Condition Based Maintenance of Machine Tools: Vibration Monitoring of Spindle Units

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SUMMARY & CONCLUSIONS

Machining systems (i.e., machine tools, cutting processes and their interaction) cannot produce accurate parts if performance degradation due to wear in their subsystems (e.g., feed-drive systems and spindle units) is not identified, monitored and controlled. Appropriate maintenance actions delay the possible deterioration and minimize/avoids the machining system stoppage time that leads to lower productivity and higher production cost. Moreover, measuring and monitoring machine tool condition has become increasingly important due to the introduction of agile production, increased accuracy requirements for products and customers' requirements for quality assurance.

Condition Based Maintenance (CBM) practices, such as vibration monitoring of machine tool spindle units, are therefore becoming a very attractive, but still challenging, method for companies operating high-value machines and components. CBM is being used to plan for maintenance action based on the condition of the machines and to prevent failures by solving the problems in advance as well as controlling the accuracy of the machining operations. By increasing the knowledge in this area, companies can save money through fewer acute breakdowns, reduction in inventory cost, reduction in repair times, and an increase in the robustness of the manufacturing processes leading to more predictable manufacturing. Hence, the CBM of machine tools ensures the basic conditions to deliver the right ability or capability of the right machine at the right time. One of the most common problems of rotating equipment such as spindles is the bearing condition (due to wear of the bearings). Failure of the bearings can cause major damage in a spindle. Vibration analysis is able to diagnose bearing failures by measuring the overall vibration of a spindle or, more precisely, by frequency analysis.

Several factors should be taken into consideration to perform vibration monitoring on a machine tool's spindle. Some of these factors are as follows: the sensor type/sensitivity, number of sensors to be installed on the spindle in different directions, positioning of the vibration accelerometers, frequency range to be measured, resonance frequency, spindle rotational speed during the measurements, measurement condition, including the no-load condition with tool clamped or without a tool, measuring tools and technologies, automatic or manual run of measurement, measurement routine, warning limits, and data handling and analysis, among other factors.

The aim of this paper is thus to address CBM and particularly the implementation in the manufacturing industries focusing on the use of vibration monitoring techniques to monitor the condition of the machine tools' spindle units. To conduct this study, a pilot project was followed in real time. The pilot project was performed at a manufacturing company in Sweden. The company's product is gearboxes for the automotive industry, with a production volume of approximately 135,000 units per year. CBM, by on-line and off-line condition monitoring, using vibration monitoring, has been implemented on different types of machine tools, including horizontal and vertical turning machines, multi-task milling machines and grinding machines.

1. INTRODUCTION

CBM has been widely applied in practice and is currently one of the most effective predictive maintenance approaches for reducing the uncertainty involved in maintenance activities [1, 2]. CBM identifies and prevents potential failures of a system, reduces the failure consequences of the system, and as a result, ensures a lower life-cycle cost of the system [3, 4]. It monitors the system during its operating lifetime and under different operating conditions [5]. Most equipment failures are preceded by certain signs, conditions, or indications that such a failure is going to occur. Therefore, different monitoring parameters can be investigated by using CBM techniques, including vibration, temperature, lubricating oil, contaminants, and noise levels [6]. Advancements in information technology have added accelerated growth in the area of CBM technology by enabling network bandwidth, data collection and retrieval, data analysis, and decision support capabilities for large data sets of time series data [7]. Condition monitoring as the core aspect of CBM can be conducted in different forms and under various technology levels [8]. It can be implemented at predefined intervals, with the aid of different monitoring instruments, and/or using human senses as subjective

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monitoring [6]. Condition monitoring can be carried out either continuously (on-line or real-time), or periodically. Each has its advantages and disadvantages, which are summarized in [8, 9]. In condition monitoring, information concerning internal effects must be captured externally during the operating time of the machines [10]. According to [8], one of the principal techniques for obtaining information on internal conditions is vibration analysis. A machine in standard condition has a certain vibration signature, and the growth of a fault changes that signature in a way that can be linked to the fault.

