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Effect of alignment errors on operation of machine tool spindle with active bearing preloading module

The article describes a test stand with a spindle equipped with an active bearing preload system using piezoelectric actuators. The proper functioning of the spindle and the active system was associated with the correct alignment of the spindle shaft and the drive motor. The article presents two methods of shaft alignment. The use of commonly known shaft alignment methods with dial indicators is insufficient from the viewpoint of being able to control this preload. This work aims at making the readers aware that, for systems with active bearing preload, the latest measuring devices should be used to align the shaft. The use of commonly known methods of equalization with dial gauges is insufficient from the point of view of controlling this preload. Increasing the accuracy of shaft alignment from 0.1 to 0.01 mm made it possible to obtain a 50% reduction in the displacement of the outer bearing ring during spindle operation.

1. Introduction

In the generally available literature on the subject, one can find many design solutions with an active bearing support in the machine tool spindle system. Such solutions are used to apply a variable (currently desired) preload to angular ball bearings. Many of the solutions are prototype designs dedicated to a given spindle, favourably affecting spindle operation quality only and exclusively under specific conditions [1–5]. Among the conditions, one should mention a narrow range of spindle rotational speeds and a small change in the preloading force. Although there are solutions where the preload changes during spindle operation, the change is not

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controlled or adjusted online. In order to correctly design an active preloading system for angular bearings one must accurately describe its operating conditions and determine the characteristics of the preload controlling and changing components. Also, the influence of all the external disturbances adversely affecting the operation of the active preloading system and the whole spindle should be minimized. In the case of spindle bearings, the range of relative displacement of the bearing raceways needed to obtain the required initial tension is from 10–20 to a few hundred micrometres [6] and its value determines the stiffness of the spindle [7]. For this reason, even the smallest disturbances stemming from spindle-drive motor non-coaxiality have a significant effect on the operation of the spindle. For this reason, even the smallest disturbances resulting from the misalignment of the drive motor and the spindle have a significant impact on the spindle operation. The occurrence of misalignment in the case of shafts connected with couplings leads to excessive wear of the elements of these machines, increase play and the appearance of excessive spindle vibrations [8], which are particularly unfavourable in the case of spindles with an active preloading module. The coaxiality problem was noticed by the authors during a larger research project devoted to the effect of bearing stiffness adjustment on the dynamic properties of the machine tool spindle [9]. A complete test stand, equipped with a spindle with an active preloading system for which rotational speed was transmitted from an external motor, was built (Fig. 1) for the investigations.

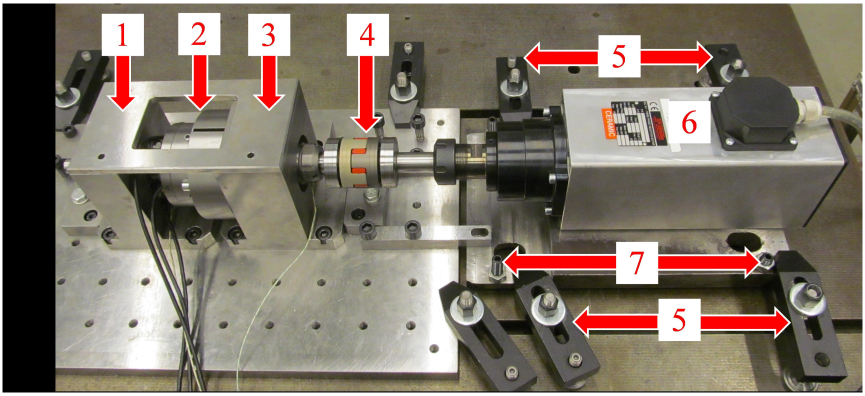


Fig. 1. Investigated spindle system: 1 – front support, 2 – active preloading module, 3 – rear support, 4 – ROTEX coupling made by KTR, 5 – clamping arms, 6 – high-speed motor type C5160D-DB-PER32 made by TEKNOMOTOR, 7 – adjusting screws

In the investigated system, the driving force from an external drive motor was transmitted via a backlash-free coupling. In such designs, the precise coaxiality of the spindle and the motor shaft is critical for the functioning of the active preloading module and the operation of the whole spindle. Proper alignment significantly affects the operation of spindle bearings and their reliability and the thermal stability of the spindle [10, 11]. The wider the range of tolerance for coaxiality, the larger the radial run-out, the greater the generated dynamic forces and the higher the spindle operation noise level. Such phenomena significantly disturb the operation of the spindle system and raise doubts about the use of active preloading systems for bearings. Often errors arising from spindle-drive motor non-coaxiality result in so unstable operation of the bearings that it exceeds the full preload adjustment range for the latter and for the active components.

