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MEASUREMENTS OF DEVIATIONS FROM CIRCULARITY OF ROTATING PARTS OF THE MACHINE BY USING FIBRE SIGNALLING BASED ON THE EXAMPLE OF THE LATHE SPINDLE

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Abstract. There are many machines, devices and production lines that are equipped with rotating elements (shafts, axes, spindles, trailing and drive wheels, etc.). Correct geometry of these elements ensures trouble-free operation, and, in the case of machine tools it decides about the correct geometric parameters of the manufactured semi-finished articles and products. In this respect, the newly manufactured and operated lathes are checked against the correct geometry of their parts which determine the location of the work-piece and the lathe and their movement These parts are geometrically correct if the errors of their geometrical shape (deviations) do not exceed values designated in the standards. The wearing of lathes reveals the so-called spindle run-out (deviation from circularity).

These deviations are determined using mainly the workshop methods. However, due to the considerable sizes of machine tools surveying methods and new methods which use electronic and optoelectronic devices also apply.

Authors of this work present the measuring set (which they designed and built themselves) which relies on the two-point fibre signalling device which is installed in the lathe spindle chuck jaws. The position of the signalling device during the lathe spindle rotation is recorded with CCD/CMOS digital camera, and the images are stored on the camera memory card.

The aim of the presented research and experimental works was to determine the internal conformity of measurement results that were obtained using the designed and constructed measuring set, to check whether there is a correlation between the results obtained using the dial indicator and to analyse the accuracy of observations that were made using the test set.

The designed measuring set enables to determine deviations from circularity during the lathe spindle rotation with the accuracy of ± 0.02 mm.

Key words: measurement of lathe, mono-photogrammetry, CCD/CMOS camera, fibre signalling devices, optoelectronic technique

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INTRODUCTION

In the national economy production processes utilize machines, equipment and production lines which contain various rotating elements (shafts, axles, spindles and trailing and drive wheels, etc.). Correct geometry of elements ensures trouble-free operation, and, in the case of machine tools it impacts the quality of the manufactured semi-finished articles and products. Among the machine tools (milling machines, planers, sanders, etc.) lathes are the largest group. The production process features a gradual wear of machine tools. The results of lathes wearing are: spindle run-out, clanging or creaks in the mechanisms of propulsion and steering, axle spindle and tail-stock sleeve mismatch, clearances in mechanical components. Due to the fact that the lathe accuracy depends on the precision of its production, lathes undergo control that encompasses checking the accuracy at which various components of the lathe were built, their geometrical location with reference to one another, the quality of materials that were used and general performance of the lathe. When describing the lathe quality, it is necessary to imply procedures in order to check geometrical properties of the lathe parts which are responsible for the location and motion of the work-piece and the lathe [Dudik 1985]. These parts are geometrically correct if the errors of their geometrical shape (deviations) do not exceed values specified in the standards [PN-ISO-230-1, PN-M-55651].

While assembling and operating the lathes, their basic geometrical parameters are checked periodically. These parameters are responsible for the occurrence of the following errors:

- deviations of runners shape - these are the existing shifts in the vertical or horizontal plane;
- surface roughness deviation caused by the lack of stiffness of the mounted object or device, these are clearances in the machine tool mechanism;
- deviation of tailstock shift from the spindle axle;
- deviation from circularity when the spindle rotates.

Values of these deviations are determined using the workshop methods [Dudik 1985]. Due to large dimensions of lathes geodetic methods and additional geodetic equipment are used [Gocał 1993]. New methods have been also developed. These methods use electronic and opto-electronic solutions, e.g. optical fibres [Ćmielewski 2010, Ćmielewski et al. 2011, Gołuch et al. 2012, Setan and Ibrahim 2003].

METHODS OF SIGNALLING COMPONENTS OF ENGINEERING OBJECTS

Industrial equipment, machines and technological lines are often characterized by limited access to items subject to observations. It is caused by covers on guiding or rotating elements (e.g. runners rails of milling machines, lathe machine spindles, sliding elements of planers, etc.). Location of these elements in the working space is also important (for example, paper machines, turbo-generators) as it restricts (forces) setting geodetic instruments and devices. The shape of the machine components (i.e. cylinders, rotating elements) makes it difficult to perform measurements using standard measuring methods.

Optical fibres enable to build various signalling devices, which, after attaching to the observed component constitute measuring targets. Figures 1 and 2 present targets of the elongated elements, while Figure 3 depicts elements of a more complex shape (simple, flexible, polygonal and complex) [Ćmielewski 2007].

