PROCESS MONITORING FOR A MACHINE TOOL SPINDLE WITH MAGNETIC BEARINGS

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ABSTRACT

This paper talks about the application of active magnetic bearings (AMBs) in a high frequency machine tool spindle, emphasizing the possibility of direct process monitoring with the AMBs.
Process monitoring, i.e. the measurement of cutting forces and the recognition of process anomalies (tool breakage, tool wear), is a very important task in machining technology today, as it is necessary for automation in machining lines. For conventional motor spindles, several approaches have been made, including force measurement by a piezoelectric equipment, power measurement, spindle current measurement and acoustic emission.
AMB motor spindles provide the possibility to do the process monitoring directly with the AMBs. The control output of each bearing is proportional to the magnetic force applied to the rotor shaft. By measuring these control outputs, the cutting forces of the milling process can be determined without any extra equipment.
Short-time variations of the cutting forces, as e.g. the entrance of each cutting edge into the material, can be determined by measuring the spindle shaft dislocation with the position sensors of the AMBs.
Good results could be achieved by this method. The cutting forces could be determined, and tool breakage and tool wear could be well recognized.

1. INTRODUCTION

The AMB technology has been implemented in high rotation spindle applications for more than ten years. Nevertheless, it still has not reached great spread in the milling industry. The reasons may be the higher cost and the higher operational complexity, which requires specially trained personnel. The spread of high speed cutting (HSC), the need of high precision parts at a high production rate, and other advantages as for example the built-in process monitoring described in this paper may change this trend.

1.1. Process Monitoring

Process monitoring is the automatic recognition of tool wear, tool breakage and other process anomalies during the process. This is a very important task in the milling industry today. It is necessary for automation in machining lines, i.e. to stop the milling process immediately if any process anomaly occurs and react accordingly (i.e. to change the tool and continue the process, or to stop the line and call an operator).
Several approaches have been made in order to obtain a reliable process monitoring. They are based on the following principles:

- Power measurement
- Spindle current measurement
- Acoustic Emission (AE)
- Vibration/Acceleration measurement
- Force measurement

For milling applications, force measurement is the most promising method. It is much more dynamic than power or current measurement, and it is more easily understandable than AE or vibration measurement. The expectable cutting forces can also be modelled by CAD/CAM software and then be compared to the real forces.
Several equipments have been created to realize force measurement:

a) Piezoelectric table dynamometer: A piezoelectric platform which is fixed under the workpiece.
b) Rotating cutting force dynamometer (RCD): A device fixed between the spindle shaft and the tool. Only for experimental applications.

c) Spindle integrated flange force ring: A ring with piezoelectric sensors which is placed at the spindle fixation between the spindle and the machine tool.

d) Spindle integrated bearing force sensor: A ring with piezoelectric sensors which is placed between or next to the ball bearings of the spindle shaft.

All these equipments have one disadvantage: They have to be mounted on the machine tool, i.e. under the workpiece (a), at the spindle shaft (b), at the spindle housing (c) or in the spindle housing (d). In the case of (d) also a special design of the spindle is necessary.

The advantage of the AMB process monitoring method presented in this paper is that *no extra equipment* is necessary. All data can be obtained directly from the AMB control with a common PC, with a software interface written in MATLAB®.

In chapter 2, the equipment used in this work and the methods of data processing are described. Chapter 3 talks about the different tasks of process monitoring and how they are solved. In chapter 4, another advantage of an AMB spindle is shown: The possibility to compensate machine and tool deformations by repositioning the spindle shaft inside the housing. Chapter 5 gives the conclusions and outlook.

2. EQUIPMENT

2.1. The Spindle

For this work, a high frequency AMB motor spindle, type HF 200 MA-40 produced by IBAG, Switzerland, was implemented in a conventional machining centre (Thyssen Hüller-Hille, model nb-h 65). The spindle reaches a rotation speed of 40,000 rpm at 40 kW. It is equipped with active magnetic bearings produced by Mecos Traxler AG, Switzerland: Two radial bearings A and B in the rear and the front of the spindle, and one axial bearing Z between the radial bearings. The motor is acting on the shaft between the rear radial bearing A and the axial bearing Z. Figure 1 shows a schematic of the spindle.

2.2. The Data Interface

For the data acquisition, Mecos Traxler AG supplies a special software interface written in MATLAB®, which permits data exchange in both directions, i.e. the control outputs or sensor signals can be obtained, as well as spindle parameters can be set through this interface.

