1. Introduction

Condition-Based Maintenance (CBM) is a maintenance policy that recommends maintenance actions (decisions) based on information collected through the condition monitoring process [1]. In industry systems, any product damage can have serious consequences. CBM enables us to identify and solve problems in advance before product damage occurs. In CBM, the lifetime of the equipment is monitored through its operating condition, which can be measured based on monitoring parameters such as vibration, temperature, lubricating oil, contaminants, and noise levels [2]. Advancements in information technology have contributed to accelerated growth in the area of CBM technology by enabling network bandwidth, data collection, data analysis, and decision support capabilities for large datasets of time series data [3].

Manufacturing industry is very important for society, which is evident in current discussions on industrialization agendas. Digitalization, the Industrial Internet of Things and their connections to sustainable production are identified as key enablers for increasing the number of jobs in industry. Agendas like “Industry 4.0” in Germany [4], “Factory 2050” in the UK [5], “Smart Industry” in Sweden [6], “Horizon 2020” in EU [7], “Revitalize Manufacturing Plan” in the US [8], and the “4th Science and Technology Plan” in Japan [9] are promoting the connection of physical items such as sensors, devices and enterprise assets, both to each other and to the internet [10]. Machines, systems, manufactured parts and humans will be closely interlinked to collaborative actions. Every physical object will formulate a Cyber-Physical System (CPS) and it will always be linked to its digital footprint and to intensive connection with the surrounding CPSs of its on-going processes [11]. Therefore, the role of CBM and condition monitoring as a part of CPS framework is increasingly important.

The core aspect of CBM is condition monitoring, which can be performed using various approaches and employing different levels of technology [1]. Condition monitoring can be performed either periodically or continuously. Typically, periodic monitoring is conducted at certain intervals, such as every day or at the end of every working shift, with the aid of portable indicators such as handheld measurement instruments, acoustic emission units, and vibration pens. The condition monitoring process also includes evaluations based on human senses (subjective monitoring) to measure or evaluate equipment conditions, such as the degree of dirtiness and abnormal color [2]. In online or real-time monitoring, one continuously monitors a machine and triggers a warning alarm whenever an error is detected. However, there are two limitations of online monitoring in literature: it is often expensive, and continuously monitoring raw signals with noise produces inaccurate diagnostic information [1]. In comparison, periodic monitoring is used because of its low cost and because it provides more accurate diagnostics using filtered and/or processed data. However, the risk of using periodic monitoring is the possibility of missing some failure events that occur between successive inspections [12]. In general, the purpose of the condition monitoring process is twofold. First, it collects the condition data (information) on the equipment. Second, it increases knowledge regarding the causes and effects of failure and the deterioration patterns of equipment [2].
One of the most common concerns of rotating equipment is the bearing condition. Bearing failure can become major damage of shafts, rotors, and housings. The majority of bearings fail before the natural fatigue limit of the bearing steel has been reached [13]. The most common causes of bearing damage are: inappropriate lubrication; fatigue due to normal loads and parasitic loads; poor installation; and contaminations [14]. Bearing condition monitoring provides information about the condition of bearing lubrication, possible damage in bearings, and hence the need for special maintenance or bearing replacement. The Shock Pulse Method (SPM) and vibration analysis are two common bearing condition monitoring techniques. SPM is the monitoring and analysis of high-frequency compression (shock) waves created by a rotating bearing [13]. Damage on the bearing surface causes a significant increase in shock pulse strength. In rotating equipment, vibration analysis is also able to diagnose failures by measuring overall machine vibration or, more precisely, frequency analysis [15]. Shock pulses are measured with a transducer and vibrations with an accelerometer. Both of the techniques can be performed either by portable analyzers or online continuous monitoring systems.

2. Research Methodology for Case Study

In this paper, to illustrate the extent to which advanced CBM techniques (in this case, vibration analysis and SPM) are applicable and cost effective in a manufacturing company, a pilot project was followed in real time. The pilot project was performed at a large manufacturing site in Sweden. The purpose of the project was to implement online condition monitoring of five critical gas circulation fans in the hardening process of the manufacturing company. The empirical basis for the study is thus a case study. The case company’s product is gearboxes, with a production volume of 135,000 units per year. Based on the study performed in [16], CBM by online condition monitoring technology was implemented at the case company and therefore the data were mainly collected by direct observation. The following result presentation has focused on the online condition monitoring of the fans for a period of three years, followed by a discussion of the major findings.

