Multi-criteria synthesis of standing connections of the support of the running screw CNC machine

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Abstract. The creation of modern CNC machines requires the development of the design of machine feed drives with specified performance criteria. Ensuring the characteristics of feed drives that meet these criteria is largely related to the reasonable choice of design and technological parameters of standing connections available in the design. It is shown that this task, due to the presence of several conflicting criteria and a significant number of variable design parameters (VDP), is the task of parametric multi-criteria synthesis of compounds. The stages of the procedure of parametric multi-criteria synthesis of stationary machine tools are considered. The design variables and the formation of permissible regions of their variation, determined by the presence of parametric, functional, and criterion constraints, are analyzed in detail. It is indicated that the determination of the solution search area (the Pareto region) is most conveniently performed by scanning using the LP_τ-sequence. It is proposed, in connection with the complexity of describing the boundaries of the Pareto region, to use its approximation by the described hyper-parallelepiped. Since the area of the search for solutions is characterized by the fact that any solution belonging to it cannot be improved simultaneously by all criteria, it is proposed to use a generalized criterion, calculated during scanning, when selecting possible deviations of the VDP from nominal values. Calculations performed according to the proposed procedure for the left support of the running screw of the longitudinal feed drive of the CNC machine mod. 1P426DF3, allowed to determine the nominal values and deviations of each of the VDP standing connections.

1. Introduction
Providing performance criteria for CNC machine feed drives is a prerequisite for the creation of equipment with the required performance characteristics [1, 2].

The creation of feed drives that meet the performance criteria is largely associated with a reasonable choice of design and technological parameters of standing connections available in the design.

A feature of the synthesis of machine-tool connections is the presence of several conflicting optimization criteria and a significant number of the variables of the design parameters (VDP).

Thus, the problem of parametric multi-criteria synthesis of compounds takes place. This task can be formulated as the problem of choosing in the Pareto-optimal region solutions the nominal values of the geometric parameters of the connection elements and the possible tolerances for them, at which the maximum possible performance criteria of the connection are achieved at the lowest cost.

2. Procedure for Parametric Multi-criteria Synthesis of Machine Standing Connections
In accordance with the main provisions of the optimal design [3-6], the process of parametric synthesis of machine standing connections in the case of several criteria must include a number of specific steps (figure 1).
During the synthesis of connections, the boundaries of the subsystem are determined by the surfaces of the parts involved in the contact.

The main goal in the design of units with standing connections is to ensure the stability of the position during assembly and during operation, as well as to achieve high dynamic characteristics (rigidity, damping) at minimum cost during production and assembly.

In accordance with the goal, the following should be taken as quantitative criteria (goal functions): the spatial position of the contacting parts; contact deformation (stiffness) of the connection; joint damping; cost of manufacture and assembly; the mass of parts included in the connection.

The following are the variables of the design parameters: the force compressing the connection during assembly (the preload force); outer and inner diameter of the end contact surfaces; the parameter that determines the geometry of the surfaces and the material properties of the contacting
elements; deviations from the correct geometric shape and the relative position of the surfaces of the connection; radial clearance; contact length over a cylindrical surface.

The range of variation of parameters $D_{VP}$ is determined by the intersection of three areas

$$D_{VP} = D_x \cap D_R \cap D_F,$$

where $D_x$ is the area of parametric restrictions, which is formed either in a subjective or objective way; $D_R$ is the area of functional limitations, determined by the possibility of functioning of the designed structure; $D_F$ is the area of criterion restrictions resulting from the analysis of the criteria and the weakening of the requirements imposed on them, when for some criteria it is not necessary to achieve the greatest possible decrease (increase), but only the satisfaction of a certain level.

3. **Determining the Region of Variation of the VDP**

Let us consider in more detail the listed VDP, the areas of their variation and functional limitations, which will be determined by design, technological and operational factors.

3.1. **The preload force**

The range of variation of the preload force $P_N$ is determined by the following restrictions.

Considering that the majority of standing connections work under alternating load conditions, in order to exclude the connection opening, the following condition must be met $P_N \geq P$, where $P$ is the operational effort.

