Two-Year Operational Evaluation Of A Consumer Electronics-Based Data Acquisition System For Equipment Monitoring

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ABSTRACT— Oak Ridge National Laboratory (ORNL) has performed a two-year evaluation of the performance of an in-house developed consumer electronics-based data acquisition system (DAS). The main advantage of this approach compared to conventional instrumentation grade systems is cost; instrument grade data acquisition systems average costs range from $800 to $2,000 per channel compared to a range of $200 - $400 per channel for a consumer electronics-based system.

The DAS is operated as a full-time in-situ vibration monitor. The resulting data stream is streamed over the ORNL network, at an aggregate rate of approximately 2 megabytes/s, to a Linux server. The server includes the capability to implement event-triggered data stores, as well as real-time files for the implementation of continuous display monitoring of the spectra. Detailed spectral analysis is performed post event.

The DAS is installed on a large industrial chiller and cooling water pump associated with ORNL's Titan supercomputer. These mechanical systems include rotating components that operate at fundamental frequencies within the range of 30 Hz to over 3 KHz.

Evaluation of the DAS data over a two-year operating period leads to the conclusion that for many industrial processes this system could form the basis for a cost effective means of obtaining operating health data in real time from rotating machinery. The deployment has also shown that the DAS technology is reliable. Furthermore, because the cost of the DAS is low, the other significant advantage of this approach is that the DAS can be deployed in a dedicated manner and operated on a full-time basis.

Keywords- data acquisition, in-situ equipment monitoring, diagnostics, accelerometers

INTRODUCTION

A two-year evaluation of the performance of a consumer electronics-based data acquisition system (DAS) has been performed by ORNL. This system was developed in late 2013 and deployed in 2014 to monitor the vibrations associated with two rotating machines. The original motivation for this research was the potential to drastically reduced per-channel costs of these systems compared to systems that use conventional electronics, software, and instrumentation.

The DAS was configured as a 20 channel monitoring system using a combination of development level board CPUs and consumer grade electronics. Four conventional accelerometers were included in the system along with sixteen Microelectromechanical systems (MEMS) accelerometers. The DAS was installed on a 1,200-ton chiller and 3,000 GPM chilled water pump at ORNL. These components are part of the infrastructure used to cool ORNL's Titan supercomputer.

This research resulted in a robust high frequency spectral monitoring system that provides continuously monitored data on two large rotating machines. The data acquired by the DAS has yielded information about the mechanical condition of the two monitored units.

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This paper will provide an overview of the consumer electronics-based DAS architecture and components, describe the installation of the system, discuss the application of the system for condition monitoring, and summarize its operating performance over a two-year period.

CONSUMER ELECTRONICS-BASED DAS ARCHITECTURE DESCRIPTION

System Architecture Based On A Very Powerful Micro-Controller

Fig. 1 shows the overall architecture of the DAS system. While it is based on several inexpensive consumer electronic components, the capabilities of each component yield an overall system design that is remarkably robust and provides high-performance.

The key component of our design is a pair of micro-controller-based boards called the BeagleBoard-XM, which is manufactured by Circuitco, a subsidiary of Texas Instruments. The BeagleBoard-XM is an Advanced RISC Machine (ARM) based circuit board. There are five important characteristics of the BeagleBoard-XM that enable it to be a powerful solution for real-time monitoring; it is a low power device which means it requires no special provisions for cooling, it uses the Linux operating system which is a powerful foundation for data acquisition usage, it includes a very robust audio codec subsystem that can be used for vibration monitoring, it provides robust support for Universal Serial Bus (USB) devices, and it includes powerful network functionality.

Probably the most important performance feature of this design is its ability to throttle and manage the aggregate data load in a deterministic manner. For accurate vibration spectral representation, all data samples must be consistently sampled, processed, and stored. Significant testing in this area was conducted on the components and several commercial microcontroller boards were rejected because of non-deterministic sampling. The BeagleBoard-XM performed quite well, and no data loss was ever detected in our pre-design testing or after the DAS was deployed.

