Device for automatic control of non-roundness and eccentricity of small rotating parts

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ABSTRACT

In the field of mechanical engineering, one of the key tasks is quality control of manufactured products. Particular attention should be paid to quality control of small parts used in precision devices, metalworking machines, and equipment for the metallurgical and defense industries that operate at high rotational speeds. The aim of this study is to develop a device for controlling the out-of-roundness and eccentricity of rollers weighing up to 10 g. The paper proposes a device using a new method of free rotation of cylindrical products with a radius of r = 4 mm on support rollers rotating at a speed of up to 15000 rpm. The advantage of this work is that the geometric and kinematic parameters of the device were determined depending on the mass-geometric characteristics of the controlled products in the absence of radial displacement of the center of mass: e=0. Five products with a conditional displacement of the center of mass e=4; 6; 8; 12; 15 µm, artificially created by removing a certain amount of material from the average outer surface. The mass of the product before and after removal was determined on analytical scales. The number of measurements of one product at each roller rotation speed was n=12. Based on the data obtained, the average angle of product breakage from the rollers was calculated, which can be used to judge the quality of the controlled products: as the eccentricity increases, the angle at which the product breaks from the rollers decreases. The measurement accuracy of the device was evaluated for the case when measurements were taken for a product with e=8 µm at n_r=9000 rpm.

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Introduction

Rapidly rotating products are widely used in various applications such as machinery and instrumentation, machine tools, metallurgical and defence equipment, and bearing systems. The quality of low mass and small size rotating body type products has an important influence on the accuracy, performance and service life of equipment. As soon as cracks, scratches, rust [[1], [2]] or material defects [[3], [4]] appear on their surface, the quality and performance of, for example, a bearing [5] will be significantly impaired

and even lead to major accidents. Therefore, the quality of products such as bodies of rotation must be fully checked before leaving the factory in order to fulfil the reliability requirements of the entire mechanical system [6].

Parts of the body of rotation type, for example, steel balls [[7], [8], [9]] are manufactured by various processes, including cold drawing, melting and heat treatment, crushing, grinding and rough (fine) lapping [10]. Due to this, various kinds of defects may occur at each stage of the manufacturing process. It is quite difficult to inspect these defects due to the curved and shiny surface of these balls.

As a result, manual visual inspection is still widely used in current inspection of steel balls. The inspector takes a sample of the entire batch of parts and compares it with a control sample. Although this method requires less investment and does not require high-precision equipment, however, it is difficult to improve production efficiency due to the large testing error [[11], [12]]. Moreover, the quality of visual inspection is easily influenced by personal factors, which leads to uneven testing quality of steel balls because the checker works under bright light for a long time, besides visual inspection can only detect obvious spots, cracks, etc., but cannot detect surface micro-cracks and subsurface cracks. For this reason, it cannot meet the needs of automatic defect detection with large batch, high accuracy [[13],[14], [15]] and high reliability [[16], [17], [18]].

The quality of small rotating bodies operating at high speeds is determined by the degree of eccentricity, i.e., the radial displacement of the center of mass. The displacement of the center of gravity from the geometric axis occurs due to material heterogeneity and manufacturing inaccuracies. The dynamic characteristics of rotating bodies are radial and axial displacements of the center of mass, misalignment of surfaces, and product shape errors (out-of-roundness), which create unbalanced forces and moments during operation, causing dynamic imbalance.

Currently, the machines used worldwide to determine dynamic imbalance are mainly designed for large and heavy rotating bodies (weighing from 20 g to 200 g), such as machine spindles, motor rotors, and car wheel hubs. In contrast, cylindrical rollers, which have a smaller volume and mass, pose a problem when determining dynamic imbalance. The development of high-tech equipment requires appropriate precision measurement technologies that can measure the inevitable micro-insignificant residual imbalance of cylindrical bearing rollers, which seriously affects the performance and service life of high-speed precision rolling bearings. A tiny cylindrical roller is a shaftless rotor that cannot be mounted directly on rotary bearing systems, and the vibration response excited by micro-imbalance is difficult to detect and easily confused with background noise. This article describes a device for controlling the quality of cylindrical roller manufacturing to determine eccentricity from 4 μm, which is equivalent to a microdynamic imbalance of 18.1 mg*μm. This device solves problems associated with detecting eccentricity in cylindrical rollers with a radius of $4*10^{-3}$ m, thus offering a new solution for detecting dynamic imbalance in other micro- and small rotating components.