When considering connections that ensure the creation of preload in bearing assemblies, its magnitude is limited by the conditions of normal operation of bearings.

For example, for bearings with combined thrust-radial roller bearings, which are widely used for the supports of the running screw, the value of the preload must satisfy the condition

$$P_N \geq \Delta B \cdot j_B,$$

where $j_B$ is the calculated axial stiffness of the bearing; $\Delta B$ is axial clearance in the bearing.

According to [7] for feed drives with a screw diameter of 40 ... 50 mm and a length of about 1000 mm, the preload value should be $1000 ... 1500$ daN.

In addition, when determining the restrictions on the possibility of variation of this VDP, the recommendations of the work [8] can be used: for ball bearings $P_N = 0.354P_{\text{max}}$; for flat joints $P_N = 0.25P_{\text{max}}$, where $P_{\text{max}}$ is the maximum possible load.

The upper limit of the possible change in the preloads of standing connections should be clarified taking into account the recommendations and methods for eliminating the work of the joint in the case of incomplete contact, described in [5].

3.2. **The shape and area of the contacting surfaces**

Since most of the standing connections of the running screw unit are ring-shaped (parts mounted on shafts; flanges of shaft supports, etc.), two VDP must be taken into account: the outer and inner diameter of the part.

Restrictions on the size of the joint are formed depending on the location of the connection (parts on the shafts, in the bores of the body, flanges, covers, etc.) and as their for the running screw assembly can be shaft diameter, diameter of the body bore, dimensions of standard elements (for example bearings), assembly conditions.

3.3. **The parameter that determines the microgeometry of the surfaces and the material properties of the contacting elements**

As such a parameter, the coefficient $c$ can be chosen, which relates the pressure $\sigma$ applied to the joint and elastic displacements $\delta$ in the joint [9]:

$$\delta = c\sigma^{0.5},$$

(3)
where $C$ is the coefficient depending on the geometry of the surfaces and the properties of materials ($c = 0.07 \ldots 1.5$ [9]).

### 3.4. Deviations from the correct form and relative position

As was shown in [5], such location errors as deviations from the perpendicularity of the end surfaces and deviations from their parallelism have the greatest influence on the connection parameters. The method of determining the effect of these errors is given in [5].

Functional limitations are formed based on the use of an approximate dependence of the tolerances $\Delta$ on the errors in question from the average values of the diameter intervals $D_m$. Applied to a circular surface $\Delta = 10^{-3} k \sqrt{D_m}$, where $k$ is the coefficient: for example, for the tolerance of flatness $k = 1.37$ (7 quality of accuracy) and $k = 2.2$ (8 quality of accuracy); for the tolerance of parallelism and perpendicularity $k = 2.2$ (7 quality accuracy) and $k = 3.7$ (8 quality accuracy).

For the most applicable in machine tool size $D_m = 20; 32; 51; 81; 130 \text{ mm}$.

### 3.5. Radial clearance

The need to take this VDP into account during optimization arises when a cylindrical surface participates in a contact, which depends on the chosen base scheme of the mounted part [10]. It is known that, depending on the ratio of the length $l$ and the mounting diameter $d$, all parts mounted on the shafts are conventionally divided into sleeves ($l/d \geq 0.8$) and rings ($l/d < 0.8$) [11]. From the theory of basing it is known [10], that for landings with tightness or a small gap of the sleeves, the main base, which determines the position of the part on the shaft or in the body, is the cylindrical interface, and for the rings - the front surface of the parts.

As a rule, taking into account this VDP makes sense only during transitional landings with a gap, the value of which, taking into account the minor angles of rotation of the part during contact, ensures the participation of a cylindrical surface in contact during assembly.

The need to take into account the radial clearance as the VDP for different transitional landings in the range of diameters $30 \ldots 120 \text{ mm}$ can be determined by the probability of connection with a gap for various transitional landings (Table 1) [8].

| Landing   | H7/js6 | H7/k6 | H7/m6 | H7/n6 |
|-----------|--------|-------|-------|-------|
| Probability | 0,96  | 0,4   | 0,04  | 0     |

Thus, the radial clearance should be taken into account when landing H7 / js6 and H7 / k6.

