EUROPEAN ASSOCIATION OF PUMP MANUFACTURERS
ASSOCIATION EUROPÉENNE DES CONSTRUCTEURS DE POMPES
EUROPÄISCHE VEREINIGUNG DER PUMPENHERSTELLER

Europump Guide

Improvement of Reliability of Pumps by Condition Monitoring

Consequences for MTBR/MTBF

July, 2012

Table of Content

1. SCOPE

In any industrial application, the general availability of pumps can be enhanced by adopting general or customised programs for in-service equipment monitoring, to minimise risks of unpredicted failures and consequent plant outages.

The present guide intends to highlight the importance of “in-service” monitoring of pumping systems through the description of the main parameters to monitor and the ways to acquire them. Also, it will be briefly illustrated how they can be effectively processed and analysed to retrieve valuable information on the status of the equipment under surveillance.

This guide is intended to be mainly addressed to operations managers of plants or systems, maintenance engineers, sales and procurement officers, with the aim of offering a clear and concise picture of the importance and the complexity of a condition monitoring system in an industrial environment.

The document consists of two main parts:

- review of the main indicators for condition monitoring of a pumping system;
- description of techniques to acquire and monitor main indicators to predict pump deterioration patterns and plan timely maintenance operations;

Auxiliaries and accessories of pumping systems are not included in the scope of the guide.

2. INTRODUCTION

An effective pump Condition Monitoring System (CMS) should be capable of monitoring the operating conditions of pumps, issue advance warnings of possible faults and predict the residual life span of critical machine components, prior to final breakdown.

In order to be successful, the CMS must be based on an in-depth knowledge of the operational process, permitting the identification of critical duties and machines.

A combination of process data and conditions of machine components, resulting from an adequate amount of operating hours, represents the fundamental requirement. Hence, the CMS must include the ability to collect and store process data as well as pump operational data.

On board sensors should feed process data (such as fluid temperature, flow and pressure, etc) and mechanical data (vibration levels, bearing temperatures etc.) to a higher level system of analysis and interpretation. This system of analysis must be capable of an early detection of the existence of faults and give indications of possible causes, with reference to historical data.

In more detail, the CMS must be able to elaborate so-called “deterioration patterns”, obtained from fault related symptoms. Deterioration patterns can be extrapolated, using sound engineering judgement, or more sophisticated predictive methods, to anticipate the operating conditions of the pumps in the near future.

The elaboration of deterioration patterns can be performed using predictive methods, with the help of expert know-how, more recently supported by advanced statistical techniques, such as: neural networks or neuro-fuzzy techniques, helping to separate spurious symptoms from true fault-related behaviour of the pumps.

Contrary to preventive maintenance, whereas components of a system are replaced preventively during periodical maintenance, CMS should allow “condition-dependent” maintenance activity, based on accurate prediction of the residual life of critical components.

Conceptually, *“Mean Time” Between Repairs* (MTBR), which is the target of predictive maintenance, should be replaced by specific *“Time” Between Repairs* for the individual components of the plant, reducing the costs of repairs.

CMS can be considered as a tool for “process optimisation”, achieved by upgrading the life span of critical components to match the time between periodical maintenance activities.

3. GENERAL ASPECTS OF “IN-SERVICE” CONDITION MONITORING

3.1 Review of the main indicators

In order to explain the essence of Condition Monitoring it is a prerequisite to identify and briefly list the main indicators on which it is based and ways they can be obtained or acquired, together with the main outcome they can offer:

Flow

Liquid capacity is a difficult parameter to measure on site accurately. However, monitoring of flow is essential to understand the actual operating conditions of the pump and/or to detect wear of internal pump components.

Capacity monitoring of flow may be accomplished by fixed in-line devices such as turbine flow meters, orifices, Venturi meters or magnetic flow meters.

However, non-invasive devices such as ultrasonic meters may also be used, when in-line meters cannot be installed.

Pressure

Pump pressures can be monitored for several reasons, such as obtaining indications on the operating point of the pump with reference to the performance curve (when used in conjunction with another parameter such as flow, power or NPSH curve); avoiding over-pressurisation of the casing that may cause joint seal leakage. Pressure values can be acquired automatically with pressure transmitters or visually with analogic pressure gauges.

