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Abstract

Emerging technologies are expanding the implementation of Condition Monitoring to markets and applications not previously practical or economically feasible. This trend is particularly observable as Industrial OEMs develop CBM programs for their own hardware. Data driven analytic approaches to CBM can result in the development of additional monitoring tools and expanded suite of condition indicators using both existing and new instrumentation, augmenting traditional approaches developed for rotating/reciprocating equipment. Transferring learning from the lab to the field introduces challenges and obstacles to deployment that can be overcome by leveraging the convergence of IIoT technologies.

The paper will highlight a pump condition monitoring case study, which used data driven analytics to develop new health indicators from vibration signals.

Pump Vibration Analytics Case Study and the Need for More Deployable Instrumentation

Introduction

Condition Monitoring techniques, systems and services today represent a mature eco-system that has been developing for decades. CBM services have traditionally been provided by service providers and CBM equipment vendors, often in collaboration with plant maintenance engineers. This after-market installation and service of condition monitoring instrumentation means that plant maintenance, system vendors or service providers capture the value of CBM by measuring and analyzing machine data once installed in the plant.

An observable trend to expand CBM coverage to new equipment involves the industrial component OEMs themselves, who are developing machine health programs of their own. Implementing a program for a new class of machines can be a multi-faceted challenge for the OEM requiring mastery of new analysis skills, the capture and application of tribal knowledge, and deployment of new sensor technologies.

This is particularly true for specialized or complex machines that are not currently or easily monitored with traditional tools and techniques. In many cases, end users of complex machinery are the first movers in this direction, as they encounter problems in the field which are opaque to the OEM buffered by their sales channels. Field experience and recommendations from plant maintenance or other service providers may be adapted by the OEM as the foundation for a program to pre-instrument their equipment.

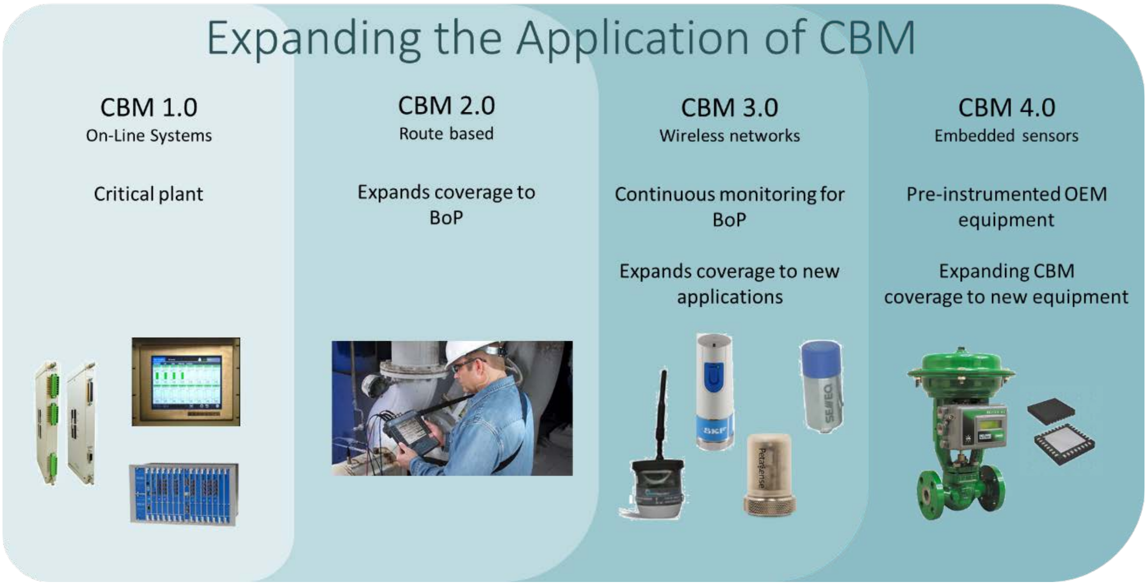

Figure 1 The emergence of CBM as applied by the Machine OEMs may be considered a fourth wave of market expansion, extending CBM coverage to previously unmonitored hardware.

In this universe of specialized equipment, the machine behavior or operating environment often resists traditional vibration analysis approaches. Automation equipment or machines with complex mechanics, mobile platforms or hardware that doesn't rotate at fixed frequencies present challenges to tradition tools. Extending the art of CBM to new equipment with effective monitoring and diagnostics may require development of new health indicators and deployment of new instrumentation. In particular, data engineering and advanced pattern recognition algorithms are joining traditional signal processing approaches to help identify patterns within available sensor data. Once the various signals associated with machine behavior and operation are modeled, higher accuracy machine health indicators can be developed, providing earlier identification of new faults, and leading to more detailed diagnostics.