Machining systems (i.e., machine tools, processes, and their interaction) can only produce accurate parts if the degradation in their subsystems and components (e.g., feed-drive systems, spindle units, etc.) is identified, monitored, and controlled [11]. Machine tool maintenance delays the possible deterioration in machines and reduces the machine stoppage time that leads to lower productivity and higher production cost. To be competitive, it is possible to reduce the fabrication downtime by applying CBM. On the other hand, measuring and monitoring machine tool accuracy and capability have become increasingly important, due to increasingly stringent accuracy requirements on industrial products and the products' functional and legislative requirements [11]. The increased capabilities of manufacturing in measuring and monitoring will provide fewer machine failures, less spare parts inventory, and, as a result, will reduce the production and maintenance cost [12]. This paper presents the use of a recently developed vibration-monitoring technology on spindle units. The measurements are based on developed standards and comparing current spindle vibration values with those taken as its fingerprint when the machine was new.

2. RESEARCH METHOD

To illustrate the extent to which advanced CBM practices are applicable and cost effective in a manufacturing company and to serve as a guide for further research and development in this area, a pilot project was followed in real time. The pilot project was performed at a large manufacturing site in Sweden. The company's product is gearboxes, with a production volume of 135,000 products per year. The company expressed interest in investing in and conducting this pilot study in its machining production process. The purpose of the pilot project was to implement CBM on machine tool spindles. Thus, CBM by vibration monitoring technique was implemented on different types of machine tools, including horizontal and vertical turning machines, multi-task milling machines and grinding machines. The measurement results were documented in the company's Computerized Maintenance Management System (CMMS) for future use [2]. In addition, to provide a more generic view of the area of the study, a similar manufacturing company, as a reference company, was visited and an interview was carried out with a CBM specialist. The results of these studies are presented in this paper. The results can be used for both maintenance and production purposes, i.e., they can provide a strong base for predictive maintenance at the manufacturing company and can also be used to optimize a machine's operations and quality of the products.

3. SPINDLE UNITS

The spindle system is one of the critical subsystems of a machine tool which supplies the necessary power to the cutting process [12]. The spindle is a high-precision component which comprises several parts, e.g., the rotor shaft, bearings, and the clamping system. The key components of the spindle can be listed as follows: 1) the spindle design, i.e., belt driven or with an integral motor; 2) the bearing design, including the type, tolerance, and method of lubrication; 3) the motor design, which comprises the belt type, motor spindle, capacity, and kW rating; 4) the spindle shaft, which can be a tool retention drawback, and the tooling system used; and 5) the spindle being used, which comprises the size, mounting style, and capacity [13]. All these components need to be in a perfect balance to achieve the required high accuracy at elevated rotational speed and high material removal rate under stable conditions. Furthermore, forming the interface between the machine tool structure and the cutting tool, the spindle dynamic characteristics play a critical role in machining centers [14]. Spindle requirements include accuracy, speed range capability, high rigidity, high damping capacity, and stable operating temperature [15].

As explained above, the components of the spindle should be carefully selected. To have the required spindle speeds, there are many factors that need to be taken into consideration, e.g., using a precision bearing, using an effective bearing lubrication system, and utilizing the most effective cooling and cleaning system [13]. The literature demonstrates that the bearing has the most significant effect on the spindle design [11]. The spindle shaft should also be designed in a way that provides a strong motor and appropriate tooling retention system, along with stiffness without developing bending problems when all rotating components are operating in a balanced condition [13, 15]. In addition, the spindle housing, which transfers all factors from the spindle to the machine tool, should be robust and stiff in a way that completely supports and accurately locates the bearing, and provides the required utilities for the spindle system [13].

In summary, different factors can affect the speed of the spindle, such as bearing size and type and precision tooling systems, among other factors. Stiffness can be increased when the pre-loads and the number of tandem bearings increase; however, these variables will reduce the speed. Higher speeds require higher-precision tooling systems, better balance, and cleanliness to obtain the desired results [13].

Similar to other rotating equipment, the most critical part of a spindle unit is the bearing. However, as long as the lifespan of the spindle bearings remains unknown for different machines and each machine is working in a different work environment, it is hard to decide on the spindle renovation. Vibration monitoring can be a solution to predict spindle bearing failure and prevent long production stops.

4 MACHINE TOOL SPINDLE VIBRATIONS BY MEASUREMENTS ON SPINDLE HOUSING

In this study, the Swedish standard for machine tool spindle vibrations by measurements on the spindle housing [17], called SS 728000-1:2014, was used. Based on the standard, the scope of the measurements is machine tool spindles with integral drive, operating speeds between 600 and 30,000 rpm and spindles with rolling element bearing types.