Power

Monitoring the power consumed by a pump can give advance indications of the following failure modes: bearing failure, coupling failure, shaft breakage and hydraulic degradation.

Absorbed power can be derived from reading or the acquisition of electrical parameters as voltage, amperage and power factor. On the contrary, direct measurements can be obtained with the installation of torque-meters or power meters directly between the driver and the pump.

Speed

Pump speed is monitored to check for speed changes that may cause loss of head or flow, or to avoid operation near a critical speed.

Most of the pumps are driven by an electric motor: it is unlikely that the motor speed will change significantly, unless a major electrical problem has occurred.

Speed monitoring becomes important in variable speed systems, which rely on frequency change to control head/flow.

Operating speed can be constantly monitored or acquired with the installation of optical devices such as digital tachometers and spot readings with portable instrumentation.

Temperature

Temperature is a relatively simple parameter to monitor. It can be used to monitor a number of potential failure modes, such as: bearings, seal faces, corrosion, NPSH variation, cooling system blockage, decoupling of magnetic couplings, motor winding insulation breakdown, etc.

Temperatures are normally monitored with thermocouples directly mounted on the equipment in various locations (i.e. bearing housings, casings etc.)

Vibrations

Monitoring pump vibrations is by far the predominant and most widely used method to determine the conditions of pumps. Many different failure modes can cause an increase in pump vibrations. Hence, it is difficult to pinpoint the failure mode by vibration monitoring and it is essential to select the appropriate vibration sensor suitable for

- bearing housing vibrations
- shaft vibrations
- casing vibrations (surface pumps or pumps with submerged pumping element).
- cavitation
- misalignment

Vibrations are normally and mostly monitored by recording accelerometers signals, either continuously acquired or obtained with periodic inspections of the equipment. More details will be illustrated in the following paragraphs.

Corrosion/Erosion

Pumps may be monitored for corrosion or erosion attack to prevent failure of the pressure containment shell.

Corrosion or erosion phenomena, when they occur, are indicative of improper material selection for the duty. Consulting with knowledgeable corrosion engineers and replacement of improper materials may be necessary.

Visual inspections or more sophisticated ultra-sonic measurements are widely used as a means monitoring the progression of the corrosion and erosion phenomena.

Lubrication and wear

Lubricant analysis gives indications on the wear rates of bearings and, more generally, the rate of internal wear of pump components by detecting the presence of metal particles.

It is normally conducted by periodic inspection and analysis of lube oil. The analyses are mostly conducted by external laboratories.

Leak detection

Leakage is monitored to identify the failure mode of the pressure containment boundary (seals are not included in the scope of this document).

Leakage from installed pumps is detected in a number of ways depending on the hazard posed by the fluid being pumped and the surrounding environment: by visual inspection, by sniffer inspection, by pressure build-up or by flow increase.

3.2 Monitoring frequency

While visual inspections are the most rudimental form of Condition Monitoring, the regular acquisition and data storage of a defined number of control indicators to be compared with a predetermined set of historical data, is nowadays the most common method of applying condition monitoring.

The frequency at which the above indicators are acquired defines the monitoring frequency and may vary from “periodical” to a virtually “continuous” interrogation.

It depends on the probability of failure or the severity of the potential failure. Both need to be evaluated for the correct implementation of the CMS.

A third variable impact on the monitoring frequency is the accessibility of the equipment. Remote locations or harsh environment may impact on the data acquisition frequency. In this case one of the aspects to be evaluated is the possibility of installing remote instrumentation with local acquisition systems able to transmit data packages to a central hub for further evaluation and analysis.

Overall, a CMS programme must be a balance of safety, environmental and economic aspects.

3.3 Deterioration patterns

This document aims to guide the user towards establishing an “equipment performance base line”, by selecting the most appropriate indicators to be monitored.

Deviations from this base line, during the operation of the plant or the system, must be carefully evaluated to establish a trend line or deterioration pattern, anticipating or predicting a failure pattern of the equipment.

