ANALYSIS OF THE PERFORMANCE OF AN AMB SPINDLE IN CREEP FEED GRINDING

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ABSTRACT
An Active Magnetic Bearing (AMB) electrospindle has been used in the process of creep feed grinding. This process requires high speed, power and accuracy. The AMB spindle complies with these requirements and brings additional advantages coming from the signal processing characteristics and rotor position control. The operation experience extends over 8 years and 12 spindles. This opened the door to other CBN grinding applications and motor technology development.

INTRODUCTION

More than 8 years ago, when a new very high speed grinding process (300 m/s) was being finalized, the only available electrospindle for this job was the S2M 60,000 rpm – 15 kW Actidyne[r] Magnetic Bearing (AMB) spindle. Today, it is still the best electrospindle for heavy duty of this kind (high speed, high power, high precision). This performance requires a robust and intelligent AMB control.

THE CREEP FEED GRINDING PROCESS

The starting point of this development is the constant search for productivity by the European car industry. New machining methods are favoured when they allow a drastic reduction of manufacturing time or any other cost factor.

The present case deals with the machining of narrow slots (around 1.25 mm) in steel parts. The former production method used 2 machine tool operations : milling before hardening, grinding after hardening. The milling job used to be the removal of the chips in the steel. The grinding of the hardened steel was necessary to achieve the required precision and surface smoothness. It was not thinkable to remove the chips and achieve the required precision in just one operation before the existence of Cubic Boron Nitrid (CBN) grinding material.

This new material, now more and more widely used in the industry, has been a major step forward in the evolution of grinding machines. The main feature of the use of CBN grinding wheels is the increase in efficiency through higher cutting speeds.

Further to extensive AMB spindle tests, Kapp, a machine tool manufacturer (Coburg, Germany), designed a fully new machine concept to take advantage of these extreme high speeds, unknown before in grinding technology.

Kapp HGS machine works with a cutting speed of 300 m/s (!). The tool (CBN galvanic deposits on a diameter 90 mm steel wheel) enters directly into the workpiece, in one pass, with full power (15 kW). This is the creep feed grinding. Those special grinding wheels are also manufactured by Kapp.

The Kapp machine can grind slots from 1 mm to 1.4 mm width.

The precision tolerance is H7 (the sum of all drifts must be under 8 micrometers) but in fact, the machine acts to bring at least 60 % of the parts in a tolerance interval of 4 micrometers.

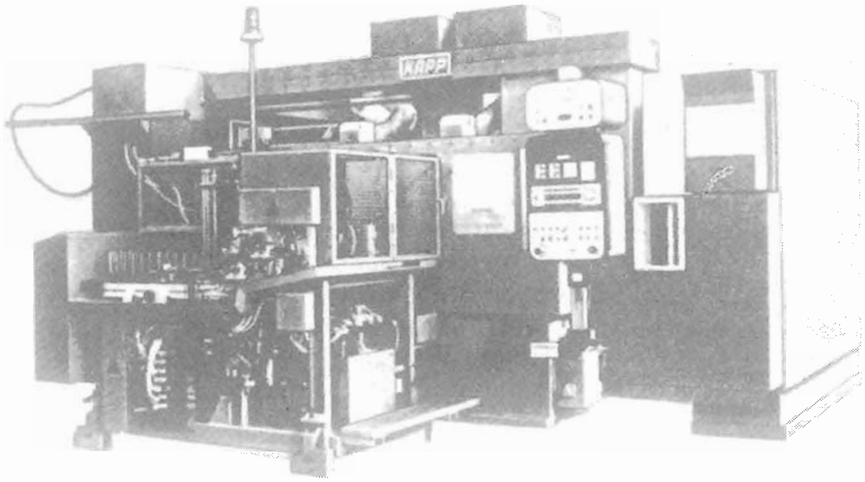

FIGURE 1 : Kapp HGS Grinding Machine
(Hochgeschwindigkeits-Schleifmaschine)
Very stiff and compact grinding machine unit with S2M AMB spindle B15/1000 type, multiprocessor CNC control, fully automatic grinding cycle, integrated lubrication unit, automatic slot width control and automatic workpiece loading system (to be seen on the front of the machine). These features allow a night (3 shifts) unmanned operation.