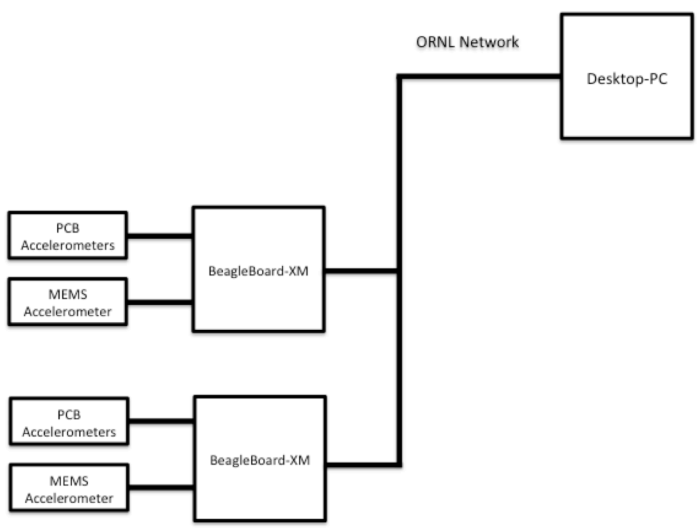

Fig. 1 System architecture

The BeagleBoard-XM supports a variety of peripheral devices, including a stereo audio interface. On each BeagleBoard-XM this interface is used to input one pair of high-speed analog signals.

Another powerful feature of the BeagleBoard-XM is its USB expansion capability. Four USB host interfaces are provided on each board. Our design uses all of the USB ports to connect to four external expansion USB-audio devices. Each expansion

USB-audio device provides a pair of audio input channels. The resulting high-speed channel capability is 10 channels per BeagleBoard-XM board. Since our design uses two of these boards, the system total is 20 channels of high-speed analog monitoring at sample rates of up to 48 KHz for each channel.

Sensors and Signal Conditioning

Transducer selection is a critical step in building an effective monitoring system. The emergence and maturity of micro-electronic mechanical systems (MEMS) accelerometers presented an opportunity to evaluate and re-purpose these low cost sensors in a typical balance of plant monitoring scenario. Within this DAS system 16 Analog Devices MEMS sensors are used. The MEMS sensors were procured as demonstration boards from Analog Devices. For reference purposes, four Standard Integrated electronic piezoelectric (IEPE) industrial accelerometers are used. These sensors are manufactured by Industrial Monitoring Instrumentation (IMI), a division of PCB Piezotronics, Inc.

Signal conditioning for the system is implemented two ways. Each BeagleBoard-XM processes two channels of conventional accelerometers that are conditioned by IEPE signal conditioning. Eight additional channels are implemented using Analog Devices MEMS accelerometers along with signal conditioning provided by Texas Instrument instrumentation amplifiers.

Other components of our setup were three modular DC power supplies and interconnection hardware (terminal strips and Deutsches Institut für Normung (DIN) rail connection points). One power supply provides 5 volts for the operation of the BeagleBoard-XM boards. Another 5-volt power supply provides the operating power for the MEMS accelerometers. The third power supply provides plus and minus 12 volts that powers the instrumentation amplifiers associated with the MEMS accelerometers.

A separate desktop-PC running the Ubuntu Linux operating system functions as a data stream manager and server for the storage of data files. Data is streamed over the ORNL network using secure shell (ssh) tunneling between the two BeagleBoard-XM boards and the desktop-PC.

Sensors and Signal Conditioning

The BeagleBoard-XM supports numerous operating systems but for the DAS implementation the Angstrom Linux operating system was selected. The operating system and root file system are both contained on a 4 GB micro-SD flash card that operates like a normal disk drive.

Linux is a powerful operating system and one of its strengths is its networking capability. This is true of the Angstrom version of Linux, which has a small footprint and is relatively fast. Not only does it provide a robust TCP stack and full-featured network capability, it also includes the benefit of ssh that provides both network encryption and tunneling of data streams.

The Linux operating system (OS) includes a robust set of audio processing tools based on the Advanced Linux Sound Architecture (ALSA) libraries. They provide OS-level commands for acquiring data from the audio devices and outputting that data to a file or as a data stream in the form of a pipe. Our application needed the capability to provide the ability for continuous monitoring as well as on-demand data captures. These features were implemented in a specialized software application called the data stream manager.

The data stream manager is a software application written in Python that is responsible for the flow control of the sampled data. It receives the incoming stream of sampled data from the audio codec, buffers the data, and monitors for operating system directives that specify actions to be taken with the data, such as storage to a file.

The data stream manager currently supports three file types for storing raw vibration data. First, a monitor file is continuously updated that contains the last second of sampled data. Other programs can access the monitor file for implementing real-time features, such as spectral monitoring. Fig. 2 shows an example of this where the spectra from all twenty channels are displayed and updated each second.

A second type of file produced by the data stream manager is the on-demand capture file. This file contains 300 seconds of data. Normally, data is maintained in a ring buffer in memory that is continuously refreshed. The on-demand capture file is produced when an operating system event is received. This event can be initiated on a pre-scheduled interval, or as an interrupt using a hardware trigger. For the interrupt trigger, a counter is started at the time of the event and when the ring buffer appends a new amount of data that is equal to 50% of its capacity all of the data is then written to disk. This approach results in a data file where the time of the interrupting event is exactly in the middle of the data file. This provides for both pre and post event data to be available for subsequent analysis.

