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USING HIGH-SPEED ELECTROSPINDLES WITH ACTIVE MAGNETIC BEARINGS FOR BORING OF NON-CIRCULAR SHAPES

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Abstract

For boring of non-circular shapes the active magnetic bearings of a high-speed work spindle can be used as an actuator to generate the required deflections of the tool. For a profitable boring process with good surface finish high cutting speeds need to be reached. The resulting rotational speed of the tool requires a fast radial movement of the spindle shaft for boring of non-circular shapes. Here the spindle cannot follow the reference signals without delay. A phase lag between displacement and rotation of the tool causes deviations from the predetermined shape. For this reason transfer functions and physical limitations of the spindle have to be taken into account to attain precise manufacturing.

1. Introduction

Main targets of research and development in the field of cutting technologies are the increase of flexibility in mass production, higher automation level in small-lot fabrication and the reduction of time for manufacturing. One aspect is the decrease of essential operating time: To raise the chip removal rate, higher cutting force or speed is needed. Due to the limited load capacity and stiffness of machine, tool and workpiece, increasing the cutting speed is a better solution than using high cutting forces [5,6]. Therefore the availability of rapid work spindles with high stiffness and power is fundamental to the use of high-speed cutting in industrial production. The demand for small cutting forces is very important in fine machining, because a high accuracy of the workpiece is reached only if deflections of tool and workpiece due to cutting action are low [2].

High-speed spindles with ball bearings are a good choice for many applications, but when best performance is needed active magnetic bearings have advantages compared to other bearing types due to low friction, high stiffness and big shaft diameter. Work spindles with active magnetic bearings are mainly used for milling and grinding, when high cutting speed and power is recommended [1,3,7].

A disadvantage lies in high expenditures for spindles with active magnetic bearings. The expenditure however, can be justified in using its additional capabilities: Inherent control signals are helpful in process monitoring and control without additional sensors. Furthermore it is possible to apply reference signals of the servo loops for radial and axial movement of the shaft within the air gap of bearings. This is sometimes used to increase accuracy of workpieces: Machining offsets are compensated by static displacement of the tool [4].

The final shape of a workpiece is determined by tool movement and tool geometry. Due to the higher flexibility there is a tendency to replace special purpose machine tools with specific tool geometries by numerically controlled machines with standard tools. Turning and boring in general is used for circular parts. For manufacturing of noncircular shapes are manufactured by modulating the rotation of the work spindle with an additional movement. For a profitable boring process with good surface finish, high cutting speeds should be reached. The resulting spindle speed requires a fast radial movement of the actuator for boring of noncircular shapes.

Using an electrospindle with active magnetic bearings as an actuator has the following advantages:

- Point of application of force and deflection measurement is close to the process.
- Combination of bearing and actuating functions.
- No wear or fatigue even at high frequencies.
- Low moving mass.
- Easy control of magnetic forces.

Applications of non-circular bores are found - for example - in piston engines: Holes for the gudgeon pin in a piston sometimes need to have an oval shape with a deviation from circle of about 50µm at bore diameters between 20 and 30mm. Generally bore bars with a high ratio of length to diameter have to be used for manufacturing. Due to the vibration behavior of these tools, additional damping is recommended to achieve chatter-free cutting.

2. Bore geometry and cutting edge movement

A special feature of the boring process is the generation of workpiece shape with a single cutting edge similar to turning. The cutting edge is fixed at the end of a rotating bar (radius r_{ko} from tool center line) generating a circular hole when using pure axial feed. Non-circular shapes are generated with additional radial movement $\mathbf{r_o}$ as function of tool rotation. The resulting orbital movement $\mathbf{r_t}$ of the cutting edge can be described by (Fig. 1):

$$\mathbf{r_t} = \mathbf{r_o} + \mathbf{r_k} \qquad (1)$$

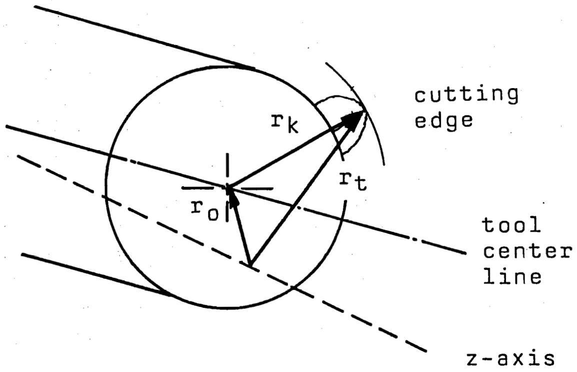

Fig. 1 Vector diagram of tool movement.

