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condition monitoring at machine tools,
diagnostic parameters,
main spindle, axis drives,
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CONDITION-BASED PREVENTIVE MAINTENANCE OF MACHINE TOOLS

Machine tools are expected to be highly available. Unintended failure incurs high costs for repairs and through production losses. Maintenance is a major cost factor and is still mostly reactive today, as a result of failures. Maintenance plans by manufacturers that require preventive maintenance based on running hours are often not implemented consistently. It would be ideal to perform condition-dependent preventive maintenance of the most critical and cost-intensive assemblies of a machine tool. This would make it possible to move repair times into non-productive periods and to procure 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 ways of monitoring the most critical machine tool assemblies.

1. INITIAL SITUATION AND OBJECTIVE

Availability of production facilities is becoming more and more important. Machine Tool Manufacturers who can guarantee a high availability 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, and

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- 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 consequence 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 the companies included in the polls 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% and
- 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 to 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 poll [2] at 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 failure rate and in view of the costs incurred when they fail:

- Main spindles (bearings, tool clamping system, rotary connection)
- Axle drives (ball-and-screw spindle drive, guide system, cover)
- 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 at 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 baseline state (relative measurement). This method should be applied particular to monitoring bearings and axle drives [4]. This is especially important for machine tools because the processes running here are not continuous; 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 in such a way that both methods of measurement can be implemented.

3. DESIGN OF A CONDITION MONITORING SYSTEM

Requirements to 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.

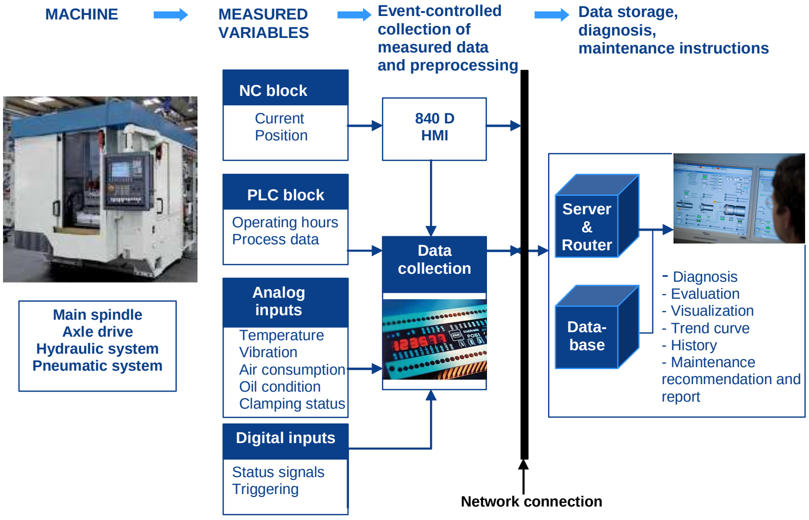


Fig. 1. Schematic diagram of a condition monitoring system

The task of condition monitoring system is it, to monitor selected machine assemblies by using existing signals from the control unit and drives and with additional sensors. A snap-on rail-mounted PC is integrated for this purpose 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, machine 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

A number of sensors is nowadays integrated into modern machine tools, such as sensors for temperatures, filling levels, hydraulic and pneumatic pressures, end positions, etc. Numerous pieces of status information are thus already available, each of which viewed alone would not be sufficient for a comprehensive evaluation of a 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, that means, the connection between measuring signals and machine condition. Under a project sponsored 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 are presented below.

4.1. SPINDLE DIAGNOSTICS

Main spindles are the "heart" of any machine tool. Failure of the main spindle inevitably brings the machine to a standstill and incurs high costs for repairs and production losses. The main reasons for spindle failures are:

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

4.1.1. 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),
- Structure-borne sound sensors in the spindle shaft and on the outer bearing ring,
- Acceleration sensors integrated into the spindle housing, and
- Signals from motor and control system (current, RMS power, etc.).