Experimental part

To control non-roundness and the value of radial centre of mass displacement (RCMD), a method of free rotation of the product on support rolls [19] and an automatic control device based on it were developed.

Structurally, the inspection device in Figure 1 consists of a frame with rotating rolls and a drive of rotating rolls.
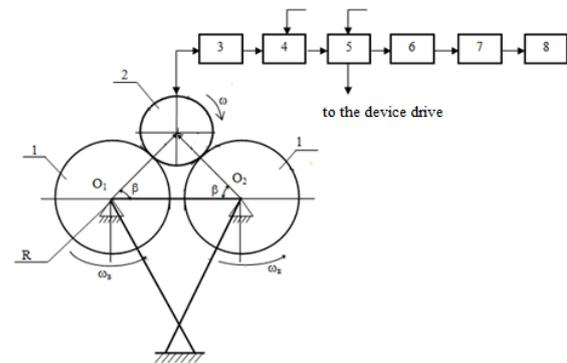
1 - rotating rollers, 2 - controlled product,
3 - speed sensor, 4 - amplifier, 5 - comparator,
6 - second pulse generator, 7 - pulse counter,
8 - digital indicator

Figure 1 - Functional diagram of the device

Controlled products are loaded onto rotating rollers using a piece-by-piece dispensing mechanism, thus starting the rotation of these products with simultaneous measurement of their rotation speed and acceleration time to the set speed. Cylindrical products with a radius of r=4 mm and a length of l=18 mm were used as the controlled parts. Eccentricity was artificially created by removing a certain amount of material from the middle of the outer surface. The drilling pattern is shown in Figure 2. The mass of the drilled-out material is calculated using the formula:

$$m = \pi r_0^2 h\sigma, \qquad (1)$$

where r_0 is the radius of the drilled hole; h is the drilling depth; σ is the specific weight of the material.

From Figure 2, the following equation can be derived:

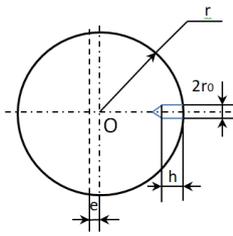$$2rl\sigma e = \pi r_0^2 h\sigma. \qquad (2)$$

Figure 2 – Drilling diagram for the part

Then the eccentricity will be equal to:

$$e = \frac{\pi r_0^2 h}{2 r l}, \qquad (3)$$

where r and l are the radius and length of the part being examined.

Then, for a given value of e=4 μm (device sensitivity), the mass of the drilled material should be:

$$m = \pi r_0^2 h \sigma = 3,14 * 0,00018344 * 7,85$$

$$m = 0,00452 \ g.$$

The measurement method is based on the following physical principle: when accelerating the product to a set speed, additional energy is required due to the need to overcome the momentum from inertial forces due to the radial displacement of the centre of mass.

To develop a method for calculating the center of mass displacement and other errors in cylindrical products, we will justify the choice of certain characteristics of the device and its main parameters.

Required initial data for calculation: r – radius of the controlled product, m; f – coefficient of sliding friction between the roller surface and the surface of the support rolls; e_{max} – maximum permissible eccentricity, m; e_{min} – specified sensitivity of the device to the minimum displacement of the center of mass, m. The maximum angular velocity of rotation of the product (roller) from the surfaces rotating it when the displacement of the center of mass is less than the maximum permissible value $e \leq e_{max}$. At $e \geq e_{max}$, the roller will vibrate on the rolls with periodic detachment from their surface. The maximum angular velocity of the roller is calculated using the formula:

$$\omega_r \leq \sqrt{\frac{g}{e_{max}} \cdot \frac{(\cos \beta - f \sin\beta)}{\sqrt{1+f^2}}}, \qquad (4)$$

where g –acceleration due to gravity, m/s²;

β - angle determining the postion of center of rotation on the rolls and calculated using the formula the roller's:

$$\beta = \arccos \frac{R + \delta/2}{R + r}, \qquad (5)$$

where R is the roller radius, m; δ is the gap between rollers, m. Parameters R and δ are specified by design.