Help Wanted: A CBM Program Development Process for New Types of Equipment

The process for development of a program starts with knowledge of the common problems. FMEA results, maintenance experience and other 'tribal knowledge', coupled with existing operational and monitoring data can all contribute to better modeling of machine behavior. With this foundation, machine characterization based on available data can proceed. Data engineering techniques and algorithms are selected and applied to extract unique features from the data. Once the features are extracted from the measured data, informed by domain experts, new health indicators can be defined and tested. With effective health indicators in place, more accurate diagnostics are also possible. The duration of this stage is often limited by the availability of useful data.

It may turn out that additional data would further enhance the ability of this process to deliver highly effective indicators. In these cases, new instrumentation will have to be deployed to collect additional field data. This requires the cooperation of supportive end users, who can benefit from the program by early identification of problems that lead to down time, and a front row seat to the prospect of extending CBM coverage to equipment that wasn't previously monitored or can now be monitored more effectively.

Thankfully, new CBM systems developed with IIoT capabilities minimize the time and effort to deploy new instrumentation. New solid-state sensor technologies, low cost wireless joins data engineering analytics to enable new CBM instrumentation solutions tailored toward the machine. A pilot study can determine in a relatively short time whether progress on new health indicators can be accomplished with available data, or whether new instrumentation is needed.

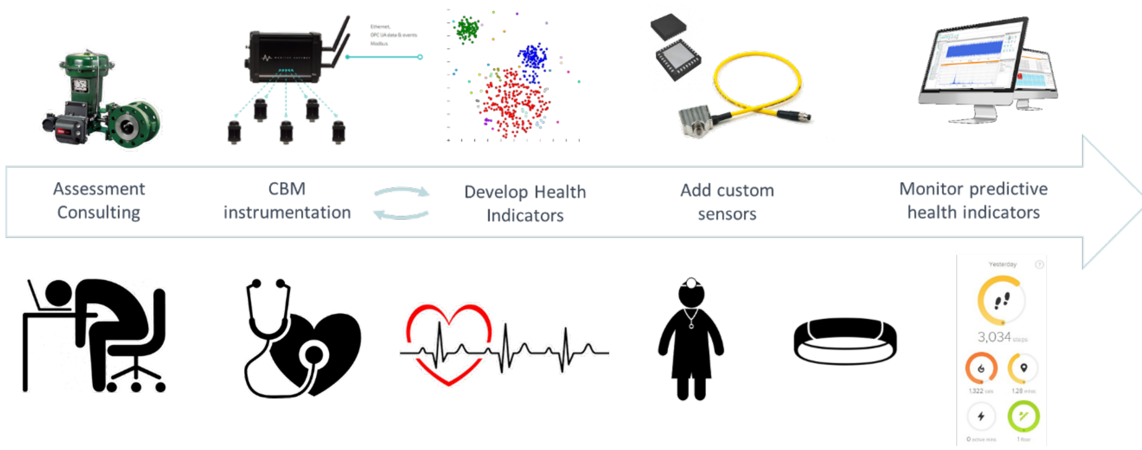

Figure 2 A process for development of CBM instrumentation on new equipment may start with analysis of existing data. A short-term pilot study should help determine whether new instrumentation (sensors) are needed or not.

New Instrumentation Options:

Acquiring the new field data necessary for the development of effective health indicators may be accomplished by deploying a wireless sensor system that enables relatively easy access to the data. More and more wireless CBM systems are appearing on the market. Equipped with low power accelerometers, many systems also have the ability to deploy additional sensors measuring temperature, rotation speed, pressure, etc. For OEM field testing, it's also necessary that the system have the means to transport the data to a location within the test site, so that it can be easily extracted by the OEM for analysis. Many wireless systems today provide data via OPC/UA, Modbus, Ethernet and other standard protocols to port the data to a PLC, SCADA system or even a local server or laptop set up for the purpose of collecting data for later analysis.