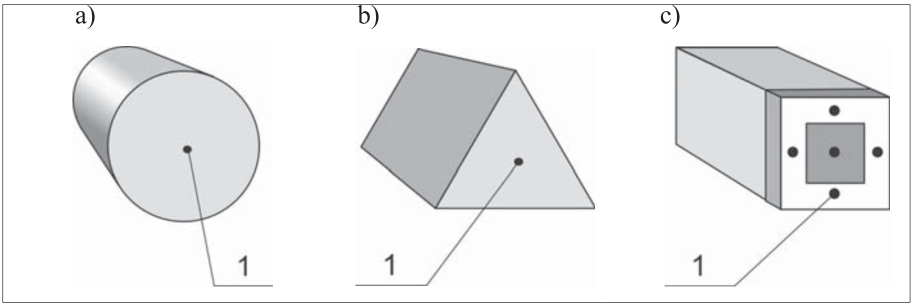

Fig. 1. Examples of body shapes of the fibre signalling devices:
a) cylinder,
b) triangular prism,
c) cuboid
Symbols: 1. optical fibre face

Rys. 1. Przykłady kształtów korpusów sygnalizatorów światłowodowych:
a) walec,
b) graniastosłup trójkątny,
c) prostopadłościan
Oznaczenie: 1. czoło światłowodu

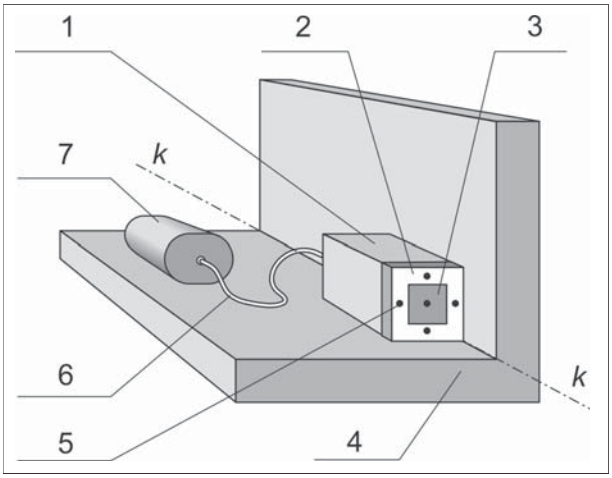

Fig. 2. The view of the signalling device set on the element that is subject to investigation
Symbols: 1. target signalling device body, 2. point target disc, 3. reflector, 4. structural element, 5. optical fibre face, 6. fibre, 7. light source

Rys. 2. Widok sygnalizatora ustawionego na badanym elemencie
Oznaczenia: 1. korpus sygnalizatora celu, 2. tarcza punktowa, 3. reflektor, 4. element konstrukcyjny, 5. czoło światłowodu, 6. światłowód, 7. źródło światła

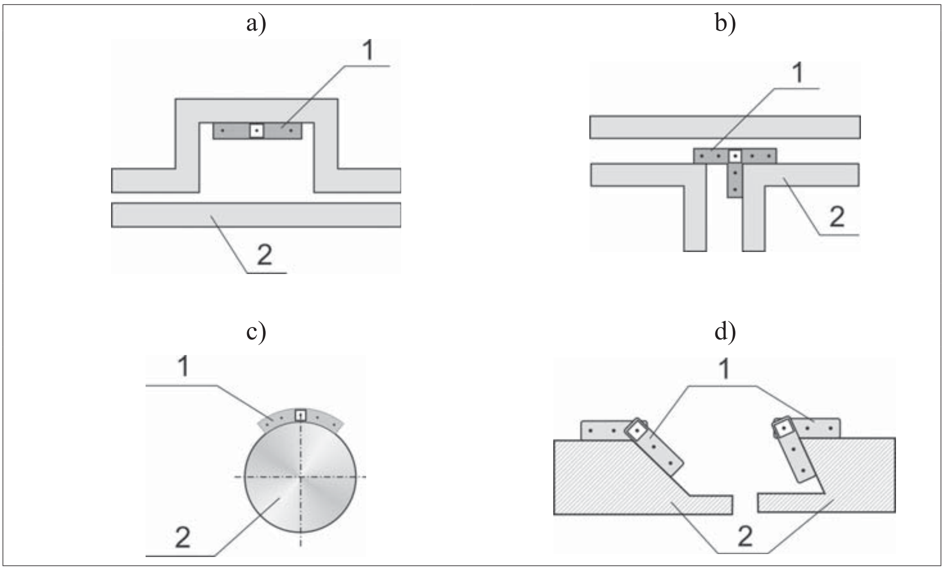

Fig. 3. Measurement of structural elements with the use of fibre signalling devices
a) simple signalling device, b) complex signalling device, c) flexible signalling device
d) polygonal signalling device
Symbols: 1. signalling device 2. measured structural element

