# SPINDLE ON THE CONICAL GAS SUSPENSION THEIR DESIGN AND RESEARCH PERFORMANCE

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**Abstract:** *Spindles on the gas suspension are simple in design and perspective for use in production. But their active implementation is constrained by lack of researches and recommendations for calculating the characteristics and design options.The main problems facing the developers of conical suspension are to determine the static characteristics (capacity, stiffness, flow of compressed gas), the dynamic characteristics (resistance, resonant frequency) and the rational choice of design parameters. This is obviously guided by the desire to achieve certain optimality in tough expensive properties and performance characteristics.*

**Keywords:** *spindle, conical suspension, slot, force, design, performance*

## The main part

Spindles with conical suspensions '**Figure 1**' as opposed to the spindles with radial supports have fewer surfaces with respect to their exact location. Conical spindles oppose both radial and axial force. Spindle taper on gas bearings with longitudinal grooves '**Figure 1**' has a symmetrical structure and consists of two identical towers, separated by an interval length $L_1$. To get the best possible strength and stiffness characteristics it is necessary to chose both macrogeometrical parameters (cone angle α, the length of the suspension L), and microgeometrical parameters that characterize the size of the slots.

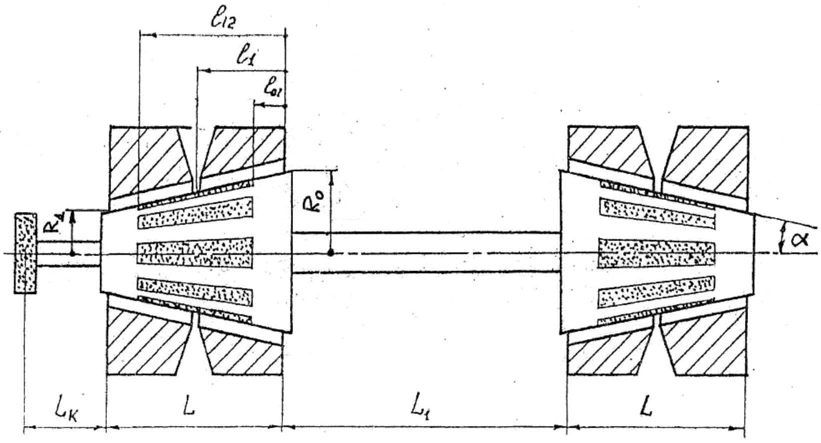


**Figure 1:** *Spindle taper on gas bearings with longitudinal slots*

When applying the technological radial force '**Figure 2**' the shift of point of application is

$$e_{\eth\grave{a}\ddot{a}} = -e_y + \left(L_{\hat{e}} + L + \frac{L_1}{2}\right)\vartheta .$$

From the spindle equilibrium condition (made for the middle of the spindle) we can find radial and angular movement of the spindle as a whole

$$e_{\hat{e}} = \frac{F_e}{2K_p},\ \vartheta = F_e\left(L_{\hat{e}} + L + 0,5L_1\right)K_{\Sigma M\vartheta}$$

and the shift of point of application of force $F_e$.

$$e_{\eth\grave{a}\ddot{a}} = \frac{2\left(L_{\hat{e}} + L + 0,5L_1\right)\cdot K_p + K_{\Sigma M\vartheta}}{2K_p \cdot K_{\Sigma M\vartheta}} \cdot F_e.$$

