CONDITION-BASED PREVENTIVE MAINTENANCE OF MAIN SPINDLES

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Abstract

Machine tools need to be highly reliable with minimal down time. Unintended failure incurs high costs due to repairs and production losses. Maintenance is a major cost factor and is still handled reactively to a great extent. Maintenance plans by manufacturers that recommend preventive maintenance based on operating hours are often not consistently implemented. Ideally condition-dependent preventive maintenance of the most critical and cost-intensive assemblies of a machine tool would be performed. This would enable a shift of planned maintenance times to non-productive periods and would also enable procuring any spare parts at the right time. Eventually, this would lead to cost savings. This article describes the design of a condition monitoring system for machine tools and shows examples of main spindle monitoring.

Keywords

Machine Tool, Availability, Condition Monitoring, Main Spindle

1 INITIAL SITUATION AND OBJECTIVE

Availability of production facilities is becoming more and more important. Machine tool manufacturers that can guarantee a high availability and reliability of their products have a competitive advantage over their competitors because the decision of purchasing a machine is increasingly determined today, besides technical parameters and investment costs, by the costs of operating the system (TCO, **T**otal **C**ost of **O**wnership). In addition to the classic determinants of costs for machine (depreciation), tool, power, operator and operating costs, maintenance costs play an important role. Maintenance (service, inspection, repair, improvement, / DIN 31051/) of machines and plants today is predominantly performed

- as a result of failures -> reactive, not preventive,
- according to the manufacturer's data -> time-dependent, preventive,
- when time is favorable -> e.g. during vacation close-downs, also time-dependent preventive,
- based on personal experience -> time-dependent preventive, optionally somewhat condition-dependent, however strongly employee-dependent.

The consequences of such procedures include

- stochastic failures with machine downtime,
- frequent repairs,
- a large inventory of spare parts, and
- increased costs.

As a result of this current situation, there is a need for predictive condition-dependent maintenance. Current studies [6], [12] on potentials for condition-oriented maintenance prove that companies included in the survey expect from introducing condition-oriented maintenance procedures that

- production losses will go down by 36%,
- downtime will be reduced by 35...40%,
- maintenance costs will drop by 23....30%,
- a return on investment of 10:1.

It is therefore necessary to provide opportunities for machine operators and manufacturers to carry out a preventive condition-dependent maintenance and upkeep. Machine operators and manufacturers must be enabled to track the condition of machines based on characteristic values and evaluate the remaining life of the assemblies monitored. This will eventually result in

- cost reduction (reduction of the spare part inventory, maintenance operations can be planned),
- an increase in productivity (reduction of downtime), and
- an increase in reliability and availability.

2 ASSEMBLIES THAT REQUIRE MONITORING AND MEASURING STRATEGIES IN A MACHINE TOOL

A survey [2] of manufacturers and operators of machine tools from the automotive industry revealed that the following assemblies of machines are favored for condition-dependent maintenance, both because of their high failure rate and in view of the costs incurred when they fail:

- Main spindles (bearings, tool clamping system, rotary union)
- feed axis (ball screw, drive, guideway, cover) [8]

- Hydraulic and pneumatic components (pumps, valves, operating resources).

First, measuring strategies must be developed for these components [2]. In principle, two different methods of measurement are to be distinguished:

- Continuous measurement under normal production conditions, and
- Periodic measurement under defined comparable measuring conditions.

Both methods of measurement have to be applied to machine tools. Continuous measurement can be used for measured variables that yield absolute values, allowing a diagnostic statement. These can be, for example, temperatures, flow rates, or conditions of operating materials (water content or particle content in oil). Continuous collection of measured data also makes sense when it comes to the detection and prevention of machine overloads (crash situations, too large machining forces).

Periodic measurements are required if the diagnostic statement is made based on changes from a defined initial state (relative measurement). This method should be applied particular to monitoring of bearings and feed axis [4]. This is especially important for machine tools because the processes not continually run, but rather, machine loads constantly vary due to different machining processes. To obtain comparable results of measurement, repeatable measuring conditions have to be established in a test run.

A condition monitoring system must be designed so that both methods of measurement can be implemented.