Angular velocity of roller rotation

$$\omega_R = \frac{r}{R} \cdot \omega_r \qquad (6)$$

and the rotational speed

$$n = (\omega/2\pi) \cdot 60, \ min^{-1} \qquad (7)$$

required to accelerate the product to its maximum angular velocity with zero center of mass displacement

$$t_r = \frac{R \cdot \omega_r (1 + f^2) \sin\beta}{2 f \cdot g}. \qquad (8)$$

The maximum angular speed of the frame rotation is determined by the condition of continuous movement of the product from the roller, which can be represented as

$$g \left[\cos(\varphi + \beta) + f \cdot \sin(\varphi + \beta) \right] \geq \rho \cdot \omega_p^2 (\cos\beta + f \cdot \sin\beta)$$
$$+ e (\omega_f + \omega_r)^2 \left[\cos(\beta - \gamma) + f \cdot \sin(\beta - \gamma) \right], \qquad (9)$$

where φ is the angle of rotation of the frame from its initial position, degrees; ρ - distance from the center of the product to the axis of rotation of the frame (specified by design), m; γ - angle of rotation of the product, degrees.

It can be shown that the right-hand side (9) is maximal when

$$\gamma = \beta - \operatorname{arctg} f. \qquad (10)$$

The displacement of the center of mass of the product is assumed to be equal to the sensitivity of the device $e=e_{min}$. The maximum angle of rotation of the frame is determined by its design and is assumed to be equal to:

$$\varphi = \varphi_{max} \leq 90 - \beta \qquad (11)$$

Taking into account (10) and (11), expression (9) determines the maximum angular velocity of

the frame rotation at which the product with the eccentricity value at the sensitivity limit of the device will break when the frame rotates to the maximum angle. As the value of *e* increases, the breakaway angle will decrease, and at the value of e_{max}, the product will break away at a frame rotation angle of zero.

Results and Discussion

Experimental verification of the method was carried out on the developed device, the photo of which is shown in Figure 3.
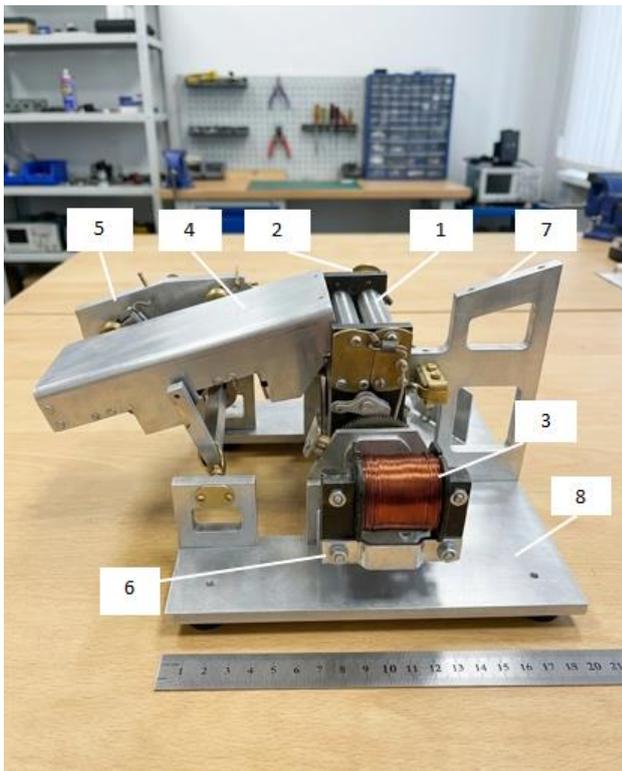
1 - rotating rollers, 2 - rotating frame, 3 - DC drive motor, 4 - guide chute, 5 - angle gauge, 6 - toggle switch, 7 - tray bracket, 8 - base of the device