When aligning the shafts, the commonly used method is based on the use of two dial gauges or displacement sensors [12], which allow for determining the relative radial and axial inaccuracies of the alignment of two mating shafts. This method is presented in [13]. However, its accuracy is often at the level of 0.1 mm and is not sufficient for modern machines. The main disadvantage of this method is the mapping of shape errors of the shafts that are set, which are particularly unfavourable in the case of ultra-precise spindles [14]. Nowadays, in the industry, as-built and post-assembly measurements with the use of laser techniques are increasingly used. An example can be e.g., a 3D scanner, the operation of which is described in [15]. This technique makes it possible to more accurately determine the coaxiality of the shafts connected by a clutch, taking into account not only the accuracy of the shaft surfaces, but also considering them as a comprehensive system. Based on laser techniques, various manufacturers of measuring equipment develop instruments that allow precise alignment of two shafts [16]. Examples include solutions from SKF (TKSA system), Fluke, AMC Vibro. Their common advantage is the reduction of the time needed for alignment and higher accuracy than in the case of existing measuring methods. One such instrument was used for research in this article. By developing a specific test stand, it was possible to present how increasing the accuracy of the concentricity affects the behaviour of the outer bearing race for an angular contact bearing. So far, the research on improving the alignment has focused only on the measurement of spindle vibrations or the reduction of the life of the bearings. This work allows one to determine how the instantaneous value of the preload of the bearings changes on the basis of the relative displacements of the bearing races. At the same time, the paper draws attention to the importance of this problem in the case of active preload systems, which are increasingly used in machine tool spindles.

2. Test stand

A system of three low-voltage piezoactuators, positioned symmetrically relative to the shaft axis and pressing against the outer bearing race of the rear support, was used in the model spindle to apply and adjust preload. A schematic diagram of this design solution is shown in Fig. 2.

Angular bearings FAG B7206-CT-PS4-UM working in the “O” system [17, 18] were used in the spindle. The preload range from no preload to the maximum operational preload amounted to about 0.011 mm.

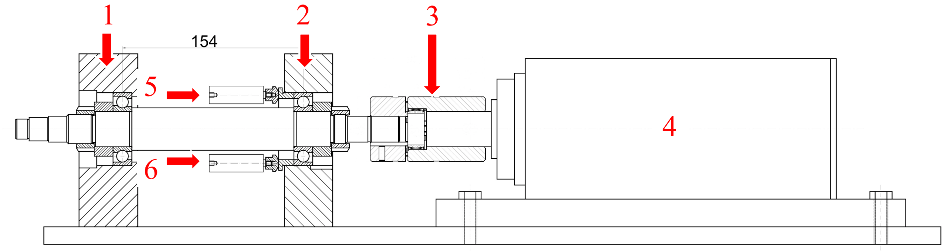


Fig. 2. Schematic diagram of investigated spindle with drive motor: 1 – front support, 2 – rear support, 3 –ROTEX coupling made by KTR 4 – high-speed drive motor, 5 – piezoactuator PSt 150/10/40 VS15 made by Piezomechanik GmbH, 6 – touch displacement transducer MDKa-F1 made by VIS

The spindle frame was made in the form of two separate supports (a front support and a rear support) seated in the base plate. Each of the supports was equipped with a thermocouple sensor for monitoring the operation of the bearings. The position of the supports (in both the radial and axial direction) could be fixed and they could be mounted on the base plate thanks to the use of location pins with an accuracy of below 0.01 mm. A high-speed three-phase induction motor (4) made by TKNOMOTOR with a Siemens frequency converter was used to drive the spindle. Rotational speed was controlled by a National Instruments data acquisition board USB 6211. From the motor, the driving force was transmitted to the spindle via a Rotex backlash-free jaw coupling (3) suitable for operation at elevated rotational speeds thanks to the use of a compression sleeve (no key joints). Considering its weight, the spindle system was placed on a cast-iron table with T-slots in which the arms clamping the base plate of the spindle and the motor were secured. Three commercial piezoactuators (5) for preload changing were installed in the active support. Their principle of operation was based on the inverse piezoelectric effect [19], consisting in a change in the dimensions of the piezoelectric pile elements under the applied voltage. The voltage was generated by a three-channel amplifier SVR 150/3 made by Piezomechanik GmbH, capable of working in a feedback loop. Prior to its installation, each of the piezoactuators had been calibrated on a separate stand. Its hysteresis and characteristic for the full extension range (0–0.055 mm) were determined (for piezoactuator P1 see Fig. 3).