Monitoring of bearings using vibration sensors and temperature sensors on the outer bearing ring is most common because these are 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. Thus this measured variable can at best be used for an emergency shutdown, not for preventive maintenance. Evaluation of the vibration signals in the time range (RMS of vibration velocity).is similar. Longer lead times can be reached if the vibration signals are transformed into the frequency range and special evaluation methods such as envelope-curve analysis are used. However, the lifetime of the bearing cannot be extended with this method either since envelope analysis only works if bearing damage by pittings has already occurred. Envelope analysis is unable to detect a change of the lubricating condition in the bearing (grease wear). It is indicated here to measure Acoustic Emission 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, natural frequencies) 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 attenuate the AE signal considerably.

In an endurance test, static and dynamic loads were applied to a motor spindle at a test bench (Fig. 2). Test runs were performed at periodic intervals and various measured variables were captured. Figs. 3-6 show the curves for vibration velocity (RMS), bearing temperature, RMS power and the parameter k(t) that was calculated from the AE signals by equation 1[7].

It is evident that k(t) is most sensitive to bearing. k(t) = 1 for a new bearing and approximates zero with increasing wear. Fig. 6 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. 4000 hours of operation. This is only because the grease is used up, the raceways of the bearing have not yet been damaged. If there is a chance to relubricate the bearing, an extension of the bearing life can be achieved. k(t) drops more after approx. 7000 hours of operation. Now the frequency spectrum of acceleration (measured at the outer bearing ring, envelope analysis, Fig.7) shows a first clear peak at the roll-over frequency of the inner bearing ring. The bearing is worn out after 8600 operating hours (Fig. 8) and can no longer be used. This is also clearly reflected in the envelope spectrum. The sidebands around the damage frequency are a clear indication of a worn bearing.

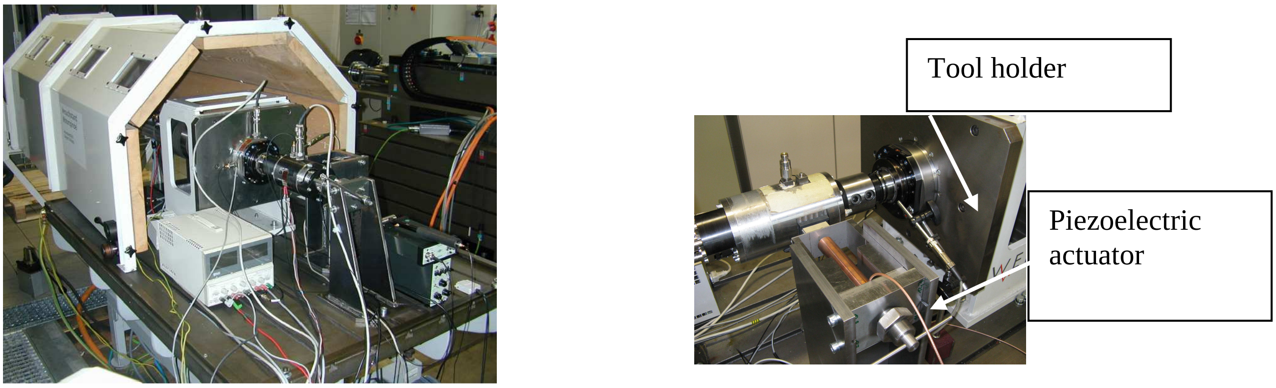


Fig. 2. Spindle test bench with included force exciter

$$k(t) = \frac{\tilde{a}(0)\cdot\hat{a}(0)}{\tilde{a}(t)\cdot\hat{a}(t)} \qquad \text{(Formula 1)}$$

