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ANALYSIS OF DESIGN AND CALCULATION OF PARAMETERS OF NON-CONTACT DRIVE SINGLE-SUPPORT SYSTEM

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Summary: The design variants of rotary motion non-contact drive single-support system are analyzed. A design model and determination of bearing capacity, inflexibility and air consumption of single-support system with aerostatic conical angular contact bearing are suggested. Calculation of parameters and comparative analysis of single-support system aerostatic bearing in traditional design is being done and also with up-to-date ring shape cage and labyrinth packing in outcome gas lubricant.

Key words: non-contact bearing, single-support system, backpressure, bearing capacity, inflexibility.

INTRODUCTION

We understand non-contact drive single-support system of rotation moment as self-sufficient, in terms of stability, system with an aerostatic angular contact bearing. The purpose of contact is to put the drive into the rotational movement of working bodies, such as a diamond cutter or pumps impellers, compressors, etc., which are held supporting by bearing systems [1].Non-contact rotation is made by dividing movable and fixed parts of a drive with gas-lubricated gap, and electromagnetic forces transfer rotating moment to the moving part (rotor).Aerostatic suspension single-support system has minimal friction losses and other advantages, but sufficient bearing capacity and stiffness level at low cost air consumption and the lowest feed pressure should be reached.

Single-support system that is being considered has several features taking it research and calculation beyond existing techniques because of short bearing length ratio, bearing face incline relative to the rotation axis. The article objective is to engineer design model and design procedure of single-support system to provide rational choice of geometric parameters and to improve structure of aerostatic suspension drive for maximal inflexibility and bearing capacity.

CALCULATION OF KEY PARAMETERS OF SINGLE-SUPPORT SYSTEM

The typical example of single-support system is spindle assembly of mono-crystal automatic plating machine – "Almaz-150 ASA" [2]. It's 3D model spindle assembly with inward cutting detachable circle (IBDC) **6** and mono crystal **7** fixed on holder **8** [3] are shown on fig.1. Single-support system consists of aerostatic (gas-static) angular contact bearing, strainer **3**, direct drive magnetic system **4** for rotation moment non-contact drive due to interaction with stator **5**. Aerostatic bearing has movable support **1** and stable support **2**. Their conical bearing have contact angle α relative to the axis that determines relation between radial and axial loads of gas lubricate. Contact angle has to be minimum permissible for the systems with dominant radial load at the same time secure with axial stability of single-support system.

The system under consideration is a single-support system. The movable support **1** is one piece part of wide ring shape having two conical bearing faces and non drainage gas lubricant between them. It is divided in two equal parts that have contact angle α relative to the axis reacting axis loads.

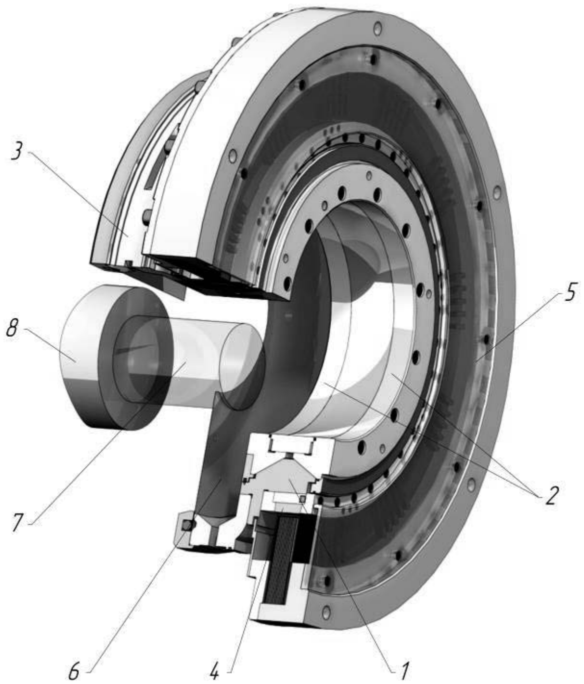

Fig.1 Spindle assembly 3D model

The air is supplied via inlet to the annular space under pressure (0,4 – 0,63) MPa, from annular space through feed-hole gets to the air gap, separating movable support **1** from stable support **2**. Pressure distribution in air gap is a function of constructive parameters, inlet and outlet gas pressure and place of movable support to stable one, which is determined by eccentricity. It occurs at load and leads to pressure difference in air gap producing elevating power. If there is no mechanical contact, single-support bearing is functional [4 – 7].