In a fixed system of coordinates:

$$x_t = x_o(\phi) + r_{ko}\cdot\cos(\phi) \qquad (2)$$

$$y_t = y_o(\phi) + r_{ko}\cdot\sin(\phi) \qquad (3)$$

$$\phi = \Omega\cdot t = 2\cdot\pi\cdot f_n\cdot t \qquad (4)$$

If the non-circularity is small compared to the mean bore diameter (e.g. 1%), radial movement of the tool center line $\mathbf{r_o}$ is much smaller than the radius r_{ko} of the tool and it is possible to neglect movements x_c normal to vector $\mathbf{r_k}$. Only the infeed movement x_p changes the bore shape. The non-circularity r_d - i.e. the deviation from circle - can be described in polar coordinates:

$$r_d \approx x_p = x_o(\phi)\cdot\cos(\phi) + y_o(\phi)\cdot\sin(\phi) \qquad (5)$$

The orbit of cutting edge results from a modulation of tool deflection and rotation. Only a very short section of the hole is manufactured at every turn. For producing a predefined non-circularity the radial movement has to be repeated periodically.

Assuming sinusoidal deflections various shapes are possible using different amplitudes and frequencies. A specific frequency relation between rotation and deflection results in a characteristic shape of the bore. Fig. 2 shows the orbit of the tool lip for a number of revolutions up to repetition of the contour. This point is reached when rotation and deflection of tool have both finished an integer multiple (n_n and n_a) of periods. Therefore a rational ratio between deflection frequency f_a and rotational frequency f_n is required:

$$f_a/f_n = n_a/n_n \qquad n_a, n_n \in \mathbf{N} \qquad (6)$$

The period of repetition is:

$$T = n_n/f_n \qquad (7)$$

To attain a low surface roughness the repetition time T should be kept as low as possible. Therefore a high rotational speed f_n together with a small number of revolutions n_n per repetition cycle should be attained. For practical use three cases are of special interest:

The deflection frequency f_a is
A) an integer fraction ($n_a = 1$) of
B) direct synchroneous ($n_a = 1$; $n_n = 1$) to
C) an integer multiple ($n_n = 1$) of
rotational frequency f_n.