$\tilde{a}$: RMS of AE-Signal $\hat{a}$: Maximum Value of AE-Signal

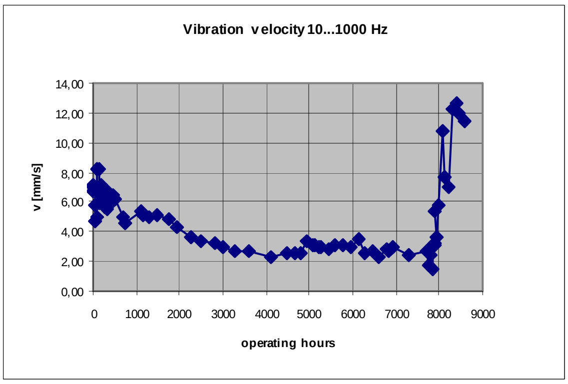


Fig. 3. trend of vibration velocity

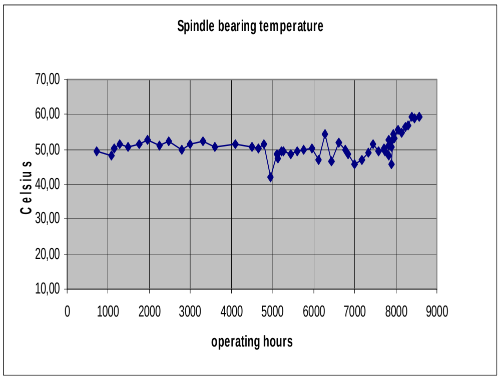


Fig. 4. trend of spindle bearing temperature

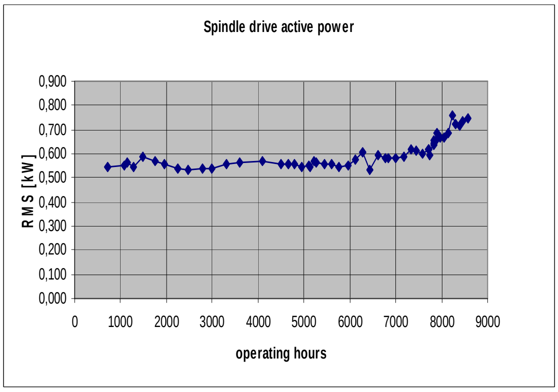


Fig. 5. Trend of spindle drive active power

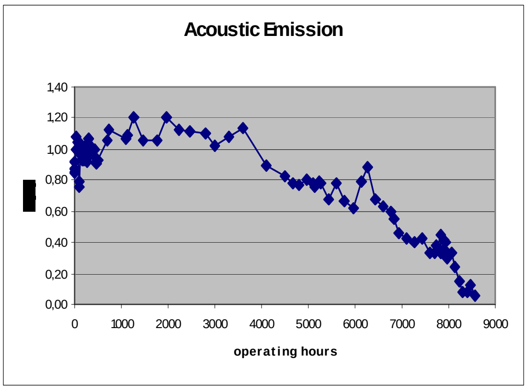


Fig. 6. Trend of Acoustic Emission parameter k(t)

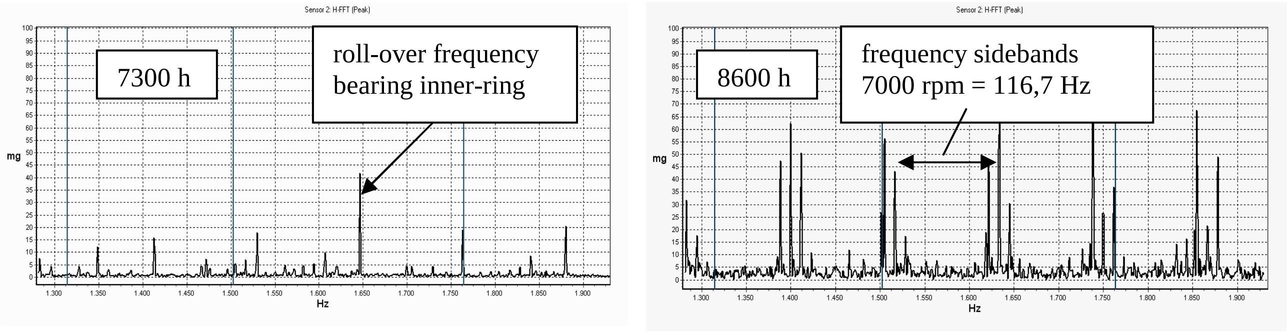


Fig. 7. Envelope frequency spectrum of acceleration (sensor at spindle housing)

Fig. 9 provides an overview of which measured variable can be used at what point in time to capture bearing wear. The parameter k(t) is best suited for preventive maintenance. There is enough time left to prepare the replacement of the bearings in the main spindle or to procure a replacement spindle. Envelope analysis can also still be applied here. All other measured variables examined can at best be used for emergency shutdown but are not suited for planning repairs under preventive maintenance due to the short residual life of the bearings.

