DIAGNOSIS AND OPTIMISATION OF THE INTERNAL GRINDING PROCESS BY MEANS OF AN AMB HIGH SPEED SPINDLE

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ABSTRACT

This article focuses on the improvement of the performance of the internal grinding process by using Active Magnetic Bearings (AMBs) as sensor and actuator.
The grinding process with its requirements is described and the possible measures to improve the process are shown in general.
The signals available from the AMBs and from that the derivable quantities are described. Furthermore the possibilities of the AMBs as actuator for the process are presented.
The process normal force is the essential characterising quantity to evaluate the process. Therefore the determination of the process force out of the displacement and current signals of the AMBs is discussed in more detail.
Finally experimental results are presented, for instants showing the dressing and the first cut detection

INTRODUCTION

Internal grinding is applied on products such as outer rings of ball bearings or injection parts of combustion engines. The requirements for this process are very high and contradictory. On the one hand, very high shape and size accuracies as well as surface quality of the work-pieces are demanded. On the other hand short process cycles are wanted due to the mass production of the products.

In the following the internal grinding process cycle is briefly discussed to give an insight to the process. In Figure 1 the normal force and the infeed are depicted. The process normal force is the essential characterising quantity in order to assess and ameliorate the process. It permits a direct conclusion to the process state.

The process cycle can be divided into six stages. In the first one the rotating work-piece approaches the work-tool with a high infeed rate to decrease the time of air grinding. In the second stage the infeed rate is reduced to avoid an overload of the grinding tool when it touches the work-piece. During the third phase the tool is being bent due to its flexible properties causing a conical bore while grinding. Within the forth phase material is removed. Depending on the geometrical and material properties of the work-piece and the tool the normal force increases, decreases or keeps constant. It must be assured that the force does not exceed a certain limit in order to protect the grinding wheel from being damaged. In stage five the infeed is stopped to decrease the tool bending and to achieve a cylindrical shape of the bore (spark out). Finally, the work-piece is being quickly retreated.

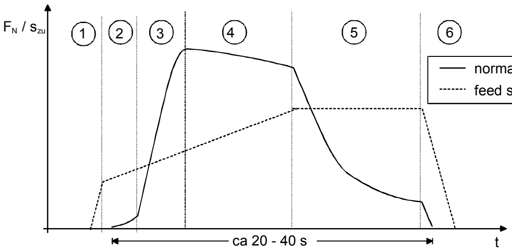

FIGURE 1: Internal grinding process

The mean measures which can be taken to met the requirements with regard to high accuracies and short process cycles are [1], [2], [3], [4]:

- increasing the rotating speed of the spindle causing a decreasing grinding force
- increasing the spindle stiffness
- reducing the wear of the bearings
- axial oscillation of the grinding tool to smear the grinding pattern
- to tilt the spindle or the spindle casing to compensate