3 DESIGN OF A CONDITION MONITORING SYSTEM

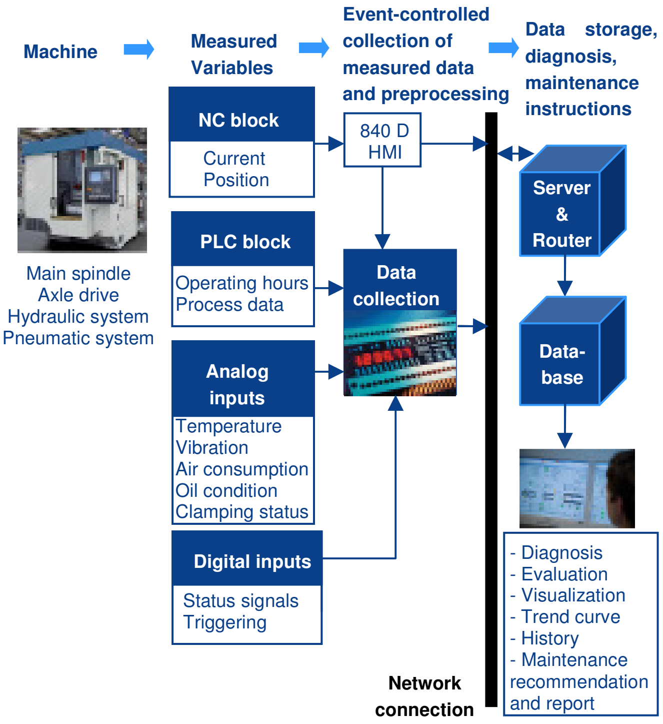

Figure 1: Schematic diagram of a Condition Monitoring (CM) - System

Requirements for a Condition Monitoring System were formulated in a seminar [1]. The general design of a condition monitoring system implemented by Fraunhofer IWU is shown in Fig.1. The task of condition monitoring system is to monitor selected machine assemblies by using existing signals from the control unit and drives, as well as with additional sensors. A snap-on rail-mounted PC is integrated into the control cabinet of the machine. It coordinates the collection of measured data from various sources (analog signals from sensors, digital triggers and status signals, link to the NC and PLC), scales and reduces the data, calculates the resulting characteristics, and stores the data until it can be transmitted to a database. The characteristics stored in the database can be retrieved via a web-capable service platform and used by various types of users (operators, maintenance center, machines manufacturer) for condition-oriented maintenance. A diagnostic statement is made based on the characteristics. Maintenance instructions can be issued to the operating and maintenance staff at a time when no deterioration in the quality of workpieces and no major changes in the machine condition have yet occurred. The design of the condition monitoring system as described here has the following advantages:

- The CM- System does not interfere with the machine itself so that the machine can continue to produce without any limitation if the CM-System fails.
- The system can easily be used with different types of machines and easily retrofitted to existing machines. Only the interfaces with the machine control unit may need to be adapted.
- The evaluation software accesses a database. Almost any number of machines can be connected to the database depending on database size.
- The evaluation software is password-protected and can be accessed via a web browser. The user of the CM- System does not need any additional software.

4 DIAGNOSTIC EXAMPLES

Nowadays a number of sensors are integrated into modern machine tools, such as sensors for temperatures, filling levels, hydraulic and pneumatic pressures, end positions, etc. Therefore, a lot of information is already available, but the interpretation of all sensor- information alone would often not be sufficient for a comprehensive evaluation of machine's condition. Multi-sensor solutions and intelligent measuring and evaluation methods are required to output a standardized variable for trend representation or to compare its output quantity with theoretically calculated models.

It is currently feasible to collect reliable measuring signals that contain the respective information. Acceptance of a condition monitoring system, however, depends on the interpretation of the measuring signals, such as the connection between measuring signals and machine condition. In the context of a project funded by the Federal Ministry of Education and Research [14], extensive studies on this topic have been performed at test benches as well as on machine tools used in the automotive industry. Several results of these studies for main spindles are presented below. Main spindles are the "heart" of any machine tool. Failure of the main spindle inevitably incurs idleness and high costs for repairs and production losses. Problems responsible for spindle failures are mainly:

- Spindle bearings,
- Clamping devices, and
- Rotary union.