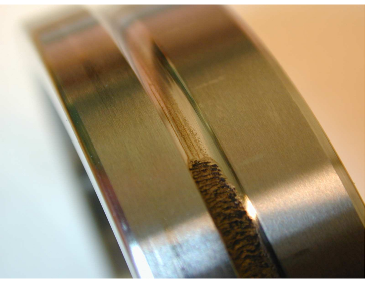


Fig. 8. Bearing damage at inner- ring

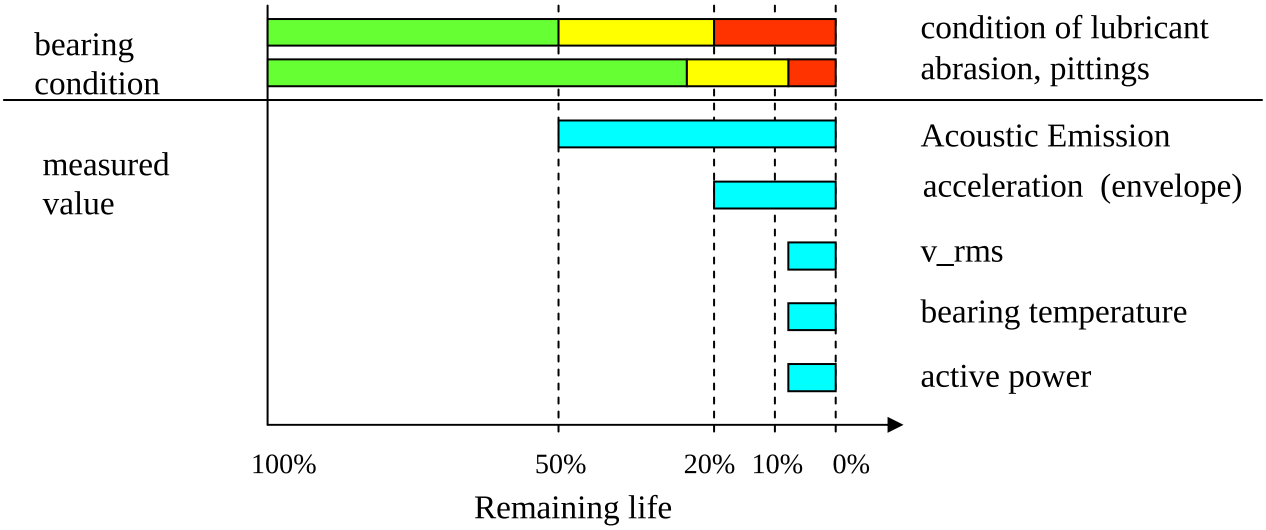


Fig. 9. Time of the detectability of bearing defects using different metrics (green: good bearing condition, yellow: prior warning, red: bearing exchange necessary)

4.1.2. TOOL CLAMPING DEVICE MONITORING

Tool clamping problems occur primarily with spindles that comprise automated tool change systems. 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 clamping force using a manually mountable clamping force measuring instrument. Thus a falling pull-in force could be captured, but it could not unambiguously 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 / position 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.

The pull-in force measurement is performed by automatic insertion of the measuring instrument (Fig. 10) 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, 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 replaced selectively.

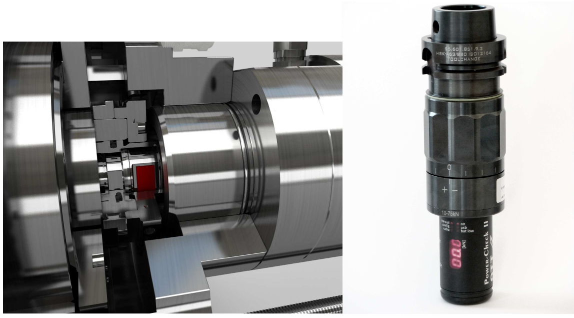


Fig. 10. Internal measuring of spring force (left) und pull-in force measurement device

4.1.3. MONITORING THE 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. 11 shows a practical solution that can be processed in the condition monitoring system.