Rys. 3. Pomiar elementów konstrukcyjnych z użyciem sygnalizatorów światłowodowych
a) sygnalizator prosty, b) sygnalizator złożony, c) sygnalizator giętki, d) sygnalizator łamany,
Oznaczenia: 1. sygnalizator, 2. mierzony element konstrukcyjny

PRESENTATION OF THE MEASURING SET DESIGNED TO DETERMINE THE LATHE SPINDLE DEVIATION FROM CIRCULARITY USING FIBRE TECHNOLOGY

In the production process elements and components produced using lathes (Fig. 4) may include deviations from the values accepted for the project. The magnitude of these deviations depends on the geometric precision of the lathe. Structural components of lathes operating in the rotational motion are checked against the provisions laid down in standards and technical regulations [PN-ISO-230-1, PN-M-55651].

The basic controlled deviation for the spindle that causes the semi-finished article to rotate is the axial run-out of the spindle axis which is measured at a certain point (Fig. 5). In the workshop practice the aforementioned deviation is checked by means of a dial indicator whose stem touches the surface spots of the controlled spindle. Readings of the indicator during the spindle rotation constitute a direct measure of the determined displacement. This method requires a direct contact between the measuring instrument (dial indicator) and the surface of the test spindle.

Many machines and devices have rotating elements that require periodic control observations. Geodetic tools offered by contemporary producers do not meet the needs for these types of measurements.

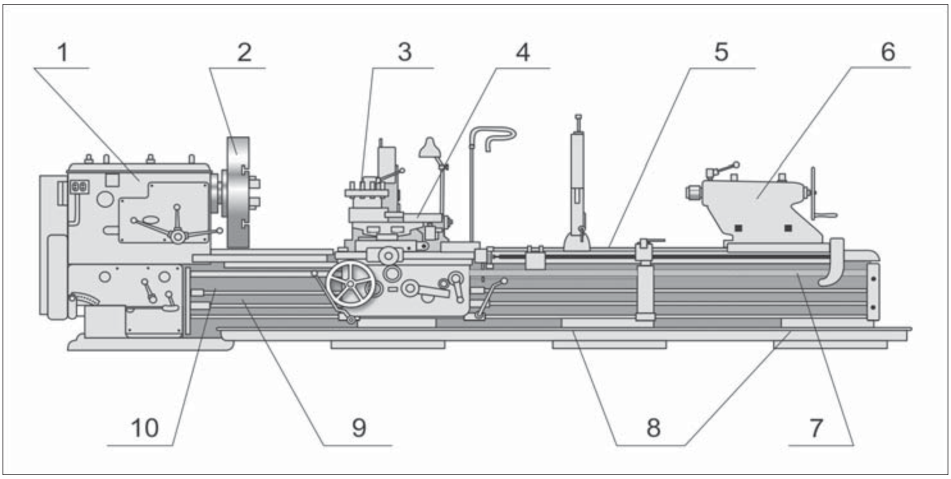

Fig. 4. General view of the lathe
Symbols: 1. headstock, 2. spindle, 3. C-clamp, 4. support, 5. runners, 6. tailstock, 7. feed screw, 8. bases, 9. shaft for starting and stopping the spindle, 10. feed rod

Rys. 4. Ogólny widok tokarki
Oznaczenia: 1. wrzeciennik, 2. wrzeciono, 3. imak nożowy, 4. suport, 5. prowadnice, 6. konik, 7. śruba pociągowa, 8. podstawy, 9. wałek do uruchamiania i zatrzymywania wrzeciona, 10. wałek pociągowy