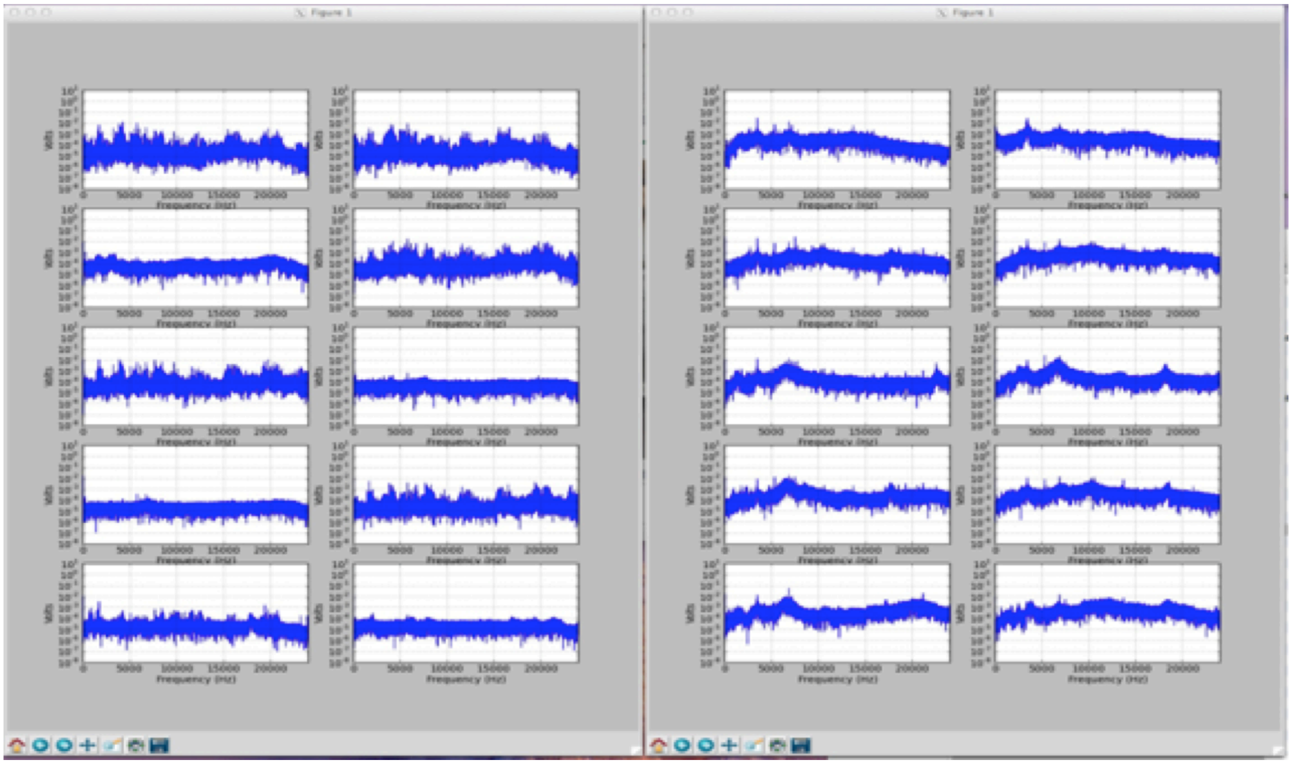

Fig. 2 Frequency plots of all 20 channels

The third type of data product produced by the DAS is the historical assessment file. This file contains a series of four-second snapshots of each channel taken on a predetermined interval, which for this deployment was 1 hour. These snapshots are appended into a file along with a time stamp record header. The resulting file is retained over the entire operational life of the system.

All data analysis of DAS data is accomplished using separate MATLAB or Python software. These applications provide all the required signal processing and data presentation functionality, both for real-time monitoring and display. The analysis is implemented on a separate computing platform, and as a result the choice of its operating system is more flexible. Choices include most variants of X86 and AMD64 Linux, Windows, and Apple's OS-X. All three were successfully used at ORNL.

SYSTEM INSTALLATION DESCRIPTION

For the evaluation, the DAS was installed on two rotating machines in a facility on the ORNL campus that is managed by ORNL's Facilities and Operations organization. A 1,200 ton chiller shown in Fig. 3 and a standard 3,000 GPM chilled water pump shown in Fig. 4 are typical of almost any large industrial facility. The pump spans the range of most industrial/commercial rotating equipment with an electrical driving component, shaft and coupler, and a driven component on a common base; the chiller provides a more specialized example of a piece of industrial rotating equipment.