The average value of the gap, taking into account the existing asymmetry of dimensional deviation [11]:

$$Z_m = Em - em - 0.1 \cdot (t_1 + t_2),$$

where $Em$ and $em$ are the average deviation of the size of the hole and shaft; $t_1$ and $t_2$ are the tolerances of the dimensions of the hole and shaft.

The range of the specified VDP is formed by its change from zero (no gap) to the largest value, which is determined when calculating by the method of maximum-minimum:

$$Z_{max} = ES - ei,$$

where $ES$ is the upper deviation of the hole; $ei$ is lower shaft deflection;

when taking into account the probabilistic nature of the resulting dimensions:

$$Z_{pmax} = Z_m + 0.5 \cdot \sqrt{t_1^2 + t_2^2}. $$
4. Pareto Area Definition

When solving optimization problems with several conflicting criteria, it is impossible to specify a VDP combination that best meets all the criteria, and you can only define a certain area (Pareto region) characterized by the fact that any solution belonging to it cannot be improved simultaneously by all criteria.

The determination of the solution search area (Pareto region) is most conveniently performed by scanning using the LP-τ-sequence [12-14].

To estimate the values of the criteria at the points of probing using the LP-search method, it is necessary to use mathematical models connecting the adopted VDP and optimization criteria.

Mathematical models connecting VDP connections and criteria determining the spatial position of the parts to be joined and contact stiffness are given in [5].

To assess the normal damping, you can use the value of relative energy dissipation [9]:

$$\psi = \frac{A}{\sqrt{\sigma_c}},$$  \hspace{1cm} (7)

where $\sigma_c$ is constant pressure at the junction; $A$ is coefficient depending on the type of oil.

The cost of the connection will consist of the cost of its parts and the cost of assembly [15, 16]:

$$c = \sum_{i=1}^{n} c_i(\delta_i) + c_a,$$  \hspace{1cm} (8)

where $c_i(\delta_i)$ is the cost of the $i$-th part or the cost of achieving accuracy within tolerance $\delta_i$:

$$c_i(\delta_i) = \frac{b_i}{\delta_i^{a_i}} + c_{i0}. \hspace{1cm} (9)$$

The coefficients $a_i$, $b_i$ can be obtained from the processing of statistical data linking the manufacturing cost with a tolerance of $\delta_i$.

As a result of scanning in the space of the VDP, we obtain $m$ points corresponding to the smallest values of the criteria:

$$\bar{x}_j^0 = \left(x_{j1}^0, x_{j2}^0, \ldots, x_{jm}^0\right), j = 1, m.$$  \hspace{1cm} (10)

It is natural to assume that the Pareto region is located inside the space bounded by points $x_{j}^0, j = 1, m$.

In connection with the complexity of describing the boundaries of the obtained Pareto region, you can use its approximation by the hyper-parallelepiped described:

$$D_0 = \left\{ x \in \mathbb{R}^n \left| x_i \in [a_{xi}^D, b_{xi}^D] \right| i = 1, n \right\},$$  \hspace{1cm} (11)

where

$$a_{xi}^D = \min x_{ji}^0, b_{xi}^D = \max x_{ji}^0 : j = 1, m.$$  \hspace{1cm} (12)

Moreover, this approximation will be the more accurate, the greater the number of criteria.

The set $D = D_{VP} \cap D_0$, which is the intersection of regions $D_{VP}$ and $D_0$, is the domain of the search for solutions.

When choosing in the area $D$ VDP nominal values due to a large number of production factors determining their real values, it is possible to accept the symmetric law of variation of possible deviations of the VDP.

Since the region $D$ is characterized by the fact that any solution belonging to it cannot be improved simultaneously by all the criteria, when choosing possible deviations of the VDP from the nominal value, one can use the generalized criterion calculated during scanning
\[ F = \sum_{i=1}^{m} \frac{F_i(x)}{F_{i\text{min}}(x)}, \]  

where \( F_i \) is the objective function; \( m \) is the number of optimization criteria.