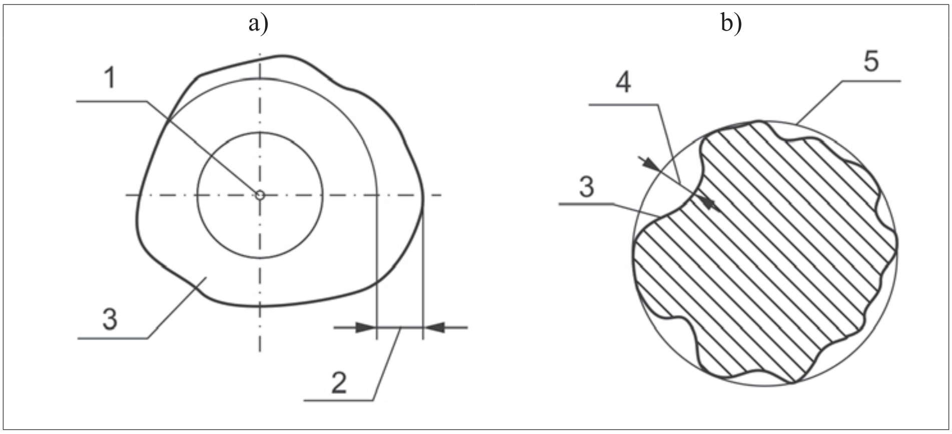

Fig. 5. Graphic illustration showing how deviations occur:
a) deviation of the axial run-out during the lathe operation, b) deviation from circularity when the spindle rotates. Symbols: 1. reference axis, 2. deviation of the axial run-out, 3. the lathe spindle, 4. deviation from circularity, 5. adjacent wheel

Rys. 5. Ilustracja graficzna istoty występowania odchyłek:
a) bicia promieniowego podczas pracy obrabiarki, b) od kołowości podczas obrotu wrzeciona. Oznaczenia: 1. oś odniesienia, 2. odchyłka bicia promieniowego, 3. wrzeciono tokarki, 4. odchyłka kołowości, 5. koło przylegające

Opto-electronic components offered on the market enabled the development of a contactless method for measuring the lathe spindle rotation using a set of fibre signalling devices.

The authors of this paper presented in this work the measuring set they designed and built (Fig. 6). Three variants of the measuring set were developed. In the first variant a single-point fibre signalling device (Fig. 6a) is used in measurements. It is mounted in the lathe spindle chuck jaws. In the second and third variant two-point fibre signalling devices were used. They were installed for the duration of measurements in the lathe spindle chuck jaws (Fig. 6b), or on the surface of the examined lathe spindle (Fig. 6c). In each variant the position of the signalling device during the lathe spindle rotation is recorded with CCD/CMOS digital camera, and images are stored on the camera memory card.

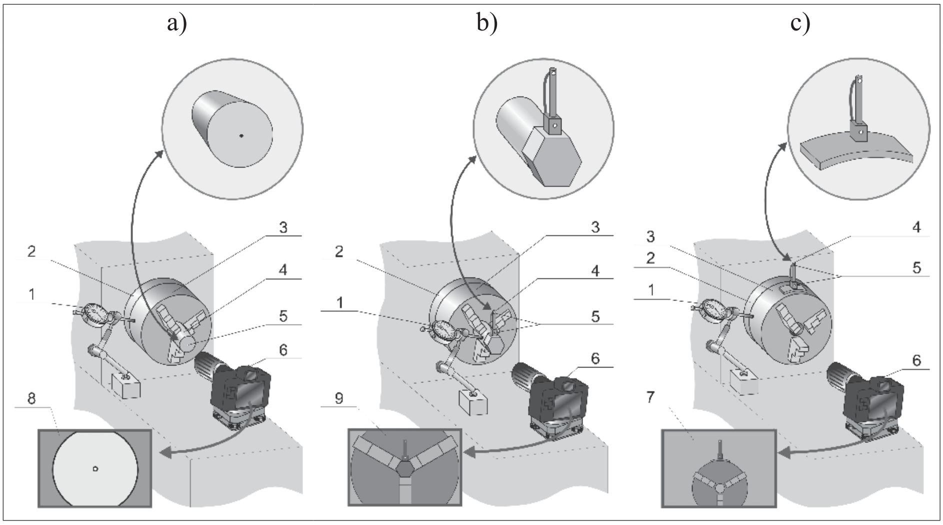

Fig. 6. A sample diagram of measuring equipment deployment during measurements of the lathe spindle circularity: a) single-point fibre signalling device mounted in the chuck jaws, b) two-point fibre signalling device mounted in the chuck jaws, c) two fiber-optic light mounted on the surface of the test spindle:
Symbols: 1. dial indicator, 2. spindle shield, 3. lathe chuck, 4. fibre signalling device, 5. the fibre core end face, 6. CCD/CMOS camera, 7. the image of the signalling device with the fibre core end faces lit, 8. the image of the signalling device with the fibre core end face lit, 9. the image of the signalling device with the fibre core end faces lit