Accelerometer sensor placement was done per typical machinery diagnostic methodology i.e. radial at each inboard and outboard bearing location and at least one thrust load measurement point on the structure. Mounting was accomplished with magnetic attachment as an acceptable means of temporary mounting on the equipment.

The sensors required different signal conditioning. The four conventional accelerometers required a power supply and amplifier to supply 4-20 mA at 24 volts DC; the amplifier drives a high impedance analog-to-digital converter with an AC coupled signal. The MEMS sensors required a buffering amplifier to provide sufficient current to drive the analog-to-digital converters. Fig. 5 shows the electronics enclosure in a standard Hoffman box. At top left are the IMI signal conditioners mounted on a DIN rail. Directly below are the two stacked BeagleBoard-XM boards. The smaller boards in the center of the cabinet are the TI amplifiers for the MEMS devices. The small boxes below them are the audio two-channel USB analog-to-

Fig. 3 Chiller compressor

Fig. 4 Water pump

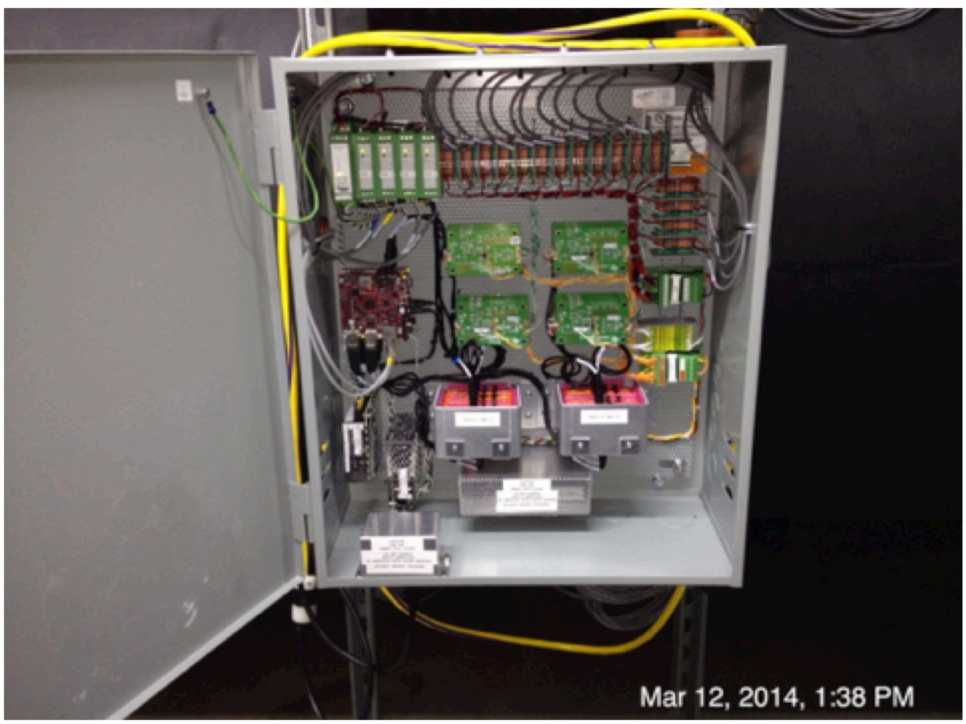

Fig. 5 DAS components mounted in enclosure

digital devices. Power supplies are on the bottom of the box. The remainder of the cabinet's contents is related to wiring and interconnection cables. The system is installed in close proximity to the chiller. Some of the analog cable runs approach a length of 100 feet.

The desktop-PC that functions as the data manager and file server was located in a separate building approximately ¼ mile away from the location of the main DAS components. This meant the network topology connecting the two was rather complex and spread over a large area through the ORNL campus.

DATA ANALYTICS FOR ROUTINE MACHINE HEALTH ASSESSMENT

The consumer electronics-based DAS system has been operating two years at ORNL by continuously monitoring two large rotating machines. This dedicated deployment has effectively made the DAS an in-situ sensing device. Since operation began in March 2014, 722 gigabytes of raw binary data has been saved. From this data, 104 thousand plots have been generated. These plots are periodically reviewed to determine if changes in the machine spectra are occurring.

Deterministic Sampling Yields Very Detailed Spectra

Fig. 6 shows a typical baseband spectral plot for one sensor channel. This plot was produced from a file containing 300 seconds of data for one channel. A single FFT was used yielding a spectrum with over 7 million frequency bins. The highest frequency that can be resolved, based on the 48 KHz sampling rate, is 24 KHz. An FFT with a time-bandwidth product of 300 seconds produces spectra with 1/300th of a Hz spectral resolution (i.e., the bin spacing is 1/300th of a Hertz).

