition variables from on and off-line sources. These technologies have been significantly improved over the past 20 years and their use has greatly expanded among industry-best companies. Many credit broad use and integration of condition assessment and performance monitoring technologies as major contributors to many of their successes.

These same leaders will cite the necessity of a comprehensive reliability program and effective use of reliability tools as primary factors in their overall success. Web based reporting (eliminating paper reports) and mining process data (cumulative affects of how equipment has been operated) are other major contributors to the success of a comprehensive asset optimization program.

**Expert Systems** – No review of condition monitoring technology would be complete without mentioning expert systems. One of the first machinery vibration expert systems (Amethyst) was introduced by IRD in the mid 1980s.

Also in the mid 1980s, DLI Engineering Corp. developed a vibration expert system to increase accuracy, quality and consistency to the U.S. Navy aircraft carrier Condition Based Maintenance program for which they provided data and analysis. The expert system was very successful and continues in use. In 1988, Design Maintenance Systems, Inc. (DMSI) in Vancouver, Canada was awarded a contract by the Canadian Government to develop a rule-based expert system for vibration predictive maintenance aboard icebreakers. The system was developed in a generic way for use on land based applications where a diagnosis of vibration caused by breaking ice would not lend much credibility to a system installed on a paper machine. In a highly refined form the core of this system is in use today.

CSI developed and introduced a rule based machinery vibration expert system, Nspector, in the early 1990s. Both the CSI and DMSI systems have reportedly proven very successful.

**Personnel Training and Certification** – Commencing in 1998, ISO began issuing the series 18436 standards. To date, two standards have been issued: ISO 18436-1 for certifying bodies and ISO 18436-2 for vibration analysts. As this is written, ISO 18436-3 on training for certification is very close to completion. The Vibration Institute administers the ISO certification for vibration specialists in the U.S. Approximately five additional ISO standards covering certification of condition monitoring personnel in lubrication, infrared, acoustics, electric current and ultrasonics are in progress.

#### What to Expect Next

Continuous shaft displacement monitoring systems are, and will continue to be, an essential requirement for protection of large, production critical machinery equipped with fluid film bearings. These systems are evolving into a closer connection with process control and the facility safety shutdown systems. As leading operating companies recognize the importance of controlled shutdowns, even upon equipment failure, critical machinery will no longer shut down automatically and independently with a resulting process crash. Instead, the machine will be kept operating for a short time while the process is shut down in a safe, orderly fashion. One chemical company stated that seconds to reduce process temperatures could extend the metallurgical life of critical components by years, thereby saving millions of dollars. The fourth edition of API 670 facilitates this eventuality as well as recognizing that machine protection functions will continually become more closely integrated within process control systems.

Reducing the cost of continuous monitoring for general-purpose equipment is necessary to expand coverage. Innovations such as "smart sensors" with built-in wireless transmission to a central concentrator will revolutionize and dramatically increase this area – provided installed cost per monitored machine can be reduced below a few hundred dollars. Visionary companies such as Azima are working to accelerate this development.

Analysis technology seems adequate for the medium term. There is clearly a requirement for more accurate methods for prognostic estimates of remaining lifetime.

Software and internet technology are the likely keys to enhancement of condition monitoring effectiveness. Within the coming decade, rule-based expert systems will likely merge with learnable software to form real condition assessment and accurate prognostic lifetime estimates. This combination combines a basic education with the ability to "learn with experience." As these systems develop, they should be able to identify and diagnose the cause(s) of machine problems with a high degree of certainty, accurately assess the severity of the problems and predict remaining lifetime (prognosis). With internet transmission capable of making vital condition information available anywhere in the world in real time the knowledge and experience of skilled individuals can be leveraged and made significantly more effective. These advances are designed to improve screening and provide more timely and accurate decision support by making skilled analysts more effective. Replacement of the human is one major hurdle that must be surmounted to gain total acceptance.