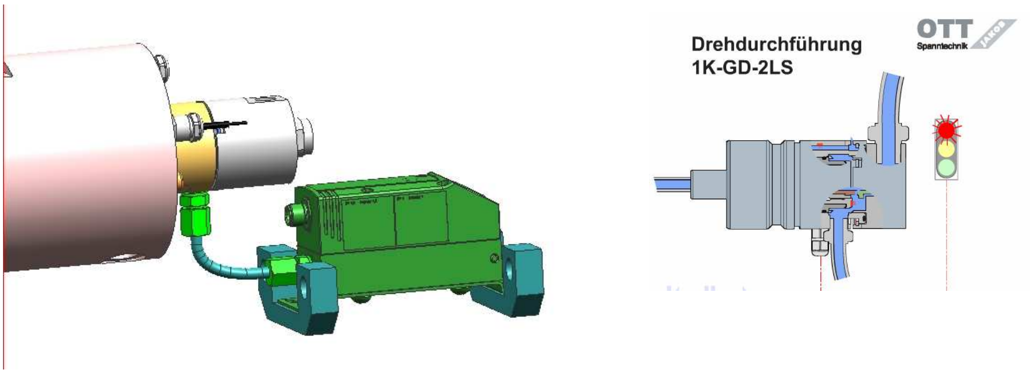


Fig. 11. Rotary union and additional flow sensor

Figure 12 shows together, which sensors for spindle monitoring technically appropriate and economically feasible.

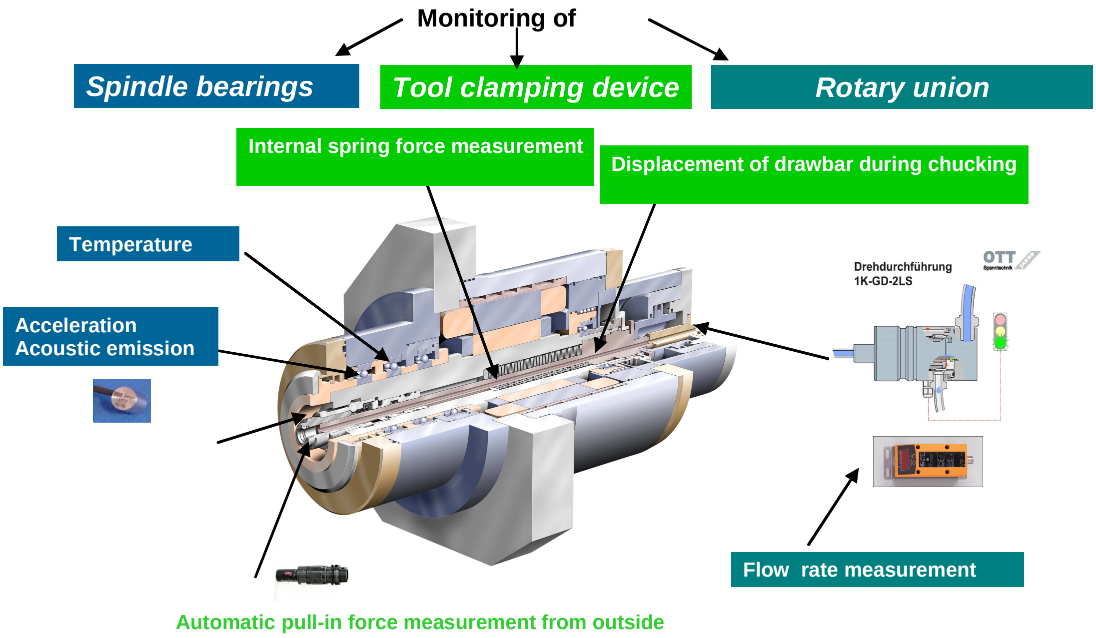


Fig. 12. Meaningful sensors for spindle monitoring

4.1.4. MONITORING OF AXLE DRIVES

The general design of an axle drive with a ball screw drive is shown in Fig. 13.