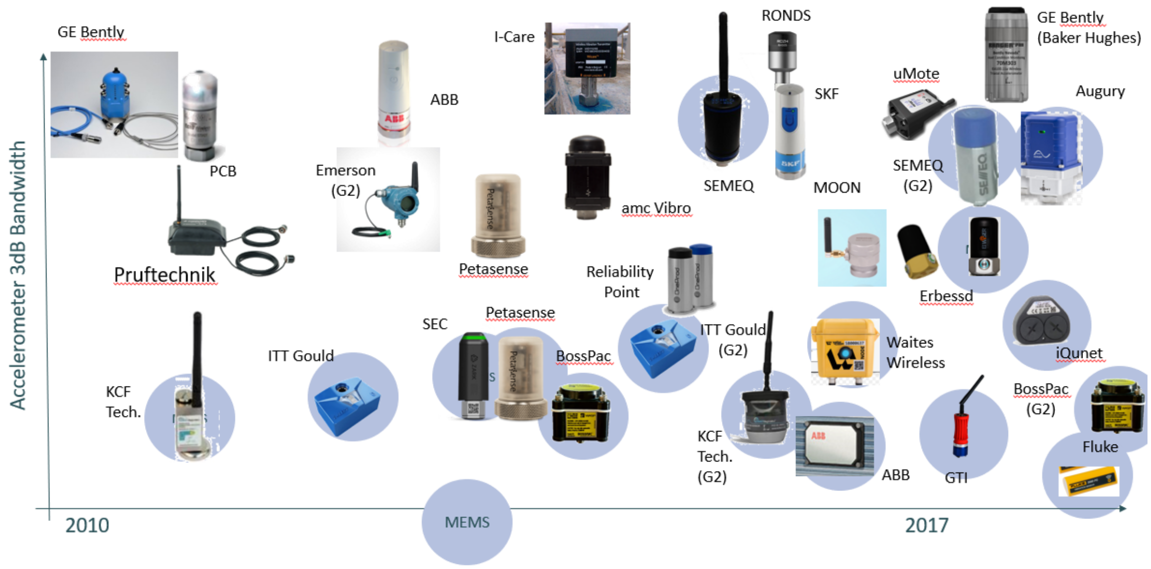

Figure 3 An example of the convergence of IoT related technologies is the explosion of wireless options for CBM instrumentation. Many of these products were developed by vendors with an industrial or CBM pedigree, with interface options enabling relatively easy integration within current plant OT.

Another relatively recent and potentially game changing development is the emergence of MEMS (solid state) accelerometers. Measurement of machine vibration with a solid state sensor enables several characteristics useful to the machine vendor. For starters, high integration levels are now more achievable, offering the potential for 'smart' sensors with embedded pre-processing of the data. Small form factors, low power operation and standard electronic interface options also contribute to the design flexibility of a new sensor solution. In particular, enabling implementation of standard digital interfaces in small form factors is particularly useful for the placement of the sensors, as well as data transport and management of the output data. If the problem is understood well enough, some sensor-based processing can be performed as well, generating useful information (indicators) rather than simply data. Adding this all up, fully integrated and highly capable CBM sensor solutions can be defined - in collaboration with the OEM - specifically for the machine.

Case study: Development of a Health Indicators for a Water Processing Pump

For this application, the end-customer wanted to develop a predictive health monitoring system for their pumps in which they wanted to have an early indication and diagnosis of any potential degradation that was occurring in the pump. In terms of the signal measurements, accelerometers were installed for measurements at several locations, along with a tachometer signal (to measure the speed of the pump) and a pressure signal. Much of the analysis focus was spent on developing analysis methods for the vibration signal, however the pressure and tachometer signal provided important context information. For this study, there was data from seeded faults conducted in a laboratory setting and data from two pumps in the field. The laboratory data was used to develop some of the initial analysis methods. However, the emphasis of this case study will be on the field study since there was an actual failure in the field and it provided an interesting data set for evaluating the pump health monitoring analysis methods.

Signal Analysis and Feature Extraction Methods:

The pump vibration might offer important insight in both the temporal and frequency domain. With this mind, a short-time Fourier transform of the vibration signal was calculated and the spectrogram was one of the vibration analysis tools used in this study. This spectrogram provided a wealth of information for visually understanding the vibration signal and for extracting information to infer the health condition of the pump. An example spectrogram from a pump in the field is shown in Figure 4, in which the left plot contains the time signal and angle-frequency spectrogram from the pump at the start of the data collection (assumed to be healthy) and the plot on the right is from a data record that is one day prior to a failure event occurring on the pump.