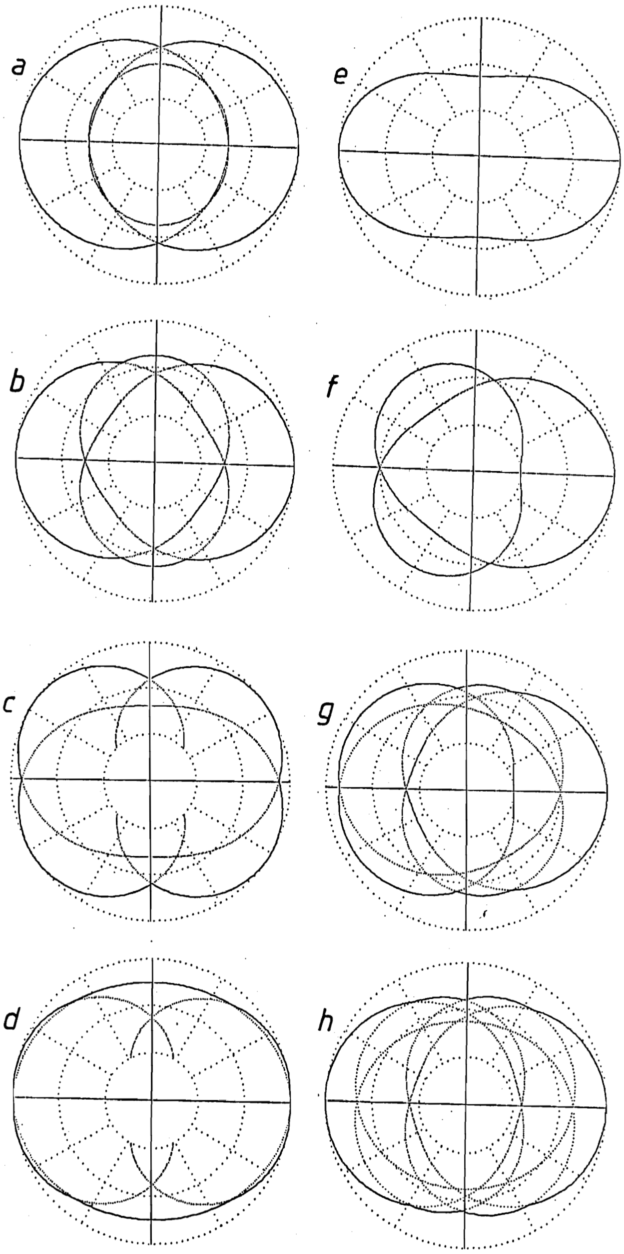

Fig. 2 Examples: Tool lip movement as deviation from circle; $|x_{o1}/y_{o1}|=4$

	a	b	c	d	e	f	g	h
x_{o1}/y_{o1}	++	+-	--	-+	+-	+-	+-	+-
f_n/f_a	3	3	3	3	1	2	4	5

To describe rotational processes it is often favourable to use complex numbers instead of two-dimensional vectors. The formulation for the tool rotation in this case is:

$$r_k = r_{ko} \cdot e^{j \cdot \phi} = r_{ko} \cdot e^{j \cdot \Omega \cdot t} \qquad (8)$$

The cutting edge movement results from a transformation of the tool deflection into rotating coordinates:

$$r_t = (r_k + r_o) \cdot e^{-j \cdot \phi} \qquad (9)$$

$$r_t = r_{ko} + r_o \cdot e^{-j \cdot \phi} \qquad (10)$$

The deviaton of cutting edge movement from circle is:

$$x_p = \mathrm{Re}\,\{ r_t - r_{ko} \} \qquad (11)$$

$$x_p = \mathrm{Re}\,\{ r_o \cdot e^{-j \cdot \phi} \} \qquad (12)$$

Non-sinusoidal but periodic deflections r_o of the tool are described by Fourier series:

$$r_o(t) = \sum_{i=-\infty}^{+\infty} r_{oi} \cdot e^{j \cdot i \cdot \Phi} \qquad (13)$$

$$\Phi = 2 \cdot \pi \cdot f_a \cdot t \qquad (14)$$

The complex coefficients r_{oi} build up the discrete spectrum of the tool centre movement. Using the frequency domain for signal description has several advantages:

- Periodic signals are signified by discrete spectra, digital processing is easy.
- The process has low-pass characteristic, only a few coefficients are needed.
- Easy compensation of dynamic responses of transfer elements by multiplication of signal spectra and frequency responses.
- Transformation from rotating to fixed coordinates and vice versa is acomplished by shifting the signal spectra.

3. Requirements on process control

High rotational speeds of the tool require fast radial movements of the spindle shaft for boring of non-circular shapes. Due to the dynamic response of the active magnetic bearings the spindle cannot follow the reference signal without delay. On the other hand a phase lag between displacement and rotation of the tool causes deviations from the predetermined shape. For this reason transfer functions have to be taken into account to attain precise manufacturing.