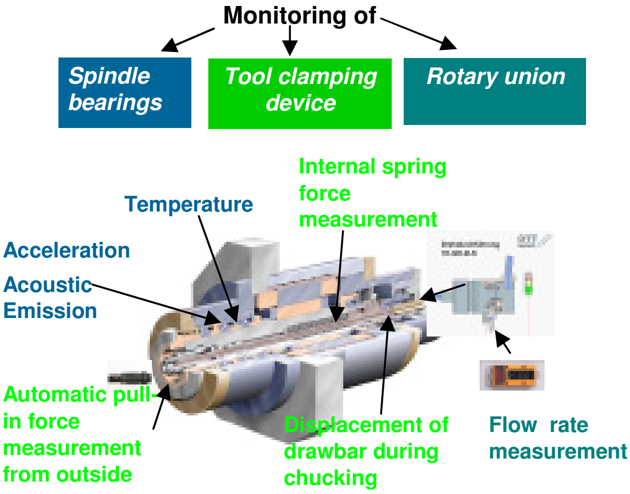

Figure 2: Used sensors for spindle monitoring

Figure 2 shows together, which sensors for spindle monitoring are technically appropriate and economically feasible. The main spindle described here, was tested in a machining center in the automotive industry. The results described in chapter 4.2. and 4.3. were made at this spindle.

4.1. Spindle Bearing Monitoring

Several solutions are known for monitoring spindle bearings [3, 5, 11]. The following variables are measured:

- Radial and axial shifting of the spindle shaft using eddy-current sensors [9, 10],
- Spindle bearing temperature (stationary at the outer ring, rotating at the inner ring),
- Acceleration sensors integrated into the spindle housing, and
- Signals from motor and control system (current, RMS power, etc.).

On a test bench, some of these known measuring signals are checked for their suitability for condition-based maintenance and additionally compared with Acoustic Emission (AE) signals. Static and dynamic loads were applied to a motor spindle on this test bench (Fig. 3). The forces are transferred into the main spindle via a loading device, which is mounted on the tool holder (Fig. 4). With screws, which are supported against the machine table, axial and radial static forces are transferred on the stationary outer ring of the loading device. Force is transferred to the rotating spindle via bearings, which are arranged in the loading device similarly as in the main spindle. The spindle rotated with a speed of 7,000 rpm and was charged with an axial static force of 1,500 N and with a radial static force of 3,000 N. The radial static force was superimposed a sinusoidal dynamic force of ±400 N at a frequency of 40 Hz using a piezoelectric exciter (Fig. 4).

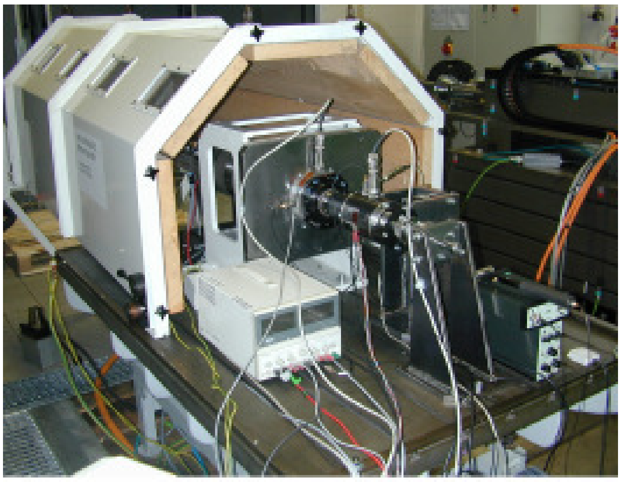

Figure 3: Test bench for bearing monitoring

The piezoelectric actuator is pressed via the screw for the static load against the loading device.

The spindle was in continuous operation for 8,600 hours until failure of the spindle bearings. After this spindle bearing was dismantled. Fig. 5 shows the damage at the bearing inner and outer ring.