Then the rigidity spindle unit, stiffness at the end of the console where the technological tools (force $F_e$) are:

$$K_{oc} = \pi p_a R_0^2 K_{oc}^{*}/c,\ K_{oc}^{*} = 2K_{\varsigma}^{*},$$

$$K_{\eth\grave{a}\ddot{a}} = \pi p_a R_0^2 K_{\eth\grave{a}\ddot{a}}^{*}/c,$$

$$K_{\eth\grave{a}\ddot{a}}^{*} = \frac{2K_{\varepsilon\varepsilon}^{*}\cdot K_{\Sigma\vartheta}^{*}}{4K_{\varepsilon\varepsilon}^{*}\left(\lambda_{\hat{e}} + 0,5\lambda_1 + \lambda\right)^2 + K_{\Sigma\vartheta}^{*}},$$

$$K_{\Sigma\vartheta}^{*} = K_{\varepsilon\varepsilon}^{*}\left(\lambda_1 + \lambda\right)^2 - \left(K_{\varepsilon\vartheta}^{*} + K_{\vartheta\varepsilon}^{*}\right)\left(\lambda_1 + \lambda\right) + K_{\vartheta\vartheta}^{*}$$

where $c$ – nominal thickness of lubricant layer, $\lambda = \frac{L}{2R_0}$, $\lambda_1 = \frac{L_1}{2R_0}$, $\lambda_{\hat{e}} = \frac{L_{\hat{e}}}{2R_0}$, dimensionless stiffness $K_{\varepsilon\varepsilon}^{*}$, $K_{\vartheta\vartheta}^{*}$, $K_{\varepsilon\vartheta}^{*}$, $K_{\vartheta\varepsilon}^{*}$.

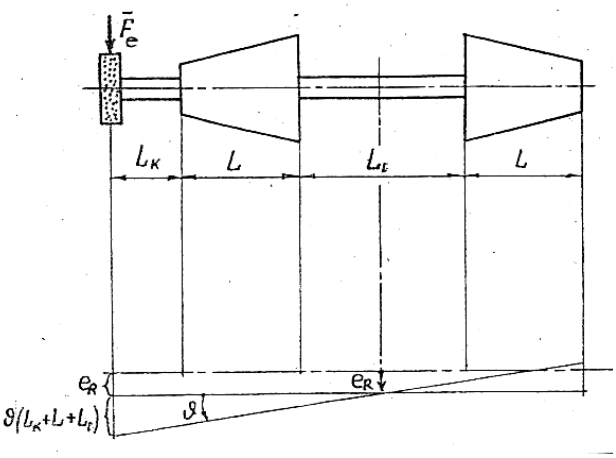


**Figure 2:** *The scheme of the shaft conical spindle unit axis movement*

Previous experience of single conical pendants optimization "[1, 2]" suggests that the lifting force and stiffness can always be made high enough by raising the expenditure of gas.

We apply the results obtained for the construction of optimization criteria conical gas-suspension spindle poles.

Developing spindle, engineers usually achieve the highest possible rigidity spindle, which in turn lead to the need to have a bearing pendant of high rigidity.

Of course in this case it is necessary to choose microgeometry parameters – length, diameter, angle and microgeometry parameters: depth, length of the slots, and their number considering the maximum possible rigidity. However, research and thorough analysis of the maximum, conducted for the suspension with cylindrical slots showed that the parameters that characterize the depth, width and length of the slots have unconditional extremes for maximum rigidity "[1]". Moreover, you can always increase the rigidity of suspension mounting, increasing the expenditures of gas through it. It is therefore proposed to include gas consumption in the optimization criterion. This approach, however, can be defined as a quite practical one.

The optimization criteria "[1]" on the ratio of the maximum radial (or axial) stiffness in the cost of gas. The proposed feature appeared unimodal and quite convenient for finding the maximum gradient method.

Described criteria can be extended to the whole spindle, formulated as optimization criterion

$$\max\left(K_{\eth\grave{a}\ddot{a}}^{*}/Q_{\Sigma}^{*}\right).$$

This optimization parameters to be microgeometry: $\xi_{01}$, $\xi_1$, $\xi_{12}$, $\gamma$. They are dimensionless because $\xi_{01} = l_{01}/L$, $\xi_1 = l_1/L$, $\xi_{12} = l_{12}/L$, $\gamma = \sigma/c$, $\sigma$ – groove depth.

Parameters $P_H$, α, λ, æ, and $\lambda_1$, $\lambda_к$ are the input, those that are set. Parameter æ – the ratio of slot width to slot-cusp width parameter.

