Applications of DSPCentric Dynamic Signal Analyzers to Industrial Rotating Machinery Diagnostics

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ABSTRACT
Vibration analysis on industrial machinery is generally performed using either route-based data collectors or permanent condition monitoring systems and in some cases, a combination of the two. While each of these options offers several benefits for monitoring of machinery health, their relative strengths and ‘expert diagnostic’ capabilities are often exaggerated by suppliers resulting in unrealized goals of investors. The rapid and accurate diagnosis of rotating machinery malfunctions requires sophisticated and flexible methods of data acquisition and analysis combined with the ability to record the raw data from multiple channels for post analysis. In the hands of expert consultants, such instruments provide an invaluable means to bridge the chasm that exists between the two ends of traditional monitoring systems.

This paper details the implementation of dynamic signal analyzer platforms that uniquely combine the use of DSPcentric signal processing and powerful graphical analysis features towards the realtime data acquisition and analysis requirements of industrial machinery. The paper also presents several case studies that highlight the many successful applications of such platforms in paper mills and power generation plants.

INTRODUCTION
Traditional condition monitoring programs generally come in two flavors; route-based data collectors and permanent monitoring systems. While either method works well for condition monitoring of machinery and serves the needs of predictive maintenance operations, neither succeeds as an effective machinery diagnostic tool.

Route-based Data Collectors: This is by far the most common approach and is conducted by trained technicians who walk around a plant following a predetermined route using either a single or dual channel data collector. One or two accelerometers connected to the data collector with flexible and extendable cables, are placed by the technician on various machine sections using magnetic bases or held against the measurement surface using a pointed spindle. The limited number of sensors being used for any data acquisition period combined with the predetermined and often rigid measurement settings makes these instruments and their users unqualified for advanced problem solving.
Permanent Monitoring Systems: This approach employs hundreds or even thousands of transducers distributed across a machine or plant, permanently mounted and connected to field signal processing units. The processing units in turn connect to a server on a local or wide area network across which multiple client computers may access measurement results and trends or be used to set up or modify test protocols and view machine state alerts (Figure 1). The major drawback with these systems is that they rarely involve the simultaneous acquisition of data from the many transducers around the machine and they do not offer the ability to record and later process the data using a variety of techniques and analysis settings. Data is typically multiplexed [1] by the processor units to the server and therefore phase between channels is generally not a measurement quantity available for the analyst. These systems do offer expert diagnostic capabilities and while such schemes might uncover several machinery fault conditions as described by Bridgford et al [2], they are never comprehensive in their offering. The inability of these systems to characterize transient phenomena in an accurate and flexible manner makes the troubleshooting of resonance conditions difficult. Furthermore, many serious machinery defects rarely manifest in the classical fashion that the expert system solutions are based on and therefore, while these systems are well suited for the observation of deviations of signals from previously established ‘safe’ levels; they usually fall short for total machinery diagnostics.

DYNAMIC SIGNAL ANALYZERS AND MACHINERY DIAGNOSTICS

Dynamic signal analyzers have been around since the 1970s and until approximately a decade ago, these instruments had a high price tag on a per channel basis, were generally very bulky and difficult to transport around and were typically offered in packages up to four channels. Four channel configurations, popular in the 1980s and 1990s, represented a significant advantage over two channel data collectors as they permitted the simultaneous acquisition of data from a reference channel plus data from a triaxial transducer ; the ability to rove a triaxial accelerometer while maintaining an accelerometer at a fixed location permits the creation of detailed operating deflection shape models that clearly illustrate the motion of structures at various excitation frequencies.

Many predictive maintenance and reliability personnel are now turning to high performance dynamic signal analyzers that offer highly mobile test platforms with significantly increased capability, both in input channels and analysis software. Dynamic signal analyzers offer a remarkably wide array of measurement and analysis options for a machinery diagnostics specialist. From the most basic power spectral density measurements to more advanced analysis methods such as transfer function and modal analysis to cross correlation, demodulation and acoustic intensity measurements, dynamic
signal analyzers are versatile tools just waiting for the experienced analyst to harness their power. Welaratna [3] and Mitchell [4] have presented unique perspectives on the historical development and application of analyzers, but even they could not have truly predicted the rapid advances in form factor reduction, computational power and application coverage these instruments would bring to test and measurement specialists today. A thirty two channel analyzer equipped with a dedicated local disk for recording raw data weighs 25% less than four channel systems used just over a decade ago, and is controlled by a PC to deliver all the additional project management and reporting tools demanded by today’s engineers. Hewlett Packard’s application note 243-1 [5] discusses dynamic signal analyzers in some detail and offers an insight into the many applications supported by them. In the age we are, it is virtually impossible to find systems and components used in the military, aerospace, industrial, electronics and telecommunications, computer and automotive sectors that are not analyzed at one or more stages in their development by engineers using dynamic signal analyzers. It is no surprise then that these tools are becoming more and more popular for machinery diagnostics, in large part due to their shrinking size and costs coupled with their growing portfolio of analysis features.