Rys. 6. Przykładowy schemat rozmieszczenia aparatury pomiarowej podczas pomiarów kołowości wrzeciona tokarki:
a) jednopunktowy sygnalizator światłowodowy mocowany w szczękach uchwytu,
b) dwupunktowy sygnalizator światłowodowy mocowany w szczękach uchwytu,
c) dwupunktowy sygnalizator światłowodowy mocowany na powierzchni badanego wrzeciona
Oznaczenia: 1. czujnik zegarowy, 2. tarcza wrzeciona, 3. uchwyt tokarski, 4. sygnalizator światłowodowy, 5. czoło rdzenia światłowodu, 6. kamera CCD/CMOS, 7. obraz sygnalizatora ze świecącymi czołami rdzenia światłowodu, 8. obraz sygnalizatora ze świecącym czołem rdzenia światłowodu, 9. obraz sygnalizatora ze świecącymi czołami rdzenia światłowodu

LABORATORY RESEARCH AND EXPERIMENTAL WORKS

Experimental test measurements were conducted in the laboratory of the Institute of Geodesy and Geoinformatics at the Wrocław University of Environmental and Life Sciences. For the purpose of testing we used two-point fibre signalling device (Fig. 6b), which was installed in the lathe (type TUE-40) spindle chuck jaws.

The aim of the research and experimental works was to determine the internal conformity of measurement results that were obtained using the designed and constructed measuring set, to check whether there is a correlation between the results obtained using the dial indicator and to analyse the accuracy of observations that were made using the test set.

The research focuses on determination of the lathe spindle deviations from circularity while it rotates using the designed measuring set and the dial indicator. Figure 7 presents the location of measuring equipment during experimental works.

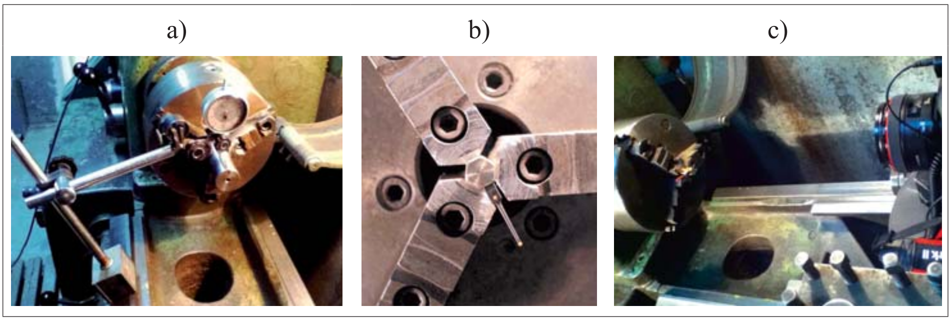

Fig. 7. Measurements of the lathe spindle (type TUE-40) deviations from circularity: a) the view of the lathe spindle circularity measurements with the use of the dial indicator, b) the view of the two-point fibre signalling device after installing the lathe spindle in the chuck jaws, c) the view of the measuring set during the research and experimental works

Rys. 7. Pomiary odchyłek od kołowości wrzeciona tokarki typu TUE-40: a) widok pomiaru kołowości wrzeciona tokarki z użyciem czujnika zegarowego, b) widok dwupunktowego sygnalizatora światłowodowego po zamocowaniu w szczękach uchwytu wrzeciona tokarki, c) widok zestawu pomiarowego podczas prac badawczo-eksperymentalnych

The measurements of the spindle deviations from circularity were performed in two independent cycles. The first model measurement was performed using the dial indicator and magnetic chuck, while the second test measurement was done using the developed measuring apparatus. The results of measurements taken with the dial indicator are a reference for the results obtained using the measuring set and enable to determine the accuracy of observations made with the measuring set.

In order to determine the lathe spindle deviations from circularity using the dial indicator, a model shaft was installed in the lathe chuck (Fig. 7a). Then, the measuring end of the dial indicator was applied to the shaft surface and the indicator readings were taken for 12 angular settings of the spindle (every 30°). The measurement was made in 3 series and averaged results are summarized in Table 1.

Table 1. Summary of averaged results of measurements that were taken with the use of the dial indicator to determine deviations from circularity while the lathe spindle rotates and selected averaged results of measurements taken with the fibre signalling device
Tabela 1. Zestawienie uśrednionych wyników pomiarów odchyłek od kołowości podczas obrotu wrzeciona tokarki z użyciem czujnika zegarowego i wybranych uśrednionych wyników pomiarów przy użyciu sygnalizatora światłowodowego