Table 1 shows the importance of optimal parameters found by the gradient method

Cone angle α can to some extent regulate the relationship between the axial and radial spindle rigidity. Then advisable also be considered include the axial stiffness in the optimization criterion and require

$$\max\left(K_{oc}^{*}K_{\eth\grave{a}\ddot{a}}^{*}/Q_{\Sigma}^{*}\right). \tag{1}$$

This angle α will be included into the number of parameters to be optimized. Table 2 shows the values of the optimal parameters considering the criterion according to Formula 1 shown above

**Table 1**

*Characteristics and the corresponding design parameters for tapered spindle assemblies gas suspension with longitudinal slots on the following criterion*

$$\max\left(K^{*}_{ðàä}/Q^{*}_{\Sigma}\right).$$

| $P_н$ | $\lambda_к$ | $\lambda_1$ | α | λ | $\xi_{01}$ | $\xi_1$ | $\xi_{12}$ | γ | æ | $F^*_ς$ | $K^*_{ос}$ | $K^*_{рад}$ | $Q^*_\Sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5,0 | 0,75 | 2,0 | 8 | 1,0 | 0,22 | 0,50 | 0,77 | 1,18 | 0,25 | 1,41 | 0,050 | 0,251 | 132 |
| | | | 12 | 1,0 | 0,23 | 0,50 | 0,88 | 1,18 | 0,25 | 1,95 | 0,119 | 0,256 | 135 |
| | | | 8 | 1,5 | 0,24 | 0,50 | 0,89 | 1,26 | 0,25 | 1,95 | 0,080 | 0,384 | 95 |
| | | | 12 | 1,5 | 0,19 | 0,50 | 0,80 | 1,92 | 0,25 | 2,72 | 0,139 | 0,205 | 89 |
| | | | 8 | 2,0 | 0,23 | 0,50 | 0,92 | 1,48 | 0,25 | 2,42 | 0,101 | 0,378 | 73 |
| | | | 12 | 2,0 | 0,17 | 0,50 | 0,95 | 1,96 | 0,25 | 3,08 | 0,200 | 0,162 | 72 |

**Table 2**

*Characteristics and the corresponding design parameters for spindle assemblies on gas suspensions with longitudinal slots on the* $\max\left(K^{*}_{oc}K^{*}_{ðàä}/Q^{*}_{\Sigma}\right)$. *criterion.*

| $P_н$ | $\lambda_к$ | $\lambda_1$ | α | λ | $\xi_{01}$ | $\xi_1$ | $\xi_{12}$ | γ | æ | $F^*_ς$ | $K^*_{ос}$ | $K^*_{рад}$ | $Q^*_\Sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5,0 | 0,75 | 2,0 | 22,02 | 1,0 | 0,11 | 0,60 | 0,95 | 1,92 | 0,25 | 2,92 | 0,505 | 0,154 | 161 |
| | | | 14,44 | 1,5 | 0,10 | 0,54 | 0,96 | 1,96 | 0,25 | 2,89 | 0,294 | 0,283 | 137 |
| | | | 9,40 | 2,0 | 0,10 | 0,52 | 0,96 | 1,97 | 0,25 | 2,82 | 0,198 | 0,388 | 113 |

Comparing the results in both tables, we can see that the criterion Formula 1 can achieve high rigidity spindle. However, this increase in stiffness leads to increased costs of compressed air. Unfortunately, this is a common flaw suspension with direct air injection into lubricant layer.

Tables of optimal parameters “[3]” enable designers to reasonably assign parameters of suspension support microgeometry and estimation of achievable specifications for conical suspension support. This estimation will result in microgeometry parameters: maximum diameter, length and distance between the clips. Thus, the results obtained can be used both for low rotating and for high speed spindles scheme.

In the process of designing conical spindles on suspensions in the traditional way ‘**Figure 1**’ have to deal with the phenomenon of self-excitation of axial vibrations. These fluctuations manifest themselves in the form of low-frequency vibrations with amplitude that can reach few millimeters.