Figure 3 - Non-roundness control device and RCMD

The process of product control consists of the following: switch on toggle switch 6, during 10 minutes the device starts to work only in idle mode to stabilise the speed mode. Then the controlled product with radius r=4 mm, length l=18 mm is placed manually on the support rollers 1 and accelerated to nominal speed. After that the frame 2 is rotated, the controlled product is torn off the rolls and at the moment of product tearing off the angle of inclination of the plane of rolls axes to the horizon is marked by the angle meter 5. Depending on a certain interval of the tear-off angle, the flap in

the guide chute 4 is opened and the product falls into one of two or three hoppers under the chute, the frame is returned to the initial position for control of the next product. Cylindrical products, which have passed the inspection, fall into the hoppers of sorting by quality groups depending on the interval of the tear-off angle α_{sa} from the rotating rolls. In the experiment there were three hoppers for sorting the products by quality, corresponding to α_{sa}: 1 hopper – $0^0 \div 15^0$, 2 hopper – $15^0 \div 26^0$ and 3 hopper – 26^0 and above.

The experiments were carried out in the following volume: the number of products - 5 pieces with RCMD e=4, 6, 8, 12, 15 μm, the speed of rotation of rolls n_r - 3000, 6000, 9000, 12000, 15000 rpm, the number of measurements of one product at each speed of rotation n=12. After the experiment, the average stall angle $\overline{\alpha}_{sa}$ for the products was calculated and a graph of the average stall angle as a function of RCMD was constructed using regression fitting (Figure 4).
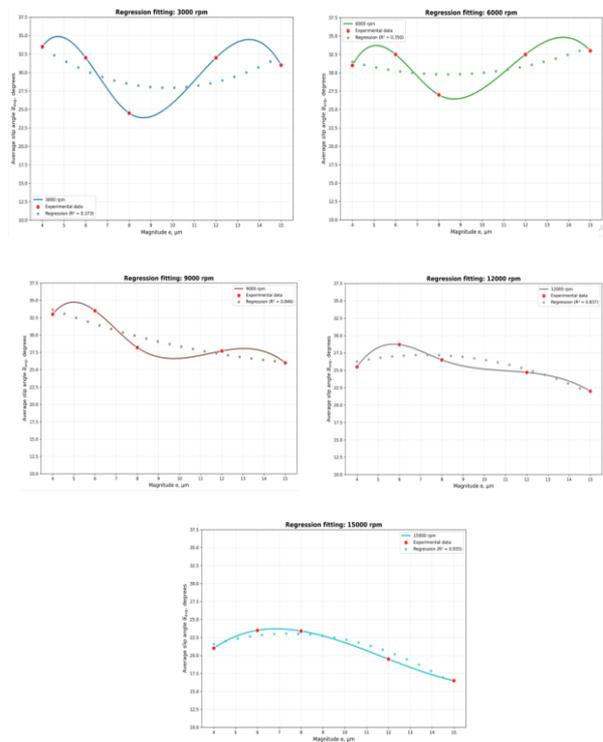

Figure 4 - Dependence of stall angle on RCMD

To evaluate the accuracy of the device measurements, 30 tests were carried out on the product with unbalance e=8 μm at roll rotation speed n_r=9000 rpm. The arithmetic mean was taken as the mathematical expectation of the mean stall angle $\overline{\alpha}_{sa} = 20,433^{\circ}$. The point estimate of the standard deviation was [20]:

$$\sigma_{\overline{\alpha}_{sa}} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{30}(\alpha_{sai} - \overline{\alpha}_{sa})^2} =$$

$$= \sqrt{\frac{41,367}{29}} = 1,194^{\circ} \qquad (12)$$

The value of the point estimate obtained in formula (12) satisfies the requirements of the experiment quite well.

