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O.V. BRESHEV¹, P.L. NOSKO¹, O.V. BASHTA¹, S.YU. BOHDAN¹, A.O. BASHTA²
O.V.HERASYMOVA¹

¹State University “Kyiv Aviation Institute”, Ukraine

²National University of Food Technologies, Ukraine

DEVELOPMENT OF AN EXPERIMENTAL STAND AND METHODOLOGY FOR EXPERIMENTAL STUDIES OF A TWO-SUPPORT NON-CONTACT PNEUMATIC SPINDLE ON ADJUSTABLE CONICAL AEROSTATIC SUPPORTS

This article presents an experimental study of a high-speed pneumatic spindle with a two-point non-contact drive, equipped with adjustable conical aerostatic bearings. The design includes asymmetrical conical aerostatic bearings with adjustable clearances, intended to improve stability and load-bearing capacity during high-speed machining. The research follows a single-factor experiment methodology to verify a previously developed mathematical model.

Key design improvements include an asymmetrical support system and a differential pair of screws for precisely adjusting the clearance. The article describes the experimental setup, measurement equipment, and the specific methodology for adjusting clearances based on total axial displacement. The results confirm the effectiveness of the proposed technical solutions and the adequacy of the mathematical model. This study lays the foundation for optimising non-contact drives by adjusting aerostatic support parameters to ensure reliable operation during high-speed material processing.

Keywords: *pneumatic spindle, conical aerostatic bearings, adjustable clearance, non-contact drive, rotor stability, load-bearing capacity, experimental setup, high-speed machining.*

Introduction. The subject of this experimental study is a pneumatic spindle—a two-support, non-contact rotary drive mounted on conical aerostatic bearings with adjustable clearance, designed for the machining of materials, including high-speed machining. (Fig. 1) [1,2].



Fig. 1. Prototype of a pneumatic spindle

To verify the adequacy of the developed mathematical model [3,4] for calculating the integral characteristics of a pneumatic spindle, experimental studies were conducted on a two-support non-contact pneumatic spindle mounted on adjustable conical aerostatic supports. The objectives of the experimental studies were:

- to investigate the static and dynamic characteristics of a two-support non-contact

drive system in suspension mode [5,6];

- to investigate the static and dynamic characteristics of a two-support non-contact drive system in rotation mode with controlled input parameters [7,8];

- to improve the experimental equipment and methodology of the experimental studies [2];

- to experimentally verify technical solutions aimed at improving the design of contactless drives with a controlled aerostatic support system [9].

During the experimental studies, the main focus was on the parameters that determine the drive's functionality: motion stability and positioning accuracy of the shaft end (rotor), load-bearing capacity, spindle stiffness during rotation and in suspension mode, process air flow rate, torque, and range of characteristic adjustments [9].

Presentation of the Main Material.

Experimental Design. Ensuring a high level of reliability and clarity in the interpretation of experimental research results (field tests of the pneumatic spindle) is based on repeated measurements of the investigated parameters and the repetition of experiments while varying factors (replication). Here, we select a sample size that ensures sufficient accuracy [10].

To develop an accurate and consistent scheme and algorithm for field tests, a methodology for experimental research was developed. In it, with the aim of maximizing formalization and improving the reliability of the research results processing, the one-factor experiment methodology was used in accordance with [11]. Due to its maximum determinism, the single-factor experiment allows the greatest possible detail in the functional relationships under investigation, minimising cross-influence from varying conditions and factors. Therefore, despite the increase in the total number of measurement experiments, the pneumatic spindle was studied exclusively in single-factor experiments.

When investigating the processes involved in the operation of the pneumatic spindle, it is necessary to consider all significant factors, i.e., the independent variables to be investigated in the experiment (supply pressure p_s , left support clearance C^l , right support clearance C^r , rotor rotational speed n). In this context, each factor has its own range of variation – the set of all values it can assume. As noted earlier, the supply pressure of process air to the bearings varies between 0.3 and 0.6 MPa [2].

The clearance of the left bearing is within the range of 38 μm to 44 μm , and that of the right bearing is from 20 to 30 μm [2]. That is, the experimental pneumatic spindle sample is investigated at a 'soft' setting of its aerostatic support system. The combination of these parameter ranges (factors) constitutes the experimental design space. The response to the influence of factors is a dependent parameter [12], which in the experiment represents a random continuous variable.