Fluctuations may occur when changing discharge pressure, suspension settings profile and others. Of course, normal operation of the precision spindle assemblies is incompatible with the risk of fluctuations.

Anyway, spindles containing conical suspensions are sometimes inclined to self-excitation of axial vibrations. The reason of their occurrence is not clear enough, and it becomes an obstacle to the specific recommendations to avoid them.

Created linear dynamic analysis of conical suspension “[4]” may become the basis for further study of this negative phenomenon and can help determine the effect of various design and operational factors on the conditions of spontaneous vibrations of high mass ‘**Figure 1**’.

In the linear approximation (small amplitude vibrations) axial motion dynamic of the system with distributed parameters, which is a gas lubricant layer can be presented as the dynamics of vibration with one degree of freedom.

This oscillator, however, is very specific because the stiffness strength and linear viscous resistance are dependent on the rate of the lubricant layer thickness change and hence the frequency of natural oscillations. In addition, this oscillator can, in principle, have a negative linear viscous resistance.

The main parameter that determines the degree of non-stationarity of the process is

$$\Gamma = 12\mu R_0^2/\left(p_a c^2 T_0\right),$$

where μ – dynamic gas viscosity;

$T_0$ – time scale (typical time), which in turn is determined by the ratio

$$T_0 = \sqrt{mh_0 / \left(\pi p_a R_0^2\right)}$$

Macro-and microgeometry of each suspension support is characterized by the following parameters "[1, 4]" cone angle α, the relative length $\lambda = L/\left(2R_0\right)$ (L – length of each suspension), their relative coordinates of the beginning and the end of the profiled area $\xi_{01}$, $\xi_{12}$, relative $\xi_1$ coordinates of the place of compressed air supply, a relatively deep slot $\gamma = \sigma / c$ (σ – groove depth, which is the entire length constant). Slots are evenly tapered off so that the relative length parameter æ also remains constant throughout the slots. Gas supply pressure is determined by the dimensionless parameter

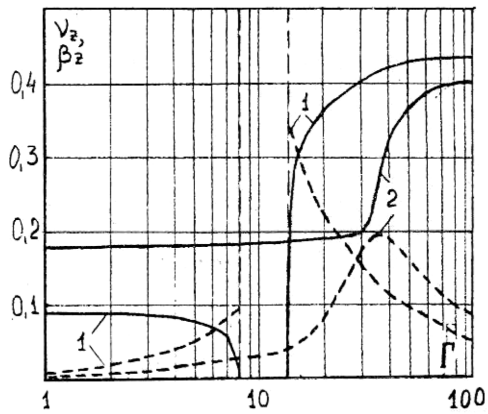


**Figure 3:** *Dependence of $\beta_Z$ parameter (chain line) and $\nu_Z$ parameter on Γ degree of non-stationary process.*

$P_i = p_i / p_a$, where $P_H$ – an absolute pressure of compressed air.

From the studied literature "[4, 5]" we know that if $\beta_Z$ coefficient is negative, it means instability and hence the possibility of self-excitation of oscillations. However, the authors found no cases where the ratio $\beta_Z$ would become negative. In addition, at a certain value of the parameter Γ $\nu_Z$ frequency becomes zero for some sets of conical support geometry parameters.

'**Figure 3**' shows typical dependence $\nu_Z$ and $\beta_Z$ (dashed line) on Γ. For curves 1 – γ = 0,3, for curves 2 – γ = 1,5. In the first case (shallow slots)

within 8 ≤ Γ ≤ 13 instability and self-excitation oscillation can be developed here.