The piezoactuators were equally distributed about the spindle axis, within a diameter of 60 mm. The system of fixing them allowed the axial adjustment of their position. Thanks to this and to the tensiometric system inside the active elements, it was ensured that each of the piezoactuators exerted the same pressure on the outer bearing race. Additionally, three touch displacement transducers (type MDKa) made by VIS (6) were installed in the active support to control the behaviour of the spindle, whereby the relative axial motions of the outer bearing race could be continuously monitored.

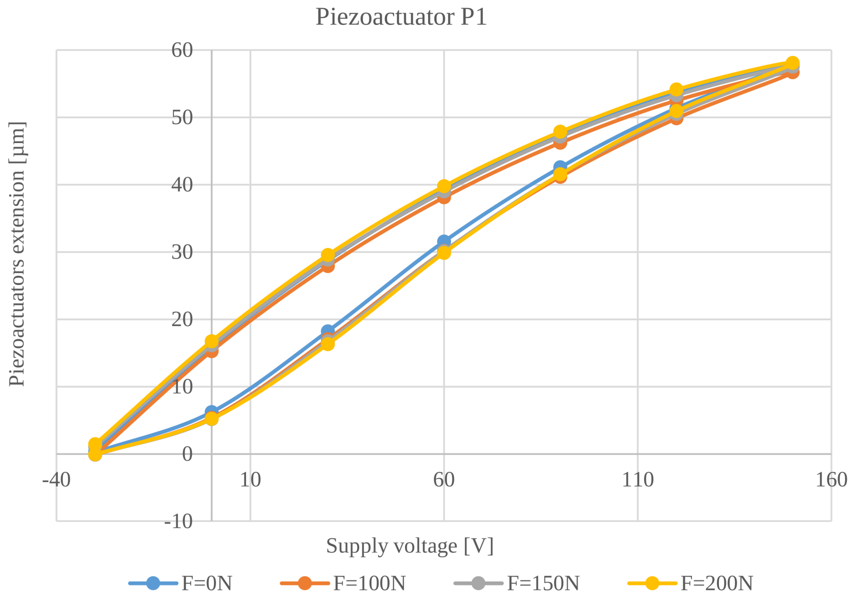


Fig. 3. Exemplary piezoactuator characteristic for different values of preloading force *F*

3. Testing methodology

The main aim of the tests was to determine how significant was the effect of motor shaft-spindle coaxiality setting precision on the operational behaviour of the spindle bearings. The behaviour of the active support bearing was determined on the basis of the measurement data acquired by the touch sensors located in the active support. The sensors had a measuring range of 4 mm and a resolution of 0.004 mm. They worked together with a measuring system of HBM QuantumX MX840 type. Along with the hardware, its manufacturer offers (sells) Catman Easy software for recording the measured signals. The main specifications of the amplifier are shown in Table 1.

Table 1.

Specifications of measuring system of HBM QuantumX MX840 type [20]

Number of channels	8 – with A/D converters with 24-bit resolution
Amplifier supply voltage	10. . . 30 [V] DC (~ 10 [W])
Sensor supply voltage	5–24 V DC (~ 0.7 [W])
Sampling frequency	to 19.2 [kHz]
Connection	Ethernet TCP/IP
Types of compatible sensors	tensometric and piezoresistive (full bridge), inductive (full/half bridge), LVDT, voltage, Pt100/Pt1000, thermocouples (K, J, T, E, N, R, S, B), potentiometric

After the test stand had been fully set up, an attempt was made to set motor-spindle coaxiality. It was decided that the spindle would remain stationary and coaxiality would be set by adjusting the position of the drive motor. Such an adjustment was possible thanks to four movable feet in the motor base plate.