Experiments conducted on a pneumatic spindle are active, single-factor (classical) experiments. The term 'active' implies the ability to influence the course of the experiment and to select the levels of the factors (p_s , C^l , C^r , n) in each trial. When planning an active experiment, the goal is to rationally select the factors and their variation ranges. The single-factor nature of the measurement experiment involves the sequential variation of each of the listed factors of the pneumatic spindle's state, while the rest are stabilised at a certain level [10]. We consider the external temperature and the pressure of the external air environment to be constant values ($p_a = \text{const}$, $t = \text{const}$).

We consider the processes simulated on the experimental installation are

deterministic (non-stochastic), since they are entirely determined by the initial conditions and are specified by mutually independent variables or factors.

The main stages of mathematical (statistical) processing of research results used in experimental studies include [13]:

- formation of measurement arrays;
- testing the hypothesis of the distribution of measured quantities;
- determining the mathematical expectation as the most reliable value (based on the hypothesis of a normal distribution of the random variable);
- estimating the variance of the random variable of the dependent parameter;
- determining the confidence interval;
- interpreting the obtained results.

Design of a pneumatic spindle on adjustable aerostatic bearings.

To conduct experimental studies, a prototype pneumatic spindle was fabricated on adjustable conical aerostatic bearings of various geometries (Fig. 1).

The operating principle and structural diagram of the pneumatic spindle under study were presented in [9].

To develop a methodology for experimental studies, we will examine the pneumatic spindle design in more detail. We will also demonstrate the assembly process for the experimental prototype of the pneumatic spindle and the adjustment of its support system based on the total clearance in the aerostatic supports (Fig. 2).

It is precisely through the total clearance set that the average clearances in conical aerostatic bearings are determined, thereby effectively regulating the characteristics of the pneumatic spindle and adjusting it to the conditions of its intended use.

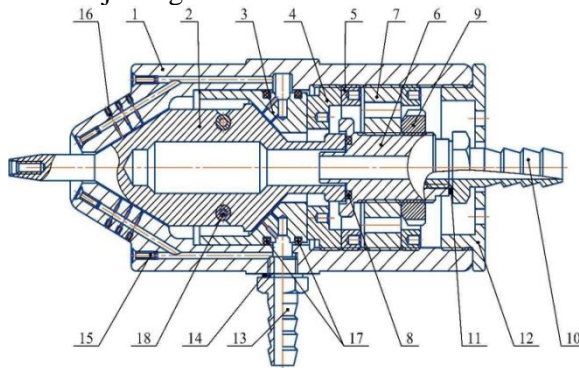


Fig. 2. Design of the pneumatic spindle under investigation

- | | |
|----------------------|---------------------------------------|
| 1 – housing; | 10 – end fitting; |
| 2 – rotor; | 11 – gasket; |
| 3 – bearing housing; | 12 – cover; |
| 4 – retaining ring; | 13 – side fitting; |
| 5 – retaining ring; | 14 – gasket; |
| 6 – bushing; | 15 – Laval nozzle of the gas turbine; |
| 7 – adjusting nut; | 16 – M2 screw; |
| 8 – graphite ring; | 17 – graphite ring (safety); |
| 9 – lock nut; | 18 – M3 screw. |

To independently regulate rotational speed and torque, independent of the supports' load-bearing capacity and stiffness, the pneumatic spindle's process air supply lines are separated. Air is supplied to the aerostatic supports via side fitting 13, which is screwed

into housing 1 and sealed with rubber gasket 14. To supply air to the supports, channels are drilled through the housing and sealed from the outside with screws 15 and 16.

The annular chamber, formed by the housing 1 and the end cap 3, ensures a uniform supply of air around the circumference into the channels and is sealed by two rubber rings 17. Air is supplied to the gas turbine via the end fitting 10, which is connected to the sleeve 6 via the gasket 11. The sleeve has no mechanical connection to the rotor, so its position is adjusted relative to the housing via a double differential screw pair. The latter comprises two screw pairs: ‘sleeve-adjusting nut’ (pitch 0.75 mm) and ‘housing-adjusting nut’ (pitch 1 mm).

One turn of the adjusting nut 7 corresponds to an axial displacement of the sleeve 6 by 0.25 mm, and the required clearance of 5 μm corresponds to a turn of 7.20. The permissible installation error of 7.20 ± 20 corresponds to a clearance of 5 ± 1.3 μm .

The adjustment of the differential screw pair is secured by the retaining ring 5 and nut 9. The small clearance between the sleeve and the rotor prevents process air losses, and potential contact is prevented by fitting a safety graphite ring 8 on the end of the sleeve. Air flows through the rotor's internal channels to the turbine nozzles 18, then, after exiting the nozzles and generating reactive forces, is discharged through the openings in the housing 1 (see Fig. 2).