The systemic deviation from the known base line will eventually describe the mode of deterioration of the equipment. Further analysis will enable the prediction, at the best, of the specific time to failure. The ultimate aim is to allow planning of maintenance interventions to restore the equipments integrity in order to avoid unpredicted catastrophic failure or, excessive performance deterioration with heavy consequences on the operational costs of the equipment.

4. MAIN INDICATORS FOR “IN-SERVICE” CONDITION MONITORING

4.1 Mechanical Parameters

Corrosion

Corrosion attack may cause insidious pressure boundary failures with catastrophic consequences. A prerequisite is that the material selection is performed after detailed service conditions are known.

Visual inspection is the easiest method of corrosion monitoring. Visual inspection of pump internals may point out the occurrence of localized corrosion phenomena as pitting or crevice: visual inspections and dimensional checks may define corrosion rates and projection of remaining casing/pressure boundary lifetime.

However, some types of corrosion such as stress corrosion may not be visually detected. Similarly, pumped fluid leakage may expose some non wetted fasteners to unexpected corrosion with critical consequences.

More sophisticated methods of corrosion monitoring may involve electrical resistance probing (ER) linear polarization resistance (LPR) and ultrasonic thickness measurements (UTM).

Electrical resistance (ER) probing is obtained by measuring the increase of the electrical resistance of a metal probe as its cross section is reduced by corrosion. The probe material should be of the same material as the casting. This method is not effective in tracing local corrosion such as pitting.

Linear polarization resistance measures the current response to an applied potential. This method requires the insertion of probes into the system. Applying a DC signal to a test electrode, the generated current is proportional to the corrosion rate determined by electrochemical principles. There is commercially pre calibrated equipment available; however, the method requires to be applied in cases where there are conductive fluids.

Non-invasive methods such as ultrasonic thickness measurements (UMT) can also be used as a corrosion monitoring system. It requires baseline values to be available to determine the corrosion intensity or rate. The method requires no painted surfaces and may be temperature affected.

Visual inspection on the contrary may require disassembling the equipment and must be evaluated on the criticality of the application.

Corrosion monitoring is recommended any time a supercritical application is involved and/or when there is a major change in the operation conditions.

Abrasion/Erosion

While corrosion is determined by either chemical or metallurgical reactions, abrasion/erosion are purely mechanical phenomena, either determined by the presence of abrasive contaminant in the fluid, as in many slurry services (abrasion), or as a consequence of high flow velocities in localized portion of casting (erosion).

Even though the presence of abrasive contaminant is known, thickness monitoring may be of the utmost importance. Monitoring techniques may be similar to the solutions adopted in case of corrosion monitoring.

Leakage

Leakage detection is present in both monitor pressure boundaries and shaft sealing systems.

Due to the variety of operating conditions and pumped liquids, leakage can be in the form of vapour and or liquid.

Several ways of monitoring can be implemented depending on the hazard posed by the service: this can go from a visual inspection to the use of a sniffer to detect volatile components of leakage. A certain predetermined leakage can be expected and planned. Leakage monitoring can detect deviations and its severity, that can alert the maintenance services to plan the equipment service before the severity of the leakage would determine unexpected operational interruptions or environmental hazard.

In case of seal leakage, monitoring systems of pressure of barrier fluid level decrease are the most practical and universally used methods.

Lubricant Analysis

Lubricant analysis is a designated method to detect i) lubricant degradation, ii) lubricant contamination and iii) wear rate of internal components such as bearings or face seals.

Lubricant should be of suitable type for the lubrication of the selected equipment. It should also free of any foreign contamination.

Contaminants may be of organic and inorganic type. Organic contamination may come from an external source (contamination from the operation) or from lubricant degradation. It may unavoidably lead to significant viscosity changes.

Inorganic contamination may be caused by the presence of dirt, abrasives and in general debris such as fibres filter media etc. Water is also considered as an inorganic contaminant and if it is in large quantities may be easily detected.

Oil samples acquisition is extremely important for the success of the lubricant oil monitoring program. Samples should be taken while the equipment is operating and on the discharge side of the operating unit. Samples from the bottom of the tank may help in detecting water contamination.

