CHOOSING A PREVENTIVE MACHINE CONDITION MONITORING SYSTEM

GRAM & JUHL APS, AXEL JUHL

Definition. The optimal preventive machine condition monitoring system is capable of determining and locating any evolving error while estimating the remaining lifetime for any machine component of interest.

Introduction:

This white paper outlines what to consider when choosing a system for preventive Machine Condition Monitoring, i.e. a MCM system. The sum of these considerations is necessary when you compare the total cost of esthablising MCM with the expected reduction in maintenance costs and the value of reduced downtime.

1. Background

Traditionally, Machine Condition Monitoring has been based on vibration measurements, but recently it has become clear that the overall performance of preventive and predictive machine condition monitoring can be largely improved by integrating and correlating other process parameters into the survayence; as well as using a combined approach of deterministic and stochastic measurement analysis.

The need for these improvements has arisen from the challenge of monitoring machinery with variable operating conditions, e.g. turbulent loads and variating speed. It has also been very clear that every machine, although of (exactly) the same type, have different "signatures " (fingerprints) which makes it very important to know these "signatures" for the healthy machine together with an estimated or known remaining lifetime.

2. Permanent versus occasional Condition Monitoring

The optimal preventive machine condition monitoring system is capable of determining and locating any evolving error while estimating the remaining lifetime for any machine component of interest. If we had a sufficient model for the machinery under survey we could with some (huge) effort describe any condition and state of the the machine components involved, but since this model would have a tremendous number of parameters and we often only know a few, we are not capable to do this in a pure deterministic way - i.e. only based on modeling. This means that we in practice will not be able to estimate the condition of the machine components by instantly made measurements, at least not very precisely. You also need to know the past to predict the future, which means we need to know the healthy "signatures" of the machine for comparison at a later stage. Therefor permanent machine condition monitoring is preferably to do predictive machine condition monitoring and combined with online facilities you can instantly get notice of any evolving damages.

3. Reproducibility and Conditional Recording

When the condition of the machinery is unchanged, measurements can always be reproduced *given the same conditions*. Therefore it is important to determine the conditions present, when a measurement is recorded or vise versa: to measure under the same conditions. As stated above, machinery with variable working conditions is a challenge since every condition in principle has its own "signature" . This means that it is very important to use "signatures" deduced from measurements made under the same condition for comparison when estimating the state of the machinery. This can be done be defining conditions from process parameters or deducing conditions from the vibrations signals collected. An example would be to use torque and speed of revolution to determine conditions of forces "transmitted" through the machinery.

4. Sensor Specifications

Obviously, the possibilities to gain information about the machinery is limited to the amount of information the sensors can capture. Therefore, the specifications of the sensors are important. Sensors must be calibrated so you can replace a damaged sensor and still be able to reproduce measurements made under same conditions within a specified accuracy. In addition, there are some characteristics (see below) which you must pay attention to. Bear in mind that whatever specifications are presented to you, one could always want them better. It is esential to determine the demands and specifications required by your application.

4.1. **Bandwidth.** The bandwidth of the sensor indicates the highest and lowest frequency it is capable of measuring. Low frequencies can be important for certain structural movements, but for machine condition monitoring in general a few hertz will do[1]. High frequencies can be important for detecting bearing damages - the higher the better - but 8 to 10 kHz will normally do well. For gear wheels, depending on rotational speed, in general 3 kHz will do for most applications. These guidlines should be reviewed with focus on your machinery if running slow or fast.

4.2. **Frequency repsonse.** The frequency response refers to sensor gain versus frequency. The ideal frequency response is flat, meaning that the sensor has the same gain at all frequencies. In practice there are often deviations toward higher frequencies, e.g. the bandwidth is often specified to be at the frequency where the gain is -3dB. The frequency response must at least be continous and preferably monotone; but most important it must be identical for all sensors used, so you can replace a sensor and within a specified accuracy still be able to compare measurements from different sensors. In practice, the resulting frequency response from the signal source, perhaps a bearing deep inside a gearbox, and to the sensing element inside the sensor, does not have a flat frequency response, since the response is made up of a number of transfer functions in the signal transmission path. In fact, envelope measurements are most often made at a frequency where the response has a resonance. Some sensor are even optimized for higher selectivity (gain) in a certain frequency band to be capable of picking up weak signals - A flat frequency response is not an ultimate demand, a non-flat frequency response can even be an advantage for detecting bearing damages.