Location Położenie	Averaged results of measurement recorded with the dial indicator Uśrednione wyniki pomiaru czujnikiem zegarowym	Selected averaged results of measurements taken with the fibre signalling device Wybrane uśrednione wyniki pomiarów przy użyciu sygnalizatora światłowodowego	The difference Różnica
[^{0}]	[mm]	[mm]	[mm]
0	0.031	0.002	-0.029
30	0.095	0.077	-0.017
60	0.130	0.135	0.006
90	0.127	0.143	0.016
120	0.090	0.117	0.028
150	0.021	0.028	0.006
180	-0.040	-0.060	-0.019
210	-0.090	-0.109	-0.019
240	-0.121	-0.124	-0.003
270	-0.123	-0.130	-0.007
300	-0.087	-0.062	0.025
330	-0.032	-0.014	0.017
360	0.031	0.033	0.002

Then a two-point fibre signalling device was installed in the lathe chuck (Fig. 7b) and after starting the lathe spindle (at minimum speed of 18 rev/min) a sequence of 71 photos was taken using Canon 5 d Mark II the camera (Fig. 7c) equipped with the lens with the focal length f = 50 mm. During experimental works the camera was set on a tripod in the distance of about 0.35 m from the signalling device. For such a camera setting the ground sample distance came to 0.042 mm.

Table 1 provides the selected averaged results of measurements taken to determine deviations from circularity while the lathe spindle rotates using the fibre signalling device. Table 1 also provides selected results of measurements (out of 71 results) taken with a measuring set. These results were compared with results obtained using the dial indicator. On the basis of these selected results the external accuracy of measurements was evaluated.

Based on the images recorded by the signalling device, $x_i y_i$ coordinates of energetic centres for both fibre signals were determined in the image local coordinate system. For this purpose, we used our own software which relies on digital image processing [Gołuch et al. 2012]. The software enabled us to determine, inter alia, coordinates of the points. Figure 8 presents the distribution of survey points when the lathe spindle deviations from circularity were measured using the two-point fibre signalling device.

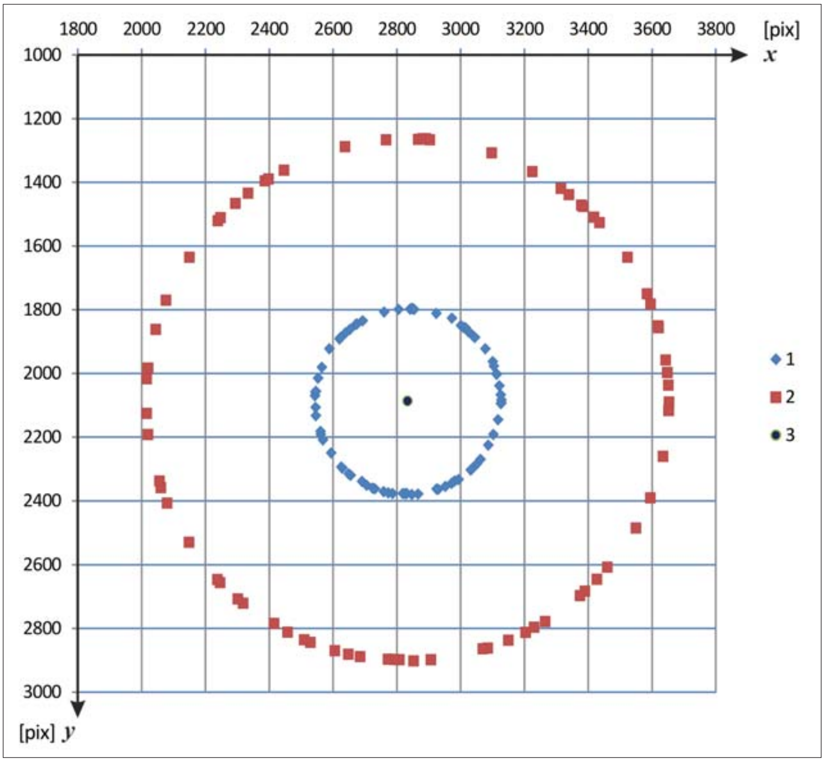

Fig. 8. Distribution of survey points when measuring the lathe spindle deviations from circularity with the use of a two-point fibre signalling device
Symbols: 1. determined position of the signal 1 (internal), 2. determined position of the signal 2 (external), 3. calculated centre of ellipses

Rys. 8. Rozmieszczenie punktów pomiarowych podczas pomiarów odchyłek od kołowości wrzeciona tokarki z zastosowaniem dwupunktowego sygnalizatora światłowodowego
Oznaczenia: 1. wyznaczone położenie sygnału 1 (wewnętrznego), 2. wyznaczone położenie sygnału 2 (zewnętrznego), 3. wyliczony środek elips

Based on the x_i, y_i coordinates of the survey points that have been determined, two ellipses were fitted using the parametric method with conditions. It was assumed that ellipses to be determined are similar figures with the proportionality factor *k* and a common centre, hence the conditions imposed on designated parameters of ellipses were conditions related to their similarity, namely:

1. mutual concentricity of ellipses (the same coordinates of both ellipses centres x_0, y_0),
2. the same inclination angle of ellipses' semi-major axes ($\phi = \phi_1 = \phi_2$),
3. the maintenance of proportionality of the respective semi-axes ($A_1/A_2 = B_1/B_2 = k$),
4. satisfying the condition of figures similarity: the ratio of the circuit length of two similar figures shall be equal to the coefficient of similarity *k*, and the ratio of similar figures surfaces should equal the square of similarity coefficient that is k^2.