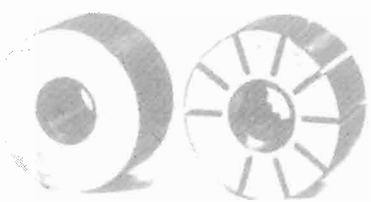

FIGURE 2 : the workpiece
Before machining, after (10 slots, width 1.25 mm)*.
This part is a vane pump rotor (oil pump for the car power assisted steering system). The dimensions are approximately : diameter 25 mm, width 10 mm.
Material : steel 100 Cr 6.
* 1 mm width is now possible.

THE AMB SPINDLE DESIGN

The optimum of an AMB spindle design is to arrange on the same shaft a given tool, the magnetic bearings with their sensors, the electric motor and the auxiliary devices without being hit by the limit of the critical speed (first bending mode).

Of course, the heavy duty of the spindle imposes a large tool (diameter 90 mm), a large motor (15 kW steady power, 22 kW peak power) and a high working speed (60,000 rpm). The design compromise consists here in the deletion of the usual thrust bearing (disk) and its replacement by two asymmetrical conical bearings. This is an efficient way to spare room and hence reduce the shaft length (consequently the first bending mode limit is lifted upwards). The front radial conical bearing takes most of the cutting load, being close to the tool. The rear conical bearing mainly takes its share of the rotor weight. Both act for the axial stabilization.

The integrated high speed motor is of the asynchronous type with very low slip, developed by S2M especially for this spindle. It is driven by a PWM frequency inverter with in-built output filter which reduces rotor losses and dv/dt applied to cables and windings. However, more can be done today to reduce motor losses further on (new motor technology, see Outlook, last paragraph, below).

The magnetic bearings control is S2M standard : inductive high precision sensors, analog control loop, power amplifiers (at the beginning 80 V / 25 A, today 120 V / 15 A, tomorrow 300 V / 8 A). But it must be pointed out that the control of conical bearings is a special know-how. A coupling between radial and axial directions must be strictly avoided although the forces are generated by the same power amplifiers and electromagnets. The high cutting loads acting in radial direction must not have any influence on the axial direction (where the very high precision is required). In this environment, analog control is still the best choice to provide the signal processing characteristics listed in the next chapter.

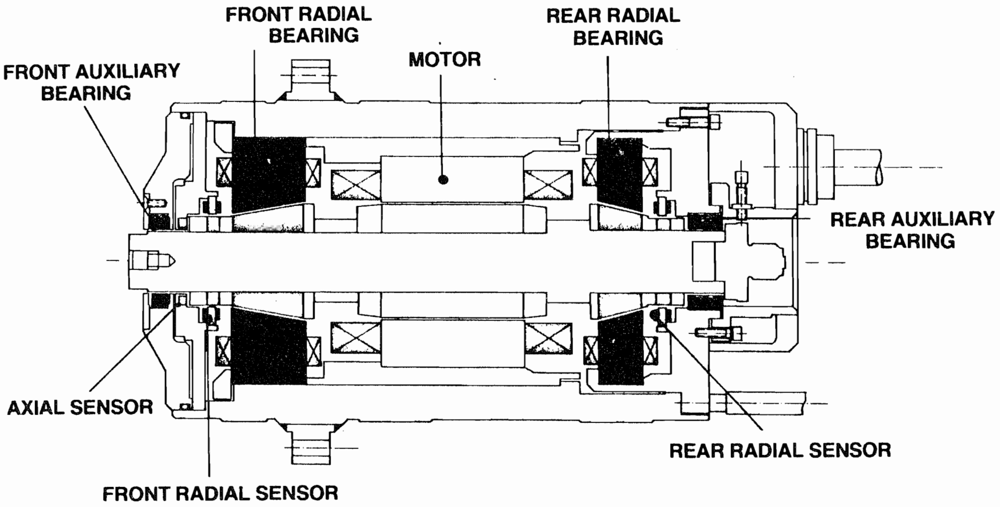

FIGURE 3 : Cross section of AMB Spindle

SIGNAL PROCESSING CHARACTERISTICS

Some of the main signal processing characteristics of the S2M AMB spindle in connection with their advantages for the creep feed grinding process are as follows:

Stiffness

The open loop transfer function of the controller plotted on the figure N°4 (TRF 5.5 software) shows the stiffness (angular phase / top and amplitude / bottom) of the front bearing of the spindle (towards the tool end of the spindle shaft). The stiffness of 34 N/μm at 10 Hz is the most relevant point of this curve regarding our subject. At 10 Hz (low frequency) the answer time of the controller is still quick enough (in the range of 0.1 second) for the grinding process. Thus, the maximum stiffness is achieved soon after the entry of the tool in the machined part. Later on, the stiffness further increases up to 170 N/μm at 2 Hz and 340 N/μm at 1 Hz. Although slightly delayed the reaction time is still fast enough for the process as creep feed grinding with high stock removal induces high cutting forces over long periods of time. Of course, the static stiffness of the total system bearing–shaft–tool–machine... is significantly lower than the bearing stiffness itself, due to the limited stiffness of other components like the quill. The results are always better with AMBs than with ball bearings spindles as pointed out by the measurements of the German IWF research centre (see ref. 1)