The measurement locations should be at the front and back ends of the spindle, as close to the bearing as possible (Figure 1). The measurement direction can be in 2 radial directions at both ends of the spindle and in the axial direction in at least one end of the spindle. Radial directions should be according to the axes of movement of the machine tool such as X and Y. A single tri-axial sensor can be used for periodic measurement. Sensors can be mounted with threaded fittings, chemical bonding wax, a magnetic base and a handheld sensor.

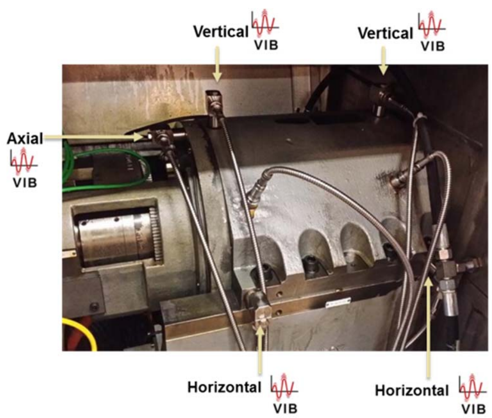

Figure 1. Vibration sensors installed on turning machine spindle housing

The measurements should be performed under no-load conditions (no cutting, grinding, or milling) either with a tool clamped or no tool in the machine. The spindle chuck mechanical settings should be recorded, such as clamped and unclamped positions. It should be recorded whether a tool is used during the measurements or not because of the imbalance in the tool. Moreover, background vibrations should be removed.

The measurement can be performed either at a specific speed or at different spindle speed levels. However, the spindle speed should not be greater than the spindle maximum speed. Moreover, increasing or decreasing the spindle speeds should permit 10 seconds of constant speed at each such selected speed. Therefore, the spindle speed changes in such a way that a steady state of vibration is achieved before recording the measurements. For spindles operating at speeds between 6000 min-1 and 30000 min-1, one or two speed ranges may be excluded to avoid unreasonable limits at resonance speeds. These ranges can be specified by the machine manufacturer. If not, the excluded speed ranges shall not exceed 10% of the nominal speed range of the spindle, for instance, 600-17000 min-1 and 19000-24000 min-1. There is no exemption for spindles with a maximum speed below 6000 min-1.

According to the standard [17], the vibration velocity parameter is measured as the broadband vibration magnitude in mm/s rms, within the frequency range of 10 Hz-5000 Hz. The vibration acceleration parameter is in mm/s2 rms within the frequency range of 2000 Hz-10000 Hz. However, individual vibration spectrum analyses can be used for machines from different manufacturers.

Alarm values can be subject to agreement between the machine manufacturer or supplier and the user. The values should normally be set relative to a baseline value determined from experience for the measurement position and direction for that particular machine type. According to the Swedish standard, the alert value can be set to 1.4 to 2.0 times the established baseline value, and the general recommendation is to set alarm values exceeding the spindle baseline values by a factor of 3. Spindle speed only affects the vibration zone boundaries for acceleration. Thus, there are the same vibration alert zone boundaries for velocity in different speed ranges.

5. STRATEGY FOR VIBRATION MEASUREMENT OF MACHINE TOOLS

To obtain the best possible effect from vibration monitoring, and thus to be cost effective, there must be a strategy for how and where to perform vibration monitoring. Different types of machines should be measured at different time intervals. Slow-moving machines need only be measured once a month. The strategy is also coupled to the rate at which the failure is developing as well as to how severe an error it is if it occurs. For example, if the spindle breaks, the whole work piece needs to be scrapped. Therefore, very fast machines should be measured every day or be provided with fixed/online vibration monitoring. Only checking vibration levels of the machines that are already suspected to have a failure cannot be considered as a feasible strategy. Vibration monitoring is aiming to find problems long before they lead to failing components. However, more advanced vibration analysis should be used to find out the exact problems with the machine.

It has been proven in the literature [11, 16, 18], as well as in industrial practice, that regularly checking vibration levels of the machines is a major step forward in preventive maintenance of machine tools. To measure a number of points on each machine every two weeks and ensure that no elevated vibration levels are developing costs relatively little, but it is very good insurance against acute breakdowns. All measurements should be documented and a trend analysis should be performed on the different measuring points. In the case of having unacceptable vibration levels, the cause must be found out immediately. If available, an FFT analyzer or machine analyzer should be used. For the more complex problems or if there is a complete lack of the necessary analytical instruments, expert assistance must be summoned.