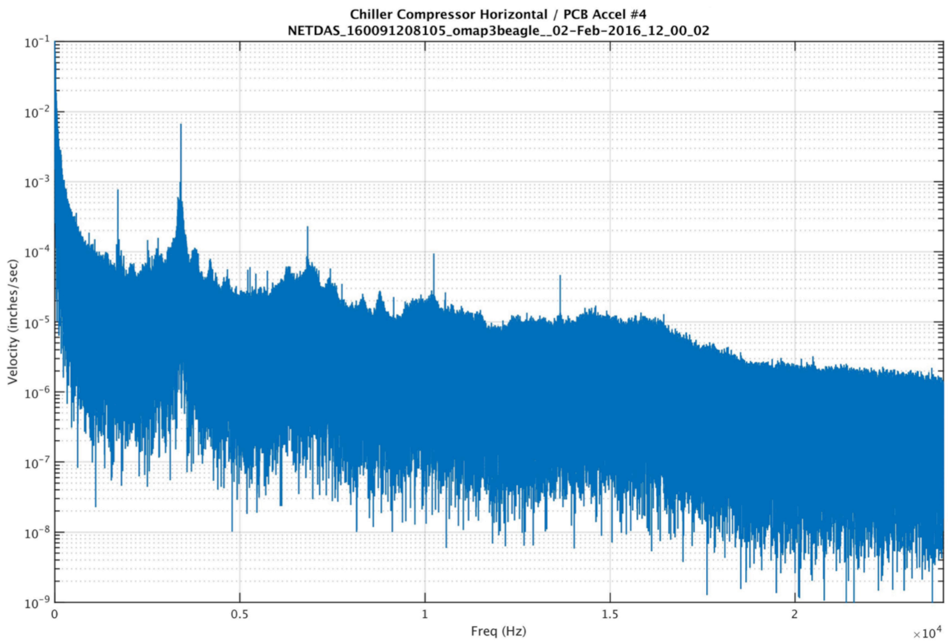

Fig. 6 Baseband plot

Comparison of Sensor Types

Comparison of the IMI sensors and the MEMS sensors showed that the frequency responses of the two sensors differ. Fig. 7 shows snapshot FFTs from both sensor types at the same geometric location and the same instance in time. The inset plots differ in overall characteristics as well as noise floor. The top inset shows the spectra for an IMI sensor. The second inset shows the spectra for a MEMS sensor. The third inset shows the MEMS spectra plotted over the IMI spectra. And, the fourth inset shows the IMI spectra plotted over the MEMS spectra. This data suggests that the IMI piezoelectric sensors have approximately 30 dB of additional signal-to-noise ratio when compared to the MEMs devices. Even so, the spectral profile for the same excitation showed that the MEMS devices performed acceptable for situation where the vibration levels were robust, such as the case with a pump. Systems running with lower vibration levels will require a more sensitive device such as the piezoelectric sensors.

Trending Over Two Years Of Operation

The historical assessment file provides a means to trend the vibration level over a long period of time. The data can be displayed as a waterfall plot; an example is shown in Fig. 8. Frequency is shown across the X-axis and time progresses along the Y-axis from bottom to top. The darker vertical traces represent tones that are contained in the data. Often these are fixed frequency where their presence or intensity indicated the on/off state of the machine. The lower part of the plot reflects data that was acquired on March 12, 2014 while the upper portion of the plot reflects data acquired on February 4, 2016. Individual tones (i.e., steady state frequencies) show up as vertical lines. The horizontal black regions in the plot are data gaps that present periods when the DAS was not operating.