First, a conventional method, which uses a touch dial indicator and a feeler gauge, was applied to set coaxiality. The dial indicator was used to set identical heights of the coupling's two halves. The feeler gauge was used to measure the distance between the individual claws of the coupling. In this way, the parallelism of the two axes was verified. The measurement was repeated after the whole system had been warmed up to the operating temperature (about 20°C). These tests were carried out in a thermostatic chamber at the Faculty of Mechanical Engineering of the Wrocław University of Technology. In the chamber, it is possible to adjust the ambient temperature with an accuracy of 1°C. During the measurements, the set value and measured temperature was 20°C. The spindle temperature was measured on the outer bearing ring for each support using a thermocouple sensor.

After all the preparatory work had been completed, investigations of spindle behaviour at a given rotational speed and at a nominal bearing preload (set in the middle of the piezoactuators' motion range) began. Bearing preload correctness was controlled on the basis of the reading of the force exerted by each of the piezoactuators. For each of them, the preload amounted to the force of 200 N. A cycle of spindle work at the rotational speed ranging from 0 to 12000 rpm (Fig. 4) was proposed. The work cycle was divided into nine fifteen-minute intervals. During spindle operation, the relative displacement of the outer bearing race in the active support was recorded by the touch inductive sensors.

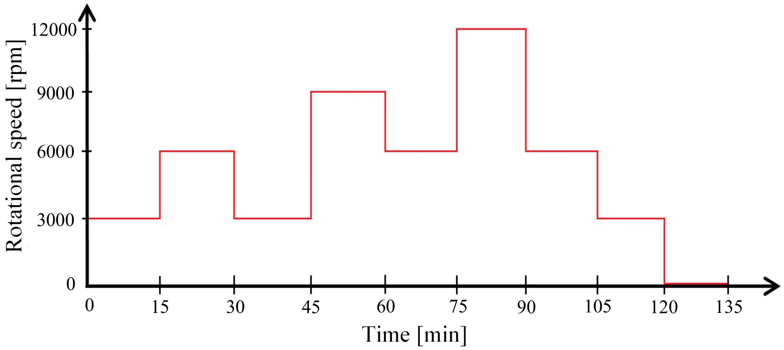


Fig. 4. Spindle work cycle

The work cycle was selected on the basis of many trials. Preliminary tests have shown that after changing the spindle speed, its thermal stabilization occurs after about 10 minutes. For this reason, it was assumed that a single time period should be 15 minutes. The spindle speed range is 0–12000 rpm. In order to select equal intervals, speed changes of 3000 or 6000 rpm were adopted. During the study, the authors of the study wanted to check the spindle behaviour in conditions similar to real ones, i.e., where the rotational speed changes either up or down.

A diagram of the relative displacement of the outer bearing race is shown in Fig. 5.

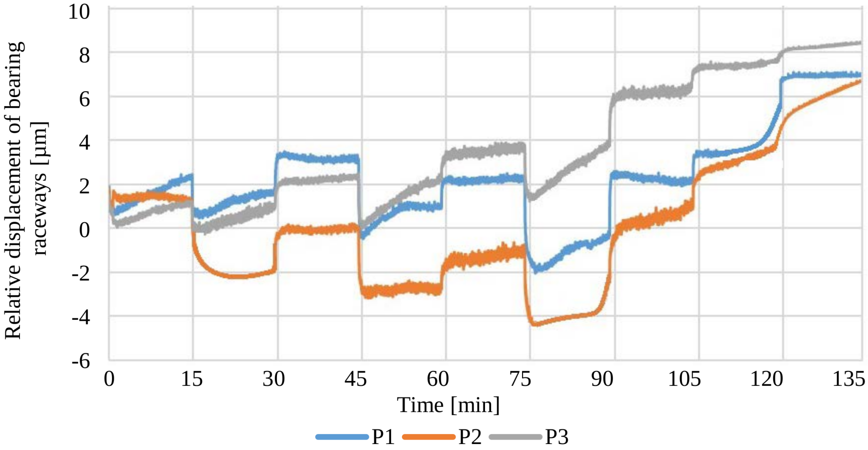


Fig. 5. Displacement values recorded by all sensors (P1. P2, P3) during full spindle work cycle after dial indicators for setting coaxiality of shafts operating in tandem had been installed