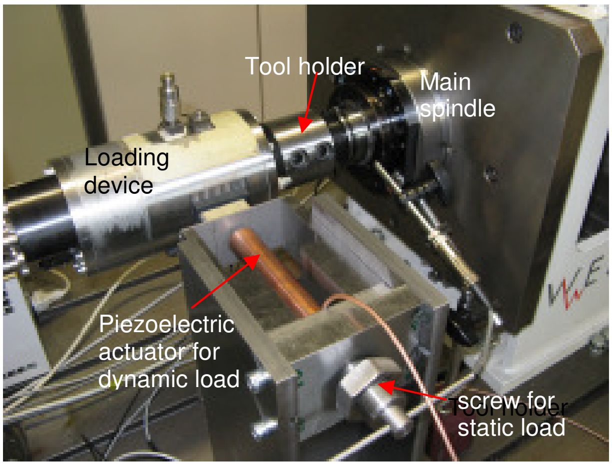

Figure 4: Arrangement to initiate the radial forces

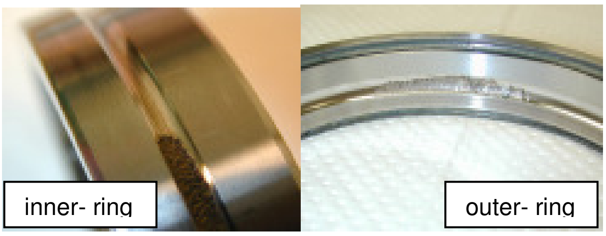

Figure 5: Damage at raceway after 8,600 operating hours

The bearings in the loading device are also spindle bearings and were included in the study.

The endurance test was interrupted at periodic intervals (about once a week) to a defined measurement of all parameters. The measurement was made at idle speed of the spindle (3,000 rpm and 7,000 rpm) without axial and radial load. The following parameters were measured at the main spindle and loading device:

- bearing temperature (stationary at the bearing outer ring)
- acceleration at housing
- RMS power
- AE at housing

Monitoring of bearings using vibration sensors and temperature sensors on the outer bearing ring is most common. This is founded by relatively cost-efficient solutions. The temperature at the outer bearing ring rises in a defective bearing. However, little time remains before the bearing will fail completely (Fig. 6). As the supply and delivery of spindles today may well take several months, even warning times of 200 hours are not sufficient for a preventive maintenance. Thus this measured signal can be used at best for an emergency shutdown, not for preventive maintenance.

Evaluation of active power and vibration signals in the time range (RMS of vibration velocity according ISO 10816, Fig.6) is similar. A significant increase in the measured values can be observed from 7,800 hours of spindle operation. At this point, the bearing condition has deteriorated suddenly and substantially. On the test bench, the spindle can run until total failure at 8,600 hours. A spindle in a production machine would have to be shut down earlier because the increased vibrations would lead to a deterioration of the workpiece quality.

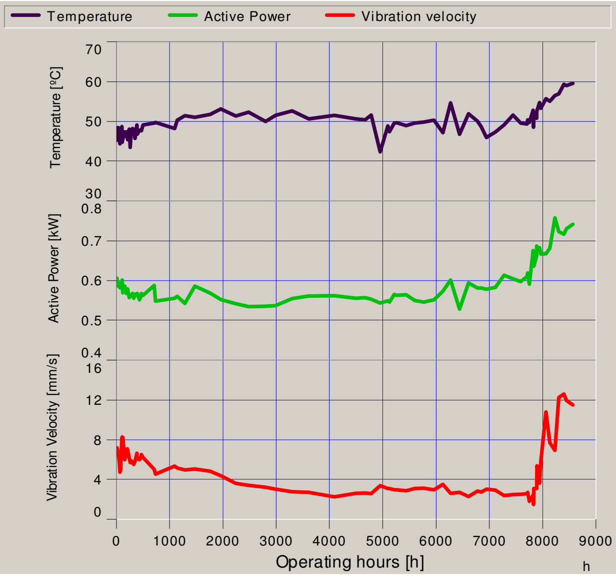

Figure 6: trend of spindle bearing temperature, active spindle power (RMS) and vibration velocity (RMS)

Longer lead times can be reached if the vibration signals are transformed into the frequency range and special evaluation methods are used, such as the envelope-curve analysis. With this method the roll-over frequencies of a damaged bearing can be determined [5]. Envelope-curve analysis only works if bearing damage by pittings has already occurred. A typical acceleration signal (burst signal) caused by pittings is shown in Fig. 7. This signal was measured at the test bench by installation of a damaged bearing (pitting at inner-ring) at the loading device (Fig. 4).

