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Active tailstock for precise alignment of precision forged crankshafts during grinding

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Abstract

Within the Collaborative Research Centre 489 at the Leibniz Universitaet Hannover a new and innovative process chain for the manufacture of crankshafts is being investigated. By burr-free and near-net-shaped precision forging the process chain can be significantly shortened. However, this new production process requires a precise workpiece alignment before the grinding process due to the characteristics of the new process chain. In this paper a new machine-integrated positioning system consisting of an optical measurement system (sensor) and an active tailstock (actuator) is presented. For the detection of positioning errors, the geometric elements of the crankshaft are measured by the machine integrated optical measurement system. An algorithm evaluates the geometry data and calculates an adjustment vector. This vector contains the correction of the eccentric and tilt error. The degree of freedom (DOF) of the pendulum stroke of the grinding machine will be used to correct the eccentric error. The tilt error of the crankshaft is corrected by a new active tailstock. This tailstock produces a counter-tilt during the grinding process. For this purpose, a dynamic drive of the tailstock center in two DOF as a function of the angular position has been realized by two new developed piezo-hydraulic linear drives (stroke 4 mm). The dynamics and positioning accuracy of the active tailstock were verified. Up to 10 Hz a positioning accuracy in the range of ±1.5 µm can be achieved by using an iterative learning control. Furthermore, active alignment tests during grinding were performed.

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Keywords: Machine; Grinding; Adaptive Control;

1. Introduction

In automotive industries, the use of forged crankshafts becomes increasingly important due to their higher load capacity and ductility compared to casted parts. These properties allow a more compact and lighter design [1]. In addition, crankshaft manufacturers are forced to shorten processing times and steps because of economic reasons.

On this demand, a new process chain for the manufacture of high performance components is investigated within the Collaborative Research Centre 489 (CRC 489) at the Leibniz Universitaet Hannover. By precision forging technology, crankshafts will be forged burr-free and near-net-shaped to allow a significant shortening of the conventional process chain [2].

Precision forging allows an omitting of deburring and soft pre-machining. Additionally, the process chain can be shortened by a direct hardening of the crankshafts after precision forging with an integrated heat treatment. The process steps of cooling and reheating can also be omitted. After precision forging and hardening, the crankshafts are finalized only by grinding [3].

However, this new process chain requires adapted subsequent process steps due to the characteristics of the new process steps. The lack of soft pre-machining leads to an unequal allowance of the bearings, which have to be ground. The forged workpiece axis differs from the optimum machining axis due to distortions and allowance distributions. An in-process alignment regarding eccentricity and tilt errors is required. To distribute the available allowance on the bearing according to technologically useful criteria such as unbalance and allowance and to ensure a reject-free

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grinding process, the Institute of Production Engineering and Machine Tools (IFW) in cooperation with the Institute of Measurement and Automatic Control (IMR) are researching the active alignment of long components inside the grinding machine. A measurement of a clamped crankshaft by an optical measuring device and its adjustment during the grinding process by an active tailstock are investigated.

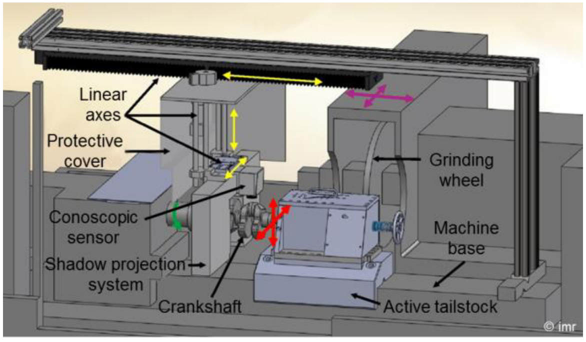

Fig. 1. Schematic construction of the precise alignment system

The geometry and position of the clamped crankshaft can be measured by an optical inline measurement system. Based on the measured geometry data an adjustment vector is calculated, which adjusts the eccentric and tilt error. In path controlled grinding, the degree of freedom (DOF) of the pendulum stroke of the grinding machine can be used to correct the eccentric error. A corresponding value can be assigned to the machine control. The tilt error of the crankshaft is corrected by a new active tailstock (see Fig. 1) by displacing the workpiece at one side on a circular path as a function of the angular position of the crankshaft.