The maximum sampling frequency is 4.8 kHz.

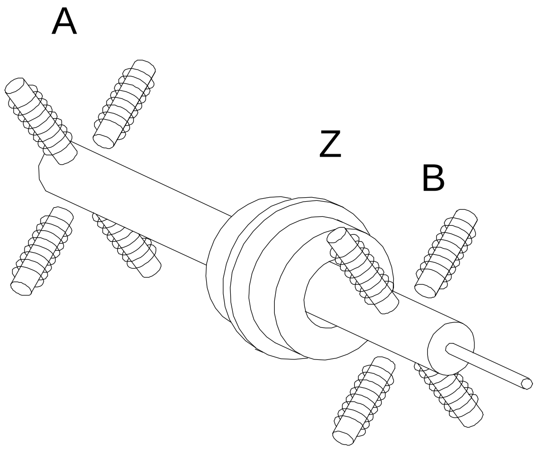

FIGURE 1: Schematic of the IBAG motor spindle

2.3. Force Measurement with the AMBs

The control outputs, which are proportional to the magnetic forces in the bearings A, B and Z, provide 5 values: AX and AY from bearing A, BX and BY from bearing B and Z from bearing Z. Z can directly be converted into the axial force F_Z, by multiplying it by a constant factor. As the directions of AX and AY, and BX and BY, respectively, are not necessarily parallel to the machine axis X and Y, these outputs have to be transformed to obtain the forces F_X and F_Y in the bearings A and B. Once calculated the forces in the bearings A and B, the radial cutting force F_C can be obtained by:

$$F_C = -(F_A + F_B) \qquad (1)$$

From the ratio of the forces F_A and F_B and from the distance of the two radial bearings ($\overline{AB}$), the distance of the point C, where the force is transferred to the tool, to the bearing B can be calculated:

$$\overline{BC} = \overline{AB} \cdot \frac{|F_A|}{|F_A + F_B|} \qquad (2)$$

At this point, it has to be said that the control outputs do not only depend on the applied force, but also on the temperature of the motor spindle. By rotating the spindle under load, the spindle was heated up. A decrease of the control outputs of about 20% could be observed for a hot spindle compared to a cold spindle (see figure 2).

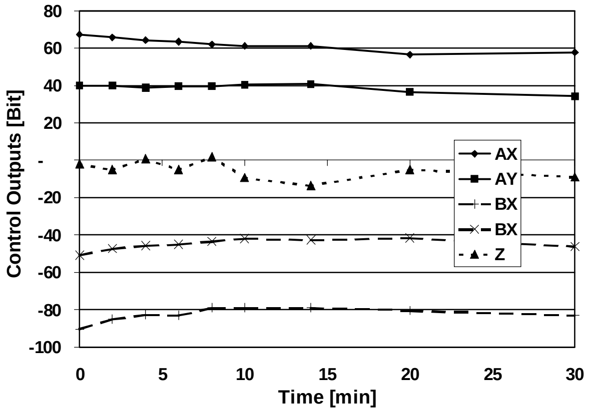

FIGURE 2: Dependence of the control outputs on the spindle temperature.

In the experiment of figure 2, a constant force of 64 N was applied to the tool in vertical direction, in the cold spindle state and after different times of rotation under load. After 20 minutes the spindle was stopped, and the spindle began to cool down again.

This fact makes absolute force measurement difficult, but it does not affect the process monitoring, which uses basically relative force measurement.

2.4. Shaft Dislocation Measurement

To detect the wear state of the cutting edges of a tool, the measurement of the control outputs is not dynamic enough, especially when high rotation frequencies are used. For this purpose, the position sensor values have to be considered. Each cutting edge causes a small dislocation of the spindle shaft. This dislocation can be measured with the shaft position sensors.

3. PROCESS MONITORING

3.1. Force Measurement

An example of force measurement is shown in figure 3. The cutting forces were measured during the entrance of the tool into the workpiece. A 10 mm diameter tool with 2 cutting edges was used at a rotation speed of 10.000 rpm, with a feed of 2000 mm/min.

The quality of the force signals is very good. After 0.6 seconds, the acceleration of the spindle in X-direction can be seen (see little negative peak). At T = 0.7 seconds, the tool enters into the aluminium workpiece.