The range of changes of VDP nominal values is determined by the parameters of VDP points that meet the condition

\[ F_{\text{min}} < F < (1 + \lambda)F_{\text{min}}. \]  

The coefficient \( \lambda = 0.1 \) is determined by the decision maker, and, as a rule, can be taken \( \lambda = 0.05...0.10 \).

5. Approbation

Calculations performed according to the proposed procedure for the left support of the running screw for driving the longitudinal feeds of the machine mod. 1P426DF3 (Figure 2), allow to determine the nominal values and deviations of each of the VDP (Table 2). In Table 2: \( P_N \) is preload, H; \( c \) is coefficient, N/cm²; \( \Delta_l \) is surface location error, μm; \( d \) is diameter, mm; \( \delta \) is radial clearance, μm; \( \Delta_s \) is shape error, μm.

![Figure 2](image_url)

**Figure 2.** The design of the left support of the running screw of the drive of longitudinal feeds of the machine mod. 1P426F3

6. Conclusion

A procedure for parametric multi-criteria synthesis of standing connections of the running screw of the CNC machine has been developed.

The dependences are obtained, allowing determining the region of variation of the VDP as the intersection of three regions defined by parametric, functional and criterion constraints.

A generalized criterion is proposed, calculated during scanning and used when selecting possible deviations of the VDP from nominal values.

The technique was tested when determining the VDP standing connections of the left support of
the running screw of the longitudinal feed drive of the CNC machine mod. 1P426DF3.

Table 2. The ranges of possible values of the variables of the design parameters and the compliance of the fixed connections of the left support of the running screw of the drive of the longitudinal feeds of the machine mod. 1P426F3

| Connection | Variable of design parameters (VDP) | Compliance, µm/N |
|------------|-------------------------------------|------------------|
| 1 - nut - spacer ring | $P_N$, $c \cdot 10^4$, $A_f$, $d$, $\delta$, $A_s$ | 0.0013 |
| min | 2171 | 2.38 | 12.7 | 55.5 | 0.4 | 9.4 | 0.0013 |
| max | 8330 | 13.44 | 43.9 | 69.8 | 11.6 | 38.7 | 0.0037 |
| 2 - spacer ring - bearing | min | 2171 | 2.38 | 12.7 | 55.5 | 0.4 | 9.4 | 0.0013 |
| max | 8330 | 13.44 | 43.9 | 69.8 | 11.6 | 38.7 | 0.0037 |
| 3 - bushing - running screw | min | 2485 | 0.87 | 13.9 | 51.2 | 0.6 | 11.3 | 0.0029 |
| max | 9129 | 14.55 | 33.2 | 55.0 | 7.6 | 37.6 | 0.0087 |
| 4 - bushing - bearing | min | 2485 | 0.87 | 15.4 | 54.8 | 0.6 | 18.2 | 0.0013 |
| max | 9129 | 12.88 | 42.5 | 69.9 | 7.6 | 43.1 | 0.0044 |
| 5 - ring - support body | min | 2000 | 0.70 | 12.0 | 75.0 | 0 | 8.0 | 0.0016 |
| max | 7469 | 8.97 | 49.2 | 77.5 | 5.3 | 48.5 | 0.0078 |
| 6 - ring - flange | min | 2000 | 0.70 | 12.0 | 75.0 | 0 | 8.0 | 0.0016 |
| max | 7469 | 8.97 | 49.2 | 77.5 | 5.3 | 48.5 | 0.0078 |
| 7 - an internal ring of the bearing - case | min | 2547 | 3.72 | 12.5 | 75.3 | - | 12.4 | 0.0040 |
| max | 9227 | 11.37 | 62.7 | 79.9 | - | 47.7 | 0.0092 |
| 8 - flange - housing | min | 2898 | 1.04 | 27.2 | 84.6 | 2.0 | 29.1 | 0.0007 |
| max | 6141 | 6.62 | 91.5 | 126.5 | 15.0 | 56.5 | 0.0031 |

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