6. IMPLEMENTATION OF VIBRATION MEASUREMENT ON THE SPINDLES AT THE CASE COMPANY

There are a number of standards that typically involve vibration-related parameters. Larger companies often have their own standards that define what is good and bad and are designed according to their own experiences. As presented in the previous sections, the Swedish standard (SS 728000-1:2014) was used in this study to perform vibration measurement on the spindle housings. Concerning the standard, several factors must be considered to perform the measurements, some of which are presented as follows: 1) the vibration sensor type (sensitivity, calibration, etc.); 2) the number of sensors to be installed on the spindle housing on the different axes; 3) the positioning of the vibration sensors; 4) sensor mounting; 5) the measurement condition, including the no-load condition, with tool clamped or without a tool (using the same balanced tool every time); 6) background vibrations; 7) the measurement at different spindle speeds or at a constant speed (e.g., near the maximum spindle speed); 8) the exclusion of speed ranges that include resonance speeds; 9) the measurement frequency range for velocity and acceleration vibration parameters; 10) the alarm values; 11) automatic or manual measurement; 12) the measurement strategy and measurement interval; and 13) the integration of measurement to computerized maintenance management system.

To install accelerometers, machine specifications should be used to identify the location of bearings and their construction. Measurement points should be selected and prepared carefully to make sure that future readings are repeatable. The signal path between the bearing and the measurement point should be in the loaded region of the bearing housing. At the case company, the vibration accelerometers have been glued to the spindle housings. The sensitivity of the vibration accelerometer is 100 mV/g. As a schematic view is shown in Figure 2, the sensor/sensors are connected to a system unit by cables. The data from the units are transferred to a computer as a database by using the company's local area network. The data are then analyzed automatically by computer software. The computer software is also able to trigger warnings.

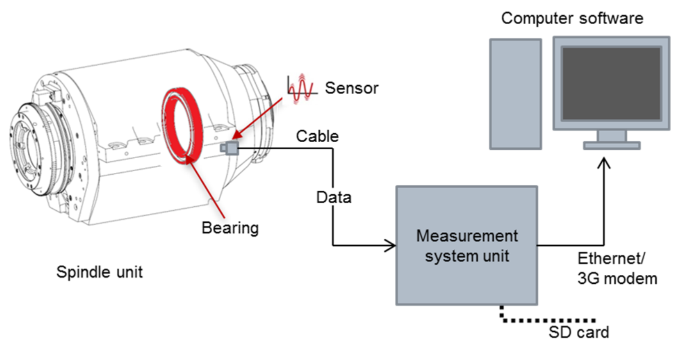

Figure 2. Schematic view of online vibration monitoring of a spindle unit

Thus, the early measurement from the objects can be used as the baseline data (fingerprint) and to set warning limits according to the standards. The maintenance personnel should also be competent to analyze and evaluate the measurement results.

The study showed that the online condition monitoring of spindles using measuring units is challenging because machine tools operate at different speeds. The vibratory condition is dependent on both the spindle speed and the frequency response function (FRF) in the region of the work area. Therefore, different values will be measured at different speeds. In addition, as it was explained in section 4, vibration measurement should be performed in an unloaded condition or not during a cutting operation, e.g., milling. Consequently, a solution was to use a switch on the measuring units and perform the measurements periodically instead of continuously. In another words, it was planned to perform the measurements manually by switching ON the measurement unit for a period of approximately 5 minutes and run the machine un-loaded at a specific speed near the maximum speed. The measurement results will automatically be saved by the computer software in the database. Furthermore, another solution that was implemented was to use handheld vibration instruments instead of using the measurement units. This means that sensors were installed on the spindle housing and were cabled to an output box. Then, a handheld instrument can be connected to the outputs for performing the measurements. The measurement procedure is the same as it was explained earlier, in an un-loaded condition and at a specific speed for a spindle. A number of machine manufacturers provide installed vibration sensors on spindle housings. Therefore, it can be possible to perform the vibration measurement by using a handheld instrument.

Figure 3 represents the vibration measurement of a multi-task milling machine spindle at different speeds. The alarm boundaries are also shown by green, yellow and red colors. The maximal operation speed of the spindle is 12000 rpm. As illustrated, the value of vibration velocity is significantly increased at the highest speeds and in the speeds close to the spindle maximum speed (14000 rpm). The variation in amplitude can be explained by local resonances in the machine tool including the spindle unit.