The so called rotor "levitation" of single-support system is provided with continuous air input. Therefore permanence of its attitude position can be viewed as stability of rotor motion in "rotor-bearing" dynamic system [8 – 16]. Bearing capacity in radial and axial directions is determined by the system of interacted parameters such as contact angle of reference plane α, its radius, feed pressure, diameter and a quantity of feed-holes etc. Air pressure is distributed axial-symmetric in any ring cross-section and its resultant equals zero in central (symmetrical) position of movable support. If movable support floats to the bearing on eccentricity e under external load W_e, ring cross-section of a gap gets variable changing pressure in the gap. The pressure is maximal in minimal gap pressure area and vice versa is minimal in maximal gap pressure area [17 – 19].

Engineering process requirements determine running speed. For instance, it is 1000 – 1500 rpm for mono-crystal automatic plating machine, 20000…200000 rpm for grinding pneumatic spindle [6]. Rotation frequency of given single-support system can be changed from 0 rpm (when bearing runs as aerostatic suspension) to limit rotation frequency, where gas lubricant flow gets turbulent (6500 to 70000 rpm).

Determining following parameters such as limit rotation frequency, natural and cutoff frequency, required power and loss power, starting and stopping time, coefficient of mechanical efficiency, axial and radial limit load, inflexibility and air consumption give single-support system design. The gas-static bearing of single-support system is specified by the last three parameters.

The existing methods of gas bearings calculation [6, 7, 17, 20 – 22] don't work for aerostatic bearing that have bearing length ratio to the diameter less than 0.5 (λ parameter) and conical bearing face with more than 20^0 angle α.

The most appropriate method in this case for single-support system design from the mentioned above is the one suggested in [17]. Non conical gas-static bearings are described there, however, we assume that all the parameters of angular contact bearing correlate with parameters of radial one in the design model of single support system (fig.2).

Given design model on fig.2 includes following changes:

- bearing faces with α contact angle relative to the axis turned horizontal ($\alpha = 0$) in point of mean radius $\boldsymbol{R} = (R_{\min} - R_{\max})/2$;
- total length of aerostatic bearing L consists of two lengths conical parts and a gap between those that is a space under pressure joining as a single bearing face;
- labyrinth packing rings are removed to fit the design method [17] most (see fig.2 a).

According to design model the radius of the bearing is R = 175 mm, the length is L = 97 mm and the mean gap is C = 10…30 micrometer. Two lines of feed-holes with diameter D_d = 0.5 mm, quantity N = 22 in one pressure boost line and the distance between lines l^* = 40 mm help the air to get in the gap. Getting through each feed-hole the air throttles twice in machining gap and feed-hole.