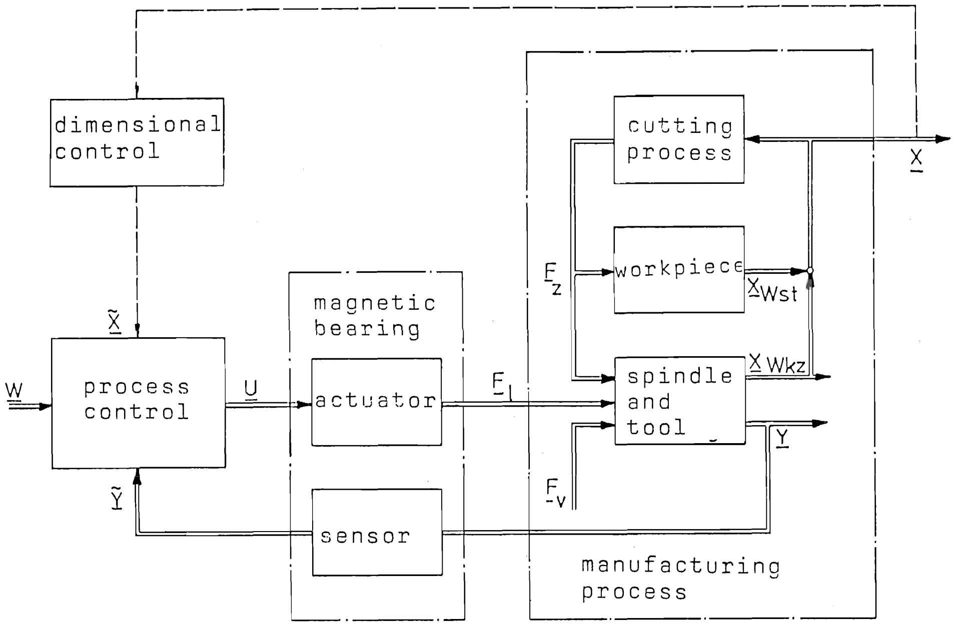

Fig. 3 Principal structure of process control.

Fig. 3 shows the principal structure of the non-circular boring process using a spindle with active magnetic bearings. The process control has to generate appropriate commands for the actuator to achieve the necessary tool movement. Main tasks of the process control are:

- Stability of control loops and sufficient damping of modes
- Suppression of disturbances and parameter variations
- Appropriate reaction on command signals

Main causes for disturbances and parameter variations of the boring process and the resulting requirements on the process control are:

- Determinable discrete changes:
  Variation of technological parameters like tool change, different workpieces, cutting speed, feedrate etc. Disturbance variable compensation or approach in mass production is possible.
- Undeterminable discrete changes:
  Variation of overmeasure or material properties of workpiece without a priori knowledge. Robust control is required.
- Slow changes with time:
  Tool wear and change of temperature. Robust control and compensation by dimensional control is recommended.
- Cutting path dependent changes:
  Changing forces due to first or interrupted cut etc. require a good stiffness for low and high frequencies.

Some of the requirements on the process control are contradictionary, so that a compromise has to be found especially in single loop controls. For an independent design of command and disturbance response two degrees of freedom in the control loop are required. Fig. 4 shows a simple example: Stability and good characteristic behavior is achieved by the feedback control whereas the feedforward control acts as a compensation filter to attain an appropriate command response. Due to the low pass characteristic of the compliance response it is not possible to realize a proportional relation between a transient command signal and the controlled quantity because a non ergodic compensation filter would be required. In this application the command signals are assumed to be periodic. Here a non ergodic response can be changed to ergodic behavior by shifting the signal one period. The same applies if the bore shape is changed as function of axial feed, because this variation is very slow compared to the frequencies of deflection movement.

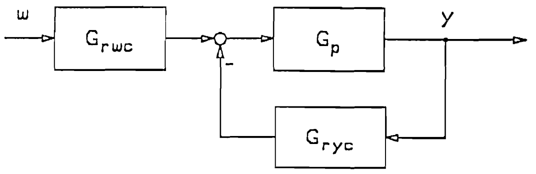

Fig. 4 Single-variable control with two degrees of freedom
G_{ryc}: Feedback controller,
G_{rwc}: Feedforward controller
G_p : Process.

Due to the use of periodic command signals the compensation filter is quite simple: Only a few discrete frequencies have to be processed. The linearity of the process is an important assumption for a proper use of the compensation filter. When limitations of the actuator are reached compensation does not work any more.

Amplitude and frequency of tool movement is restricted by physical limitations of the actuator - e.g. the active magnetic bearing. The major limitations are given by:

- Maximum static displacement
- Moving mass
- Maximum forces of the actuator
- Maximum slew rate of forces.

Fig. 5 shows the maximum amplitudes of an actuator with these limitations. For generating oscillating movements there is a quadratic increase of forces with frequency for a constant amplitude. At high frequencies the most important limitation is given by the slew rate of forces due to the maximum speed of energy exchange in the actuator.