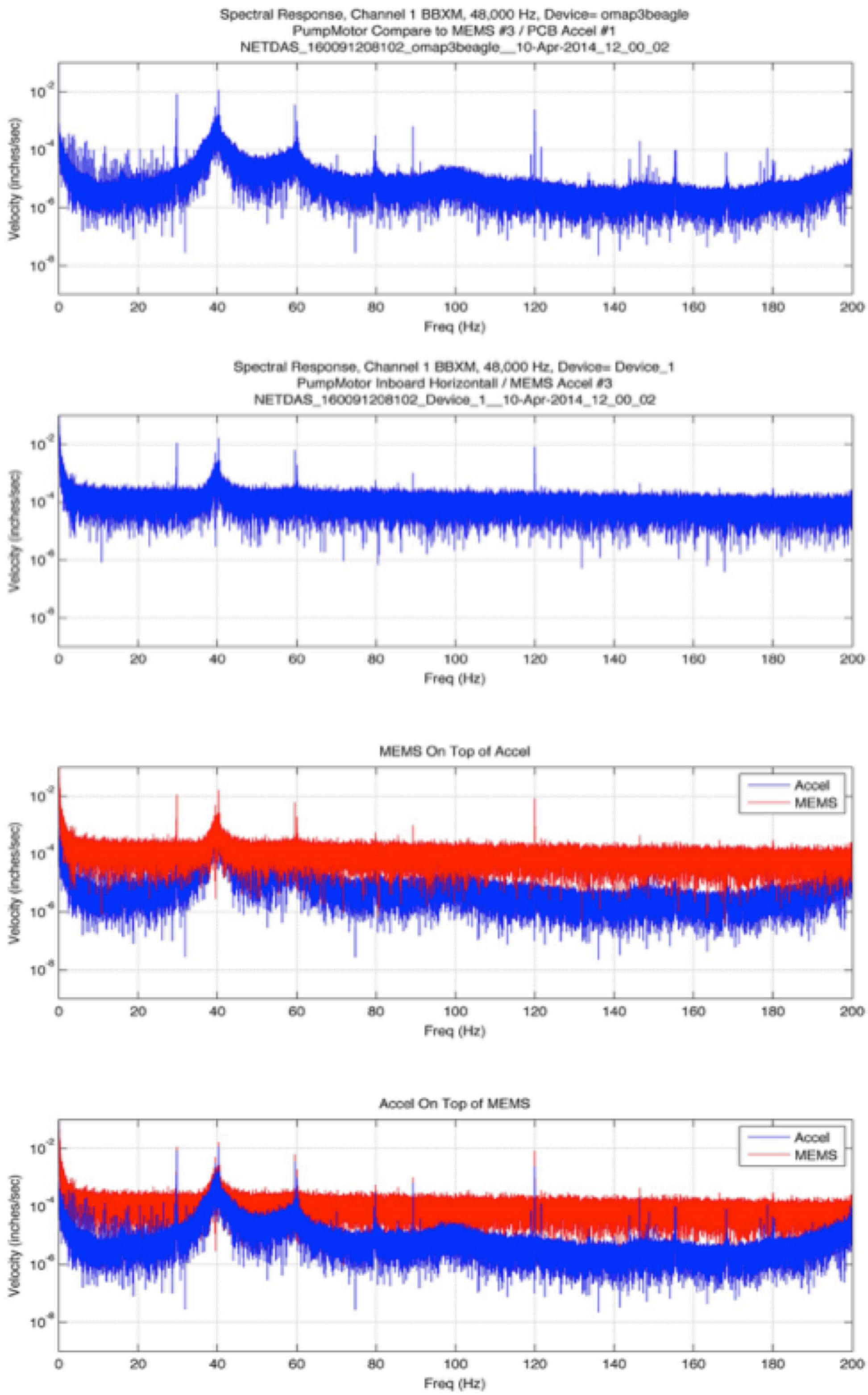

Fig. 7 Comparison of two types of accelerometers

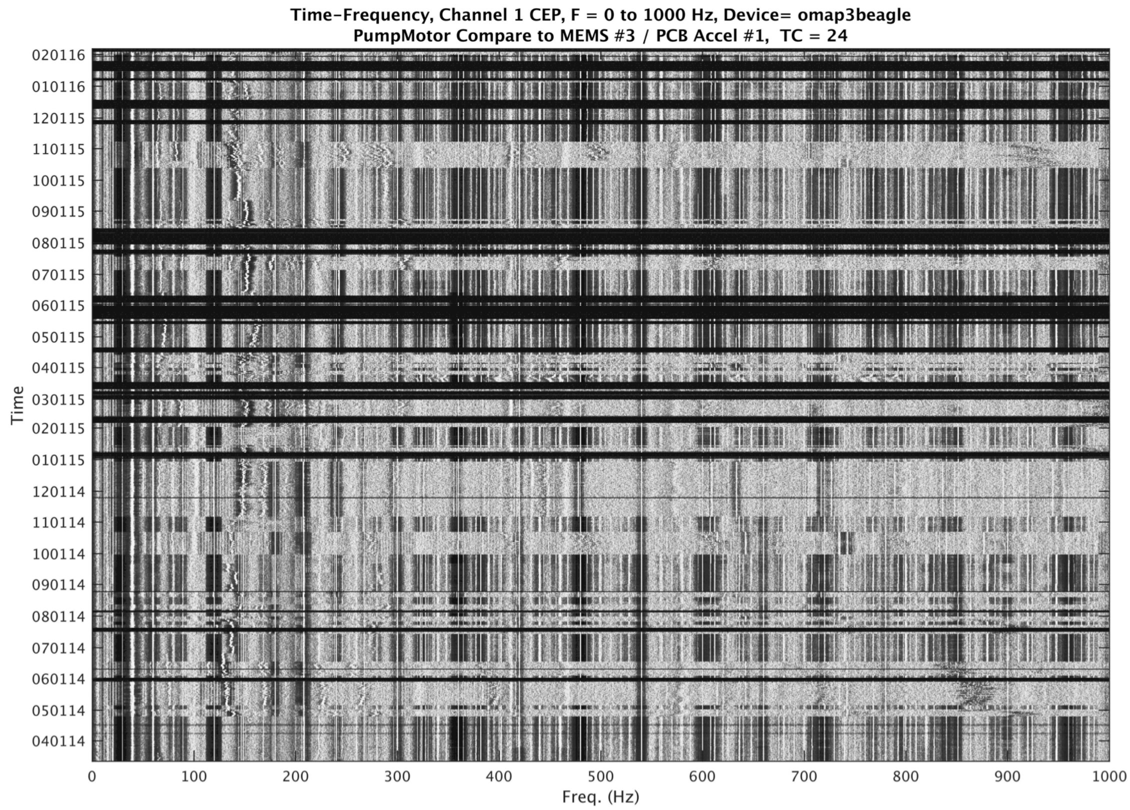

Fig. 8 Waterfall plot

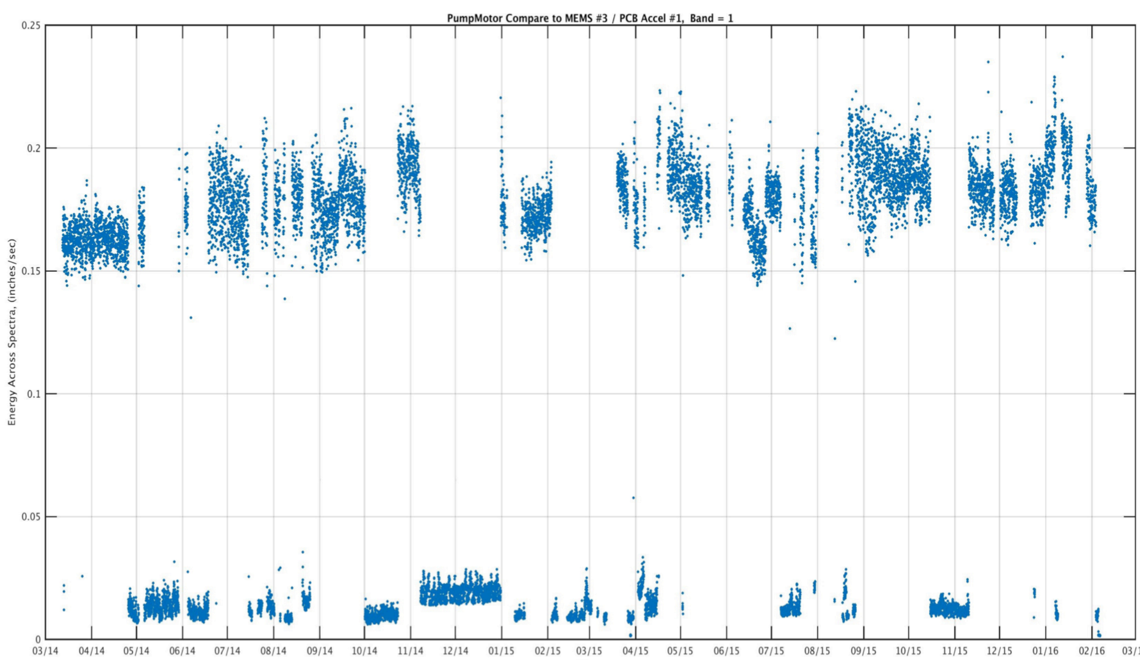

Fig. 9 Energy trend

Energy trend plots are also produced from the data. An example is shown in Fig. 9. This plot shows the effective energy in a 2 KHz wide band that contains the fundamental frequency of the chilled water pump motor. Over the two-year evaluation period there is a very slight increase in the maximum spectral energy of this band. This is considered normal and related to aging of the pump. The energy trend plot may be the most important reporting from our data analysis because it shows quite effectively how energy content in the vibration signal is trending over the operating history of the machine.