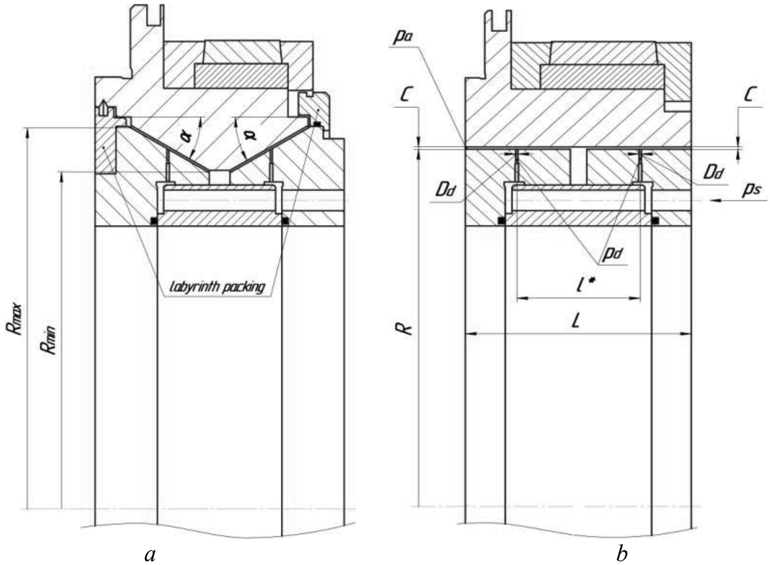

Fig.2 Construction (a) and design model (b) of single-support system

Dislocation of movable support leads to air dynamic forces calculation that is determined by confluent inflexibility matrix. If there is no rotation, there are only two elements $\overline{K}_r^{\varepsilon}$ and $\overline{K}\gamma$ – coefficients of radial and angular inflexibility. Last two characterize bearing capacity and radial suspender inflexibility. We are to determine dimensionless parameter $\overline{m}$, machine pressure difference along air lubricated layer (p_d - p_a) and in feed-hole (p_s - p_d). It depends on bearing design trait and gas feed property [17, 18]:

$$\overline{m} = \frac{12\mu a_1 \left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} N\, n_d\, D_d}{C^2 p_s}, \quad (1)$$

where: C – is a mean gap at zero eccentricity;

k –adiabatic index for two-atom gas and air is equal 1.4.

Counterpressure $\overline{p}_d$ is a relation of feed-hole output pressure (p_d) to feed pressure (p_s); $\overline{p}_d$ is determined through outflow function:

$$\overline{p}_d = \sqrt{\frac{\left(\overline{p}_a\right)^2 + \overline{m}\,\zeta}{1+\overline{m}\,\zeta}}, \quad (2)$$

where: ζ – is a function that depends on bearing geometrical parameters (λ – comparative boost lines separation – $b = l^*/L$):

$$\zeta = \frac{\lambda(1-b)}{2}. \quad (3)$$

Air outflow speed via feed-holes is specified by pressure difference:

$$\bar{p}_d = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}. \quad (4)$$

When the counterpressure gets higher air outflow speed becomes critical – sonic speed. If $\bar{p}_d \le 0.528$, flow speed surmounts sonic speed with possible shock-wave absorbing energy and dropping area pressure. Gas flow conditions via feed-holes are to be undercritical to secure stable bearing run. Usually $0.528 < \bar{p}_d < 0.9$ [6] is in aerostatic bearings. If p_a = 1atm, the counterpressure calculation on formula (2) demands boost pressure to get lower.

To calculate inflexibility index we use unified formulas:

$$\overline{K}_r^{\varepsilon} = \frac{C}{4\lambda R^2 p_s} K_r^{\varepsilon} = \frac{2}{3} \cdot \frac{0.75\pi\nu}{ch\lambda + 0.5\bar{m}U_r \cdot chb\lambda \cdot sh(1-b)\lambda} \times \left(\frac{shb\lambda \cdot sh(1-b)\lambda}{\lambda \bar{p}_d} + I_0 \frac{chb\lambda}{\sqrt{\nu\lambda}} \right), \quad (5)$$

$$\overline{K}^{\gamma} = \frac{C}{4\lambda^2 R^4 p_s} K^{\gamma} = \frac{0.75\pi}{\lambda} \times$$

$$\times \left(\frac{2}{3}\left[(2+b)\bar{p}_d - 3\bar{p}_a + \frac{2(1-b)p_a^2}{\bar{p}_d + \bar{p}_a} \right] + \frac{\left(\bar{p}_d - \bar{p}_a\right)\eta}{\lambda^2 (1-b)} \cdot \left(b \cdot chb\lambda - \frac{shb\lambda}{\lambda} \right) - \sqrt{\frac{\bar{p}_d - \bar{p}_a}{1-b}} \cdot \left[I_1 - \left(th\frac{(1-b)\lambda}{2} + \eta \frac{shb\lambda}{sh(1-b)\lambda} \right) \cdot I_2 \right] \right), \quad (6)$$

where: U_r – approximated outflow function with Prandtl formula: $U_r = 0.5\bar{p}_d$;

$$\eta = \frac{ib\lambda \; sh\bar{b}\lambda + ch\bar{b}\lambda - 1}{sh\lambda + 0.5\bar{m}U_r \, shb\lambda \; sh\bar{b}\lambda};$$