The measurement showed the system to be sensitive to each change in spindle rotational speed; spindle shift was observed at each speed change. Spindle shift commonly occurs in high-speed spindles but at much higher rotational speeds. Moreover, the displacements recorded by the particular sensors had different values. The preloading force generated by each of the piezoelectric elements was the same. Therefore, if the outer bearing race does not move axially, this indicates that additional force components have appeared in the system and caused the bearing to slant. The forces can appear due to, e.g., motor-spindle non-coaxiality or faulty bearing supports. The axial displacements of the outer bearing ring are shown in Fig. 5. For each of the sensors P1, P2, P3 was read a different value of the relative displacement, which unambiguously indicates the bearing ring swinging to the shaft axis of the spindle. Furthermore, a slight temperature effect produced the heating up of the whole system can be seen in the diagram. During the work of the spindle, it undergoes a temperature change, in this case mainly due to variable rotational speeds. Whenever the spindle speed changes (see Fig. 4 and 5), we observe shift displacement of the bearing ring. This reaction is natural, as presented in more detail by the authors of the work [21]. However, the value of this displacement is not constant for the entire time interval when the spindle is operating at the set speed. As a result of the change in bearing operating temperature, the displacement value recorded by P1, P2, P3 sensors changes. These changes, however, are not significant and are usually in the range of 0.002 mm for each of the ranges (for each rotation speed). More extensive research on the effect of temperature on the test spindle is presented in [22]. In order to rule out errors due to a faultily made spindle, each of the bearing supports was subjected to measurements. The geometric dimensions of the supports were checked using a ZEISS coordinate measuring machine. The measurement results were within the tolerance of ±.01 mm. Therefore, further investigations focused on coaxiality errors.

The active bearing preload system makes it possible to adjust preload during spindle operation. In the case of unstable operation of the bearings, their slanting and large displacements of the bearing races, the use of piezoelectric elements in the active system can be ineffective or simply unimplementable. Considering the hypothesis that the spindle behaviour observed in the diagram in Fig. 5 can be caused by the drive motor-spindle non-coaxiality, the authors decided to repeat the alignment procedure using a 710E laser measuring system made by Easy Laser [23].

The measuring system consists of an operator panel (1) and two measuring units (M – movable, S – stationary) mountable on the two shafts operating in tandem. Fig. 6 shows the investigated spindle during alignment by means of the Easy Laser 710E measuring system.

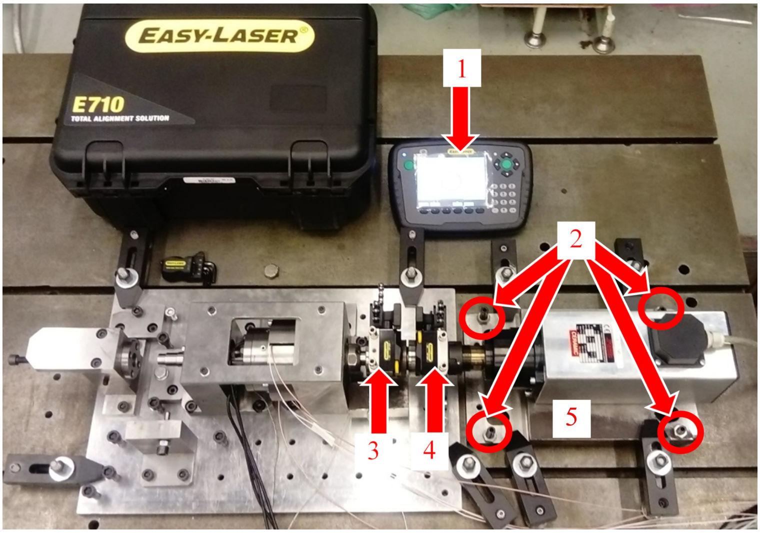


Fig. 6. View of test stand during alignment: 1 – operator panel, 2 – adjusting screws, 3 – measuring unit S, 4 – measuring unit M, 5 – high-speed motor with base plate

Also in this case, the movable element was a drive motor (5) (measuring unit M) on a base plate. The position of the motor was adjusted by means of four feet (Fig. 6, elements (2)).