Large bandwidth of the controller

The large bandwidth depicted on the figure N° 4 (phase 0° at around 1,200 Hz) is one of the aspects of the robustness of the controller. It accepts the largest number of tools, all different in weight and inertia. This spindle is very versatile from the user's point of view. The working tool may be changed without any controller modification.

Automatic Balancing System

The location of the ABS filter on the rotation frequency (1,000 Hz) can be hardly seen on the figure N°4 as this filter is very narrow : only 8 Hz. The effect of this tracking filter (following the rotation frequency) is well known. The remaining unbalance of the tool does not create any vibration in the spindle stator and thus further vibrations in the machine structure are cancelled.

Further characteristics of the signal processing of this spindle are also very important for the grinding. The **high damping factor** of bearing mode cancels chattering on the machined part. On the contrary, ball bearing spindles show long oscillating time on their bearing natural frequencies (almost not damped). This phenomenon has been analysed by the German IWF research centre (see ref.1). The **noiseless sensors** of S2M AMBs also prevent chattering.

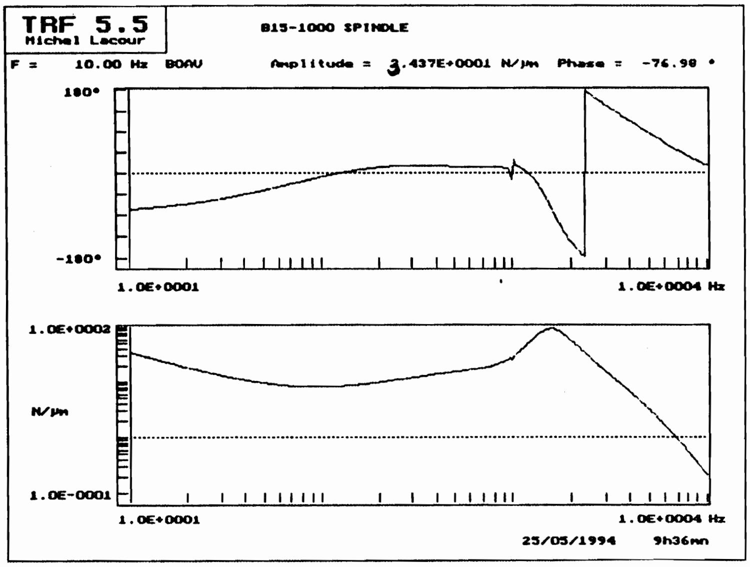

FIGURE 4 : Stiffness Curve

ROTOR DISPLACEMENT

The possibility to move the rotor inside the air gap of an active magnetic bearing is inherent in its principle. A modification of the reference signal of the control loop, for example through a tension variation, is enough to shift the rotor in the required direction. A typical reference amplitude is 10 V for 0.2 mm. Kapp machine designer was the first to implement this feature in a new grinding machine concept. 1 μm steps, free from backlash, are generated.

As one can imagine, CBN grinding material, although extremely hard (comparable to diamond) is not free of wear, especially under heavy duty (300 m/s, 15 kW). Therefore, the grinding wheel wear has to be compensated, step by step. This compensation must occur along the machine axis called Z which is perpendicular to the main machine movement, called X, which is the movement of the table carrying the workpiece against the tool. The Z axis of the machine is also the Z axis of the spindle. Therefore, a command of the rotor shift along the spindle Z axis is adequate. Consequently, a CNC axis of the machine is spared !

The operation cycle (6 minutes) of the Kapp machine includes next to the grinding itself an in situ slot width measurement (Nieberding air pressure sensor) which monitors the Z axis. The dimensional correction is made by two alternate Z shifts of the grinding wheel position. One pass finishes the right edge of the slot and the next pass finishes the left side. The opposite two shifts are symmetrically incremented by 1 μm steps in order to leave the slot absolutely centered. The rotor displacement process stops when the wear criterion of the wheel has been reached (around 40 micrometers). The wear of the wheel is slow, especially thanks to the influence of the Automatic Balancing System which reduces all vibrations in the process. More than 1,750 parts may be machined with the same grinding wheel. As a result the wheel must be changed only every second day (that is the only manual operation in the machine cycle).