I_0, I_1, I_2 – stereotyped integrals line: $I_0 = \int_b^1 \frac{sh\lambda(1-x)}{\sqrt{\beta - x}} dx$, $\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \int_b^1 \frac{x}{\sqrt{\beta - x}} \begin{bmatrix} ch\lambda\,(1-x) \\ sh\lambda\,(1-x) \end{bmatrix} dx$.

To calculate single-support system bearing capacity for linear problem we use:

$$W_e = \lambda A_{\Sigma} \cdot p_s \cdot \overline{W}_e = \lambda A_{\Sigma} p_s \overline{K}_r^{\varepsilon} \varepsilon_r, \quad (7)$$

where: $A_{\Sigma} = 4R^2$ is global area scale;

$\varepsilon_r = \frac{l}{N}$ is relative eccentricity where its maximal value equals peak bearing capacity and can reach maximal value 0.8.

Angular contact bearing with conical bearing faces under angle α to rotation axis is used in single-support system, thus gas lubricant resultant action has the same angle.

Then angular contact bearing capacity Wекy is determined by radial component (along axis 0У):

$$W_{ekó} = W_e \cdot \cos\alpha \, . \qquad (8)$$

Peak (maximal calculation at $\bar{p}_a \to 0$) volume gas consumption Q via bearing at normal terms:

$$Q = \frac{\pi \acute{N}^3 p_s^{\,2}}{12\mu\, p_a} \cdot \bar{m} \cdot 3600. \qquad (9)$$

Single-support system main parameters calculation results at gap variation and undercritical mode of gas flow are given in table 1.

Table 1. **Single support main parameters at mean gap modification**

Air lubricated mean gap ***C***, m	Feed pressure p_s, MPa	Single-support system bearing capacity		Angular limit load M_γ, N·m	Air consumption Q, m³/h
		Radial direction $W_{екy}$, H	Axial direction $W_{екz}$, H		
10×10^{-6}	0.69	8192	2364	26716	2.4
15×10^{-6}	0.38	2524	728	6470	2.0
20×10^{-6}	0.29	1131	327	2468	2.1
25×10^{-6}	0.25	600	173	1177	2.2
30×10^{-6}	0.22	335	97	611	2.3

As $\bar{p}_d = \mathrm{f}\left(\bar{p}_a{}^2\right)$, reducing feed pressure p_s (see table 1) and also increasing gap outlet pressure p_a we can obtain the counterpressure interval and avoid critical gas flow through feed-holes. Increasing gap outlet pressure will rise boost pressure and considerably increase bearing capacity or to reduce air consumption at invariant bearing capacity. Hereby, we can improve single-support system features with $\lambda<0.5$. Technically it is realized by air flows from the gap not into the atmosphere but in the annular space where the pressure gets normal in all circle and it won't get lower than the atmosphere pressure level due to labyrinth packing (see fig. 2 a). Fig. 3 shows counterpressure $\bar{p}_d$ and gap outcome pressure p_a relation.

$$\bar{p}_d = \sqrt{\frac{\left(\bar{p}_a\right)^2 + \bar{m}\zeta}{1+\bar{m}\zeta}} = \sqrt{\frac{\left(\frac{p_a}{p_s}\right)^2 + \bar{m}\cdot\frac{\lambda(1-b)}{2}}{1+\bar{m}\cdot\frac{\lambda(1-b)}{2}}} \, .$$

The calculation was done for three bearings with different elongation $\lambda = L/D$ ($\lambda = 0.15, 0.25, 0.5$).