The developed control device has the following design features. The base is made on height-adjustable legs. Support rollers are made of textolite and are mounted with their centre holes on freely rotating balls (one on each side). The support rolls rotate at a constant speed. In the initial position of the frame, the plane of the roll axes is horizontal. The workpiece is placed on the rolls and accelerated to nominal speed. After that the measurement is made: the frame is rotated around the axis and at the moment when the product comes off the rolls the angle of inclination of the planes to the horizon is noted on the angle scale. Then the frame is returned to the initial position to check the next product. The greater the unbalance of the product and therefore the influence of unbalanced forces, the smaller the limiting angle at which the product comes off the rolls. The measured value of the breakaway angle is converted into the value of the product quality parameter according to the calibration chart. Preliminary calibration is carried out using reference products with specified unbalance values.

For testing, real products were selected, whose imbalance was measured on analytical scales and conditionally expressed as the displacement of the center of mass from the geometric axis of the product (e=4; 6; 8; 12; 15 μm). Before taking measurements, the device was adjusted to compensate for the drift of the controlled product along its axis at high roll speeds.

It was found that at speed n_r=9000 rpm, this method of control of products allows sorting them into 2-3 quality groups. One and the same controlled product (for example, with RCMD e=8 μm) behaves differently at different speeds of rotation. The observed deterioration in the rotational stability of the product with e = 8 μm at low speeds (n_R = 9000 rpm) is explained by the influence of shape error (out-of-roundness), which is smoothed out at high speeds, giving way to the influence of imbalance. The mathematical justification for this effect is that imbalance causes inertial force:

$$F = m\omega^2 e \qquad (13)$$

where m is the mass of the product, e is the eccentricity, and ω is the angular velocity of rotation of the product. Thus, the product has a significant moment of inertia, which prevents instantaneous changes in the trajectory of the center of mass in response to microdefects on the surface. The experiment clearly shows that in the presence of imbalance, even ideal geometry leads to early failure of the product from the support rolls, and vice versa—at high speeds, imbalance suppresses the influence of minor manufacturing defects.

To date, certain results in measuring microimbalance have been obtained by researchers at Henan University of Science and Technology, who have developed a dynamic imbalance detection system with V-shaped supports. The results are shown in Table 1 below [[21], [22]]:

Table 1 – Parameters of prepared test rollers

Roller name	m (g)	m_0 (g)	e (m)	Length (m)	Diameter (m)
Standard	3.091	≈0	≈0	8*10⁻³	8*10⁻³
Unbalanced	3.077	14*10⁻³	3*10⁻³	8*10⁻³	8*10⁻³

According to Table 1, the developed device detects a roller imbalance equal to 42 mg*mm.

The results of the experiments obtained by the authors of the article are presented in Table 2:

Table 2 – Parameters test rollers by the authors

Roller name	m (g)	m_0 (g)	e (m)	Length (m)	Diameter (m)
Standard	7.098	≈0	≈0	18*10⁻³	8*10⁻³
Unbalanced	7.093	4.52*10⁻³	4*10⁻⁶	18*10⁻³	8*10⁻³

According to the results of experiments conducted on the developed device, the detected imbalance is equal to 18.1 mg*μm.

The sensitivity of this method for determining the stall angle in a separately conducted experiment with sample cylindrical products with given values of unbalance is 4÷6 μm of the conditional displacement of the centre of mass, which agrees well with theoretical calculations.

Conclusions

For experimental verification of the method of quality control of products, a prototype of the device was manufactured. The following main conclusions can be drawn from the testing of the prototype device:

- the method is simple in realisation and according to the above formulas it is possible for engineers and technicians to calculate geometric and kinematic parameters of the drive depending on mass-geometric characteristics of the controlled product;

- increasing values of non-circularity and eccentricity of the product lead to an increase in the time of acceleration of the product to a steady speed when rotating the product on the rolls;

- according to the angle of product breakage from the rotating rolls, it is possible to judge the quality of controlled products and sort them into quality groups;

- the device is recommended for control of fast-rotating small products of metalworking machines, equipment of metallurgical and defence industry.