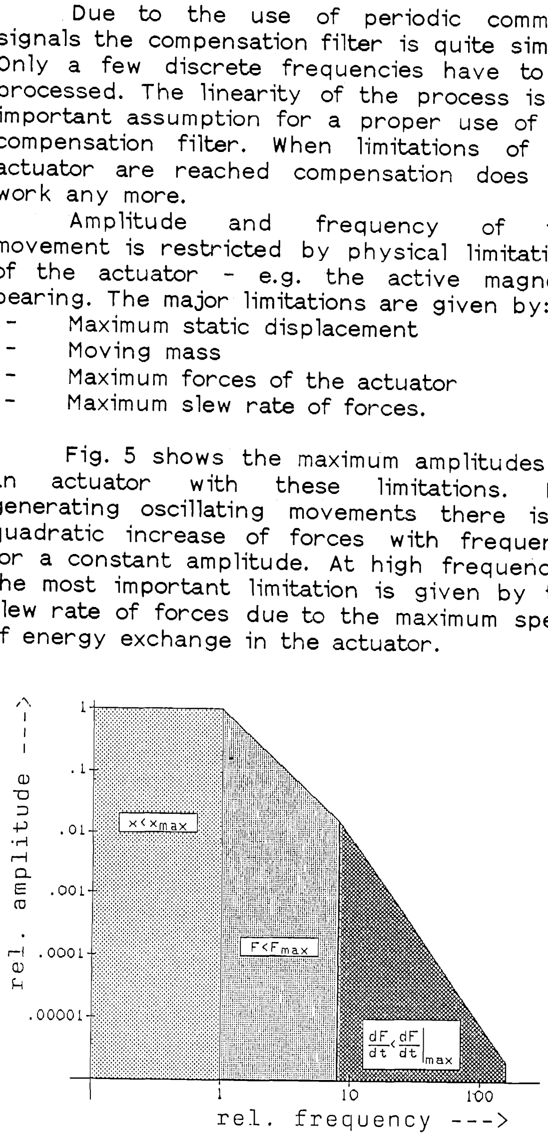

Fig. 5 Maximum amplitude of an actuator as function of frequency

4. Test results

A special machine tool for boring tests was developed at the *Institute of Cutting Technology and Machine Tools of TH Darmstadt*. The machine is equipped with a *S2M* electrospindle, type *B20/500*. Maximum rotational speed is 30000/min. One axial and two radial bearings are used to control the spindle shaft in five axis of motion. The control of translational and tilting motion is decoupled. Only the tilting modes are used for deflecting the tool, because forces of inertia are lower and maximum tool deflection is bigger compared to the translational motion. But this deflection mode has a disadvantage: Due to gyroscopic effects the tilting axes are coupled and the command response is speed dependent.

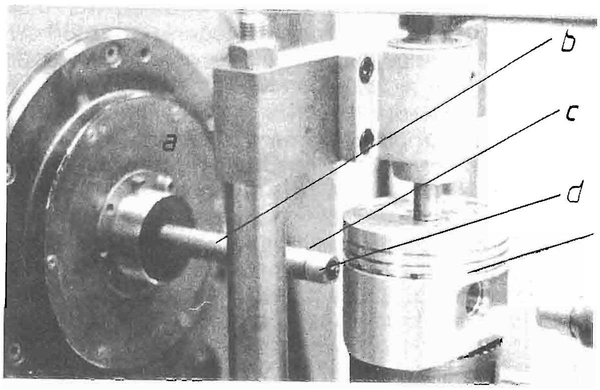

Fig. 6 Experimental set-up for non-circular boring.
(Ref.: *PTW, TH Darmstadt*)

For the conception of the boring machine the special demands of the process had to be considered. To avoid big resonance amplitudes due to the high frequency of forces, the machine frame is made of polymer concrete. Bore bars with a high ratio of length to diameter (e.g. length 100mm, diameter 18mm) were used for manufacturing tests (Fig. 6). In this case even carbide bars do not provide sufficient dynamic stiffness of the tool, additional damping is required to attain chatter-free cutting. With a mechanical vibration absorber fixed at the tip of the bore bar, it was possible to keep out-of-round less than 1µm when boring circular holes at high speeds (e.g. 22500 rpm, see Fig. 7). Using a low feed per revolution good surface roughness (e.g. Ra = 0.2µm) is possible.