Experimental setup

Structurally, the setup consists of three parts: an experimental pneumatic spindle prototype (Fig. 3), a pneumatic system supplying process air to the spindle's supports and turbine, and measuring equipment.

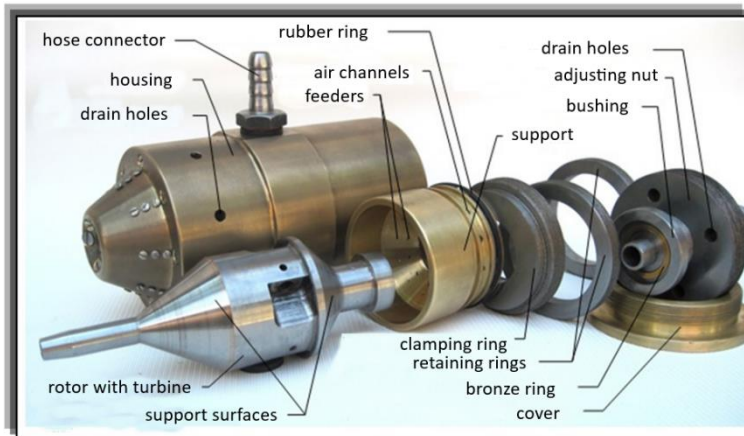


Fig. 3. Pneumatic spindle in disassembled form

A diagram of the experimental setup is shown in Fig. 4. In it, the experimental pneumatic spindle sample is fixed in a horizontal position with the clearances of the adjustable aerostatic supports pre-set in accordance with [9].

Air supply pipes from the pneumatic system are connected to the fittings; the system consists of two regulated-pressure lines (to the supports and the turbine), with valves, measuring instruments, and a common supply line from compressor 1. Process air, purified of oil vapours, water and mechanical impurities in accordance with GOST 17433-80, Class 1 contamination, is supplied to the pneumatic spindle. The compressor compresses the air to 0.6–0.8 MPa; to smooth out pressure pulsations in the compressed air, air receivers are provided in the compressor unit. Purification is carried out by filter 3 and oil-water separator 5. Valves 8 and 9 open the supply of process air to the

regulated-pressure process air mains, which feed the aerostatic supports and the gas turbine, respectively. The pressure in the lines is regulated by pressure reducers **6** and **11**. The air flow rate, after reduction to a pressure of 0.3–0.6 MPa, is measured by rotary flow meters **4** and **10**. Air pressure is monitored throughout the pneumatic system using pressure gauges **2**, **7** and **12**.

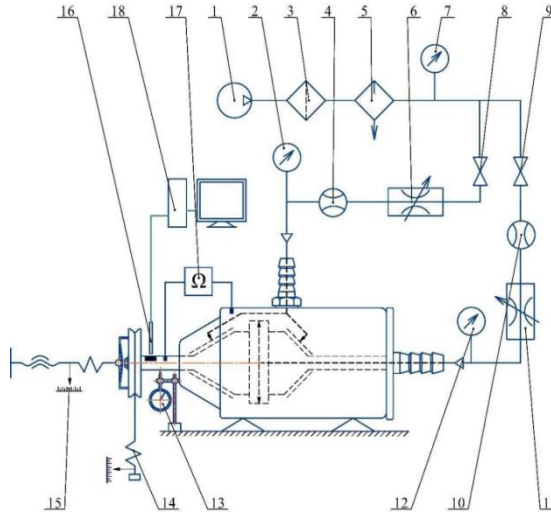


Fig. 4. Experimental setup

- | | |
|--|-------------------------------|
| 1 – compressor; | 10 – flow meter; |
| 2 – pressure gauge for air pressure on the supports; | 11 – reducer; |
| 3 – filter; | 12 – turbine pressure gauge; |
| 4 – flow meter; | 13 – clock-type indicator; |
| 5 – oil-water separator; | 14 – radial load dynamometer; |
| 6 – gearbox; | 15 – axial load dynamometer; |
| 7 – process pressure gauge; | 16 – frequency meter sensor; |
| 8 – air supply valve to supports; | 17 – ohmmeter; |
| 9 – air supply valve to the turbine; | 18 – PC with ADC. |

The experimental setup's equipment allows the following parameters to be set, adjusted and measured in real time:

- air flow rate to the supports and, separately, to the turbine;
- process air supply pressure on each line;
- the rotational speed of the pneumatic spindle rotor;
- radial load on the rotor, applied in a cantilevered manner;
- axial load on the rotor;
- rotor runout and its displacement under radial load;
- contact between the bearing surfaces of the aerostatic bearings, measured using an ohmmeter **17**;
- the torque on the rotor.