The adopted procedure was based on three measuring points. The measuring units were placed on two shafts working in tandem and spaced as far as possible from each other. Then, the shaft was manually turned left and right by the largest possible angle of rotation. The whole rotation range was divided into three points (two end positions and a middle position). As a result, it was found that the position of the motor needed to be adjusted also vertically. Then, the polarization of one of the measuring units was changed to determine the coaxiality of the shafts in the horizontal direction, as shown in Fig. 7. Measurements in the two directions were carried out after the spindle had been preheated to the temperature of 20°C, becoming thermally stable at the speed of 500 rpm.

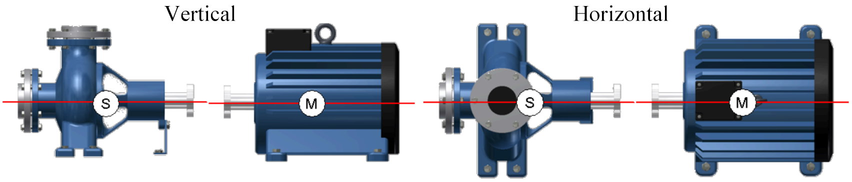
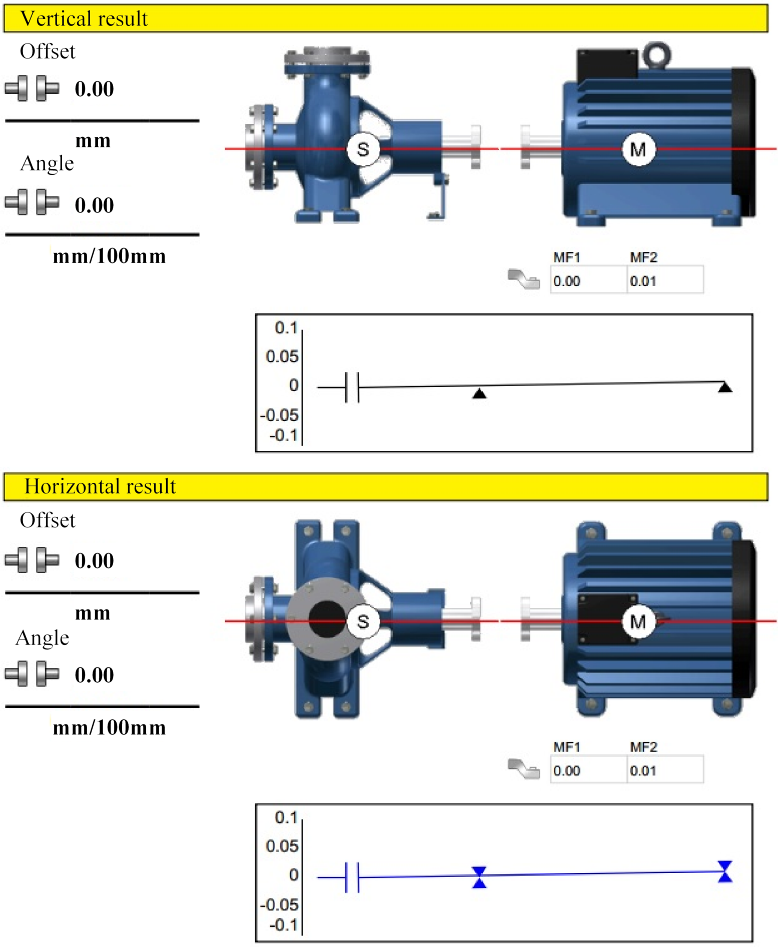


Fig. 7. Schematic showing orientation of planes for setting coaxiality in two directions (horizontal and vertical)

On this basis, the report shown in Fig.8 was drawn up.



Vertical result

Offset

0.00

mm

Angle

0.00

mm/100mm

MF1	MF2
0.00	0.01

Horizontal result

Offset

0.00

mm

Angle

0.00

mm/100mm

MF1	MF2
0.00	0.01

Fig. 8. Report on motor and spindle coaxiality measurements performed using Easy Laser 710E measuring system

To be on the safe side, the coaxiality measurement was carried out three times in each of the directions. Then the behaviour of the spindle system (the relative displacement of the bearing races of the active support) during work at a variable rotational speed consistent with the diagram shown in Fig. 4 was recorded again. The character of the work of the spindle is shown in Fig. 9. A diagram comparing the maximum mean values of bearing race displacements for selected rotational speeds and the two methods of aligning shafts is presented in Fig. 10. The diagram