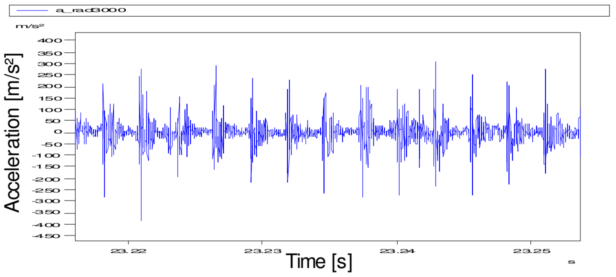

Figure 7: acceleration signal (burst signal) caused by pittings

After high- pass filtering, calculation of absolute value and envelope signal (Fig. 8) frequency analysis can be made. Fig. 9 shows the comparison of Envelope- and Fast Fourier (FFT)- Spectrum.

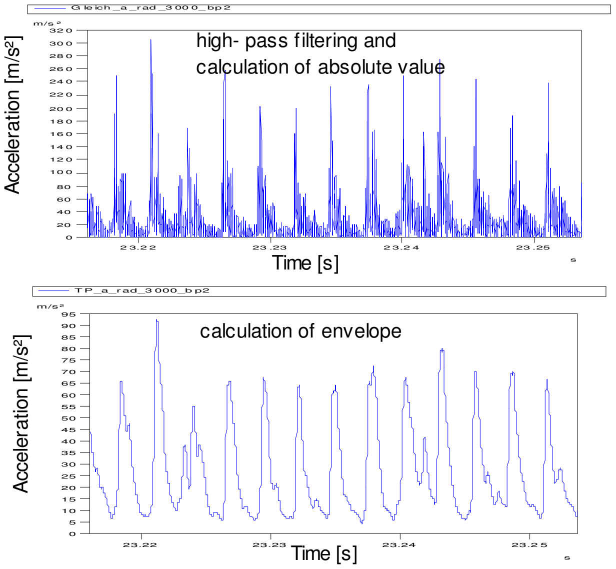

Figure 8: Calculation of envelope

An FFT- Spectrum was calculated from the original acceleration signal (Fig. 7) without calculation of envelope according Fig. 8. Using the Envelope analysis, the roll-over frequency is more visible. The FFT spectrum also contains the natural frequencies of the test bench, excited by the impact signal.

Fig. 10 shows the Envelope- Spectrum of the bearings in the main spindle at the test bench. At 7,300 operating hours the Envelope Spectrum of acceleration, measured at the outer bearing ring, shows a first clear peak at the roll-over frequency of the inner bearing ring. The bearing is worn out after 8,600 operating hours and can no longer be used (see Fig. 5). This is also clearly reflected in the Envelope Spectrum (Fig. 10). The sidebands around the damage frequency are a clear indication of a worn bearing and are caused by amplitude modulation of the acceleration signal. Using the Envelope- curve analysis bearing damage can be detected earlier than with an analysis of the acceleration signal in time domain (Fig. 6). In Fig. 6 at 7,300 hours still no change in the acceleration time signal can be seen.