The rotor's rotational speed is determined using an optical method, which eliminates the mechanical action on the rotor during measurements, a characteristic of mechanical tachometers. A black light-absorbing strip or mark is applied to the rotor. The LED of the sensing element **16** detects the transition from the reflective metal surface of the rotor end to the absorbing black surface twice per revolution. The signal is processed by the ADC **18**, and the result is displayed on the PC monitor.

Radial and axial loads are generated and measured by spring-loaded dynamometers **14** and **15**, respectively, with the forces applied via a stationary pulley simulating the tool. The pulley's immobility relative to the assembly is ensured by mounting it on the rotor via a radial thrust bearing.

When measuring torque, however, the pulley must move with the rotor. To this end, it is secured to the rotor by a thrust washer at the end of the rotor and acts as a friction block, in which the torque equals the moment due to the friction forces acting on the block. The tension force of the cable on the block (against the resistance of friction forces from rotation) is measured by a radial load dynamometer **14**, and then multiplied by the block's lever arm to determine the torque. Rotor runout and its displacement under radial load are measured using micrometre **13** (a dial-type indicator) secured to the base by a tripod.

Conditions and methodology of experimental studies

The following conditions are observed when conducting experimental studies:

- the pneumatic spindle and dial gauge are fixed immovably and rigidly to a solid base;
- process air is supplied at a constant temperature of 20°C, ensuring an isothermal flow of lubricant through the bearings;
- process air is supplied to the spindle via flexible connections to eliminate mechanical impact and the transmission of vibrational loads in any direction;
- process air enters the aerostatic bearings and the gas turbine free of oil and mechanical impurities;
- to eliminate the pressure pulsations characteristic of piston compressors, a receiver is installed in the high-pressure line, and adjustable throttles provide additional smoothing.

The experimental research methodology is presented in several stages: setting up the equipment and measuring instruments, adjusting the input parameters and monitoring the system's transition to the set operating mode, and recording and processing the measurements.

Equipment setup begins with setting the average values of the pneumatic spindle support clearances [9]. The pneumatic lines are connected, and their tightness is checked by applying a test pressure to the supports and the turbine. Once the compressor receiver has been filled to 0.7–0.8 MPa, pressure is supplied to the line feeding the supports. Using the adjustable throttle **6** (reducer), the supply pressure, p , is adjusted according to the experimental conditions. After pressure is applied to the bearing clearances, the spindle shaft is suspended in the airflow; the presence of aerostatic suspension is confirmed by an infinite increase in resistance between the housing and the rotor, as indicated by ohmmeter **17**. The frequency meter's sensing element is brought to the mark on the output section of the shaft at a distance of 3–5 mm; the ADC is switched on, and by manually rotating the shaft, the passage of the measurement signal past the mark is checked. A dial-type indicator **13** is brought into contact with the output section of the shaft. To generate and measure radial and axial loads on the end section of the rotor, where the tool is clamped during operation of the pneumatic spindle, dynamometers **14** and **15** are installed (see Fig. 4).

In the absence of an air supply to the gas turbine, we conduct experimental studies of the pneumatic spindle in suspension mode. By sequentially changing the boost pressure, average clearances, and axial and radial loads, we obtain new operating modes for the suspension. For each of the established modes, we determine the main output

parameters (air flow rate, maximum axial and radial loads, rotor displacement). The equipment is configured so that repeated measurements of a single parameter under identical conditions yield a set of consecutive measurements with a variation of no more than 5%.

For the experimental study of the pneumatic spindle in rotation mode, after applying pressure to the supports by opening valve **9**, we verify the creation of the rotor suspension by rotating it and/or by the ohmmeter readings, and supply air to the gas turbine main line. Using the adjustable throttle **11**, we gradually increase the pressure (see Fig. 4). As this happens, the rotor begins to accelerate. Each fixed pressure corresponds to its own rotational frequency in the set mode.

To investigate the dependence of the rotor speed on the air supply pressure to the turbine, we perform a stepwise increase the pressure in 0.05 MPa increments until the set rotational speed is reached.

In the set operating mode, we monitor rotor runout using a micrometre. To measure the starting torque, we brake the rotor via a brake unit and apply pressure.