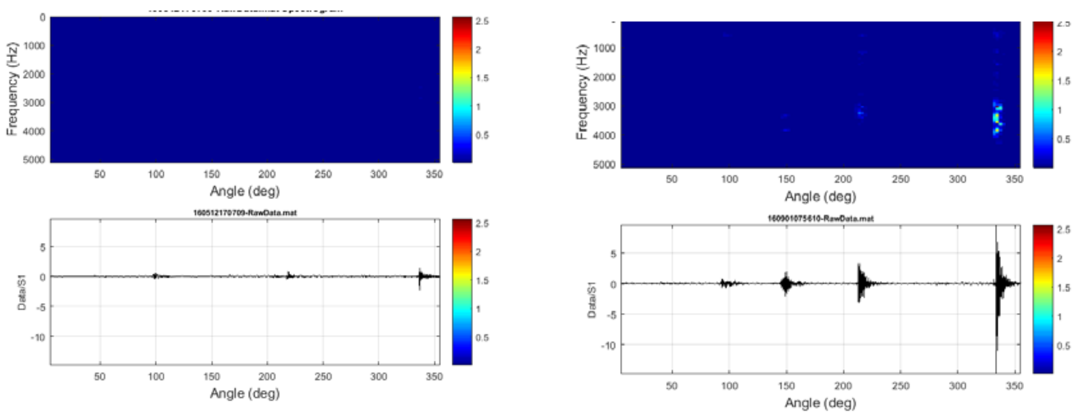

Figure 44. Angle-frequency spectrogram (left plot – healthy system, right plot – one day prior to a failure event).

Various metrics were considered from the time domain, the frequency domain, and the spectrogram in this study. This set of condition indicators were reviewed and ranked using the laboratory data, and this learned information was then applied to the field data.
An example feature plot is shown on Figure 5, in which the magnitude of a frequency band is plotted over time. This band appears to provide a very clear increase and early indication of the failure event (approximately 1 day prior to the failure event). The health index method aims to combine multiple features to provide a more robust assessment of the pump and to have better coverage for the various failure modes that can occur.

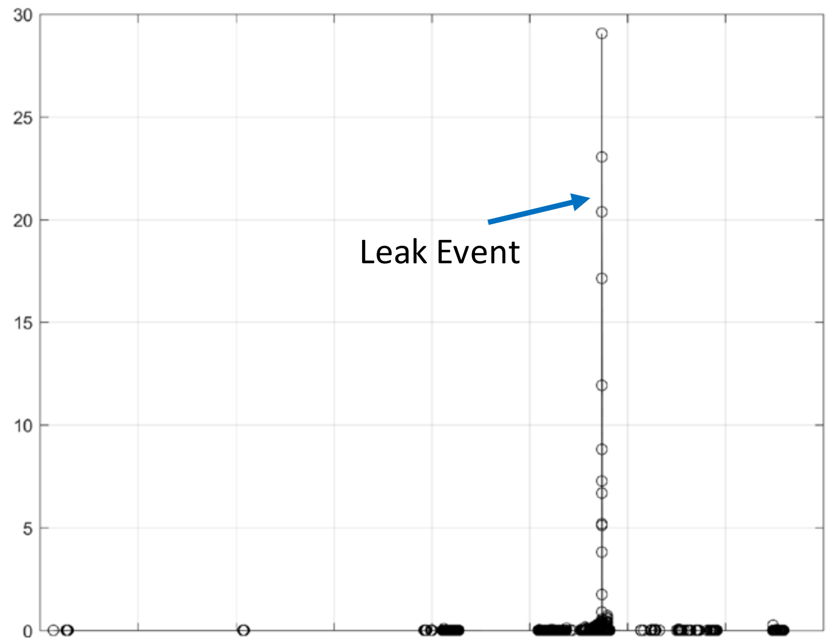

Figure 5. Example feature trend which shows a large increase prior to a failure event.

Health Indication of Pump Condition:

With this notation that a multivariate assessment of the pump might provide a more robust assessment of the pump condition and provide more coverage for the various failure modes that occur, using a baseline-based health index method was a reasonable choice for this application. What was needed was an assessment that could learn the nominal relationship between the vibration features and the operation conditions and provide a predicted vibration feature response that could be compared to the actual vibration feature value. A residual based health index method was considered, and this health index could be trended and monitored over time. It also should be noted that the health index can be scaled by an appropriate statistical threshold, in which the convention is that any health value above one is considered anomalous.

An example health index is shown for one of the two monitored pumps in the field in Figure 6. As one can observe, there is a clear increase in the health trend before one of their maintenance events (failure event). For this failure event, the health index is above the threshold rather consistently one day prior to the failure occurring. Potentially, this event could have been prevented if this system was deployed (the data analysis methods were developed with this historical data).