Degradation characteristics of the lubricant oils can be obtained through viscosity, acidity and antioxidant levels. Measurable changes in viscosity and acidity are symptoms of oil full degradation while antioxidant levels are early warning for lubricating oil change.

When a lubricant analysis is conducted, a spectrographic analysis may indicate the type of contaminant materials, however, counting the number of particles is also important to determine the rate of wear of internal equipment.

Presence of metal particles, even though it is never recommended, may be considered normal or acceptable, in low quantities. An elevated presence of metal particles may be indication of a machine serious problem.

In all cases, oil samples analysis should be compared with the baseline oil sample characteristics.

Vibrations

Vibration recording is the most widely used way of monitoring the mechanical condition of the pump. Depending on the specific mechanical configuration, and the type of bearings installed, vibrations are monitored with different types of instruments.

In case of antifriction bearings, with rolling elements, vibrations are normally monitored via accelerometers or velocity transducers. The corresponding units of measure are acceleration and velocity, respectively.

Most of accelerometer transducers produce a time integration of the signal, to give a velocity measurement, as it is the most widely used to characterize vibrations when rolling elements are installed.

Readings are normally taken in horizontal, vertical and axial directions.

When journal bearings are used, or in more specific cases of vertical pumps where the pumping elements are submersed, vibrations are acquired with use of shaft proximity probes mounted on the bearing housing and sensing a specific target surface of the shaft. Normally two probes are installed on each bearing at an angle of 90° of each other.

Probes detect the relative displacement of the shaft respect to the bearing housing, so that the unit of measure is a displacement. Analysers can derivate the displacement win order to get velocities.

The use of two probes 90° from each other allow the possibility of monitoring the shaft orbit at the plane of probes positioning (see shaft positioning).

Vertical pumps with active pumping components below liquid level can also be monitored with accelerometers or shaft displacement probes. Normally the instrumentation is placed on the pump head close to the mechanical seal system.

In order to conduct a correct equipment condition monitoring, vibration records need to be acquired in the same geometrical position (especially if portable probes are used). For this purpose, bearing housings are provided with dimples for a correct probe positioning.

Finally, and for consistency purposes, vibration readings should be taken in comparable operating conditions.

Shaft position

There are two different aspects of the shaft that would be interesting to be monitored, namely the mechanical run out and shaft deflection. Excessive shaft deflection or run out may cause seal faces to not operate correctly. This may determine a premature seal failure, resulting in seal leakage.

Dial indicators may be used to measure shaft run out in both radial and axial directions.

Dynamic shaft monitoring can be obtained with the use of two proximity probes 90° apart, similarly to the case of vibration reading. Proximity probes are rarely used when pumps are equipped with antifriction bearings while it is normally applied with pumps equipped with journal bearings.

4.2 Performance Indicators

Flow

Flow monitoring in some specific applications may be relatively difficult. Anyhow, problems such as increased clearance, clogging of passages, and excessive flow with insufficient NPSH available, do not require high accuracy and can be monitored with simple devices.

Monitoring of flow is achieved with use of rotameters, turbine flow meters, orifices, Venturi meters, magnetic or ultrasonic flow meters.

Devices that cause losses or flow distortions should be placed on the discharge side of the pump. Particular attention should be given to piping configuration immediately before and after the flow meter, in accordance with manufacturer's instructions.

Pressure

Pressure monitoring may be useful for two independent reasons:

- avoid over-pressurization to prevent casing joint seal or mechanical seal to be damaged,
- monitor the pump performance when operating on a given point.

Pressure monitoring is obtained through the use of pressure gauges (for visual monitoring) or through pressure transmitters for continuous and/or remote monitoring.

To accurately monitor hydraulic performance of the pump, suction and discharge pressures need to be acquired through pressure taps installed in accordance to ISO standards.

Pressure monitoring for hydrostatic purposes is less critical and does not require excessive care.

In case of the presence of frequency converters, pressure value alone may not be sufficient to identify degradation of the equipment performance. Pressure measurements need to be coupled with other parameters as flow or power.