4.3. **Dynamic Range - Resolution.** The dynamic range is the ratio between the largest and smallest signal the sensor can detect and represent at the same time. This is important in order to detect small details in signals dominated by strong components, e.g. the tooth mesh frequency. In practice not less than 70 dB is desirable. The absolute range depends on the application but ± 50 g is commonly used.

4.4. **Overload Detection.** Overload detection is necessary to detect if the signal applied to the sensor is out of range. If so the measurement will in many cases be distorted and should be discarded. The overload detection must be implemented as near as posssible to the signal source i.e. preferably before any filters.

5. Measuring System Specifications

Digital systems are state-of-the-art, so do not go for anything less than that. The specifications regarding the measuring system must of course at least match your sensors. This means that the bandwidth must be equal or higher, the dynamic range must be equal or higher. Regarding bandwidth, the sampling rate must be 2.5 times the bandwidth and a suitable anti-aliasing filter matching the dynamic range must be applied. For example, if the dynamic range is 70 dB and the bandwidth is 8 kHz the anti-alias filter must have a damping of 70 dB at 12 kHz. An anti-aliasing filter is a must!

[1] For some slow going machinery you need down to 10-100 mHz.

For certain measurements, e.g. phase measurements, alignment measurements, order vectors and orbit measurements it is necessary to have two or more synchronous channels, meaning that the signals are sampled simultaneously. Check if these are truly simultaneous or multiplexed channels. In the latter case phase errors and false signals due to settling of multiplexers and filters can distort the signals too much. Multiplexed systems do by design demand very match of the anti-aliasing filters which becomes more important toward higher frequencies. In other words, it will not help you to have synchronous channels if the phase match between the channels is poor. You should evaluate this based on the highest frequency where phase measurements are applied.

6. Compulsory Measurement Analysis

The system should be capable of doing standard MCM analyses as described below.

6.1. **Autospectrum and Zoomed Autospectrum (FFT).** An appropriate window, e.g. Hanning, should be applied unless synchronized periodic signals are recorded. Averages must be possible, possibly specifying a certain overlap. The higher resolution the better, but bear in mind that you expect the conditions to be stable while the measurement is ongoing, and better resolution means longer measuring time. Using the zoomed Auto-spectrum you can obtain a high resolution in a given frequency span although the implication of longer measuring time persists.

6.2. **Envelope.** Envelope is one of the strongest analysis tools for detecting bearing failures. The implementation should not be based on the old analog technique: rectification of the signal, since the filter parameters chosen could easily hide important details trying to enhance others. The best method is the straight mathematic approach, ensuring that you will see all available details in the envelope signal. The envelope must be available both in time domain and in frequency domain with averaging possible.

6.3. **Overall.** A very valuable measurement representing the power in a given frequency range. The frequency range as well as averaging should be configurable. The result is a scalar.

6.4. **Cepstrum.** This measurement is very valuable for detecting gear tooth damages and should be available. The frequency band for the measurement should be configurable.

6.5. **Measurements deduced from Time Series.** Raw time series are only usefull for postprocessing and is as such not a demand, but deduced (statistical) measurements such as peak, crest and perhaps kurtosis should be available.

6.6. **Tracking.** Tracking is technique where you resample the signal versus another signal e.g. rotational speed (RPM). It has the advantage that the frequency components are always at the same "location" in the FFT analysis, which some times are arranged as orders instead of frequencies. This can be implemented in hardware but has implications regarding the anti-aliasing filters which now also must have a varying bandwidth. In software in can be implemented with resampling techniques but requires a quite precise resampling signal (RPM).

Tracking can be applied as a pre-processing for any of the above measurements. It is a very valuable and often necessary technique when the machinery operates a variable speed. For fixed-speed machinery, it is not required.

7. Optional Measurement Analysis

More advanced measurements analysis, which could add value to the system if used in a proper way, are listed below. This is only a few and there are many more, each with their own special features. So it largely depends on the application if these have any values for the application in question. The ones listed below is the most widely used of these.

7.1. **Vectors.** This technique is valuable for determining phase jumps due to misalignment and loose machine parts. It demands a reference input to determine the phase of the signal. It can also be realised as a phase difference between two signals.

7.2. **Signal Enhancement.** This is a technique to average a signal in time. It has very good noise suppressing capabilities but requires a precise reference signal some times called a trigger or key-marker e.g. one pulse per revolution. Like tracking it is a preprocessing technique. It can even be combined with tracking.

7.3. **Motion Pattern.** This measurement requires two synchronous channels and is capable of detecting a motion in a plane limited to a range of frequencies (modes).