The radial load-bearing capacity of the bearing during rotation is measured using a dynamometer, with the pulley not fixed relative to the shaft and remaining stationary during measurements. The radial load applied via the pulley corresponds to half the dynamometer reading. The maximum permissible radial load will be 5% less than that required to cause contact between the bearing surfaces.

By sequentially and incrementally varying the supply pressure of process air to the supports, the set average clearances via the total clearance, and the radial loads, we obtain a set of operating modes for the pneumatic spindle. For each mode, we determine the main output parameters (air flow rate, maximum radial load, etc.). The equipment is configured so that repeated measurements of a single parameter under identical experimental conditions yield an array of measurements without outliers. With the laboratory equipment configured, 3–5 runs with measurements typically yield a variation of up to 5%.

Exit from the measurement mode is carried out in the following sequence: the load is removed, and the air supply to the turbine is stopped. After the rotor has come to a complete stop, the air supply to the aerostatic supports is shut off, and the measuring equipment is switched off.

Based on the experimental data obtained, tables of test results were compiled, and graphical dependencies were plotted that correlate with theoretical calculations. Each point on the experimental graph is obtained after statistical processing of a set of ten observations using the method described in [13].

The main condition for the application of statistical methods is the statistical stability of the data – the frequency with which results fall within a specified interval as the number of experiments increases. In this context, a ‘substantive interpretation’ is carried out:

- verification of the physical meaning of the results obtained in accordance with prior assumptions and theoretical data;
- verification of the results’ conformity with accepted mathematical models.

Discussion of the results.

Method for setting and adjusting the clearances of conical aerostatic bearings.

Given that the rotor ‘floats’ in the air-oil flow, its axial position is determined by the ratio of the axial stiffnesses, which determine the equality of the reactions of the left and right supports at certain axial eccentricities. It is evident that, for identical designs

and air-lubricant supply conditions of the right and left aerostatic bearings, the calculated position of the rotor will correspond to the centre – the total clearance between the pairs of conical bearing surfaces will be divided equally.

Since, in the modernised pneumatic spindle, the conical supports have different designs and shapes of the conical bearing surfaces, the equality of axial forces is established when the rotor is suspended with different clearance values in the right and left supports. In this case, the task of establishing the required total clearance becomes relevant, taking into account the prior determination of the values of its components – the clearances with air lubrication in the right and left conical aerostatic supports when the pneumatic spindle rotor is in equilibrium.

During installation and adjustment of the pneumatic spindle, the total clearance between the two aerostatic bearings is set and monitored. In [9], based on calculations and graphical constructions, the authors determine a correspondence between the clearances in the right and left supports, which self-adjust in the aerostatic suspension under the equality of axial reactions. Their total clearance is set during pneumatic spindle adjustment. It corresponds to the expected distribution of clearance values when the rotor reaches equilibrium in the absence of external load for each design case.

For example, if the design case is the rotor's equilibrium position with a clearance of 0.02 mm on the right bearing and 0.038 mm on the left, then when assembling the pneumatic spindle, a nominal total axial clearance of 0.1043 mm must be set. How the total axial clearance on a pneumatic spindle is determined and set will be explained below. As the load increases, regardless of its direction, the clearance with air lubrication decreases at the bearing whose reaction is directed opposite to the external load. The axial load reduces the clearance uniformly across the entire bearing surface, whilst the radial load reduces it only in a sector, causing the clearance to vary along the cone (or along a circle in the radial cross-section of the cone). The maximum load corresponds to a minimum permissible residual clearance of 0.003–0.004 mm, whilst contact between the bearing support surfaces constitutes an emergency and unacceptable operating condition for the pneumatic spindle, constituting an overload.

The design of the pneumatic spindle allows for reducing the nominal (average) clearance at each support to 0.010–0.015 mm. With such clearance values, the rigidity and load-bearing capacity of the supports and the entire spindle increase significantly, but the precision requirements of the support system's adjustment also increase. Such 'rigid' adjustment of the support system is typical for massive rotors of medium- and high-power spindles, but can also be applied in low-power pneumatic spindles when operating with the maximum possible radial and axial forces for them.

In the pneumatic spindle under investigation, two clearances of the two-support aerostatic system (see Fig. 2) are set and adjusted simultaneously: between the rotor **2** and the pneumatic spindle housing **1** (left support), and between the rotor **2** and the bearing block **3** (right support). The simultaneous setting of nominal values of 0.02 mm and 0.038 mm for the left and right supports, respectively, is achieved by the axial displacement of the thrust pad **3** relative to the housing **1**, as shown in Fig. 5.