Power

Power monitoring is a key factor for the detection of hydraulic or mechanical pump deterioration. There are several ways of power monitoring:

- inserting a torque meter between pump and driver. This method is considered very invasive, but may offer data on both speed and torque. The method is convenient in case the pump is driven by a gas or steam turbine;
- electrical transducer installed on the electrical motor starter to measure voltage, current and phase angle directly;
- measuring the amperage. In this case only current is actually measured and other parameters (voltage, phase) are assumed constant and are the nominal ones. This method is the most practical and widely used, but the result may be strongly affected by variations of the network load;
- by means of strain gauges applied on the pump shaft near the coupling. With opportune telemetry or split rig, the instrumentation will give information on the torque value similarly to the torque meter. This system is far less invasive at the cost of lower accuracy.

Speed
Pumps drivers may operate at constant and variable speeds.
In case of constant speed systems, it is very unlikely that the RPM will change significantly, unless severe problems occur. Normally for the most popular standards it is accepted a variation of not more than 2%. In some specific cases large changes in voltage or electrical phase may induce significant RPM variations.

On the contrary, variable speed systems are inherently designed to impose significant variation in speed to modify head/flow. These systems show behaviour similar to constant speed system but any unintended variation may determine severe damages.

Temperature
Temperature monitoring can be a key parameter to verify the mechanical conditions of bearings, casing warm up, seal faces and operational conditions as NPSH.

Thermocouples or resistance temperature detectors (RTD's) are universally recognized to be the most convenient way to monitor temperature.

Special care must be taken to carefully place the probe close to the heat source or evaluate the thermal inertia between the monitored spot and the heat source.

Examples are:

- in case of bearing temperature, thermocouples are inserted in the lube oil sump to monitor the temperature of the bearing housing
- fluid film temperature of sleeve bearings can change very rapidly if the fluid film is not correctly loaded. Thermocouples located very close to the control surface can help to detect mechanical distress well before the failure.

5. DESCRIPTION OF METHODS OF ANALYSIS OF THE MAIN INDICATORS

5.1 Mechanical indicators

Among the number of mechanical indicators listed in the previous paragraphs, the most universally adopted mechanical indicator is represented by the vibration level readings. Measurements can be taken either on the bearing housing by means of piezoelectric transducer i.e. accelerometers, measuring casing vibrations (this is the method adopted on the vast majority of smaller equipment) or by displacement sensors that directly allow the monitoring of the rotation of the pump shaft and measure its radial and axial movement.

The actual level of vibration can be compared with historical data to identify and project a deterioration process. Comparisons then need to be conducted for data acquired in equivalent operating conditions (i.e. same operating point, specific gravity, running speed etc).

Vibration signals can be further processed for a more complex analysis process that requires higher level of experience and skills.

In this respect, vibration analysis instruments that normally utilized, convert directly a vibration signal from its time domain base into frequency domain/ frequency spectra.

One of the most commonly adopted techniques is to evaluate the individual frequency components which have been isolated from the overall time domain signal. There is a large literature and standardised analysis technique to associate each of the individual frequency components to the characteristics of each pump element (i.e. bearings, coupling, wear surfaces), and from there, associate any deviation of the specific component to the malfunctioning of the associated pump component.

As an example, a frequency component coinciding with the rotating speed is associated to the residual unbalance of the rotating element. High levels of vibrations at the speed of rotation can be the indication of loss of balancing. By monitoring in time this specific frequency component one can trace the specific deterioration pattern that is linked to the loss of balance: i.e. uneven erosion of impeller or rotating wear surfaces.

It is evident that the described deterioration pattern can suggest to the maintenance management the most opportune maintenance strategy well before an unexpected catastrophic event happens.

Similarly, rolling elements of the bearings will show a distinct degradation patter of specific frequency components as they wear off. If the monitoring is correctly conducted, it can reveal an incipient failure mode that can be intercepted with large anticipation and reduce down time of equipment.

Average shaft orbit records obtained with 90° apart displacement sensors, mounted on bearing housings, can be also very useful to monitor journal bearings conditions. By comparing the actual shaft orbit patterns to historical records, again a maintenance programme can be established or early deficiency can be immediately captured for low impact refurbishment activity.

Specific vibration frequencies are selective indicators of degradation of rolling elements. This approach can be easily coupled with lubricant quality monitoring and analysis. Oil samples can be taken on regular basis for particle counting and chemical analysis, to help determining the level of wear of the rolling elements.