7.4. **Orbit Measurements.** This requires two synchronous channels connected with proximity probes. It measures the orbit of a shaft and the S_{max} quantity, which is the maximum deflection in the orbit, is often deduced from here.

8. Alarm Concept

When a damage is evolving this will lead to changes in the "signature" of the machinery, often as increased levels and new frequency components. It is often practical to operate with two alarm levels e.g. a yellow alarm, which in fact is a warning and a red alarm which is a real alarm. A good system will be self learning in the way that the alarm references are made automatically based on the healthy signature. There are in general two types of alarm monitoring: Immediate alarms when exceeding a levels, perhaps controlled by some hysteresis algorithm; and secondly alarms based on trending, i.e. the alarm levels depends on a timely based evolution. Also there should be a strategy for how to handle alarms, i.e. what to do with them and how to acknowledges them. The system should generate historical alarm statistics and - if online access is an option - it could send a e-mail. It must be easy to adjust the automatically generated alarm levels to minimize any false alarms.

9. Data Management

Permanent machine condition generates a lot of data and it must be stored in order to have access to historical data, to implement trending being one of the strongest methods to disclose evolving damages. Data should be stored in a self-documenting format, meaning that when you extract some historical measurements, all information about how they where made should by contained within. The format should be an open format for easy exchange with other systems, preferably based on the wide-spread XML standard. Also there must be a strategy for data safety, meaning the data must be guaranteed to be persistent for the expected lifetime of the machinery. This could for example be done by a remote backup. Data should be stored in a database with abilities to query data on important characteristics such as time, rotational speed, alarms etc.

10. Reporting facilities

Since the information you can extract from a permanent machine condition system is enormous, there is a need for a tool which can present the information in a condensed way. A common scenario is a semi-anual report presenting the condition of the machinery. This report must include a summary and can indicate the Time To Service parameter TTS, and a detailed appendix to document any signs of a damage evolving. When an alarm is triggered a report can be required in order to investigate the nature of the damage in more details. The reports could to some extend be automatically generated and be available instantly, e.g. by e-mail.

11. Online Access - Ad Hoc Analysis

In the situations where the evolving damage pattern is unknown, i.e. not seen before, there is a need for doing further investigations to determine the nature and seriousness of the damage. To do this, online access to both historical data as well as the possibility to configure new measurements on an ad-hoc basis is needed. These facilities could be used for generating an expert report and the feedback to change the configuration of the system, e.g. set up new measurement and adjust alarm levels etc.

12. Configuration and Setup

Configuration of the system, e.g. number and kind of sensors as well as external condition signals, should be flexible and easy to configure, preferably on an online remote basis. This is also true for setup of the system regarding measurements and alarms. If you are an operator of many similar machines, it would be very handy to configure and setup these on a template basis, meaning that you do not have to do it for every single installation, but could just apply a template setup for them all. Anything else is very time consuming.

13. Installation

The installation efforts and costs are often overseen, when selecting a condition monitoring system. The installation should be as simple and robust as possible, i.e. as few cables and boxes to mount as possible. Pay attention to that the equipment can withstand the possibly harsh environment at the installation site and whether extra covers, power supplies etc. are needed, i.e. is the delivery complete or should you be prepared for extra expenses.

14. Monitoring Services

Installing a machine condition monitoring system is only the first step. Try to clarify who is going to operate it. The owner of the machinery is not necessarily interested in the details of condition monitoring and perhaps only wants to optimize the maintenance cost as well as minimising the downtime. Therefore the possibility to out-source the monitoring task, e.g. handling alarms and generating reports, should be available as a service to apply for.

15. Check List

In summary, the checklist below has been made. Some of the check points may not be relevant to your application.

Feature	Available
Permanent Monitoring	
Conditional Recording	
Bandwidth > 8 kHz	
Dynamic range > 70dB	
Overload Detection	
Compulsory Measurements	
Advanced Measurements	
Alarm Concept	
Data management and persistency	
Historical Data	
Reporting Facilities	
Trending	
Online Access	
Ad Hoc Analysis	
Easy and robust Installation	
Monitoring Services	
Independent Supplier	
Good References	

16. Conclusion

Try first of all to judge the MCM system from an overview, meaning judging the concept. It will not help you much with the best technical specifications on sensors and measuring system if measurements made are unusable or not presented to you in a useful way etc. Try to obtain references and decide if the supplier is independent, i.e. unbiased (does he also produce the machinery and issue the warranty?). Go through the check list and finally compare the total long-term costs (consider this as a long term investment) to obtain the value for money ratio.