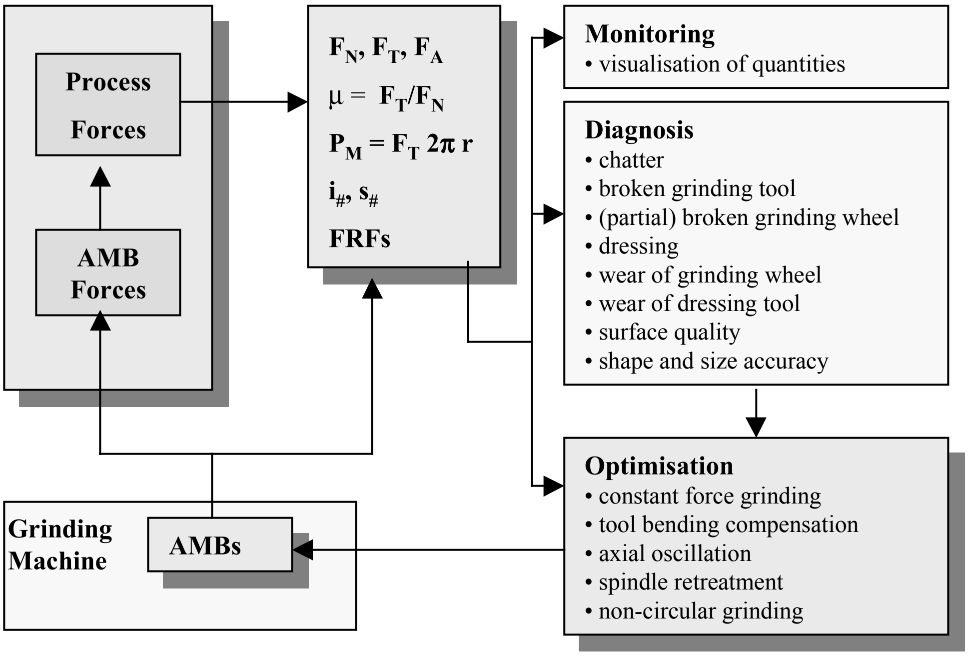

FIGURE 2: Scheme for an improvement of the internal grinding process by using an AMB spindle

the tool bending to shorten the spark out time

- using force control to decrease the time constant at the beginning of the process, to apply the maximal allowable force and to keep a constant force level at the end of the process
- high infeed rate until contact of work-piece with work tool
- monitoring and diagnosing the process to detect malfunctions or failures

To sum up, the measures can be divided into two groups: (1) the improvement of the bearing system and (2) the application of an active system in order to monitor and optimise the grinding process.

High speed spindles levitated in Active Magnetic Bearings seem to fulfil these tasks very good. It is well-known that they allow very high rotational speeds up to 180.000 rpm virtually without wear and provide a very high static stiffness[3]. This paper now focuses on the second group: how AMBs can be used for monitoring, diagnosis and optimisation

PROCESS MONITORING, DIAGNOSIS AND OPTIMISATION

Nowadays the grinding spindles are supported in ball bearings. The only information gained from the process is available through the spindle power which is proportional to the tangential process force. In order to achieve more data an additional Acoustic Emission (AE) sensor is applied providing data in a higher frequency range. Using this information it is already possible to monitor and improve the process. But, neither out of the power nor by means of the AE sensor the process normal force can be derived [1] [2].

AMBs do provide this feature. Due to its active principle the process forces must be mirrored in its signals. Furthermore the AMBs can be used as an additional actuator to move the spindle in axial or radial direction. Exploiting these possibilities should essentially improve the internal grinding process.

In Figure 2 a general concept is depicted for process monitoring, diagnosis and optimisation focusing on the features of AMB grinding spindle. The essential signals provided by the AMB systems are the currents i of the two radial bearings and the axial one and the displacements s at the bearings. They cover a frequency range up to the Nyquist frequency for a digitally controlled AMB system. Out of the currents and the displacements the tangential and normal process force can be determined. This issue is being addressed in the next chapter. But it can be already stated that the frequency content of the force signals is reduced to a limit around 200 Hz for the considered system. From the process forces the friction factor μ and the mechanical power P_m is derived. The used AMB system also allows to determine the Frequency Response Function (FRF) of the closed loop system up to the Nyquist frequency. All the signals mentioned above form the characterising quantities of the process and serve as the input of the monitoring, diagnosis and optimisation tasks.

In this context monitoring stands for a low level functionality. It just displays the measured signals in the time and frequency domain. It is thought as a display to make the ongoing process visible for the machine user.

The task of the diagnosis module is to assess the various process states listed in Figure 3 by means of limit monitoring, model based identification procedures or neural networks.

The optimisation module include control strategies to improve the grinding process. Here, the AMB system is used as an actuator.
Regarding the axial oscillation of the work tool conventional spindle systems are restricted to frequencies around 2-3 Hz due to the heavy masses of the carriers being moved. If only the AMB spindle oscillates higher frequencies are reachable. For ceramic bounded CBN (cubical boron nitride) grinding wheels the surface quality of the work piece can be improved by 50% by increasing the oscillation frequency to 10 Hz [3].
Furthermore, if the AMB spindle is tilted within the bearings to compensate the tool bending the spark out time is reduced to one revolution of the work piece saving up to 20% process time [3]. By knowing the normal force and the tool compliance the inclination angle can be exactly adjusted to the processed work tool online.
A very fast retreat motion of the work piece from the tool is crucial at the end of the process since it does influence the shape and size accuracy [3] [4]. Instead of moving the carriers to fulfil this task the AMB spindle with a higher dynamic characteristic can be retreated to further improve the work piece quality [4].
One further possibility which has not be taken into account so far for the grinding process with an AMB spindle is the grinding of non-circular shapes such as it is done by the non-circular fine boring [5]. The control process should be easier compared to the fine-boring because the oscillation frequency now depends on the rotational speed of the work piece spindle and not on the AMB tool spindle.