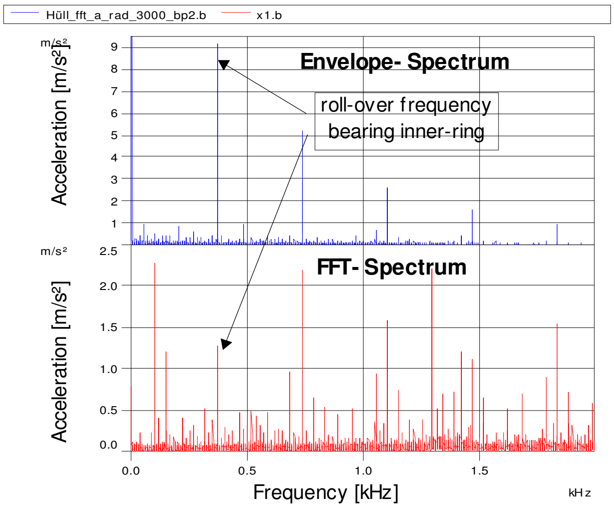

Figure 9: Comparison of Envelope and FFT-spectrum

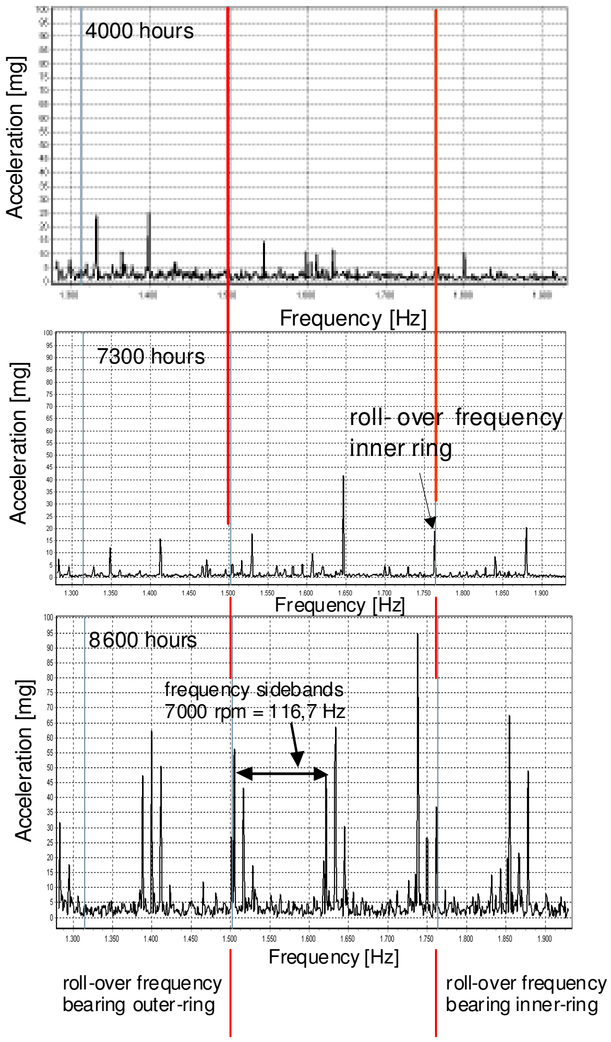

Figure 10: Envelope- Spectrum at 4,000, 7,300 and 8,600 operating hours

To extend the life of the spindle bearing, irreversible damage of the raceways must be prevented. Therefore it is necessary to detect the wear of the lubricant on time. Envelope- curve analysis is unable to detect a change of the lubricating condition in the bearing. It is indicated here to measure AE signals (AE) at a frequency range greater than 50 kHz. The advantage is that low-frequency structure-borne sound signals that are excited by the actual operation of the spindle (unbalance, process forces) hardly interfere with the measuring process. This makes it possible to measure changing friction conditions in the bearing. The AE sensor should be placed as close to the bearing as possible for the best quality of measured AE signals. Each gap between the outer bearing ring and the sensor will considerably attenuate the AE signal.

Fig. 11 shows the curve for the parameter k(t), that was calculated from the AE signals by formula 1 [7].

(Formula 1)

$$k(t)=\frac{\tilde{a}(0)\cdot\hat{a}(0)}{\tilde{a}(t)\cdot\hat{a}(t)}$$

$\tilde{a}$: RMS of AE

$\hat{a}$: Maximum Value of AE

It is evident that k(t) is most sensitive to bearing wear. k(t) = 1 for a new bearing and approximates zero with increasing wear.

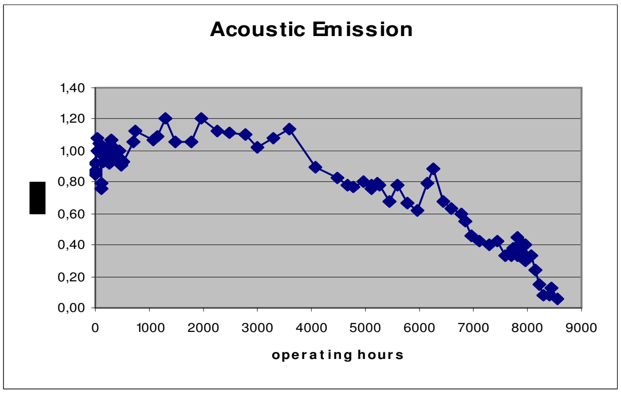

Figure 11: trend of Acoustic Emission parameter k(t)

Fig. 11 shows that k(t) initially becomes greater than 1, which means that the friction conditions in the bearing improve after a run-in period. k(t) drops after approx. 4,000 hours of operation. This is primarily due to the wear and the resulting impurities in the lubricant, though this caused no damage to the raceways of the bearing. If there is a chance to relubricate the bearing, an extension of the bearing life can be achieved. k(t) drops more after approx. 7,000 hours of operation. After this the frequency spectrum of acceleration (measured at the outer bearing ring, envelope analysis, Fig.10) shows the first clear peak at the roll-over frequency of the inner bearing ring. This is the beginning of the bearing damage by pitting.