DATA RECORDING AND PLAYBACK ANALYSIS

Until recently, the process of acquiring, recording, analyzing and reporting test data was cumbersome and inefficient. This was primarily due to the fact that most signal analyzers did not have the ability to record vast amounts of data digitally, analyze recorded data in post process mode and support report writing – all on a single platform. Recorded data is extremely valuable as it may be post processed repeatedly using a frequency bandwidth equivalent to or lower than the original recording bandwidth. This important feature is vital for users who wish to be able to modify and hone their analysis settings as they learn more from the recorded data. Measurement parameters such as triggering, windowing, overlap and averaging may be changed in an unlimited set of combinations, enabling users to appreciate subtle characteristics of the recorded data, and perform a thorough analysis of the system under test.

INDUSTRIAL APPLICATION CASES

The following sections briefly cover different cases showing the successful applications of dynamic signal analyzers in industrial environments.

Industrial Modal Analysis

Large industrial machines such as those producing paper run continuously with few scheduled maintenance shut down periods. These machines essentially consist of heavy structural components and several rolls whose primary function is to transport the paper being produced from one end of the machine to the other where it is finally wound up.

In machine sections like the supercalender shown in Figure 2 the multiple excitation frequencies from the various rolls, drives (electrical and mechanical) and other surrounding equipment coupled with ever increasing operating speeds makes frequent machinery diagnostics necessary. Additionally, identification of natural frequencies in a given machine section is a challenge. Due to the size and stiffness levels of the structures, impact testing is not practical and shaker excitation is prohibitive due to time constraints. Excitation is generally achieved by putting the machine through a run-up and coast-down.
3D waterfall or spectral maps provide a convenient method of separating vibration due to structural resonance from that due to rotating masses. The derived plots of order tracks, shown in Figure 3, provide a means of identifying vibration causing mechanisms. This invaluable tool is generally not available with portable data collectors or permanent monitoring systems and hence, analysis of transient or machine speed related phenomena is difficult if not impossible.
When special curve fitting techniques are applied to steady state measurements using commercially available modal analysis software, the analyst is able to visualize a machine’s operation deflection shapes [6]. If the data is fit to natural frequencies identified in waterfall graphs, experimental mode shapes are obtained, which is essential for knowing which operating speeds are to be avoided. Figure 4 shows a 14.5 Hz mode of the supercalender section. This information also allows analytical engineers to fine tune their finite element models for more accurate future designs. Previous efforts at monitoring and identifying supercalender vibration issues [7] had never addressed this area and were therefore never fully able to resolve the problems in the field.

**Demodulation Analysis and Synchronous Averaging Applied to Mechanical Drives**

Underlying demodulation analysis is the analytic signal, sometimes called the envelope. The analytic signal is composed of the original signal plus a 90-degree phase-shifted version of itself (the Hilbert transform), and the magnitude of the analytic signal is the envelope of the original signal, giving an outline of low-frequency events that modulate the main signal. Accelerometers situated around the drive train are connected to the analyzer and a baseband auto power spectrum measurement is first carried out to determine the general characteristics of the signals as seen in Figure 5. Zoom analysis is then used as a band pass filter around the carrier frequency. The measurements may also be combined with synchronous averaging, with a once per rev tachometer providing a trigger for linear averaging. Synchronous averaging ties the analysis to a particular event such as the period of rotation of a shaft, and allows signal characteristics that happen at fixed times relative to the triggering event to reinforce each other in the average while incoherent events average out. The resultant amplitude modulation (Figure 6) and phase modulation spectra allow analysis of the frequency and amplitude of the various modulating components in the signal.
Analysis of the amplitude modulation spectra identified an intermediate gear as being the primary modulator of the gearmesh frequency. Figure 7 shows a view of meshing gears through an inspection port that revealed severe misalignment.

**Powerplant Rotating Machinery Diagnostics**

Power generation plants have several different types of rotating machinery: motors, pumps, gearboxes, turbines, compressors, generators, etc. Until recently, one plant had been using several different solutions for addressing the needs of the various sections and equipment. Productivity was dramatically improved by employing an ultraportable dynamic signal analyzer (Figure 8) equipped with Balancing and Rotor Dynamics analysis software in addition to the tools discussed earlier.
The analyzer connects to the displacement probes mounted along the turbine-generator (Figure 9) shaft and a variety of realtime analysis solutions are used to pinpoint various rotor dynamic phenomena and bearing conditions. Figure 10 shows an orbit+timebase signal for one particular probe pair. The stationary inner loop seen in the orbit shape combined with the slight flattening of the orbit indicates possible shaft rub, misalignment and looseness. There is also some truncation of the Y probe waveform seen in the timebase section of the graph.