Note that in practically implemented spindles designs parameter Γ was within 10 ... 40. For the curves in '**Figure 3**' the remaining parameters have the following meanings: *$P_н$=5; $\alpha$=4$^0$; λ=2; $\xi_{01}$=0,15; $\xi_1$=0,5; $\xi_{12}$=0,85; æ=0,25.*

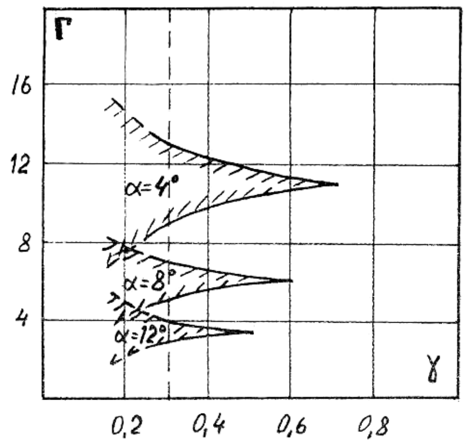


**Figure 4:** *The dependence of the relative depth of the slots on the Γ-degree parameter of the non-stationarity process.*

Elimination of self-excitation can be accomplished both with the help of special selection of microgeometry parameters and assigning of operating parameters of Γ in such a way that does not get in the region of instability, change the mass *m*, the gap *c* with radius $R_0$.

Studies have shown that the depth of the slots has the greatest impact on the emergence of self-excitation conditions, which coincides with the experimental facts and production experience. It was found that increasing the discharge pressure of the gas somewhat expands unstable region.

On the basis of these studies it can also be concluded that the risk of axial instability and self-excitation oscillations can be completely eliminated by selecting the microgeometry parameters: thickness of the lubricant layer depth, boundary slot configuration and cone angle α. '**Figure 4**' illustrates this situation, showing the shaded self-excitation areas of axial vibration. Parameters $P_H$, α, ξ and æ are the same as in '**Figure 3**'.

The following basic requirements are made to material gas suspensions "[6-8]":

- high strength and purity of suspension surface treatment;
- stability and low coefficient of sliding friction;
- structural and dimensional stability;
- high chemical, corrosion and erosion resistance;
- technological processing;
- no welding and minor surface wear of the suspension on contact surfaces.

For the manufacture of gas suspension spindle assemblies some materials are used which are commercially available at metallurgical plants in the country. Shafts for suspensions are made of steel 40X, 9X18, ШХ15, P6M5 hardened to a hardness of HRC 56-64, stainless steel, improved steel, the surface of which is saturated with nitrogen and carbon. The body of suspension can be made from the same material as the shaft, but soft materials can also be used: phosphor bronze, graphite, babbit, brass, aluminum alloys.

Reliable performance of spindle assemblies with gas suspension systems in a production process largely depends on the quality of compressed gas (air). Solid particles (products of wear and corrosion in pneumatic systems), moisture (water, oil, etc.) can be found in the gas used for gas suspensions, depending on its processing. The physical effects of gas contamination often lead to failure of gas suspensions. Solid particle and moisture can partially or completely block access gas in the working gap through the gas supply gaps or small diameter holes. That is why compressed air for spindle assemblies can be cleaned by a device П-ППВ type '**Figure 5**' which operates at air flow to $30m^3/s$.

Based on the theoretical researches and results of optimum design were designed, manufacturing and research sites on the spindle taper gas suspension systems '**Figure 6**'.

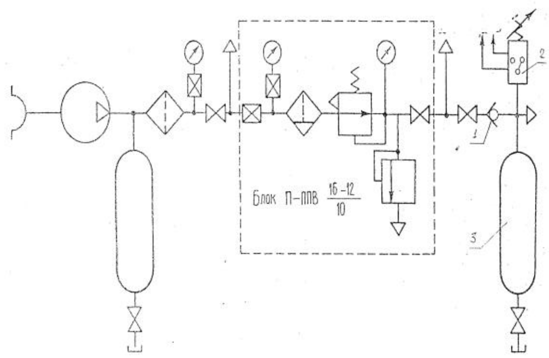


**Figure 5:**. *Air circuit power spindle assemblies on gas suspensions*

The design of low-speed spindle unit '**Figure 6**' pressured gas (air) $P_H$ through the choke 4 and pneumatic throttle valve enters the working plane axial clearances and cone suspensions. At the end of the suspension case 5 to which axle suspension 2 with a row of holes and micro slots is attached channels are made for free gas exit from the working areas suspensions. Shaft 3 is driven to move an electric motor whose rotor 8 pressed on cable to the shaft 3 and the stator is fixed with pins to the casing 5. Shaft 3, axis suspension 2 and enclosure 5 are made of steel 40X