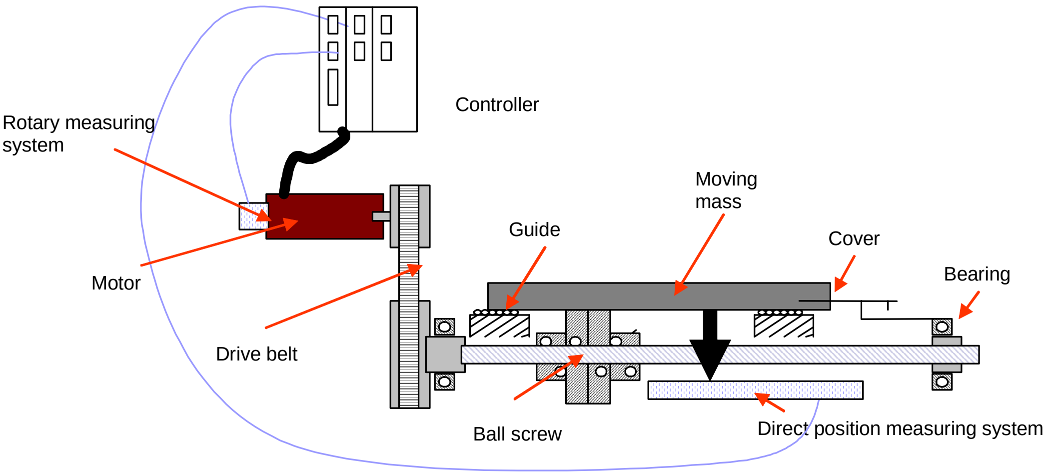


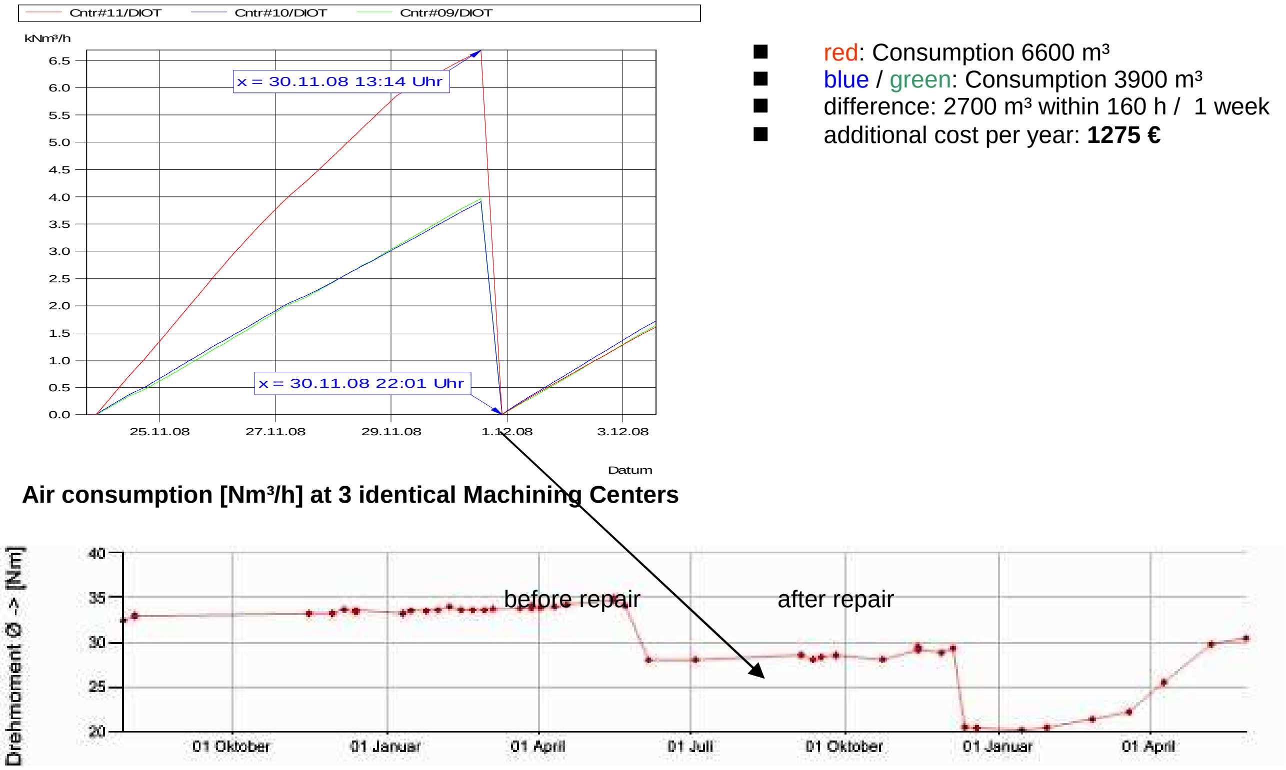
Fig. 13. General design of an axle drive