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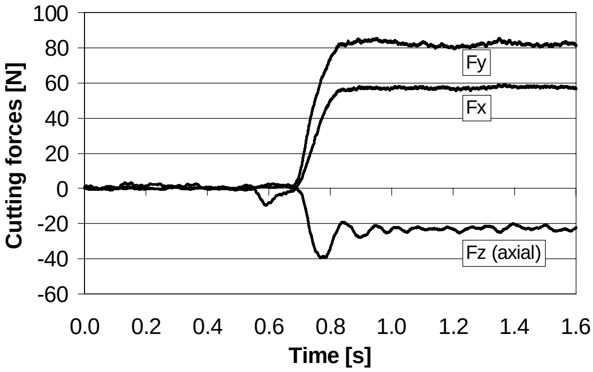

FIGURE 3: Measurement of the cutting forces Fx, Fy (radial) and Fz (axial) during the entrance of the tool into an aluminium workpiece.

3.2. Recognition of Tool Vibrations

An application of force measurement is the detection of tool and other vibrations. Vibrations, due to resonance effects of the tool, the spindle shaft, machine components etc. may deteriorate the surface quality of the workpiece. Recognizing such vibrations, the rotation speed of the motor spindle can be changed, in a way that these vibrations disappear.

Figure 4 shows an example of milling with and without vibrations. While milling at 31.000 rpm, a strong vibration in Z-direction (axial) of about 25 Hz could be observed. As a result, the surface roughness was relatively high (Rt = 10.45 µm). At 40.000 rpm, the force curve is perfectly flat, and the surface roughness consequently low (Rt = 3.4 µm).

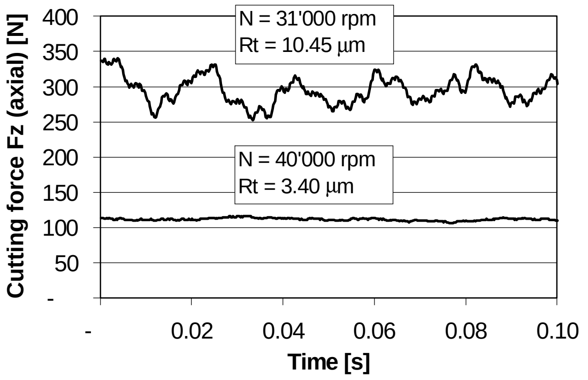

FIGURE 4: Surface deterioration due to tool vibrations. Measurement of the axial cutting force component at different rotation speeds.

3.3. Recognition of Tool Breakage

Tool breakage can relatively easily been recognized: A sudden fall of the cutting forces during the cutting process generally indicate a tool breakage. Figure 5 shows a typical tool breakage:

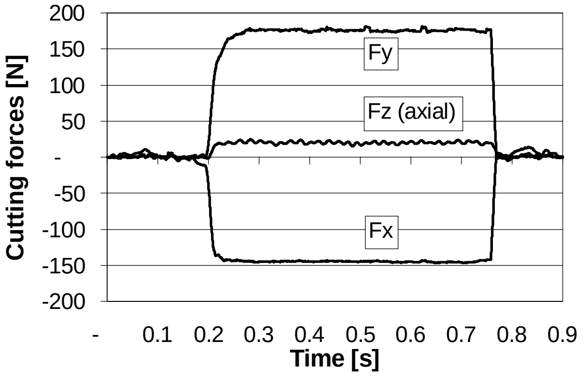

FIGURE 5: Cutting forces during tool breakage. At T = 0.77 seconds the tool broke.

3.4. Recognition of a Cutting Edge Breakage

To monitor the quality of the single cutting edges of a tool, force measurement is not dynamic enough for HSC applications. In order to recognize the wear state of each cutting edge, another signal can be used: The position sensor signals. At each entrance of a cutting edge into the workpiece material, a small momentum is exerted on the tool and therefore on the shaft, which leads to a small dislocation of the shaft during a short time. If a cutting edge is broken, this dislocation becomes smaller than the dislocations of the other (intact) cutting edges, while the cutting edge following the broken one causes a higher dislocation, because it has to remove more material in its chip.

Figure 6 shows two graphics: One of an intact tool with 2 cutting edges and one of a tool with one broken cutting edge.