DETERMINATION OF THE TANGENTIAL AND RADIAL PROCESS FORCE

In order to determine the requirements for the force calculation methods the grinding process has to be analysed in more detail. In general, the work pieces have a certain amount of eccentricity depending on the preceding manufacturing steps. This out-of-round is superimposed with the rotational speed of the work piece spindle and its higher harmonics on the quasi static process shown in Figure 1. In Figure 3 the left and the middle diagram show the measured control current (signal has been filtered with 10 Hz, grey curve, and 100 Hz, black curve, respectively) of one AMB coil due the process force. The current is related to the process maximum current. It can be seen that there are considerable differences in the signal amplitudes between the quasi static and dynamic current signal. On the right side of Figure 3 the waterfall diagram up to 100 Hz of the unfiltered signal is depicted clearly showing the rotational speed harmonics and the decrease of their amplitudes due to the reduction of the eccentricity while grinding. The conclusion which can be drawn is that the force calculation methods have to consider the dynamic behaviour of the process up to the rotational speed of the work piece spindle. In this project the maximum speed is 3600 rpm (60 Hz) [8].
The force calculation consists of two parts: determination of the AMB forces and out of these forces the process forces.

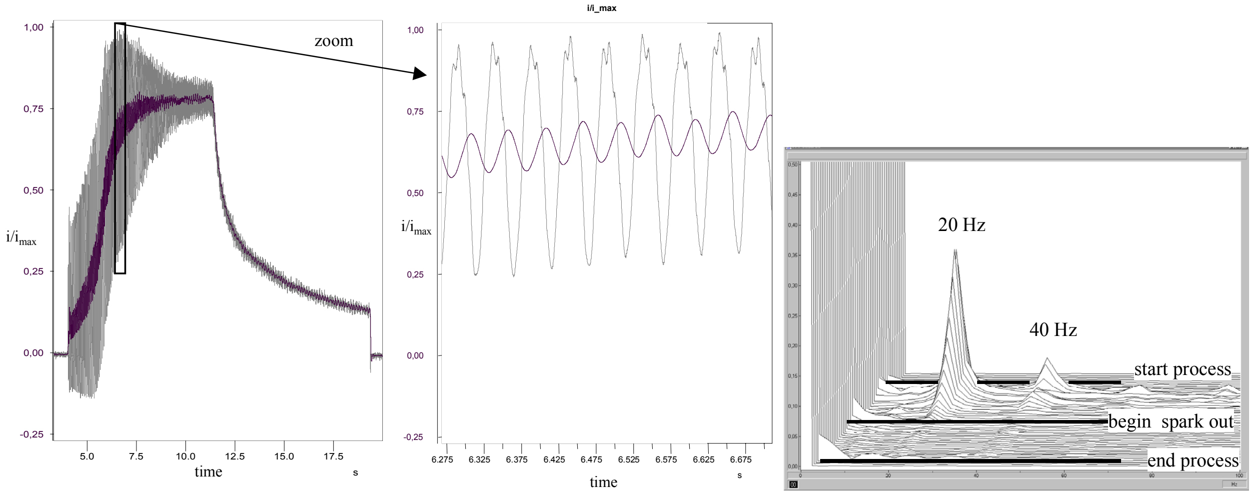

FIGURE 3: AMB control current signal in time and frequency domain

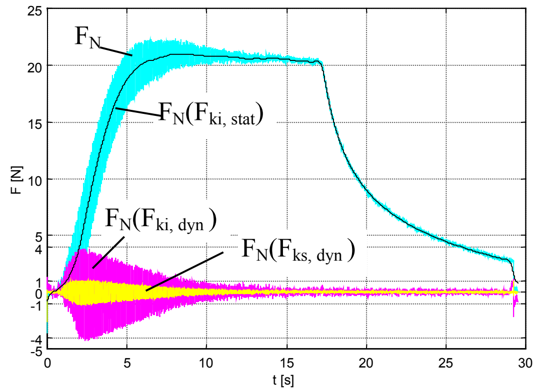

FIGURE 4: Static and dynamic force components

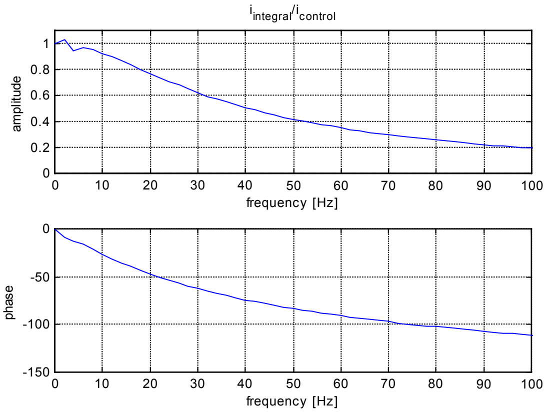

FIGURE 5: Ratio between $i_{integral}$ and $i_{control}$

AMB Forces

In the case that the AMBs are driven in the differential driving mode a linear force-current-displacement relation, the so-called i-s-method, can be expressed neglecting iron saturation for an operating point given by the bias current i_0 and the nominal air gap s_0 [10]

$$F = k_i\, i + k_s\, s \qquad (1)$$