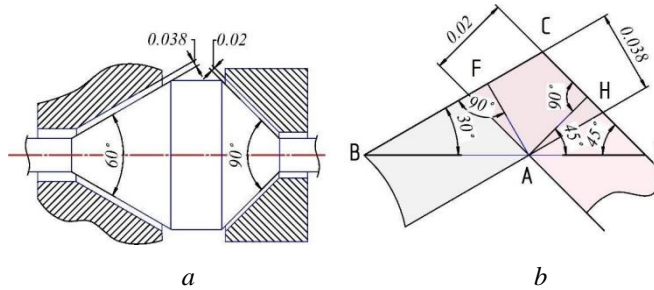


Fig. 5. Schematic of clearance adjustment

The displacement is achieved by rotating the clamping ring **4** via its threaded connection to the pneumatic spindle housing. The conical surface of the pneumatic spindle housing **1** is fixed. It serves as the reference for setting the two gas-lubricated clearances that separate the rotating rotor **2** and the stationary components – the pneumatic spindle housing **1** and the bearing housing **3** (see Fig. 2).

In Fig. 5a, the rotor is shown in the middle position, with clearances of 0.02 mm on the right-hand side and 0.038 mm on the left-hand side. The values of these clearances are set during the installation of the pneumatic spindle as the sum in the axial direction and are determined by the displacement **|BD|** (Fig. 5b) of the bearing **3** along the axis of rotation of the rotor **2**, which coincides with the axis of symmetry of the bearing **3** and the axis of the conical bearing surface of the left support belonging to the housing **1**.

To set the clearances, bearing **3** must be moved a distance **|BD|** and secured with the retaining ring from **4** to prevent it from shifting to the left. Due to the conical shape, the sum of the clearance values, normal to the surfaces, is not equal to the axial displacement of bearing **3** from the zero-clearance position (when all conical surfaces are in contact). The cone of the left support has a vertex angle of 60°, and that of the right support is 90°, so the components of the axial displacement of the bearing shell required to form equal clearances are also not the same. To determine the axial displacement of bearing **3** when setting two clearances of corresponding values, we connect points **B** and **D** on the diagram with a line parallel to the rotor's axis of rotation after the imaginary convergence of the 0.02 mm and 0.038 mm clearances until they intersect. Where the clearance lines intersect at point **A**, a triangle **BDC** is formed (Fig. 5b). The hypotenuse **[BD]** of triangle **BDC** is equal to the value of the required axial displacement of bearing **3** when setting the air clearances, provided that rotor **2** in the middle position is separated from the stationary parts by a total normal clearance of the nominal value – 0.058 mm [9]. The hypotenuse **[BD]** is equal to the sum of the hypotenuses **[BA]** and **[AD]** of triangles **ABF** and **AHD**. From triangle **ABF**, we find:

$$BA = FA / \sin 300 = 0,076 \text{ mm.}$$

From triangle **AHD**, we find the value of **[AD]**:

$$AD = AH / \sin 450 = 0,0283 \text{ mm.}$$

Thus, to ensure the corresponding normal clearances of 0.02 mm and 0.038 mm in the left and right conical aerostatic supports, the axial displacement of the bearing from the zero-clearance position (where all bearing surfaces are in contact) must be **|BD|** = 0.1043 mm.

This value must be rounded and set within the permissible tolerance limits during installation. We take $|\mathbf{AD}| = 0.10 \pm 0.01$ mm. The pitch of the fine thread on the clamping ring is 1 mm, so an axial displacement of 0.01 mm occurs when the clamping ring **4** is rotated through an angle of 3.6° , which is easily achievable during installation and can be controlled by measurement.

The procedure for installing and adjusting the clearances of the conical aerostatic bearings of the pneumatic spindle (see Fig. 2) is as follows:

- move the rotor **2** until it comes into contact with the pneumatic spindle housing **1** along the conical support surfaces;
- by rotating the clamping ring **4** clockwise, bring the thrust pad **3** to the stop and contact with the rotor **2** along the conical surfaces;
- mark the 'zero' angular position of the clamping ring **4**, which corresponds to zero clearances in the drive's aerostatic bearings;
- from the zero position, rotate the clamping ring **4** anticlockwise by an angle of $36^\circ \pm 4^\circ$, which will ensure an axial displacement of the bearing **3** of 0.1043 ± 0.01 mm and nominal clearances in the supports of 0.02 mm and 0.038 mm with permissible errors;
- secure the new angular position of the clamping ring **4** using the locking ring **5**;
- Using a micrometre (dial gauge), measure the resulting play (total clearance) of rotor **2** when it is displaced from the housing **1** of the pneumatic spindle to the bearing housing **3** (see Fig. 2); it should be 0.1043 ± 0.01 mm.