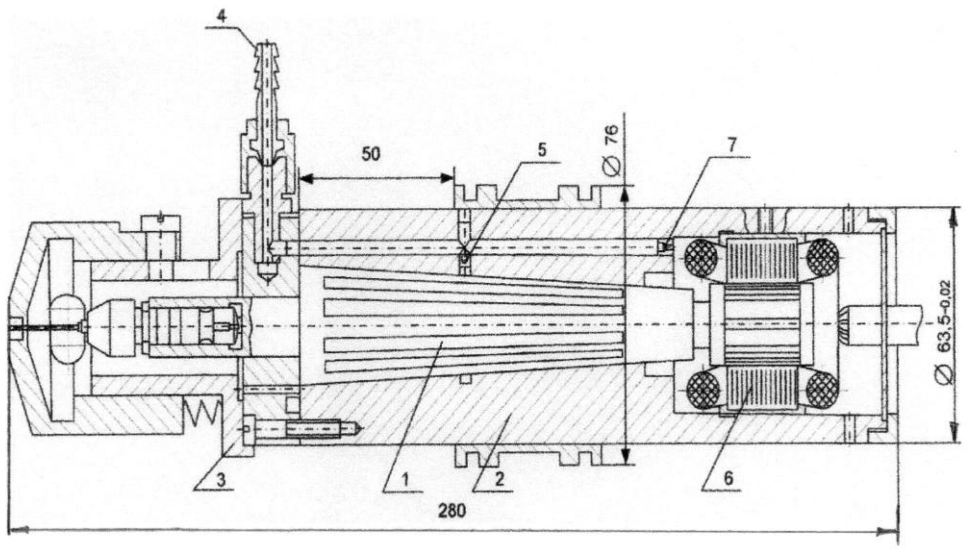


**Figure 6:** *Power spindle assemblies on gas suspensions ШВ-64T*

Spindle unit specifications '**Figure 6**'
Motor power ........................................ 0.12 kW
The angular velocity of the shaft..up to 103 1 / s
Radial lift power....................................... 220 N
Axial lift power......................................... 700 N
Air expenditures....................... 6,6 · 10-4 m3 / s
Nominal angular velocity of the shaft connecting spindle unit to the mains (220 V, 50 Hz) was 310 1/s. The angular velocity of the shaft to 103 1/s is achieved by using frequency converters ПЧС-1.

The provided electrodynamics braking scheme stops the shaft from the nominal angular velocity for 3 seconds, and the maximum – 15 sec.
Spindle assembly '**Figure 6**' was used in equipment for processing the crystals to replace imported spindle assemblies "Super-42" and "Super-64". Cylinder nodes are used to drill holes with a diameter of 3 mm thick high-strength plates to 2 mm.

**Summary**

The study of conical suspensions design parameters was to improve their performance for the design of spindle units with an angular velocity of the shaft to 10,000 $s^{-1}$.

For nodes on the spindle taper suspension systems with longitudinal slots the optimization of design parameters on the criterion of the maximum value of the ratio of dimensionless radial stiffness to dimensionless gas consumption and possession of dimensionless radial and angular stiffness to dimensionless gas flow was done.

Based on the analysis of self-excitation of oscillations in the spindle axial nodes on two tapered suspension with longitudinal slots can be concluded that the risk of axial instability and self-excitation can be eliminated by the optimization of suspensions design parameters.

Designed, manufactured and implemented spindle components in the cylindrical gas suspension systems, gas suspension conical systems with longitudinal slots which are manufactured, easy to maintain, reliable in operation and have stable operating parameters.

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