An other exclusive feature of the AMB spindle has been successfully used by the grinding machine designer to set up this new grinding process. The forces in the magnetic bearings are known through the currents in the power amplifiers. This helps to determine the forces generated by the tool in the workpiece (direction and amplitude). Thus, the machine design could be optimized. The fixation of the part of the machine table could be positioned in the right way.

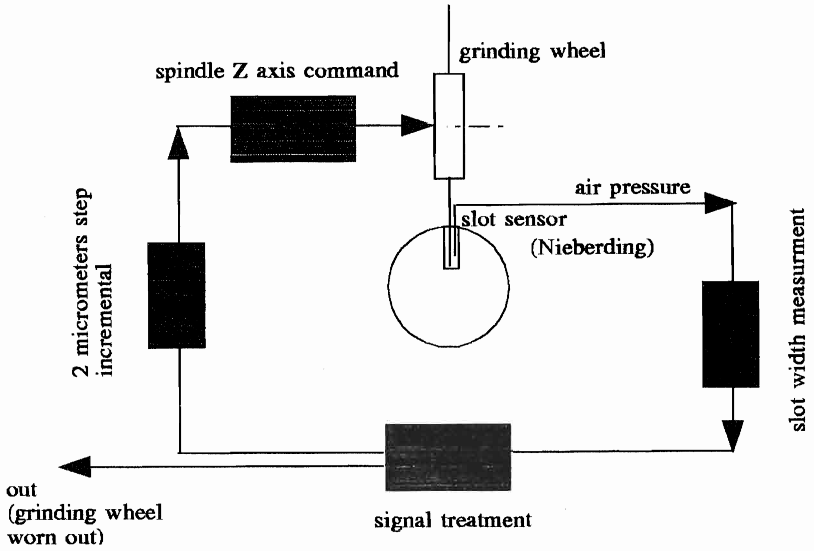

FIGURE 5 : Rotor Displacement Control Loop

OPERATING EXPERIENCE

The industrial exploitation of this new machine concept started by 1986 at ZF, the well-known car parts manufacturer. The first machines were installed in the plant of Bietigheim near Stuttgart. The next machines went to ZF plant in Berlin. The total number of spindles in operation is 12. They are mainly operated during 2 shifts a day, but 18 to 20 hours of continuous work are not exceptions. They require minimal care from the mechanical point of view. But an AMB training for electricians was suggested in order to allow them to understand the behaviour of the AMB spindle which is not the same as ball bearing high speed spindles.

At the beginning some mechanical parts of the AMB spindle showed some reliability problems, which are now solved. The position sensors have been improved to resist indefinitely to the thermal stresses caused by the heat generated inside the spindle (further developments will reduce this heat, see outlook below). On the other hand, the AMB control system was excellent from the very beginning and did not require any modification.

The machines are ready for an other 8 year operation, and more.

SUMMARY

Long time operating experience has proved S2M optimized (robust) technology for this application and has given an impetus to high speed CBN grinding such as other high speed machining process development. The creep feed application is very much demanding (speed, power, accuracy) and the AMB spindle offers exclusive features (very high stiffness, automatic balancing system, rotor displacement,...). The key of the successful application is the cooperation between the machine designer and the AMB spindle company.

OUTLOOK

For the reasons already explained, the scope of use of the AMB spindle is focused on CBN grinding, where high speed, high power and high accuracy are needed altogether. An other example of CBN grinding application is the manufacturing of linear high precision bearings (Mägerle machine used by Schneeberger, Switzerland). A further example is the grooving of gear box wheels (Prorectif machine used by Ford, France). Beyond the CBN grinding, AMB spindles are used in the industry for the internal grinding, milling of light alloys and copper tube grooving. More than 60 spindles are in operation.

The major evolution of AMB spindles is not the development of the digital control (S2M digital control technology is already used today in the turbomachines industry, the advantages of this technology are not so relevant for machine tool spindles in the short term basis) but the change of the motor technology. S2M has also fully tested, on other types of spindle, a 40,000 rpm 33 kW motor (full power test under steady state conditions with almost no air-cooling of the rotor). The rotor losses have been drastically reduced with a well suited frequency inverter. The next possible step is a 60,000 rpm 30 kW motor built in the same dimensions as the today's 15 kW motor. Thus, the power will be doubled.

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