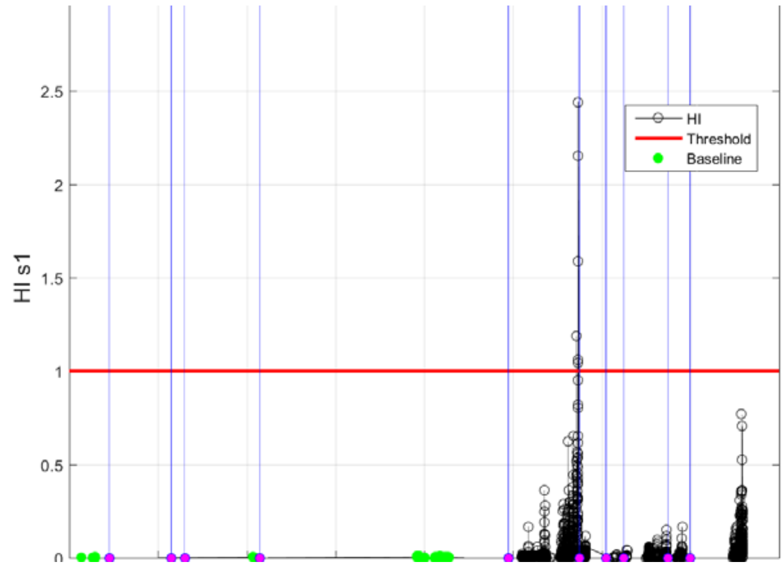

Figure 6. Health indicator result for one of the pumps in the field.

Diagnosis Method:

After reviewing the historical data from the pumps in the field, various types of anomalous vibration patterns were observed. This included the failure vibration pattern, a precursor to the failure pattern, and accelerometer related failures. In addition to using a health index method that might providing a warning that the pump vibration is anomalous, it was also important to provide more context and a potential diagnosis of what problem could be occurring. This would help provide the maintenance technicians and operators with more actionable information based on the assessment and diagnosis of the pumps health. In order to facilitate this diagnosis information, the diagnostic approach considered the frequency patterns for each fault type. This frequency domain pattern recognition method was quite effective and had an accuracy at nearly 90%. With this developed method, one could monitor the pump, assess its health condition, find early indications of potential problems, and diagnosis the problem that was occurring.

Discussion and Future Work:

Further analysis of the available data will be used to further improve and refine the health indicators, particularly if additional measurands are also available for analysis from operational and control sensors. In this case, pressure, tachometer, temperature and other sensors may provide contextual information that may increase diagnostic value of the health indicators as well as increasing the warning time of an emerging fault. Additional field data can also be acquired to increase the resolution of the known fault signals, and to identify additional fault patterns.

Optimizing the instrumentation may be considered as well, applying lessons learned to reducing the amount of instrumentation or to improve the performance of the sensors to deliver higher quality data, which may in turn may improve the resolution of the analysis. Some of the fault patterns were related to damage occurring to the sensors themselves, so finding improvements in the instrumentation will help alleviate these sensor failures in the field. In addition, if there are lower cost sensor accelerometer measurements that could be used, this would allow for more measurement points and an improvement in the fault isolation and diagnosis accuracy. Solid state MEMS accelerometers enable a higher level of integration with digital communications options that provide flexibility to connect the sensors to the existing OT, and might also be considered in the future work.

With a clearer understanding of how effectively the indicators flag and diagnose machine faults, growing confidence may lead to at least some interpretation of the signals closer to the edge of the network, transforming the transmission of data to that of information. Pre-processing in the sensor (or gateway) from raw data to condition indicators may reduce the amount of transmitted data, easing the burden of OT-side data management and integration with enterprise data bases. This can also have benefits for a wireless sensor (longer battery life) or a control network where the channel capacity is limited (less load on the channel bandwidth).

Application of data engineering techniques to characterize the machine, coupled with the deployment of IIoT technologies provides the hardware OEM with both the process and the tools to implement their own CBM strategy, delivering higher uptime by shipping ‘smart’, pre-instrumented equipment that incorporates domain specific intelligence. This paper highlights the emerging trend in instrumentation technology, the OEM’s desire to incorporate this technology into a future service business, and how the analytics can be used to convert sensor data into actionable health information. Although this concept was demonstrated with a pump condition monitoring case study, the same methodology is being considered by various OEM’s and can be readily applied to other engineering assets.