Equation (1) can be further simplified by neglecting the displacement term [3] [4]. Figure 4 shows a measured normal grinding process force and its static and dynamic parts resulting out of the terms of equation (2)[1] for calculating the AMB forces

$$F = k_i\, i_{stat} + k_i\, i_{dyn} + k_s\, s_{dyn} \qquad (2)$$

The mentioned simplification seems to be valid in the case of a static process, here when the out-of-round of the work piece has been worked out. However, it leads to an dynamic force error at the beginning of the process. The same counts for only using the integrator part of the control current of the digital controller [5]. The control integrator is like a low pass filter. The advantage is that no further filter has to be applied for the current signal. The drawback is that the boundary frequency is quite low. In Figure 5 the rate from integrator current to control current is depicted for the used controller set up showing that for frequencies higher than 20 Hz an amplitude error greater 25 % arises as well as an phase error.

The i-s-method is valid for small deviations from the operation point s_0 [10]. In the case of the grinding spindle this condition is violated when the spindle is tilted in order to compensate the tool bending. Then the spindle is moved out up to 40 percent of the nominal air gap. Another method, which has been applied, to determine the AMB forces by current and displacement signals is a reluctance network taking into account the bearing's non-linear force-displacement behaviour [6] [9]. The bearing is modelled as a network of magnetic reluctances as shown in Figure 6.

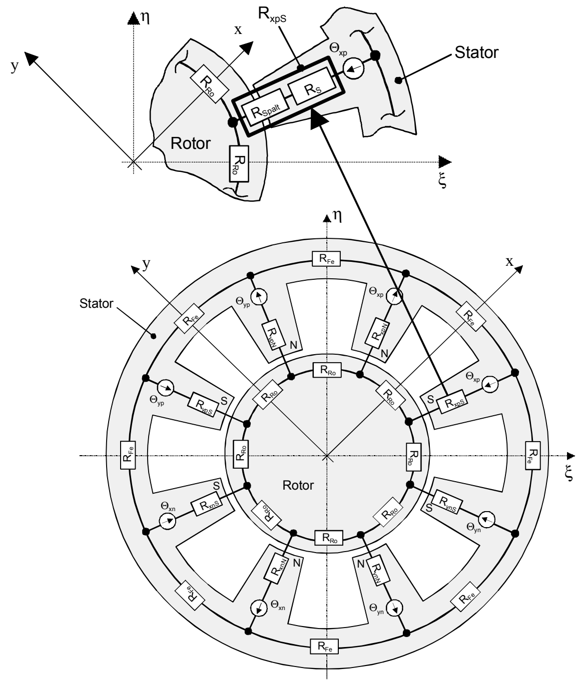

FIGURE 6: Magnetic reluctance network model

It can be analysed like an electric network. The magnetic flux ϕ corresponds to the electric current i, the magnetic potential ΔV corresponds to the electric potential U and the magnetic reluctance R corresponds to the electric resistor R. By applying Ampere's law a set of algebraic equations is obtained leading to the unknown fluxes ϕ_i at the poles. Then the force at each pole is given by