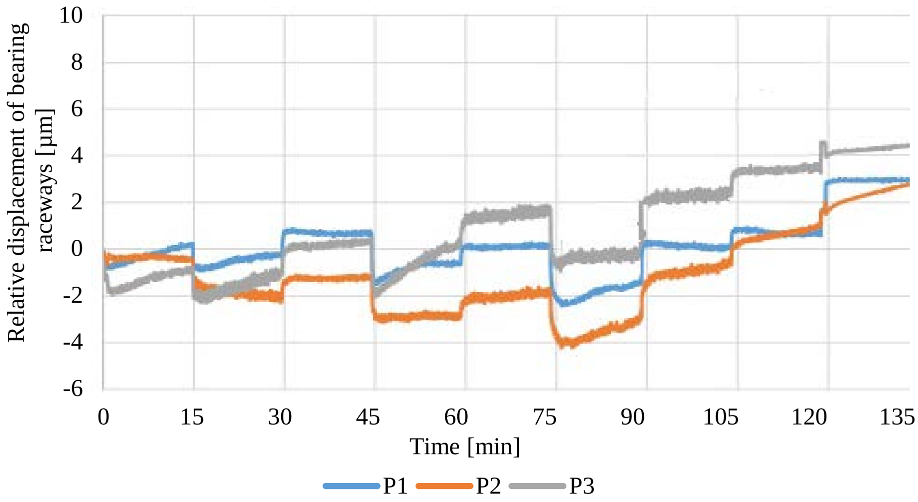


Fig. 9. Displacement values recorded by all sensors (P1. P2, P3) during full spindle work cycle after laser device for setting coaxiality of shafts working in tandem had been used

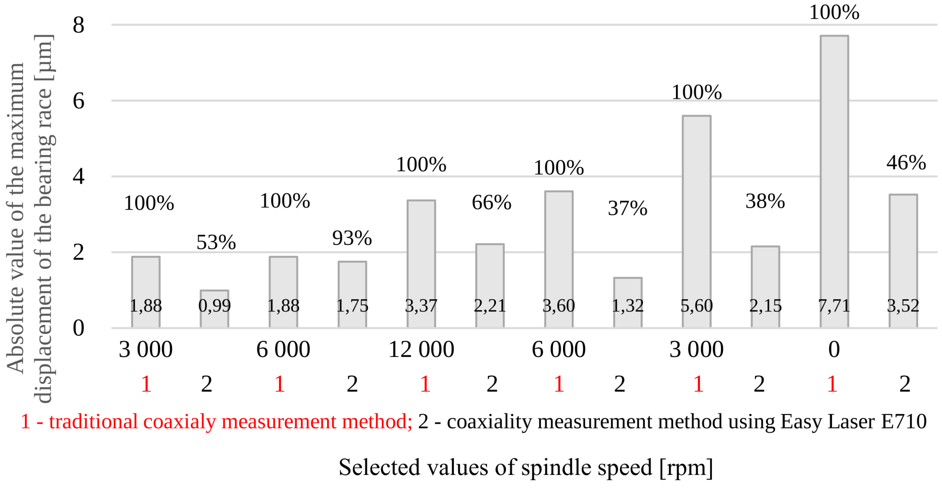


Fig. 10. Comparison of results obtained using two methods of aligning shafts

better illustrate the benefits stemming from the more precise setting of coaxiality. It also indicates that the use of the Easy Laser device brings notable benefits in each of the presented ranges of spindle system operation.

4. Conclusions

The tests have shown how important it is in practice to precisely align the mating motor and spindle shafts in a machine tool. After using the Easy Laser E710E device, a more stable spindle operation was achieved, resulting in smaller displacements of the outer bearing ring. The reduction in measured axial displacements in various ranges of spindle speed ranged from 7 to 63 percent. It has a very significant impact especially when in the spindle system we touch the system to active preload. It is clear that the most modern laser devices help the users to achieve much higher precision in aligning the shafts. The article shows that the increase in its accuracy improves the stability of the entire spindle. Although the measurements used were not carried out in this test, it can be conclusively stated that, through higher coaxial accuracy, less clutch noise, less system vibration, and more stable bearing performance are achieved. In the future, work is planned in terms of the influence of concentricity on the thermal stability of the spindle.

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