There are various ways of monitoring axle drives. Common ways include:

- Circular form test;
- Constant velocity axle test, universal axle test;
- Measurement of the transfer function, slip, axes current [8], temperature, vibration.

A disadvantage of most measured variables is that they always reflect the behavior of the entire drive train from the motor via belts, ball screw, guide system, and cover. Expert knowledge is still required to isolate specific causes for defects in the drive train. Different measured variables have to be combined into reliable characteristics to make of a condition monitoring system largely independent of expert knowledge. An example is shown in Fig. 14. The maximum torque of the axle was determined using a constant velocity axle test. The averaged torque are plotted in Fig.14 for several months. The torque will be smaller after the repair of pneumatic operated weight balancing system of this vertical axis. The cause of this error can`t determined by the constant velocity axle test alone. At the same time, air consumption of the machine was recorded as well. It is clear that the affected machine (red curve in Fig.14) clearly consumes more air. Both values return to normal after replacing the worn seals. However, after a few months later already see an increase in torque, the next repair is becoming apparent.

Fig. 15 shows the AE signals (rms value) on a guideway at the gantry axles Z1 and Z2. The goal is to detect any changes in friction conditions within the guide system. Specific defects were introduced to axle Z1 while axle Z2 remained unchanged. A clear change of the AE signal is detected after installing a defective profile rail. More studies are required to make the measuring method suitable for practical applications.



- red: Consumption 6600 m³
- blue / green: Consumption 3900 m³
- difference: 2700 m³ within 160 h / 1 week
- additional cost per year: **1275 €**

Air consumption [Nm³/h] at 3 identical Machining Centers

Test with constant velocity, vertical axes, Machine 3

Fig. 14. Constant velocity axle test and air consumption at a vertical axes with pneumatic operated weight balancing system