2.1. Implementation of Online Condition Monitoring on Gas Circulation Fans

The asset objects selected for study are five gas circulation fans mounted on top of a furnace in the hardening area. The fans are running 24 hours per day / 7 days per week to maintain the gas atmosphere of cracked methanol and nitrogen smooth and steady. According to the information collected regarding the fans’ replacements and breakdowns, the expected running time for a fan is twelve months. However, the history of the fans, before implementing online condition monitoring, has shown different working times. The earliest breakdown of the fan has been recorded after approximately eight months of working time. In addition, the entire fan replacement process takes approximately 20 to 22 h of production time. However, because there are scheduled maintenance shutdowns, in case an impending failure is detected, it is possible to schedule the replacement for a time that does not affect production.

The gas circulation fan is attached to a 4 kW electric motor. The bearing in the electric motor is exposed to a high load owing to the extra-long motor shaft and a relatively large impeller. Therefore, it is of great importance that the balanced unit of the electric motor and the impeller be precisely balanced. Obviously, imbalances can cause a failure in the electric motor’s bearing. Owing to the working conditions of 920°C in the furnace, the motor shaft and the impeller are exposed to a high wear due to material fatigue/metal dusting, which causes imbalance, and in the long run vibration, that places an extra and rough load on the electric motor’s bearing. In addition to this, the furnace in its processes creates some degree of particles. These particles gradually build up and stick to the wings of the impeller, which can contribute to the vibrations.

An imbalance in a fan and electric motor or a fault in a bearing results in extra vibrations and noise. These parameters can be the failure indicators for the fans’ electric motors, which are measurable by vibration analysis and SPM. These techniques can be applied either online or offline with handheld tools. In this study, online condition monitoring was selected to continuously monitor the vibrations and shock pulses from the fans and to trigger a warning alarm when an error was detected. Measuring points for a vibration sensor (accelerometer) and shock pulse transducer should be carefully selected and set to ensure the value of future analyses. Machine specifications can be used to identify the location of bearings and their construction. To select a measurement point, the signal path should have only one mechanical interface between the bearing and the bearing housing. It is essential that the signal path between the measurement point and the bearing be in the loaded area of the bearing housing. It must also be solid and straight. The sensors can be installed using glue or a steel screw, although a slender steel screw can give a better result. In this study, a shock pulse transducer and one vibration sensor were glued to the drive side of the electric motor. The reason for not using a screw to install the sensors was the lack of access to drill for the mounted fan on the furnace. However, the spare fans were later drilled to mount the sensors by using a steel screw. The sensitivity of the vibration sensor is 100 mV/g, which is appropriate for 945 rpm of the fan. The sensors are connected to a system unit by cables. Depending on the type of the unit, it can have several channels for vibration and shock pulse. The condition monitoring data are collected on an SD card in the unit. The data from the unit are transferred to a computer database using either the company’s Ethernet or 3G modem. Using computer software provided by a condition monitoring supplier, the data are analyzed automatically. The computer software is also able to trigger warnings. Hence, the early measurements from the objects can be used as the baseline data, and warning limits can be set based on the standards [17], [18]. The employees responsible for using CBM should thus be trained and able to analyze the results. Fig. 1 shows a schematic view of the online condition monitoring of a gas circulation fan.

![Figure 1. Schematic view of online vibration monitoring of a gas circulation fan](Image)
2.2. Results of Condition Monitoring

By implementing online condition monitoring with a time interval of one hour, two breakdowns on two fans were observed at the beginning of the measurement. In the first case, as illustrated in Fig. 2, the vibration trend was unstable for a long period of time and was at a higher level compared with the other fans. However, the significant increase in the vibration trend occurred a very short time before breakdown, approximately 12 h. In the second case, there was also a rapid increase in vibration in a short time, beginning three days earlier and ending with an extensive vibration. In the latest time before failure, extra noise in the fan was observed in the strong shock pulses in the shock pulse measurement in a very short period of time, almost 20 h. However, the shock pulses were at a high level approximately twenty-three days before the failure. The alert and alarm values are indicated by yellow and red colors in the figures.