2. Measurement System

The measurement system consists of a shadow projection system, a conoscopic sensor and three linear axes (see Fig. 1). Before grinding, it measures the crankshaft. During the measurement the center point of the active clamping tailstock is in its zero position. With the help of the linear axes, the measurement system can be positioned. The shadow projection system measures the geometry of the crankshaft and detects the position of the bearings in combination with position signal of the linear axis. The conoscopic sensor measures line profiles of the crank webs and bearings while the crankshaft is rotating. A protective cover shields the measurement system from cooling lubricant and chips during grinding (see Fig. 2).

The measured geometries are converted into one coordinate system. The allowance distribution on the bearings is analyzed and an adjustment vector of the current clamping axis to the ideal machining axis is calculated. If enough allowance is available to ensure a final grinding, the ideal machining axis is calculated with regard to the residual unbalance by using a mass approximation. In this way, the unbalance can be minimized in the grinding process.

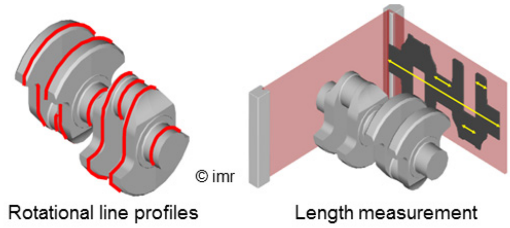

Fig. 2. Line profiles and longitudinal sections of the measurement system

The adjustment vector contains the correction of the eccentric and tilt error. The relevant data will be assigned to the grinding machine and the active tailstock. Further information concerning the measurement system are published in [4].

3. Active Tailstock

3.1. Assembly

To correct a tilt error a circular movement has to be produced by the active tailstock. To position the center sleeve in a plane, a box-in-a-box principle with two linear axes is chosen (Fig. 3).

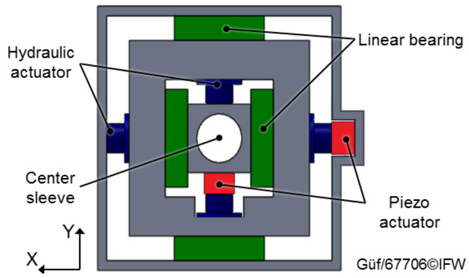

Fig. 3. Box-in-a-box principle for a piezo-hydraulic hybrid positioning in two degrees of freedom

The dynamics of the active tailstock is currently designed to a rotational speed of the crankshaft up to 600 rpm (10 Hz) with an accuracy of ±1.5 µm within an adjustment travel of ±2 mm.

As a drive for each axis a piezo-hydraulic hybrid positioning has been developed. Two hydraulic screw-in short stroke actuators (stroke: 4 mm) were serial combined with one piezo actuator (stroke: 60 µm at 1,000 V) per axis. Hydraulic screw-in cylinders offer the advantage of compactness because of their integrability into the structure [5].

Piezo actuators can generate only compressive forces and have to be protected against tension. In [6] a piezo-hydraulic positioning with a double-acting hydraulic cylinder is presented. For the protection against tension and to generate tensile forces, the piezo actuator is preloaded. This is not necessary by the use of two single-acting hydraulic cylinders. By the antagonistic arrangement of the actuators, a preload is generated. In addition, a backlash can be avoided during positioning. The hydraulic cylinders are actuated by one servo valve per axis.

Piezo actuators are characterized by high dynamics, positioning accuracy and stiffness [7]. The disadvantage is their limited travel range of approximately 0.2% of the actuator length [8]. To enhance the position accuracy and dynamics especially by external forces, one hydraulic positioning axis is combined by one piezo actuator.

The aim is that the developed piezo-hydraulic hybrid positioning can fulfill the requirements in regard to positioning accuracy and dynamics.

3.2. Control Structure

Fig. 4 shows the control structure of the piezo-hydraulic hybrid positioning. For a circular positioning, a sinusoidal dynamic reference value for each axis is specified. By measuring the position of the mass, the control deviation is calculated. On the one hand, the control deviation is compensated by the piezo controller. The piezo controller consists of a simple PI-controller. The integrator has to adjust the hysteresis of the piezo actuator. In addition to the control deviation, the deflection of the piezo actuator is added and fed to the input of the hydraulic control so that the piezo actuator can return at its zero position as soon as the control deviation is corrected by the hydraulic.