Ұсақ айналмалы бұйымдардың дөңгелек еместігін және эксцентриситет шамасын бақылауға арналған құрылғы

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ТҮЙІНДЕМЕ

Машина жасау саласында негізгі міндеттердің бірі – өндірілген өнімнің сапасын бақылау. Жоғары айналу жылдамдығымен жұмыс істейтін дәл құрылғыларда, металл өндеу машиналарда, металлургия және қорғаныс өнеркәсібінің жабдықтарында қолданатын ұсақ бұйымдардың сапасын бақылау ерекше назар аударуды талап етеді. Осы зерттеудің мақсаты салмағы 10г. дейінгі роликтердің дөңгелектігі мен эксцентриситетін бақылауға арналған жаңа құрылғыны әзірлеу болып табылады. Бұл жұмыста 15000 айн/мин жылдамдықпен айналатын тірек роликтерінде радиусы r = 4 мм цилиндрлік бұйымдарды еркін айналдыру әдісін қолданатын құрылғы ұсынылған. Бұл жұмыстың артықшылығы құрылғының геометриялық және кинематикалық параметрлері бақыланатын бұйымдардың масса-геометриялық сипаттамаларына байланысты, е=0 масса центрінің радиалды орын ығысуы болмаған жағдайда анықталды. Тәжірибеге масса центрінің шартты ығысуы е=4; 6; 8; 12; 15 мкм болатын бес бұйымдар қойылды, бұл ығысу сыртқы ортаңғы беттен белгілі бір мөлшерде материалды алып тастау арқылы жасанды түрде жасалған. Материалды алып тастағанға дейін және кейін бұйымның массасы дәл аналитикалық таразыларда анықталды. Әрбір бұйым үшін біліктердің әр айналу жылдамдығында өлшеулер саны n=12 болды. Алынған деректер негізінде бұйымдардың біліктерден ажырау бұрышы есептелді, бұл бақыланатын бұйымдардың сапасын бағалауға мүмкіндік береді: эксцентриситет артқан сайын ажырау бұрышы азаяды. Алайда, төмен айналу жылдамдықтарында эксцентриситеті бар бұйымдар е=8 мкм пішін дәлсіздігіне байланысты тұрақсыз болады, бұл жоғары жылдамдықтарда тегістеліп, эксцентриситеттің әсеріне ұшырайды. Құрылғының өлшеу дәлдігі бұйым үшін е=8 мкм болған жағдайда, n_6=9000 айн/мин жылдамдықта жүргізілген өлшеулер негізінде бағаланды.

Түйін сөздер: ұсақ бұйымдар, бұйымдардың дөңгелек еместігі, бақылаудың дәлдігі, эксцентриситет, бақылауға арналған құрылғы.

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Устройство для контроля некруглости и эксцентриситета мелких вращающихся изделий

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АННОТАЦИЯ

В сфере машиностроения одной из ключевых задач является контроль качества изготовляемых изделий. Особое внимание требует контроль качества мелких изделий, применяемых в точных устройствах, металлообрабатывающих станках, оборудовании металлургической и оборонной промышленности, работающих с высокими скоростями вращения. Целью настоящего исследования является разработка нового устройства для контроля некруглости и эксцентриситета роликов массой до 10г. В работе предложено устройство с применением метода свободного вращения цилиндрических изделий радиусом r=4 мм. на опорных валках, вращающихся со скоростью до 15000 об/мин. Преимущество настоящей работы заключается в том, что геометрические и кинематические параметры устройства были определены в зависимости от массо-геометрических характеристик контролируемых изделий при отсутствии радиального смещения центра масс: e=0. На эксперимент были поставлены пять изделий с условным смещением центра масс e=4; 6; 8; 12; 15 мкм, искусственно созданного путем удаления определенного количества материала со средней наружной поверхности. Масса изделия до и после удаления определялась на точных аналитических весах. Количество измерений одного изделия на каждой скорости вращения валков составило n=12. По полученным данным был вычислен средний угол срыва изделий с валков, по которому можно судить о качестве контролируемых изделий: с увеличением эксцентриситета уменьшается угол, при котором происходит срыв изделия с валков. Точность измерений устройства была оценена для случая, когда измерения проводили для изделия с e=8 мкм при $n_в$=9000 об/мин.

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