Parameters characterizing fitting the ellipses: coordinates x_0, y_0 of ellipses centres, lengths of semi-axes (A_1, B_1, A_2, B_2) and the inclination angle of ellipses' semi-major axes (ϕ) are given in Table 2. In special circumstances survey points may be located on circles. In calculations it is assumed that the distribution of measuring points for each signal is similar to the ellipse rather than a circle. It is caused by the fact that during the image registration concentricity of the camera optical axis and the lathe spindle rotation axis is not maintained.

Table 2. Summary of the parameters characterizing the ellipse fitting in the survey points of both signals
Tabela 2. Zestawienie parametrów charakteryzujących wpasowane elipsy w punkty pomiarowe obu sygnałów

Id. Lp.	The ellipse parameters Nazwa parametru elipsy		The parameter values – Wartości parametrów	
			Ellipse 1 (internal) Elipsa 1 (wewnętrzna)	Ellipse 2 (external) Elipsa 2 (zewnętrzna)
1	the centre coordinates współrzędne środka x_0 / y_0	[pix]	2834.07 / 2086.66	
3	inclination angle ϕ kąt nachylenia ϕ	[°]	-33.548	
2	length of semi-major axis (*A*) and semi-minor axis (*B*) axis długość półosi dużej (*A*) i małej (*B*)	[pix]	290.60 / 289.83	823.46 / 821.26

The designated coordinates x_0, y_0 of ellipses centres were used to calculate averaged distance pairs between each of the signals and the centre of ellipses. Each pair of points of the two-point fibre signalling device is located along a single line, at the same angle with reference to the ellipses' semi-major axis (on the same radial radius).

On the basis of these averaged distances a plot (curve 2 Fig. 9) was drawn. It represents values of the lathe spindle deviations from circularity when the fibre signalling device is used.

In order to determine the internal conformity of results of measurements taken with the fibre signalling device the trend curve was fitted analytically (curve 3 Fig. 9) and the differences between coordinates from measurements and coordinates of the points lying on the set curve were calculated. The average error characterizing the internal compliance of measurement results came to ± 0.01 mm.

We checked whether there is a correlation between the results obtained using the dial indicator and the results obtained with the use of the fibre signalling device and we analysed the external accuracy of observations using the test measuring set. We relied on selected 12 averaged measurement results which are given in Table 1. Graphic distribution of results compiled in Table 1 is illustrated in Figure 9. Curve 1 (Fig. 9) shows the deviation from circularity when the lathe spindle rotates with the use of the dial indicator. The analysis of results compiled in Table 1 demonstrates that there is a strong correlation between the averaged results of measurements taken with the test measuring set and with the dial indicator. The computed correlation coefficient was 0.987. This relationship can be also noticed in Figure 9 as curves illustrating the distribution of survey points with two independent methods have the same phase and a comparable amplitude. On the basis of the differences compiled in Table 1, an average error of measurements taken with the measuring set was determined. It was ± 0.02 mm.

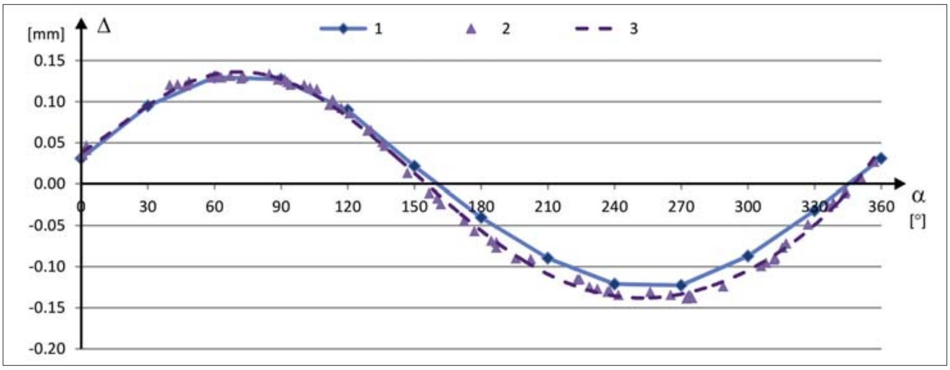

Fig. 9. Averaged results of measuring deviations from circularity when the lathe spindle rotates using the dial indicator and the fibre signalling device
Symbols: 1. measurement with the dial indicator, 2. measurement with the fibre signalling device, 3. the trend curve fitted in the measurement results using the fibre signalling device