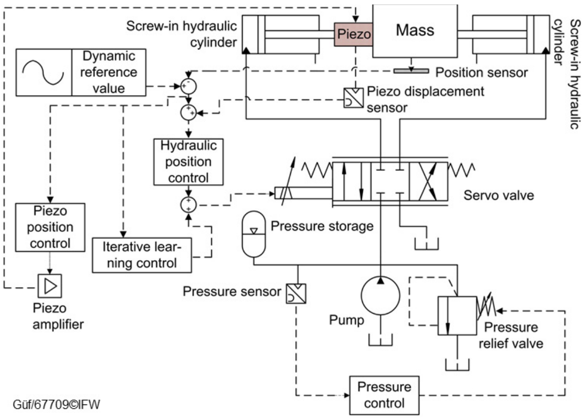

Fig. 4. Control structure of the piezo-hydraulic hybrid positioning

The hydraulic control is a model-based IMC-controller (Internal Model Control) with Smith-predictor and additional integrating element. Using the Smith-predictor, the dead time of the servo valve of about 2 ms is taken into account. The I-contribution of the hydraulic controller is necessary to adjust external forces and the neutral position of the servo valve. By using a model-based hydraulic controller, the dynamics and the overshoot can be improved significantly compared to a simple PI-controller. Due to the dynamic reference value, a lag between set and actual values is inevitably. For this reason, a velocity feed-forward control for the hydraulic positioning system is used to minimize the lag. Since the circular positioning leads to a cyclical repetition of the reference value, an iterative learning control is used. The scheme of the iterative learning velocity control is shown in Fig. 5.

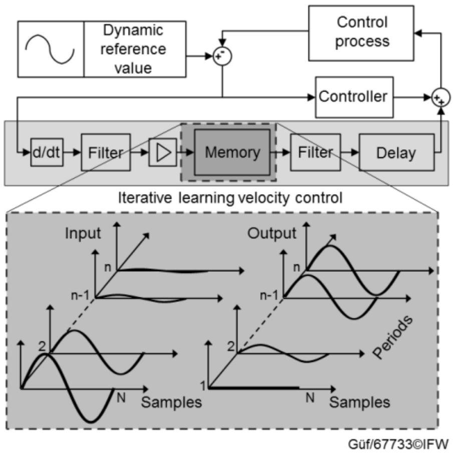

Fig. 5. Scheme of the iterative learning velocity control

If the cycle length of the reference value and the delay time of the control process are known, the velocity feed-forward control can be optimized during a disturbance-free positioning and thus the control deviation will be minimized. Low pass filters are used to avoid a summation of measurement noise into the feed-forward control. The time delays of the filters and the hydraulic drive are taken into account in the delay. To achieve an iterative learning feed-forward control, the error of the last cycle is stored and delayed so that it is taken into account in the following cycle. Further information concerning the iterative learning control can be found in [9].

4. Experimental results

4.1. Positioning accuracy

The position of each piezo-hydraulic axis is measured by eddy current sensors with a measuring range of 6 mm. In addition, the deflection of the piezo actuators can be measured with strain gauges. To verify the positioning accuracy with different controllers, circular orbits have been analyzed.

Fig. 6 shows the comparison of a circular orbit of a hydraulic positioning compared to the piezo-hydraulic hybrid positioning. The orbit has a radius of 1 mm and the positioning dynamics was 1 Hz. In these first tests with the active tailstock no feed-forward control was used.

By analyzing the positioning accuracy of the hydraulic control it can be clearly seen that it comes to major differences in the reversal points of the axes due to inertia, friction and stick-slip effects. Furthermore, the limited dynamics of the hydraulics leads to a lag. The positioned circular path is greater than the reference. By switching on the piezo control, the dynamics can be improved. The differences in the reversal points can be minimized as well as the lag.

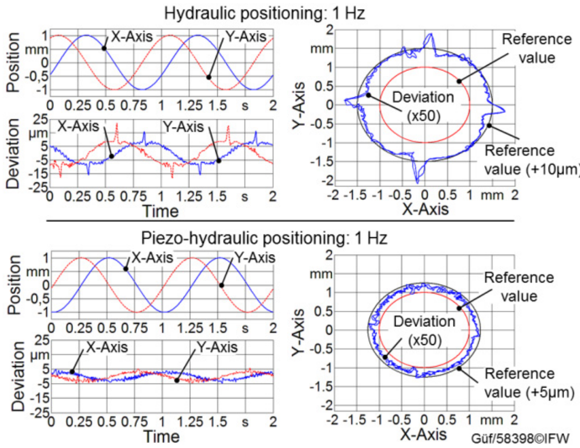

Fig. 6. Comparison of the positioning accuracy without feed-forward control.