Figure 2. Vibration measurement on the fan two days before breakdown [16]

After experiencing these two breakdowns, the result indicates no fan breakdown in the furnace since the implementation of online condition monitoring for a period of three years. Five fans were replaced owing to the high vibration and shock pulses. In one of the cases, illustrated in Fig. 3, an increase in the vibration value by more than thirty percent indicates a variation in the bearing condition or a fault in the bearing. Therefore, the fan was replaced. In the five cases, planned maintenance was too far ahead, so replacements were performed before the planned furnace shutdown. In some cases, when the faults were diagnosed near the time of planned maintenance, extra lubrication was performed on the bearing to extend its lifetime (Fig. 4 shows an example). Therefore, it was possible to replace the fan in the planned time for maintenance without affecting production time.

Figure 3. Vibration measurement on the fan eighteen days before replacement

2.3. High Frequency Analysis

In extension to the previous studies, further analysis has been performed by using high frequency methods [16]. The vibration velocity parameter is measured as the broadband vibration magnitude in mm/s rms (root mean square). The vibration acceleration parameter is measured in mm/s$^2$ rms. Frequency range of measurements varies for different rotational speeds, bearing types, and using different measuring methods for the analysis. Vibration velocity parameter can be measured within a frequency range of 100 times of the operational speed frequency (e.g. a fan with an operational speed of 1200 rpm and 20 Hz can be measured in the frequency range of 10-2000 Hz). However, measuring methods such as demodulation or enveloping techniques are using different and higher frequency ranges for detecting the rolling bearing damages (e.g. 0.5-10 kHz and 5-40 kHz frequency ranges are used to detect bearing damages) [19]. Demodulation and enveloping are two names referring to the same technique. These techniques take the high frequency vibration that are observed as bearing damage and make it available as low frequency vibration that can be analyzed [14].

In one of the studied cases, as illustrated in Fig. 5, a damage in inner race of the ball bearing was found two months earlier than the failure by using enveloping technique by frequency range of 5-40 kHz. As shown in the figure, the higher peaks in the spectrum are corresponding with the bearing damage frequencies in inner race (Ball Pass Frequency Inner Race - BPFI). Furthermore, as illustrated in Fig. 6, the bearing damage both in inner and outer race was observed clearly one month before the failure, using enveloping technique by frequency range of 0.5-10 kHz. As shown in the figure, the bearing damage frequencies in outer race are indicated as BPFO (Ball Pass Frequency Outer Race) in the spectrum. “BPFI is the rate at which a ball or roller passes a point on the inner race of the bearing” [14]. If there was a damage on the inner race, periodic pulse of vibration are observed at this rate. “BPFO is the rate at which a ball or roller passes a point on the outer race of the bearing” [14]. If there was a damage on the outer race, periodic pulse of vibration are observed at this rate.
By considering these analyses in addition to performing the trend analysis (Fig. 6), the fault was successfully diagnosed and the fan replacement has been performed without having a breakdown or disturbing the production time.

3. Conclusions

Given the observed breakdowns of the fans, one of the main issues to be discussed was the reason for the late warnings before breakdowns. Obviously, late warnings do not allow the company to schedule maintenance work outside production time to reduce production losses. Therefore, some factors have been reconsidered in implementation, such as the type of sensors and their positioning and placement. Furthermore, a failure analysis was performed on one of the broken fans, and the results showed that the grease in the bearing was burnt since it was blackened and contaminated with metal particles (Fig. 7), which might be related to factors such as heat in the operational environment of the system. Based on this experience, better control of the condition of the fans was implemented by altering the warning limits, shortening the measurement intervals and better controlling the bearing lubrication. Therefore, the bearing failures were predicted, and they did not cause any breakdown.

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Acknowledgments

This research work has been funded by the Knowledge Foundation of the INNOFACTURE research school, the Mistra project “Circular Models for Mixed and Multi Material Recycling in Manufacturing” (CIMMREC) and supported by the research initiative for Excellence in Production Research (XPRES) in Sweden.
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