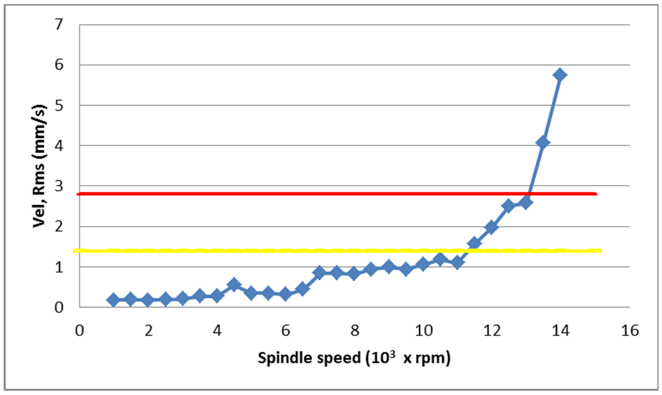

Figure 3. Vibration measurement of a new multi-task milling machine spindle at different speeds. The vibration level varies with spindle speed due to the structural dynamic properties of the spindle and machine tool

Figure 4 shows the vibration measurement of an old lathe spindle at a specific speed for a period of 4 months. As illustrated, there is not a considerable change in the vibration value. The measurement is performed with a clamped chuck of the lathe and in a constant speed of 2000 rpm, near the spindle maximum speed.

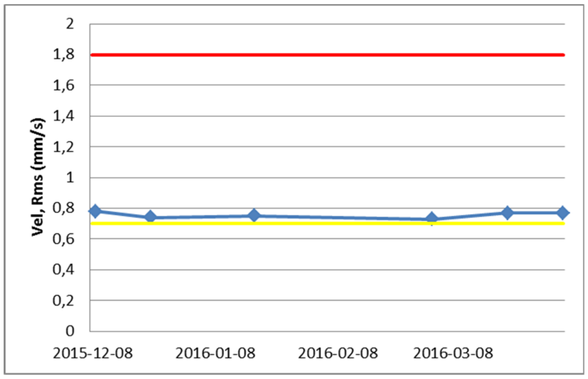

Figure 4.Vibration measurement of an old turning machine spindle at 2000 rpm

Figure 5 shows the rms values of vibration measurements on machine tool spindles at the reference company that had a bearing failure (Figures 6 and Figure 7). In this case, the company replaced the spindle before having maximal damage.

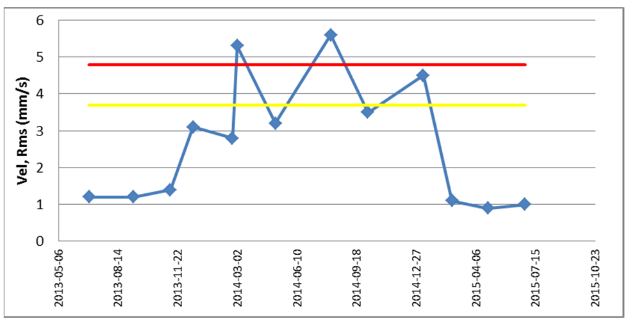

Figure 5. Detected failure of a spindle bearing at the reference company

Figure 6. Bearing wear in the inner race

Figure 7 - Wear on bearing ball of ball bearing

7. CONCLUSIONS

The aim of this paper was to address CBM implementation in manufacturing industries, focusing on the use of vibration monitoring technique to monitor the condition of the machine tools' spindle units. CBM has become an important field of research with recent development in sensors, signal processing and computing methods. However, it is challenging to detect the faults or damage by vibration monitoring of complex structures such as spindle units because there are different sources of frequencies from spindle bearings, gearbox, gear mesh, etc. The frequency response function is speed and position dependent. It is difficult to measure the spindle vibration during actual machining operations because of the spindle's different speeds and extra noises due to the cutting operations. In addition, there is not a common standard of vibration monitoring for different types of machine tools. Therefore, the data from condition monitoring should be analyzed mostly by trend analysis and comparing the measurement results with the data from when machines were new. By dealing with these implementation challenges, it is expected that the machine condition monitoring systems will enable companies to ensure equipment health management, reduce life cycle cost, and avoid catastrophic failures.

8. ACKNOWLEDGMENTS

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