$$F_i = \frac{\Phi_i^2}{2\mu_0 A_i} \qquad (3)$$

where μ_0 is the magnetic permeability of vacuum and A_i the cross sections of the poles. The resulting bearing force is obtained by vector addition of the pole forces.

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[1] Due to the PID controller no static force displacement term needs to be considered.

Process Forces

A model-based linear analysis has been performed in order to assess the influence of the dynamic behaviour of the rotor on the process force determination.

The closed loop simulation system consists of a Finite Element rotor model, linear descriptions for sensors, power amplifiers and AMBs (i-s-method). Furthermore the sample and dead time of the system is being considered. The controller parameters have been taken from the test rig.

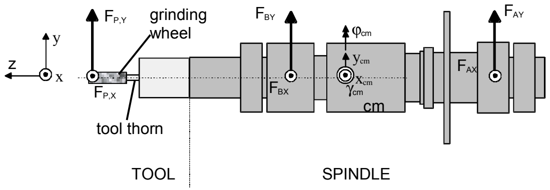

FIGURE 7: Rigid body model

By neglecting the dynamic properties of the rotor a static forces equilibrium can be set up to calculate the process forces as follows

$$0 = \boldsymbol{F}_p + \boldsymbol{F}_{AMB} = \boldsymbol{F}_P + \boldsymbol{F}_A + \boldsymbol{F}_B \tag{4}$$

To account for the dynamic behaviour a rigid body model of the rotor has been set up as given by

$$\boldsymbol{M} \cdot \ddot{\boldsymbol{x}}_{cm} + \boldsymbol{G} \cdot \dot{\boldsymbol{x}}_{cm} = \boldsymbol{T}_P \cdot \boldsymbol{F}_P + \boldsymbol{T}_{AMB} \cdot \boldsymbol{F}_{AMB} \tag{5}$$

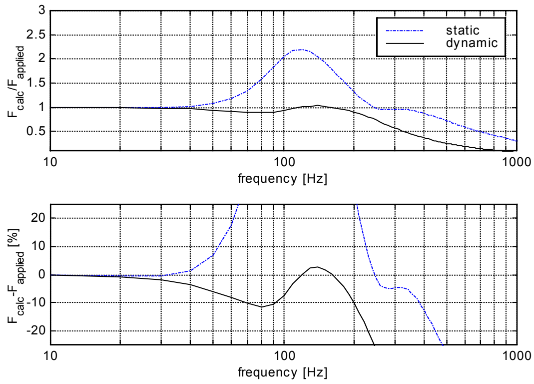

FIGURE 8: FRF of applied to calculated process force

In order to assess the dynamic influence the Frequency Response Function from the applied process force at the work tool to the calculated process force has been determined and is shown in Figure 8 as well as the resulting force error. It can be stated that for the regarded system the process force can be determined by the static force equilibrium up to a frequency of 50 Hz. Then the force error increases strongly. Taking into account the rigid body modes of the rotor the process force calculation up to 200 Hz. is allowed. A drawback of this method is that the accelerations and the velocities have to be derived from the displacement signals. Due to the small amplitudes of these signals and the superimposed noise the derivates can not be directly obtained, therefore an observer is applied.

EXPERIMENTAL INVESTIGATION

The experiments has been carried out with a digitally controlled AMB grinding spindle. The maximum allowable force at the tip of the spindle is 110 N. The maximum rotational speed is 120.000 rpm (2000 Hz). A ceramic bounded CBN grinding wheel has been used. The work piece's rotational speed was 1200 rpm (20 Hz). The infeed rate varied between 0.1 and 2 mm/min.