Figure 10 – Orbit+Timebase Graph from Proximity Probes Mounted in Generator Bearing showing possible Shaft Rub, Looseness and Misalignment

**Process Flow Correlation Analysis**

Low frequency, machine direction basis weight variation in paper quality is usually traceable to problems upstream in the machine such as the stock approach system. The problems generally stem from either pulsation in the stock system or from an inability to maintain a uniform consistency in the stock. Troubleshooting an MD weight variation requires the ability to simultaneously acquire and analyze a variety of signals such as on-machine basis weight (Figure 11), thin stock consistency, stock approach system pressure at several locations (Figure 12 shows data from one location), vibration and drive motor parameters such as speed, etc. A complex array of time and frequency domain measurements is then required to properly characterize and solve the problem. Engineers often attempt to perform only frequency domain measurements to analyze the nature and sources of variation in the system with coherence function measurements to provide a measure of causality between different signals. However, in most process environments, it is essential that a degree of similarity as well as the direction of propagation along with lag time is available when comparing different signals. Correlation measurements are the perfect answer to problems like these.
Although correlation is a time domain technique, most dynamic signal analyzers compute correlation results like the one shown in Figure 13 by inverse transformation of cross spectrum measurements. The graph conveniently shows the degree of similarity between the compared signals by the y-axis values and the delay between the signals from the x-axis time reference.

DSPcentric Implementation Details

Abacus and Quattro represent significant architectural advances. The term DSPcentric refers to the fact that the design involves high performance signal processing, including digital decimation at the hardware level that in turn frees up the host computer for display and measurement storage [8]. Figure 14 shows a single Abacus chassis that connects to the host computer via Ethernet. The chassis may contain from 1 to 4 modules, each module consisting of 8 input channels, 2 output channels and 2 tachometer channels. Each module contains a GigaFlop Digital Signal Processor to provide the computational power. The input and output channels use 24 bit ADCs and DACs. The chassis uses a Pentium processor to supervise traffic and supports streaming data to a 160 Gigabyte local disk at an aggregate rate of 20Mbytes/sec.
Each contains its own signal processor as shown in Figure 15. The DSPcentric design is essential to the high realtime analysis bandwidth of the systems. Even after decimation filtering the 1 Gigaflap DSP has plenty of spare capacity to always maintain realtime measurements. Whether operating at its maximum bandwidth of 49 kHz or a low 1 kHz, tri-spectrum average measurements with selectable overlap are available in realtime.

Figure 15 – Architecture of Single Abacus Board

Apart from the obvious difference in maximum available input channels, Abacus differs from Quattro in some important ways. First, Abacus uses Ethernet to connect to the host PC whereas Quattro uses USB. Second, an Abacus chassis contains its own disk storage. The local bus disk is essential to the high realtime recording rate of the system. The system uses the 132 MHz PCI bus within each chassis for optimum performance and availability of off-the-shelf components. Ethernet connectivity enables host PC-to-front end as well as wide area network communication. Perhaps, the most important
difference is that multiple Abacus chassis may be networked together when more than 32 channels are needed in the field to maximize data acquisition on a large machine when time is critical. This incredible expandability on demand is delivered by the Ethernet based architecture and a special clock synchronization circuit that maintains the phase match specification across any number of channels.

Specifications for Dynamic Range, Signal to Noise ratio, Total Harmonic Distortion, Alias Rejection and Channel-to-Channel match show that Abacus and Quattro are analog front ends that do justice to the 24 bit digitizers. Figure 16 shows the flow of data through the ADC. At its full bandwidth, the input dynamic range is 120 dB, a testament to the analog design and the 24-bit Delta-Sigma technology. At lower bandwidths the dynamic range increases, reaching 150 dB at bandwidths below 1000 Hz. The answer lies in signal processing; onboard DSP is used for decimation filtering with selective noise rejection. The front end analog anti-alias filter (AAF) has a cut-off frequency of 350 kHz. Following anti-alias filtering the data passes through various stages of the Delta-Sigma ADC (stage 1 being a 12.8 MSps modulator or high frequency converter), where the data begins with 1 bit resolution. After that the data is digitally downsampled 128 times to yield one of three primary sample rates, all around 100 kSps (42 kHz), and the resolution is now 24 bit. Finally, the captured data is further processed in the DSPs, where further downsampling may precede spectral analysis as needed. For the example in Figure 16 the final data is 5 kSps, and is 32-bit floating point precision. It should also be noted that the incoming data stream can be recorded to the local bus disk at the analysis bandwidth or at any decimated bandwidth, derived from the same initial clock rate.

CONCLUSION

It has been shown that dynamic signal analyzers have a comprehensive set of tools ready to tackle any machinery diagnostics challenge. Incorporating a DSP-centric design, further ensures that analysts can conduct real-time measurements on an unlimited number of channels, while also recording raw data to the PC disk for future playback analysis. The author wishes to emphasize that route based data collectors and/or permanent monitoring solutions are not to be replaced by dynamic signal analyzers, but neither approach includes the analysis techniques needed for diagnostics and with the growing demands on companies to maximize their return on assets, a high performance dynamic signal analyzer platform is an essential element in the toolset used by predictive maintenance and machinery diagnostics personnel.

REFERENCES

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