EVALUATION OF CONSUMER ELECTRONICS-BASED DAS PERFORMANCE

Availability

Detailed analysis of historic data indicated the overall system availability of the DAS was approximately 85%. Based on post outage analysis, the initiating event for all of these data gaps was either loss of power at the DAS or file server system, or a disruption of the network over which the streaming data passed. Often the disruption was short. However, because the DAS design does not currently include an auto-start capability, a manual start is required. In many cases the outage went undetected for several days and that is why some the data gaps are so large. With the exception of one outage, the DAS system was successfully restarted using a manual procedure.

After consideration that the cause of these outages was related to power and network availability, the 85% availability is viewed as excellent. If provisions had been made for uninterrupted power on the critical components and improved network availability, it is felt the system would have demonstrated near 100% availability over this period.

Flash Card Selection

The one case where a manual restart was not successful occurred about three months after installation. The failure was due to a faulty micro-SD flash memory card on one of the BeagleBoard-XM boards that prevented the board from booting. The flash card failure was due to a hard error on the card (i.e., a reformat of the flash card was not possible). Further investigation revealed that this flash card was one that was supplied with the BeagleBoard-XM and was manufactured by Kingston Technology. This flash card did not include provisions for single-bit error detection and correction. ORNL had previously run into this same issue on another project using BeagleBone microcontroller boards. In that case and with the DAS deployment, the solution was to use a micro-SD flash card that included single-bit error detection and correction, such as offered by Transcend Information Inc. No failures have occurred since upgrading to the higher quality flash cards manufactured by Transcend.

The reason single-bit error detection and correction is important is the flash card is functioning as the root file system of the Linux operating system. The operating system continuously updates a large numbers of files as part of its normal operation. Notably files in the */var* and */dev* directories are heavily accessed and changed.

Connectors

The MEMs accelerometers proved to be an acceptable and cost-effective means of monitoring devices that had moderate levels of vibration, such a pumps. However, the usage of evaluation boards proved to be problematic due to reliability problem with the electrical connections. In almost all cases, electrical connectivity failed to the MEMs sensors after a two-month operating period. It is believed this issue would be resolved by the use of more conventional industrial connectors. No connectivity issues were encountered with the piezoelectric accelerometers.

Simultaneous Sampling

Each pair of sensors is processing using a stereo audio channel pair associated with a codec. This means that each pair of channels used a separate timing source as the basis for its sampling. This means that coherent analysis is only possible on channel pairs that share the same clock. For machine monitoring this is not considered a limitation, but it would be for more complex modal analysis. Subsequent testing by ORNL has identified alternative audio-to-digital conversion technology that can provide eight or more channels of synchronously sampled channels at 24-bits resolution for applications that require that level of performance.

AC Coupling of Signal

Another limitation that should be mentioned is related to how in frequency the audio signal is processed prior to digitization. For the codecs used in this design, all of the sensor channels were AC coupled. This resulted in a first-order high-pass filter effect that attenuates signals below 30 Hz. In the case of the MEMS sensor this could be a significant issue. In the case of the IMI sensors it is likely that roll-off can be mitigated by the additional 30 dB of SNR those sensors provide.

CONCLUSIONS

A preliminary evaluation of the performance of a consumer electronics-based data acquisition system (DAS) has been performed by ORNL. Evaluation of the data provided by the consumer electronics-based system leads to the conclusion that for many industrial processes this system could form the basis for a cost effective means of obtaining operating health data in real time. The technology seems well suited for applications to monitor the operating health of balance of plant components.

The availability of the DAS over this operating period approaches 85%. Since the design of the DAS did not include auto-restart once an outage occurred, a manual restart was required and often the need for this was not identified for several days. In all cases, the DAS system outages were traced to disruptions in power or network outages. As a result, the 85% availability is viewed as excellent. If provisions had been made for uninterrupted power, improved network availability and auto-restart of the DAS, it is felt the system would have demonstrated near 100% availability over this period.

The consumer grade system has a hardware cost of less than $5,000 for the entire 20-channel system including the sensors and cabling. The software is based on public domain based resources and is configurable from one system to another. Thus, once a monitoring system is developed and installed for a specific application, it can be efficiently duplicated or modified to expand the monitoring effort to multiple machines.

The main advantage of these systems compared to conventional instrumentation grade systems is cost and opportunity; instrument grade data acquisition systems average costs range from $800 to $2,000 per channel compared to a range of $200 - $400 per channel for a consumer electronics-based system. And, this technology makes it possible to monitor lower-value systems that would otherwise not be a candidate for this type of monitoring due to cost and logistics. It is now possible to install this monitoring as a permanent feature of the monitored system (i.e., as an in-situ measurement as opposed to a temporary measurement). The potential low cost of these systems, combined with their reasonable monitoring performance, ease of upgrading and scalability, and impressive reliability, makes them an attractive alternative to conventional systems for industrial monitoring applications.

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