The above examples are only indicative about the larger variety of method of analysis of mechanical indicators. Nevertheless, these brief notes should have highlighted the importance of implementing a correct CMS in order to operate the equipment in the best possible mode without incurring any unexpected failures. This approach immediately points to the overall improvement of MTBF aspects.

5.2 Performance indicators

Performance monitoring is a less known aspect of condition monitoring although it can be of great importance and attraction since it can help in detecting changes in the equipments behaviour at relatively early stages of operation and either anticipate the occurrence of catastrophic events or predetermine the rate of performance degradation. This may help to predict/plan the optimum for the overhaul to restore degraded performance by evaluating the increased energy consumption caused by pump wear.

Performance monitoring is widely used for large size rotating equipment like pumps but also turbines, compressors, heat exchanger etc.

Typical measurement parameters are physical quantities such as pressures, flows, speed and power and are overall related to the determination of the actual pump efficiency. This intuitively leads to the operational cost of the equipment and is essential for a correct plant management. Values are normally not needed in high accuracy but rather on a continuous base.

Equipment efficiency analysis is conducted by comparing the instantaneous parameters to an ideal model or to the equipment conditions at start up or at the time of commissioning. Overall energy consumption trend is derived to evaluate the economical opportunity for equipment restoration.

5.3 Predictive methods

The basic concept behind any CMS is based on the capacity to precisely determine the actual condition of the equipment and the status of its components which are exposed to wear.

In order to evaluate the condition of the equipment a large variety of techniques are used, from very simple to the most sophisticated and are still in the experimental phase.

Historical

Once the equipment has completed its start up phase commissioning reference parameters are acquired and analysed to identify the various components. These values are stored as baseline and they constitute the “fingerprints” of the specific pump. During the normal operation of the pump newly acquired data is continuously analysed and compared to the baseline data or “fingerprints”. Any deviation or discrepancy is highlighted for further evaluation

Statistical

Similarly to the previous method, acquired data are preliminarily analysed to isolate the individual components and then are statistically evaluated against a historical population of similar equipments.

Advanced

Methods based on neural intelligence or fuzzy logic are at experimental level and are under evaluation. Most leading pump manufacturers are involved in the subject at research and development level.

Fuzzy logic or artificial neural logic are non-linear statistical data modelling tools. They are normally used to model complex relationship between inputs and outputs to predict specific patterns of data. These mathematical methods are extensively used in a large variety of applications from surveillance to medical, and have recently found interesting application in the field of monitoring the operating conditions of large equipment.

Several pump manufacturers are focusing on development of predictive systems based on these advanced methods and some have already proposed predictive systems to the market.

6. CONSEQUENCES FOR MTBR / MTBF

When the analysis comes to the evaluation of the impact of the Condition Monitoring on the sensible issue of the Mean Time Between Failure (MTBF), it has to be underlined that the main thrust is not only to promote condition monitoring as good or best practice but to establish a realistic base or datum, essential for both existing installations and for new projects.

For new equipment is strategically essential Mapping Pumps to Systems on commissioning, when pumps should be fully tested not just for mechanical condition and “foot print”, but for hydraulic performance and efficiency including issues such as NPSHa against NPSHr. Only when these parameters are established, the actual specification can be compared with the design datum.

Once this procedure has been applied and the system optimized or the pump “Mapped” to the system then condition monitoring can be most beneficial. Under these conditions target hours for mean time between repair (MTBR) or change out (MTBC) can be realistically estimated. Mean time between failure (MTBF) should be all but eliminated apart from material failure.

7. CONCLUSIONS

The systematic measurement of the above mentioned indicators and their analysis by means of techniques of predictive maintenance is instrumental to:

- improve the availability of pumping systems focus on "time between repairs" versus "mean time between failures";
- reduce the cost of maintenance (planned maintenance versus unpredicted failures);
- reduce the risk of unpredicted plant outages;
- Identify areas of design improvement of the installation and eliminate causes of pump malfunctions, such as cavitation, part load operation, abnormal wear etc.

8. REFERENCES

ANSI/HI 9.6.5 – 1999