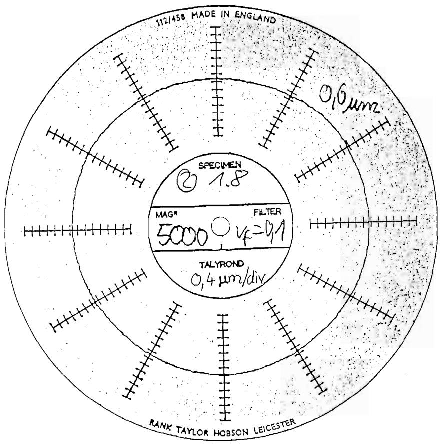

Fig. 7 Out-of-round of a circular bore. (feed rate: 100mm/min; rotational speed: 22500/min)

For generation and adaption of the periodic command functions required for non-circular boring, a function generator on the basis of a real-time computer with VME-Bus (Processor MC68020) was developed. An important feature of this system is the use of a special function generator card, with the capability for a fast output of periodic signals without loading the main processor (Fig. 8). The main processor handles the different control functions and computes the time series from Fourier coefficients (inverse FFT).

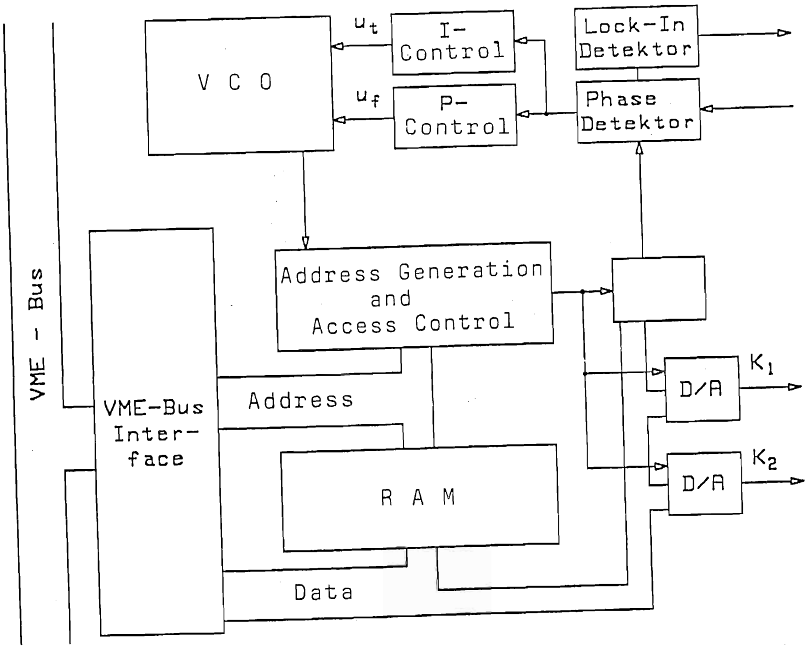

Fig. 8 Block diagram of function generator

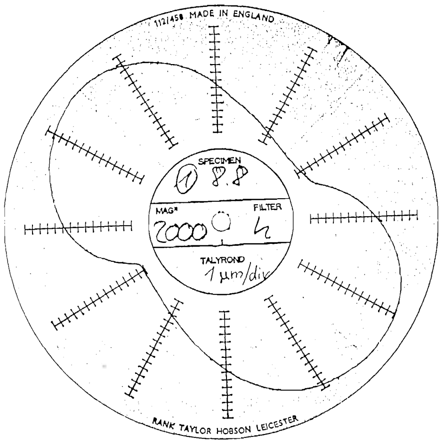

Fig. 9 Geometric distortion due to phase offset.

For generating the proper shape of the bore with a single cutting edge - in contradiction to grinding - an exact phase relation between rotation and deflection movement is required. Geometric distortions are caused by constant phase offsets (see Fig. 9) as well as beat frequencies due to asynchroneous deflection (Fig. 10). A phase locked loop is used for sychronisation of the control signals with spindle rotation.