This result shows that the concept of hybrid positioning can combine the advantages of both types of drives. Thus, the high actuator travel of the hydraulics can be improved by the high dynamics and positioning accuracy of the piezo technology. However, the lag cannot be compensated completely. For this reason, the iterative learning feed-forward control was developed.

Fig. 7 shows the positioning results with iterative learning feed-forward velocity control. Circular paths with an radius of 1 mm were positioned at different frequencies up to 10 Hz. In this tests, only the hydraulic controller was used as drive. The presented results illustrate that the iterative learning feed-forward control can significantly enhance positioning accuracies of hydraulic drives to the range of ±1.5 microns. For a good iterative feed-forward control it is recommend that the dead and cycle times are precisely known and that the iterative learning can run free of disturbing forces. To adapt the optimum feed-forward signal some learning periods are necessary. The learning speed can be adjusted in the control by a gain factor. In the present case, 30 learning periods are used. The iterative learning feed-forward control enables a compensation of all cyclical positioning deviations.

By combining the iterative learning feed-forward control with the piezo-hydraulic hybrid positioning, a sufficient accuracy should be achieved also during the grinding process. The iterative learning takes place before grinding. The piezo control will be activated after the iterative learning to find the optimal feed-forward control for the hydraulic system. Because of its higher dynamics, the piezo control has the function to compensate positioning errors due to process forces during grinding. Currently, the piezo control will be optimized. Due to high measurement noise of the eddy current sensors (±1.5 microns), which is amplified by the high dynamics of the piezo actuator, currently no improvement during the disturbance-free positioning can be achieved. However, the results of Fig. 6 show the potential of hybrid positioning.

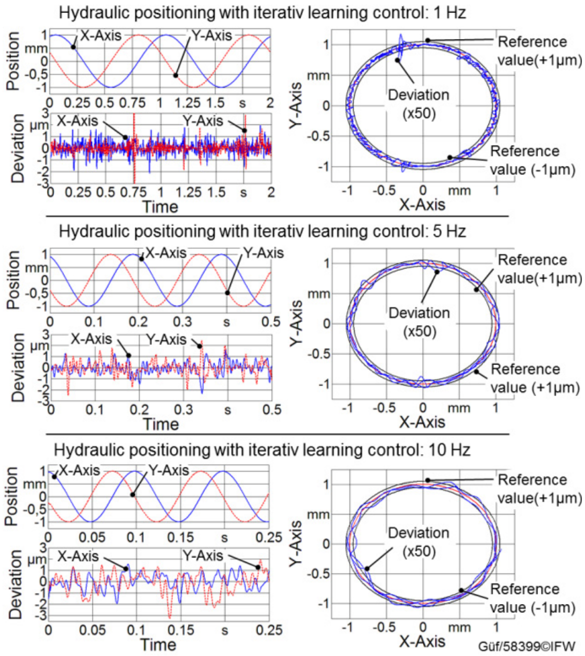

Fig. 7. Positioning accuracy with iterative learning velocity control

4.2. Active Alignment during Grinding

To verify the properties of the active tailstock during grinding, it has been installed a grinding machine. In Fig. 8 the grinding machine with the active tailstock and the integrated measuring system is shown.

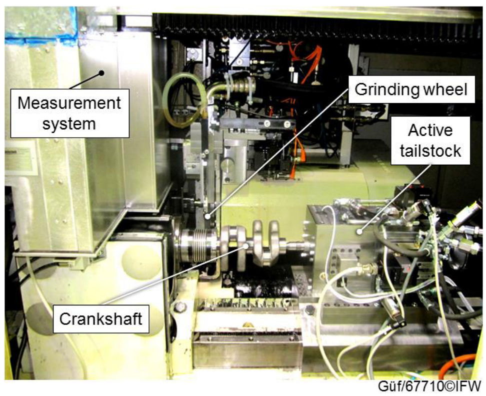

Fig. 8. Grinding machine with active tailstock and measurement system

To position the tailstock quill during the grinding process, the knowledge of the exact angular position of the crankshaft is necessary. For this reason, the rotation angle signal has been tapped off of the grinding machine and fed to an input of the signal processor card, in which the control of the active tailstock is implemented. By reading the angle signal, the tailstock quill can be positioned on a circular path synchronic to the rotational angle and speed of the crankshaft.