Fig. 12 gives an overview concerning performance of measured variable as a function of wear. In the upper part of Fig. 12 bearing condition is shown. Green indicates a good bearing condition, yellow indicates that first wear has occurred, and red indicates a need for action because of significant wear. The possible warning times for the different parameters are plotted below.

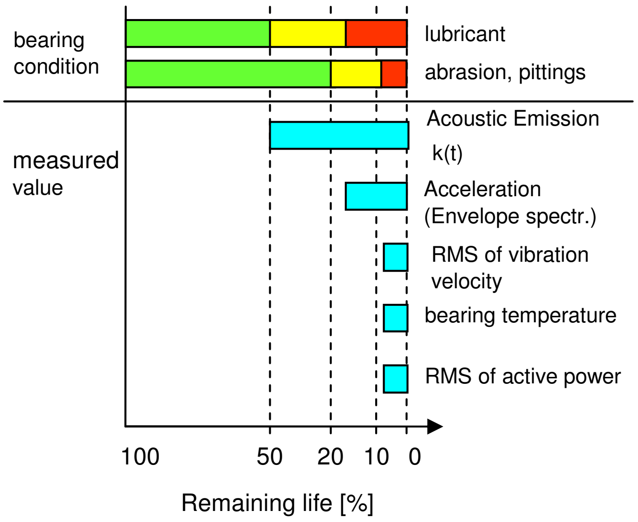

Figure 12: Performance of measured variables for predictive maintenance

The parameter k(t) is best suited for preventive maintenance. Starting from about 50% of bearing life wear in lubrication can be seen. There is enough time to arrange the replacement of the bearings in the main spindle or to procure a replacement spindle. Envelope analysis can also still be applied here. Wear on the runways can be seen about 15-20% before the end of bearing life. All other measured variables examined can at best be used for emergency shutdown but are not suited for planned maintenance due to the short residual life of the bearings.

4.2. Tool Clamping Device Monitoring

Primarily, clamping problems of tools occur at spindles with automatic tool changer. Typical errors include:

- Incorrect adjustment dimensions;
- Broken spring / drawbar;
- Frictional corrosion / contamination;
- Worn-out collet chucks.

As a result of these defects, proper tool change can no longer be performed or the tool is not held reliably in the tool holder during machining.

Until now it has been possible to check the clamping force using a manually mountable measuring instrument. Thus a falling pull-in force could be captured, but it could not clearly detect the cause of this decline. Often the complete tool clamping device was replaced. New components [13] today allow not only measuring the internal spring force of the tool clamping device but also automatic measuring of pull-in force and displacement of the drawbar clearly. Joint analysis of these measured variables in the condition monitoring system allows detection of the cause for the defect in the tool clamping device. The spring force is measured using strain gages. Data transmission from the stator to the rotor is of a non-contact type. The force signal is provided as a 4...20 mA analog signal. Fig. 14 shows the internal spring force of the tool clamping device together with the displacement of drawbar and the calculated pull-in force. The pull-in force was calculated from spring force by multiplying by 3.8, because the spring force is increased mechanically 3.8 times. This can be controlled with the pull-in force measurement device (Fig. 13).

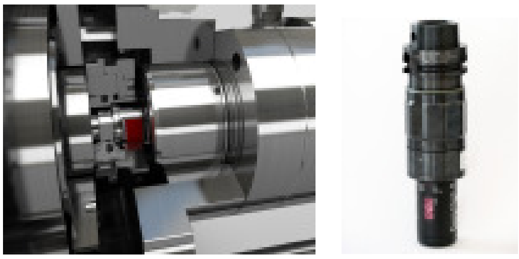

Fig. 13: Internal measuring of spring force (left) und pull-in force measurement device

The pull-in force measurement is performed by automatic insertion of the measuring instrument from the tool magazine into the spindle. The measured values are stored internally in the measuring instrument and can be read out periodically via a USB interface. In this way, the overall condition of the tool clamping device can be constantly monitored and drops in chucking force and changes in the adjustment dimensions of the chucking system can be tracked as trends. Repairs can be planned and any worn-out assemblies can be selectively replaced.