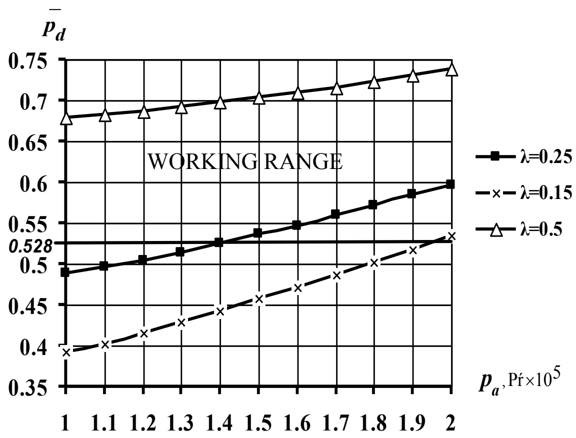

Fig. 3 Counter pressure relation to p_a for different length bearings

Thereby due to labyrinth packing we get gap outlet pressure increase that helps to avoid undercritical bearing behavior with bearing length reduce. According to mentioned above we are going to calculate single-support system pressure outlet variation.

Single-support system pressure outlet and mean gap variation calculation results are given in table 2.

Table 2 **Single-support system main parameters**

Air lubricated mean gap ***C***, m	Pressure inlet and outlet quotient p_a/p_s, MPa	Single-support system bearing capacity		Angular limit load M_γ, N·m	Air consumption Q, m^3/h p_a, Pŕ×10^5
		Radial direction W_{eky}, N	Axial direction W_{ekz}, N		
10×10^{-6}	0.1/0.45	5524	1595	17616	1.6
	0.1/0.55	6694	1932	21422	1.9
	0.1/0.63	7568	2185	24236	2.2
15×10^{-6}	0.143/0.45	2599	750	6007	1.7
	0.2/0.55	2681	774	5672	1.5
	0.24/0.63	2768	800	5613	1.4
20×10^{-6}	0.19/0.45	1180	340	2225	1.7
	0.245/0.55	1196	345	2158	1.6
	0.28/0.63	1248	360	2111	1.6
25×10^{-6}	0.21/0.45	621	179	1075	1.9
	0.262/0.55	634	183	1069	1.9
	0.304/0.63	640	185	1064	1.8
30×10^{-6}	0.22/0.45	365	105	605	2.2
	0.271/0.55	373	108	608	2.1
	0.313/0.63	376	109	606	2.1

Analyzing table 2 data, we can see that applying labyrinth packing gap outlet secures undercritical bearing behavior and improves technical characteristics. For example, if there is no outlet pressure regulation, single-support system bearing capacity obtains 2524 N with mean gap C = 15 μm and air consumption 2 m^3/h (see table 1), but with outlet pressure regulation bearing capacity can obtain 2724 N with air consumption 1.3 m^3/h.

CONCLUSIONS

Non-contact drive single-support mechanical system that is based on aerostatic angular contact bearing with conical bearing faces is able to secure sufficient bearing capacity, inflexibility and speed range condition for effective application on cutting machine tool, pumps and compressors. It is characterized by minimal friction loss, high vibration resistance and considerable speed range, it has regulating inflexibility. The suggested here design procedure is based on design model conversion and allows to research bearing systems parameters with diverse bearing faces contact angle. Single-support system retrofit consists of placing labyrinth packings allowing to 10% raise bearing capacity and 30% reduce process gas.

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АНАЛИЗ КОНСТРУКЦИЙ И РАСЧЕТ ПАРАМЕТРОВ ОДНООПОРНОЙ СИСТЕМЫ БЕСКОНТАКТНОГО ПРИВОДА

Павел Носко, Алексей Брешев, Павел Филь, Владимир Брешев

Аннотация. Проанализированы варианты конструкции одноопорной системы бесконтактного привода вращательного движения. Предложена расчетная схема и методика определения несущей способности, жесткости и расхода воздуха одноопорной системы с конусным радиально-упорным аэростатическим подшипником. Выполнен расчёт параметров и сравнительный анализ одноопорной системы с аэростатическим подшипником традиционной конструкции, а также с модернизированной – с кольцевой камерой и лабиринтным уплотнением на выходе газовой смазки.

Ключевые слова: бесконтактная опора, одноопорная система, противодавление, несущая способность, жесткость.