Rys. 9. Uśrednione wyniki pomiarów odchyłek od kołowości podczas obrotu wrzeciona tokarki przy użyciu czujnika zegarowego i sygnalizatora światłowodowego
Oznaczenia:1. pomiar czujnikiem zegarowym, 2. pomiar z zastosowaniem sygnalizatora światłowodowego, 3. przebieg krzywej trendu wpasowanej w wyniki pomiarów z zastosowaniem sygnalizatora światłowodowego

CONCLUSIONS

The presented work refers to testing the usefulness of fibre signalling devices for establishing the position of survey points on the rotating parts.

On the basis of studies that have been carried out, it may be noticed that:

1. both curves (Fig. 9) representing deviations from circularity are compatible with each other, and the differences between them are in the range of -0.015 mm to 0.020 mm;
2. application of the two-point fibre signalling device enables to control results of observations made with the measuring set and to increase accuracy and reliability of measurements;
3. differences (at the level of the hundredths of a millimetre) are caused mainly by the fact that the camera optical axis is not parallel to the spindle rotation axis of the studied lathe when the two-point signalling device registers images;
4. the curve approximating the measurement results and determined deviations indicate a very high internal compatibility of observations that were made using the proposed measuring method;

5. advantage of the presented method with the use of the two-point fibre signalling device is the possibility to take measurements when the researched component rotates.

Further research works will focus on verification of the presented results and their application in the industrial conditions.

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POMIARY ODCHYŁKI OD KOŁOWOŚCI ELEMENTÓW OBROTOWYCH MASZYN Z ZASTOSOWANIEM SYGNALIZACJI ŚWIATŁOWODOWEJ NA PRZYKŁADZIE WRZECIONA TOKARKI

Streszczenie. Istnieje wiele maszyn, urządzeń oraz ciągów technologicznych, które mają elementy obrotowe (wały, osie, wrzeciona, koła toczne i napędowe itp.). Prawidłowa geometria tych elementów warunkuje bezawaryjną pracę, a w przypadku obrabiarek właściwe parametry geometryczne wytwarzanych półfabrykatów i zespołów. W związku z tym nowo wyprodukowane i eksploatowane tokarki podlegają sprawdzeniu pod względem prawidłowości zachowania geometrii ich części, które nadają przedmiotowi obrabianemu i narzędziu wzajemne położenie i ruch. Części te są pod względem geometrycznym prawidłowe, o ile błędy ich kształtu geometrycznego (odchyłki) nie przekraczają wartości ustalonych w normach. W odniesieniu do tokarek ich zużycie objawia się m.in. tzw. biciem wrzeciona (odchyłki od kołowości).

Odchyłki te wyznacza się głównie metodami warsztatowymi, jednak z uwagi na znaczne wymiary obrabiarek stosuje się również metody geodezyjne oraz nowe metody wykorzystujące przyrządy budowane na podstawie elementów elektroniki i optoelektroniki.
Autorzy w pracy przedstawili opracowany i wykonany zestaw pomiarowy bazujący na dwupunktowym sygnalizatorze światłowodowym, mocowanym na czas pomiarów w szczękach uchwytu wrzeciona tokarki. Położenie sygnalizatora podczas obrotu wrzeciona tokarki rejestruje kamera cyfrowa CCD/CMOS, a zapis obrazów dokonywany jest na jej karcie pamięci.
Celem przedstawionych prac badawczo-doświadczalnych było określenie wewnętrznej zgodności wyników pomiarów uzyskanych opracowanym i wykonanym zestawem pomiarowym, sprawdzenie, czy istnieje korelacja miedzy wynikami uzyskanymi z użyciem czujnika zegarowego oraz dokonanie analizy dokładności obserwacji wykonanych testowanym zestawem pomiarowym.
Opracowany zestaw pomiarowy pozwala wyznaczyć odchyłki od kołowości podczas obrotu wrzeciona tokarki z dokładnością ±0.02 mm.

Słowa kluczowe: pomiary tokarki, fotogrametria jednoobrazowa, kamera CCD/CMOS, sygnalizatory światłowodowe, technika optoelektroniczna

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