Experimental results are presented in regard of the monitoring , diagnosis and optimisation purposes.

Process Forces

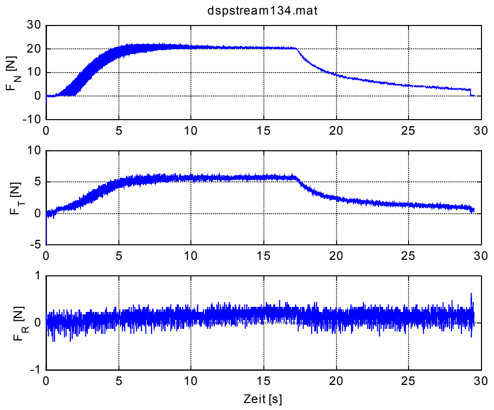

FIGURE 9: Process forces

In Figure 9 the normal, tangential and axial process force are shown. The characterisation of the curves have been discussed in the previous sections. The current and displacement signals have been low pass filtered with 100 Hz. The i-s-method and the static equilibrium have been applied.

Dressing Detection

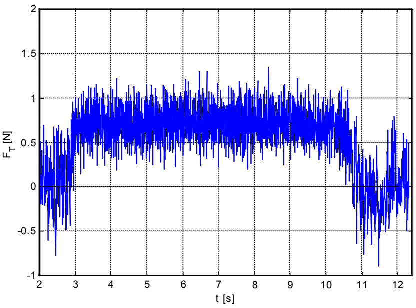

FIGURE 10: Dressing force

In order to re-sharpen the grinding wheel it is pulled along a rotating diamond dresser tool removing ca 3µm material diametrical. In Figure 10 the measured tangential force is depicted during one dressing cycle showing that this process is clearly detectable and assessable.

First Cut Detection

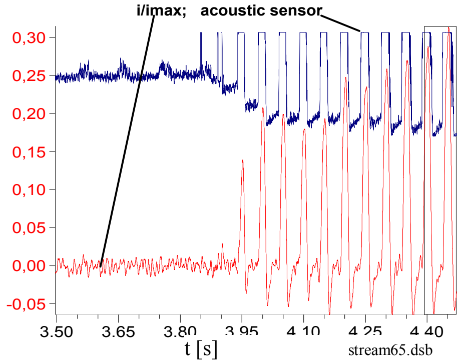

FIGURE 11: First cut detection

The acoustic emission sensor is a proven tool to detect the first touch between work tool and work piece. Its signal is shown in Figure 11 together with a measured current signal related to the maximum current of this process cycle. It can be seen that the AE sensor detects the first cut two work piece revolutions earlier than the AMB. However, the infeed of 1,6 µm during these two revolutions is relative low.

Broken Tool Thorn

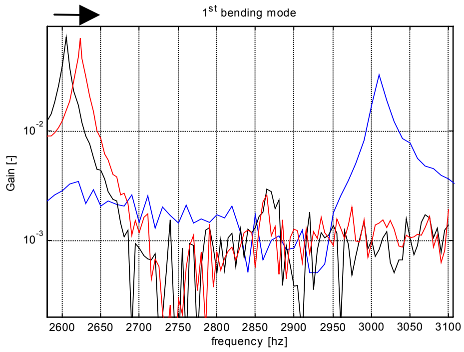

FIGURE 12: Shift of the systems eigenfrequencies due to a broken tool thorn

In Figure 12 the closed loop FRFs for the spindle without tool, with tool and with broken tool thorn (Figure 7)are shown. The size of the broken part is only 2.5 mm in diameter and 16 mm in length but it causes a shift of the first bending eigenfrequency from 2605 Hz to 2623 Hz.

CONCLUSION

An AMB grinding spindle fulfil all requirements to improve the grinding process. It allows to determine the process forces which are important to evaluate the process. Due to the out-of-round of the work pieces dynamic force components arise with the frequency and its harmonics of the work piece rotational speed. Therefore the rigid body modes of the rotor have to be considered for a rotational speed higher than 50 Hz for the investigated system. Experimental investigations have been carried out for instant showing that the dressing cycle with a material removal of 3 µm diametrical is detectable.

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