For the verification of the tilt error correction by the active tailstock, grinding tests were performed with and without active positioning. Fig. 9 shows a shaft with a total length of 195 mm, in which six bearing surfaces were ground with a nominal diameter of 47 mm at different eccentricities and tilt corrections. The bearing surfaces 1 and 5 are reference surfaces. In this case, no eccentricity by the grinding machine and no tilt error correction by the active tailstock were set. The tailstock control held its zero position.

Fig. 9. Shaft for grinding tests with the active tailstock

The bearings 2 and 4 were shifted eccentrically 1 mm in x-direction by the pendulum stroke. At bearing 3 a tilt of 0.294° along the x-axis was additionally applied to the eccentricity of 1 mm in x-direction. This angle corresponds to a displacement of the bearing center of 0.667 mm in negative y-direction. In this case, the tailstock center is positioned on a circular path with a radius of 1 mm. At bearing 6, the same experiment as at bearing 3 was carried out, but a tilt of -0.294° was applied along the y-axis. By this, the tilt should nearly compensate the eccentricity in x-direction of the grinding machine.

For the comparison of the theoretical and real displacement of the bearing center, line profiles of the six bearings were measured. Formula 1 shows the relationship between the theoretical displacement of the bearing center Δs as a function of shaft length L (195 mm), the distance from the tailstock center A (see Table 1) and the radius R (1 mm) of the circular path of the active tailstock. Table 1 shows the results of the measurements in comparison to the calculated values.

$$\Delta s = R - \frac{A}{L} \tag{1}$$

According to [10] a roundness up to 5 microns and a diameter ø $d^{-0.02}$ of the bearings of crankshafts are required. The results show that a precise grinding is possible with the active tailstock. The roundness and diameters of all bearings meet the requirements of the bearing seats of crankshafts. The precise tilt generation at bearing 3 and 5 could be proved by the measurement. These first grinding tests indicate that the active tailstock is able to ensure a stable grinding process. In addition, a micron-precise correction of a tilt is possible.

Table 1. Measurement results of the grinding tests with active tailstock

	Displacement X [mm]		Displacement Y [mm]	
	theoretic	real	theoretic	real
Bearing 1 (A=100 mm)	0.000	0.000	0.000	0.000
Bearing 2 (A=84 mm)	1.000	1.003	0.000	0.000
Bearing 3 (A=65 mm)	1.000	1.010	-0.667	-0.674
Bearing 4 (A=47 mm)	1.000	1.000	0.000	0.004
Bearing 5 (A=30 mm)	0.000	0.000	0.000	0.000
Bearing 6 (A=11 mm)	0.056	0.054	0.000	-0.002

	Diameter [mm]		Roundness [μm]
	theoretic	real	
Bearing 1 (A=100 mm)	47.000	46.997	3.3
Bearing 2 (A=84 mm)	47.000	46.976	3.9
Bearing 3 (A=65 mm)	47.000	46.981	5.1
Bearing 4 (A=47 mm)	47.000	46.988	4.1
Bearing 5 (A=30 mm)	47.000	46.995	3.0
Bearing 6 (A=11 mm)	47.000	46.997	4.6

5. Conclusion

This paper presents a strategy for active error compensation in contour controlled grinding of precision forged crankshafts. For an allowance and unbalance oriented alignment of crankshafts a machine integrated optical measuring system and an active tailstock were developed. The discussed approaches could also be applied to camshafts and similar long, compliant workpieces. A hybrid principle combining hydraulic and piezoelectric actuation is introduced and analyzed with an active tailstock with two degree of freedom. The dynamics and precision of the piezo actuator can be used to improve the positioning accuracy whereas the hydraulic actuator makes the necessary stroke available. In combination with an iterative learning feed-forward control positioning, accuracies of ±1.5 microns are possible. In grinding tests good grinding results and the generation of precise tilts with the active tailstock could be verified.

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