Conclusions

1. The design of the developed prototype pneumatic spindle is described; compared to typical drive designs, it features the following improvements [14]:

- the system of four supports (two radial and two thrust bearings to hold the rotor during rotation) has been replaced by two radially-supported conical aerostatic bearings;
- the conical supports have different angles of inclination of the working surfaces and lengths (asymmetrical support system) in accordance with the load;
- in the conical supports, the values of the mean clearances with air lubrication (and, accordingly, the stiffness and load-bearing capacity of the entire drive) are adjusted using a screw pair;
- an increased number of supply lines for delivering air lubrication to the most heavily loaded left-hand conical support.

2. The content of the experimental research plan for the pneumatic spindle prototype has been outlined, ensuring a high level of reliability, accuracy and clarity in the interpretation of the experimental results (field tests of the pneumatic spindle).

3. An experimental setup has been developed, which structurally consists of three parts: the prototype pneumatic spindle, a pneumatic system for supplying process air to the supports and the turbine of the pneumatic spindle, and measuring equipment. The experimental setup allows for field testing of the developed pneumatic spindle on adjustable conical aerostatic supports of various geometries and for investigating its static and dynamic characteristics during gap adjustment: stiffness, maximum lift force (load-bearing capacity), rotor rotation speed, process air flow rate separately for the support system and the turbine, torque on the rotor, shaft runout, etc.

4. A methodology for conducting experimental studies is presented, in which the choice of statistical methods for processing the obtained results is justified, and their content is explained, as well as their evaluation.

5. A methodology for setting and adjusting the clearances of conical aerostatic supports is described, which involves controlling the total clearance of the two aerostatic supports to ensure correspondence between the clearances in the right and left supports.

Examining the issues regarding the preparation and conduct of experimental studies of a pneumatic spindle on adjustable conical aerostatic supports allows the following tasks to be addressed:

- to investigate the static characteristics of a multi-support pneumatic spindle in a suspended mode with regulation of input parameters (clearances, air pressure);

-to investigate the static-dynamic characteristics and dynamic properties of the pneumatic spindle during rotation with control of input parameters (clearance, pressure, rotational frequency, load);

-to verify the adequacy of the developed mathematical model – the results of characteristic calculations based on the analytical solution obtained using the proposed parametric reduction of conical support systems to radial and thrust systems equivalent in stiffness and load-bearing capacity;

-to verify the adequacy of the computational computer experiment [15] for determining the static and dynamic characteristics of the non-contact drive;

- experimentally verify the effectiveness of regulating the static and dynamic stability of a pneumatic spindle by varying the clearance values in its supports.

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Breshev Oleksii Volodymyrovych - PhD in Engineering, degree applicant, Department of Applied Mechanics and Materials Engineering, State University “Kyiv Aviation Institute”, 1, Lubomyr Huzar Ave. 1, Kyiv, Ukraine, 03058, E-mail: abreshev@gmail.com, <https://orcid.org/0009-0007-4176-775X>.

Nosko Pavlo Leonidovych – Doctor of Technical Sciences, Professor, Professor of the Department of Applied Mechanics and Materials Engineering, State University “Kyiv Aviation Institute”, 1, Lubomyr Huzar Ave., Kyiv, Ukraine, 03058, tel. 406-78-42, E-mail: nau12@ukr.net, <https://orcid.org/0000-0003-4792-6460>.

Bashta Oleksandr Vasylovych - PhD in Engineering, Associate Professor, Department of Applied Mechanics and Materials Engineering, State University “Kyiv Aviation Institute”, 1, Lubomyr Huzar Ave., Kyiv, Ukraine, 03058, E-mail: oleksandr.bashta@npp.kai.edu.ua, <https://orcid.org/0000-0001-7914-897X>.

Bohdan Svitlana Yuriivna - PhD in Engineering, Associate Professor, Department of Applied Mechanics and Materials Engineering, State University “Kyiv Aviation Institute”, 1, Lubomyr Huzar Ave., Kyiv, Ukraine, 03058, E-mail: svitlana.bohdan@npp.kai.edu.ua, <https://orcid.org/0000-0002-9506-6357>.