When using synchroneous deflection ($f_a = f_n$) at high rotational frequencies, amplitude is limited due to the maximum slew rate of bearing forces, i.e. the rating of power amplifiers. In this case the maximum ovality for boring at rotational speeds higher than 20000/min was less than 20µm. A bigger ovality is attainable when reducing rotational speed of the spindle or using a deflection frequency with an integer fraction of rotational frequency. In both cases surface roughness increases, if the feed rate is not reduced. A good compromise was found in manufacturing approximate elliptical shapes with a frequency ratio of one to three (Fig. 11). The frequency of deflection movement is still well above the rigid body modes determined by the feedback control of the magnetic bearings.

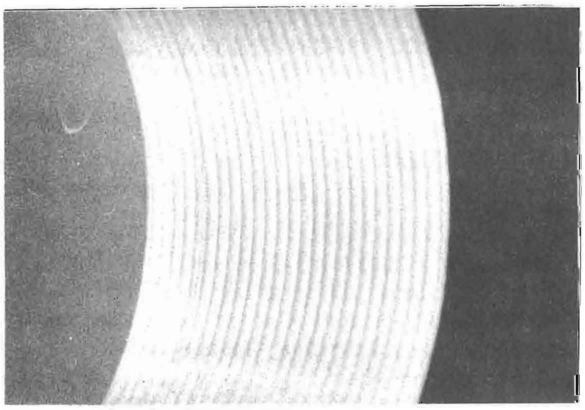

Fig. 10 Bore surface structure due to frequency offset.

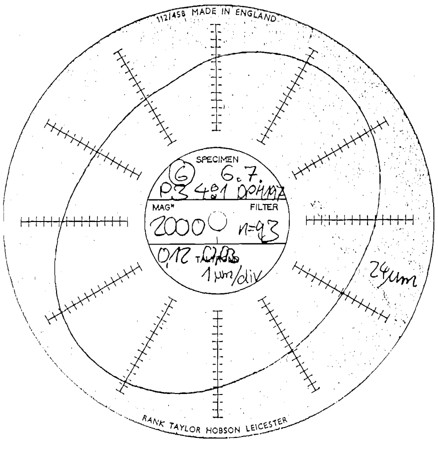

Fig. 11 Non-circular bore ($f_a = f_n/3$, $y_{o1} = -x_{o1}/4$, $f_n = 22500/\text{min}$).

For approaching and maintaining the predetermined shape of the bore, adaption of the command signals to compensate for variations of process response is necessary. In the adaption process the following steps are carried out:

1. Calculate required tool movement (Fourier coefficients) for manufacturing the predetermined shape.
2. Measure frequency response of spindle.
3. Process command signals (compensation filter).
4. Measure actual movement, compare with set values and adapt compensation filter.
5. Repeat Pt. 3 and 4 to minimize deviation.
6. Manufacture first workpiece and measure frequency response in process.
7. Adapt command signals to the actual response.
8. Repeat manufacturing and correction of command signals until actual shape is sufficient.
9. Check workpiece shape and tool movement for variations to maintain workpiece quality by adaption of command signals.

In many cases the predetermined shape is approached when manufacturing the second workpiece. For a lot with identical technological parameters reproducability in general is good without continued adaption. This applies even to intermediate retooling or switching-off, if the initial status of the machine tool is properly reconstructed.

5. Conclusions

It was proved by extensive tests that it is possible to manufacture non-circular shapes with very good accuracy and surface quality at high rotational speeds using a work spindle with active magnetic bearings as an actuator. The deflection frequencies were well above the rigid body modes determined by the active magnetic bearing. Phase offsets between rotation and deflection movement were minimized by an adaptable compensation filter. The major limitation of the process was given by the maximum deflection amplitude and frequency of the spindle: For a sufficient feed rate together with low surface roughness high frequencies are required. Here the slew rate of acceleration due to spindle mass and rating of power amplifiers limits the deflection amplitude.

The original conception of the electrospindle used for the manufacturing tests was high-power milling at fast cutting speeds. With a spindle designed for the special demands of non-circular boring, range of application could be extended significantly. For the use in industrial production integration of spindle and process control is necessary to attain easy operation of the manufacturing process. Automatic processing of command signals from reference shape and adaption to parameter variations is required. Programming should reach a level comparable to numerical controls (CNC).

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