On a larger scale, reliability software is available to manage the entire condition assessment process including the ability to conduct analyses that will identify and diagnose sources of unreliability. Meridium Corporation currently offers such a system with features heavily influenced by leading Gulf Coast advocates of optimum equipment management.

In the hardware arena, similar development will likely take

place over the next 10 to 20 years. Portable instruments will likely include expert systems to provide the user with immediate diagnostic results.

Suppliers are also opening a window to modal analysis. With their Operating Deflection Shape (ODS) software, Vibrant Technology has been a leader in this area. Greater emphasis on modal analysis will elevate condition monitoring significantly in the arena of detecting and resolving one of the most commonplace problems facing analysts – resonance of machine components, support frames and surrounding structures. Currently, many analysts correctly conclude that a resonance problem is present, but encounter difficulty when attempting to pinpoint the resonant component and develop the best solution. Modal analysis and animated deflection shapes can be used to resolve this issue. With condition-monitoring suppliers developing multi-channel data collectors with interfaces to proven modal analysis and ODS software applications, the modal frontier will be open to the entire world of condition monitoring analysts.

Greater integration and improved management of vital information defining mechanical condition, operating performance, reliability and projected lifetime is another essential if condition assessment is to contribute fully toward the optimized management of physical assets, operational decision support and greatest business value. Tighter linkage between condition assessment (vibration, lubricating oil, electrical, etc.) with maintenance management, production control and management as well as Root Cause Analysis (RCA) and asset optimization processes is key. Adding operating performance to condition, expands equipment defects to include degrading efficiency and off design operation with a resulting increase in the cost of operation and decreased reliability. Advances in this area will require linkage to and from the process historian, a connection that is greatly facilitated by conventions developed by the Machinery Information Management Open System Alliance (MIMOSA). Several companies, including OMDEC (Optimal Maintenance Decisions Inc.) and Mtelligence are moving quickly to construct these linkages.

#### The Missing Element – Clear Financial Justification

No article by this author would be complete without the usual editorial rant concerning financial justification. Despite over fifty vears 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 failures are scarce. Many new managers are said to believe that fixing equipment when it breaks is the least costly method of maintenance. "Why have people goofing off collecting and analyzing condition measurements when they could be doing real work fixing things that need attention!" Many otherwise successful practitioners are just as guilty. Analysis and details such as determining that a bearing is failing due to a defect on the outer race, are of far greater interest than demonstrating the business value they contribute to their companies. As one example, participants at a recent vibration conference 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 recent survey conducted by reliabilityweb.com, people were asked how they justified their condition monitoring programs. One replied that "we don't do money." Perhaps there is a connection between "we don't do money" and downsizing condition assessment programs!

# The key to success is not technology but awareness of value, resources and time.

It should go without saying that if the work and results developed over the last sixty plus 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 prove the essential results and value of the practice and technologies. Without a lot more emphasis on results, benefits and business value it might be as difficult to locate a skilled condition analyst in twenty years or so as an experienced captain of a square rigger or pilot of a tail dragger biplane today! The key to success is not technology but awareness of value, resources and time – that's another story for another time!

#### Acknowledgments

The author thanks Mr. Max Wishaw of Wishaw Engineering Services in 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. Max began the process with a paper delivered in Perth in 1998 on which this grew. Thanks to the wonderful 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 and Vibration; Heinz Bloch, Jack Frarey, John Hawkins and Uri Sela for comments on this revision and Uri for the van photos. Thanks to Tannis Andrews-Causey of GE Energy for digging through the Bently archives for photos. Special thanks to Dr. 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, major contribution to this version and for several illustrations. Special thanks also to Art Crawford, a pioneer and truly wonderful 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, in some places, out of chronological order. For skipping around in the narrative and any discrepancies from fact, notable developments and participants who might have been inadvertently omitted or not given full credit for their contribution, the author takes sole responsibility and apologizes ahead of time.

The author may be reached at: jsmitchell@worldnet.att.net.