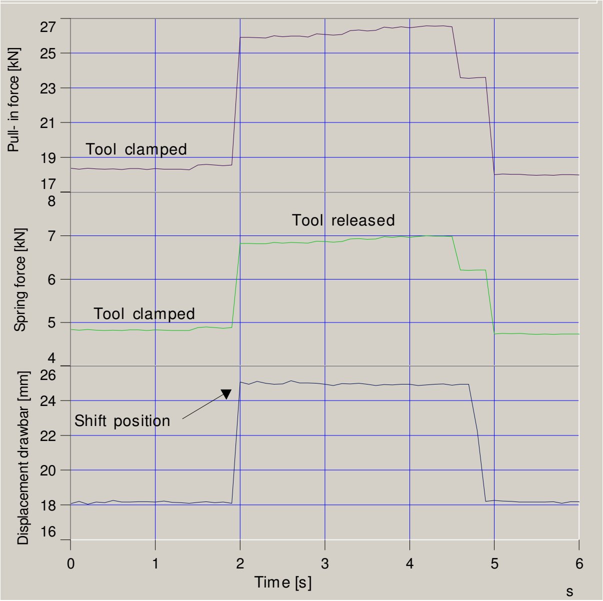

Fig. 14: Displacement of drawbar, spring force and pull- in force at tool change

4.3. Monitoring of Rotary Union

The tool is supplied with several media (hydraulic oil, cooling lubricant, purge air) via the rotary union. Failures of rotary union can be caused by high media pressure or seal wear and often result in total spindle failure. Function-related leakages of the cooling lubricant supply are drained off up to a specific quantity via a leakage hole in the housing of the rotary union. The spindle can be flooded if too much fluid leaks due to seal wear. New designs of rotary unions [13] have integrated calorimetric sensors that measure the flow in the leakage duct and output signals when specific threshold values are exceeded. For continuous leakage measurement flow sensors connected to the leakage duct of the rotary union are a good solution. Fig. 15 shows a practical solution that can be processed in the condition monitoring system.

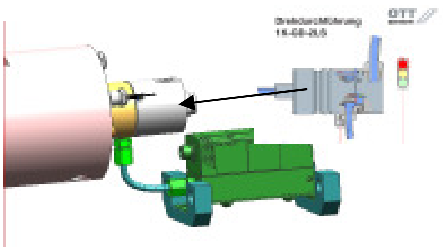

Fig. 15: Rotary union and additional flow sensor

The measuring range of the sensor is between 40 and 200 ml/min. Fig. 16 shows the crossing of the limit (red line) at 80 ml/min. When there is a break of the seal, the flow rate is rising significantly. The rotary union has to be replaced as soon as possible.

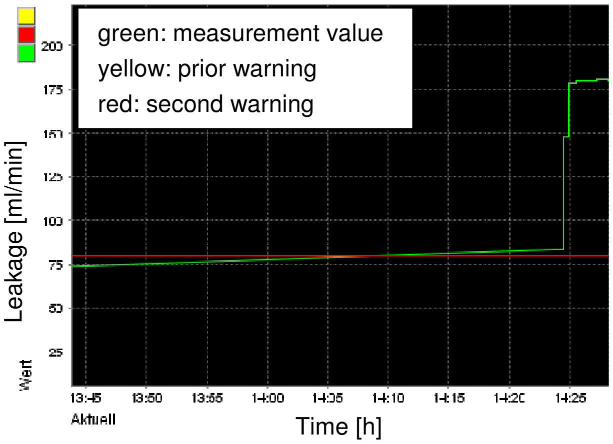

Fig. 16: Leakage measurement with flow sensor connected to the leakage duct of the rotary union

5 SUMMARY AND OUTLOOK

Efficient use of high-quality manufacturing systems requires robust production processes in combination with the highest possible availability of these systems. Preventive, condition-dependent maintenance can make a major contribution to meeting this requirement. The engineering requirements for implementing condition-dependent maintenance of machine tools are now being met. However, the organization of maintenance should also be adapted to the processes. This includes the training of maintenance personnel in the efficient use of condition monitoring systems. While even the best condition monitoring system cannot completely replace maintenance staff, it can well help them in making the right decisions.

The system as such has potentials beyond what has been described in this article. Pairing it with operational data and production planning systems would be useful. Especially in regard to the current focus on energy saving production methods, this system makes a significant contribution. It can help manufacturing companies to ensure availability and reliability, as well as to produce in a material and energy-efficient way.

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