Bashta Alla Oleksiivna - PhD in Engineering, Associate Professor, Department of Health Products Technology, National University of Food Technologies, 68 Volodymyrska str. Kyiv, Ukraine, 01601, tel. 289-54-72, <https://orcid.org/0000-0003-0310-3788>

Herasymova Olha Viacheslavivna - junior researcher of the Department of Applied Mechanics and Materials Engineering, State University “Kyiv Aviation Institute”, 1, Lubomyr Huzar Ave., Kyiv, Ukraine, 03058, tel. 406-78-42, E-mail: nau12@ukr.net

О.В. БРЕШЕВ, П.Л. НОСКО, О.В. БАШТА, С.Ю. БОГДАН, А.О. БАШТА, О.В.ГЕРАСИМОВА

РОЗРОБКА ЕКСПЕРИМЕНТАЛЬНОЇ УСТАНОВКИ ТА МЕТОДИКИ ЕКСПЕРИМЕНТАЛЬНИХ ДОСЛІДЖЕНЬ ДВООПОРНОГО БЕЗКОНТАКТНОГО ПНЕВМОШПИНДЕЛЯ НА РЕГУЛЬОВАНИХ КОНІЧНИХ АЕРОСТАТИЧНИХ ОПОРАХ

У цій статті представлено експериментальне дослідження високошвидкісного пневматичного шпинделя з двоточковим безконтактним приводом, оснащеного регульованими конічними аеростатичними підшипниками. Конструкція включає асиметричні конічні аеростатичні підшипники з регульованим зазором, призначені для підвищення стійкості та несучої здатності під час високошвидкісної обробки. Дослідження проводилося за методологією однофакторного експерименту з метою перевірки раніше розробленої математичної моделі.

Ключові вдосконалення конструкції включають асиметричну систему опори та диференціальну пару гвинтів для точного регулювання зазору. У статті описано експериментальну установку, вимірювальне обладнання та конкретну методологію регулювання зазорів на основі загального осьового зміщення. Результати підтверджують ефективність запропонованих технічних рішень та адекватність математичної моделі. Це дослідження закладає основу для оптимізації безконтактних приводів шляхом регулювання параметрів аеростатичної опори для забезпечення надійної роботи під час високошвидкісної обробки матеріалів.

Ключові слова: пневматичний шпиндель, конічні аеростатичні підшипники, регульований зазор, безконтактний привід, стабільність ротора, несуча здатність, експериментальна установка, високошвидкісна обробка.

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Брешев Олексій Володимирович – кандидат технічних наук (PhD in Eng. S.), здобувач, Державний університет “Київський авіаційний інститут”, кафедра прикладної механіки та інженерії матеріалів; м. Київ, Україна; e-mail: abreshev@gmail.com, <https://orcid.org/0009-0007-4176-775X>.

Носко Павло Леонідович – доктор технічних наук, професор, професор кафедри прикладної механіки та інженерії матеріалів, Державний університет «Київський авіаційний інститут», пр-т Любомира Гузара, 1, м. Київ, Україна, 03058, тел. 406-78-42, E-mail: nau12@ukr.net, <https://orcid.org/0000-0003-4792-6460>.

Башта Олександр Васильович - кандидат технічних наук, доцент, кафедра прикладної механіки та інженерії матеріалів, Державний університет “Київський авіаційний інститут”, пр-т Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: oleksandr.bashta@npp.kai.edu.ua, <https://orcid.org/0000-0001-7914-897X>.

Богдан Світлана Юріївна - кандидат технічних наук, доцент, кафедра прикладної механіки та інженерії матеріалів, Державний університет “Київський авіаційний інститут”, пр-т Любомира Гузара, 1, м. Київ, Україна, 03058, E-mail: svitlana.bohdan@npp.kai.edu.ua, <https://orcid.org/0000-0002-9506-6357>.

Башта Алла Олексіївна - кандидат технічних наук, доцент, кафедра технології оздоровчих продуктів, Національний університет харчових технологій, вул. Володимирська, 68. Київ, Україна, 01601, тел. 289-54-72, <https://orcid.org/0000-0003-0310-3788>.

Герасимова Ольга Вячеславівна – м.н.с. кафедри прикладної механіки та інженерії матеріалів, Державний університет “Київський авіаційний інститут”, пр. Любомира Гузара, 1, м. Київ, Україна, 03058, тел. 406-78-42, E-mail : nau12@ukr.net.