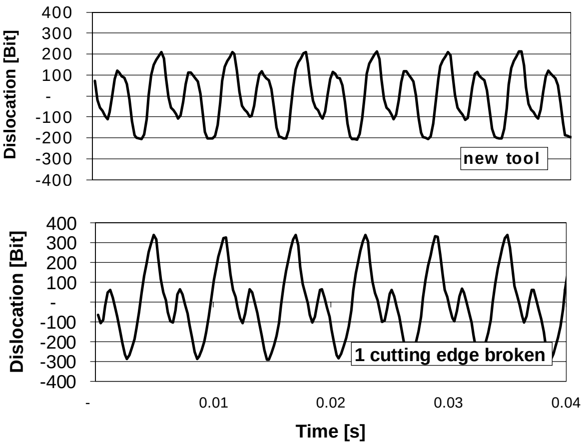

FIGURE 6: Shaft dislocations caused by the cutting edges of an intact tool (upper) and of a tool with one broken cutting edge (lower).

As it can be seen in figure 6, even the cutting edges of a new tool do not cause perfectly equal dislocations of the shaft. This is due to small fabrication errors of the tool, the tool clamping system and the shaft.

4. CORRECTION OF MACHINE AND TOOL DEFORMATIONS

AMB spindles have another advantage compared to conventional spindles: The shaft is not absolutely fixed in the bearings, there is a small range in which its position can be changed. AMB spindles have, beside the magnetic bearings, so-called safety bearings (conventional ball bearings) in the rear and the front of the spindle. These are usually not in contact when the shaft is floating; but when an overload occurs, the shaft is taken up by these safety bearings, in order to avoid damage of the spindle. In the case of the IBAG spindle, there is a gap of ± 0.2 mm between the shaft and each safety bearings in radial and axial direction (see figure 7).

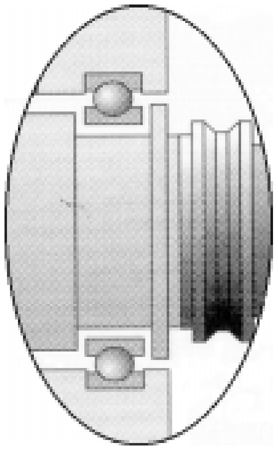

FIGURE 7: Radial and axial gaps between the spindle shaft and the safety bearings.

This gap can be used to compensate deformations of the tool, the spindle and the whole machine structure, due to cutting forces, and also thermal deformations due to temperature rise of some parts (tool, workpiece, motors) (see figure 8).

The exact spindle position can be set by simply changing the setpoint of each magnetic bearing.

Not the whole range of these ± 0.2 mm can be used, as some control reserve must be kept. About half of the gap in each direction can be used. This makes possible a linear compensation of ± 0.1 mm and an angular compensation of ± 0.015 degrees (by opposite shifting of the setpoint of the front and the rear radial AMB). This is in most cases enough to compensate the above mentioned deformations.

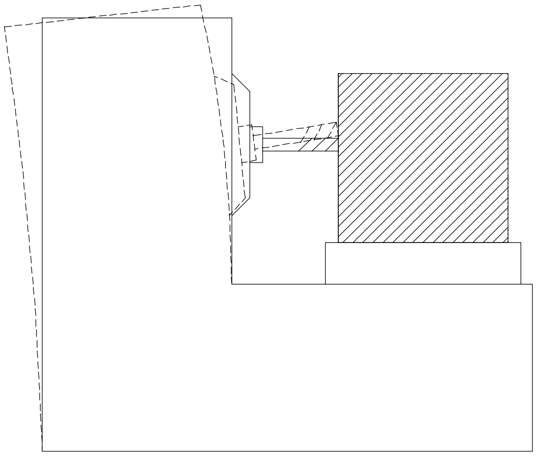

FIGURE 8: Machine deformation due to cutting forces and thermal expansion.

The setpoints can be constantly changed by the MATLAB® interface. This makes possible that the shaft position can be constantly changed, depending on the actual cutting forces. Like that, a much better dimensional accuracy of the workpiece can be reached.

5. CONCLUSIONS AND OUTLOOK

The results of the above shown experiments are satisfactory, in a way that tool breakage, tool wear and tool vibrations can be reliably recognized. The fact that for this process monitoring no extra equipment is used, makes AMB spindles particularly interesting especially for the production of a high number of parts in big machining lines.

In addition to this, the possibility to compensate tool and machine deformations lead to applications where especially small tolerances are demanded.

In the future, it is planned to automate this process monitoring, in a way that it can be installed in industrial applications.

The benefits of AMB spindles described above mean a strong advantage compared to conventional ball bearing spindles. The authors assume that this will help to spread AMB spindles more in the global milling industry.

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