Another example is shown in Fig. 15

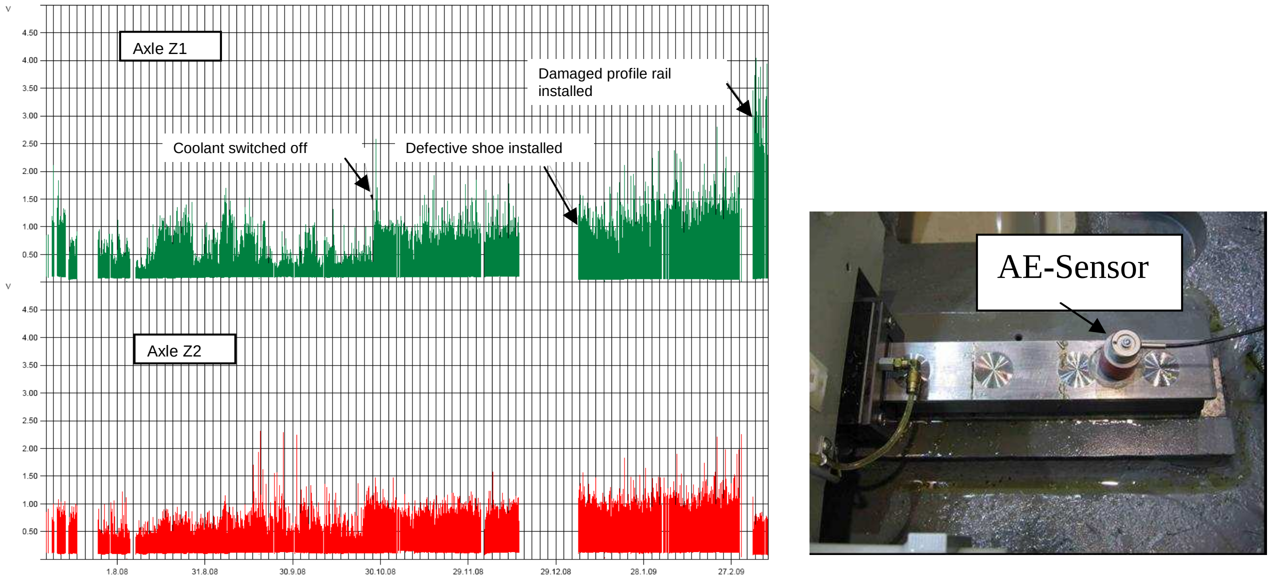


Fig. 15. RMS of Acoustic Emission

All measurements on axle drives must be performed at periodic intervals and always under defined test condition, otherwise the results of measurement cannot be compared. Furthermore, the testing procedure has to be automated. The machine operator should only launch the test program; all other test steps down to storing the data in the condition monitoring system should run without operator intervention.

4.1.5 OTHER DIAGNOSTIC OPTIONS

Hydraulic, pneumatic, lubricating, and cooling systems are used for various purposes in machine tools. To include these in a Condition Monitoring system, both the respective devices (motors, pumps, valves, filters, containers) and the media (contamination, aging) must be monitored. Suitable sensors are available, especially for hydraulic and pneumatic systems. Fig. 14 shows that leakages in the pneumatic system can be detected using a simple air consumption meter, which can save considerable costs. Here, the air consumption of three identical machines is compared over a period of one week. One machine consumes considerably more compressed air than the two other machines while producing the same output. Projected on one year, this example alone would result in cost savings in the amount of €1,275. Compressed air should be measured by a triggered system. Subdivision into individual modes (automatic, tool change, standby) helps isolate the cause for the defective consumer. Fig. 16 shows the number of particles in hydraulic oil according to ISO code. The oil was new at the beginning of the measurement. The number of particles drops after the oil has passed through the filters installed in the oil line during machine operation. The values then remain constant. A particle counter is not very useful in the case shown here. However, its use can pay off in machines with a large oil volume.

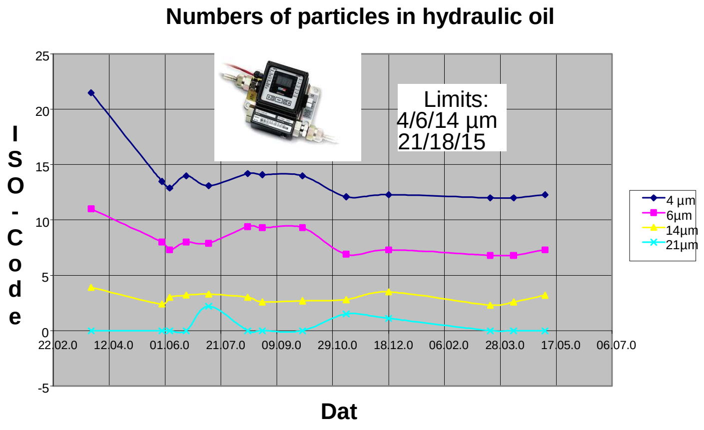


Fig. 16. Number of particles in hydraulic oil according to ISO code

5. ABSTRACT AND OUTLOOK

Efficient use of high-quality manufacturing systems requires robust production processes in combination with highest possible availability of these systems. Preventive, condition-dependent maintenance can make a major contribution to meeting this requirement. An increasing number of manufacturing companies are facing this challenge. The engineering requirements for implementing condition-dependent maintenance of machine tools are being met today. 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. Pair with operational data and production planning systems is useful. Even with regard to the future, increasingly important resource-saving production, the system can make a contribution. It can help manufacturing companies to ensure availability and additionally to produce in a material and energy efficient way.

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