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QUALITY OF DESIGN ENGINEERING: CASE OF MACHINE TOOLS HEADSTOCK

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Abstract *Determination of a product's phisical features is the responsibility of design engineering. This involves decisions related to the number of components, the role of each component, the choice of material, choice of methods etc. Those decisions depended upon the nature of relationship among customer – desired attributes of a product and its phisical features.*
Decisive criteria of machine tools quality are the productivity and working accuracy. The number of spindle - bearing systems supported on ball bearings with angular contact are proportionally increasing in accordance to this increasing demands on machine tools. By the variation of the bearings and their arrangement in bearing node, value of contact angle, magnitude of preload and type of flanges can be suitably optimised resulting stiffness and speed-ability of the spindle-bearing system.
Rapid evaluation of various spindle-bearing system variants in the preliminary design stage has great importance for the design engineer. His selection can be correct, if he has suitably chosen criteria for the spindle bearing-system design and adequate experiences in this field.
In this paper is introduced as well simplified mathematical apparatus for evaluation of basic spindle - bearing system parameters as also recommended selection criteria. In the paper, the design and verification of simplified mathematical model for computing of bearing arrangements parameter and stiffness are given.

Key words: *design engineering, quality of machine tool, headstock, spindle-bearing system, ball bearings with angular contact, bearing arrangements machine tools, lathe, static analysis, mathematical models, accuracy, productivity.*

1. INTRODUCTION

Design engineering process according [12] involves 5 major aspects:

1. conceptual design, including: function design, engineering solutions and evaluation of design variants [12],
2. form design, including design matrix and axioms [13],
3. designing using appropriate methods for calculation and analyse, design tolerancens with robust design [14, 15],
4. design sequence [13] and
5. cost of design [12].

Subject of this paper is third aspect related to using appropriate methods for calculation and analyse of machine tools with used spindle on bearing arrangements in high – speed.

The major machines in FMS with CIM, [1], [2], [11], are of course powerful CNC machine tools of different types, mainly milling and turning centres. These highly efficient systems, which are designed to operate with a very small work force, require reliable machines. The word covers in this context the ability of the machines in the system to maintain their accuracy during long work cycles over long periods of times, with a minimum of servicing.

According to demands on machine tools productivity and accuracy, the spindle-housing system is a heart of machine tool, fig 1, [7]. Radial ball bearings with angular contact are still more and more applied in arrangements. The number of headstocks supported on angular contact ball bearings is increasing proportionally with increasing demands on the machine tool quality, [4]. It is caused by the fact that these bearings can be arranged in various combinations to create bearing arrangements which can be enabling to eliminate radial and also axial loads. The possibility of variation of the number of bearings, preload value, bearings dimensions and contact angle of bearings used in bearing arrangements create wide spectrum of combination to reach

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sufficient stiffness and revolving frequency of the spindle-bearing system [2], [5]. The sufficient stiffness and revolving frequency of headstock are necessary criteria for reaching demanding manufacturing precision and machine tool productivity.

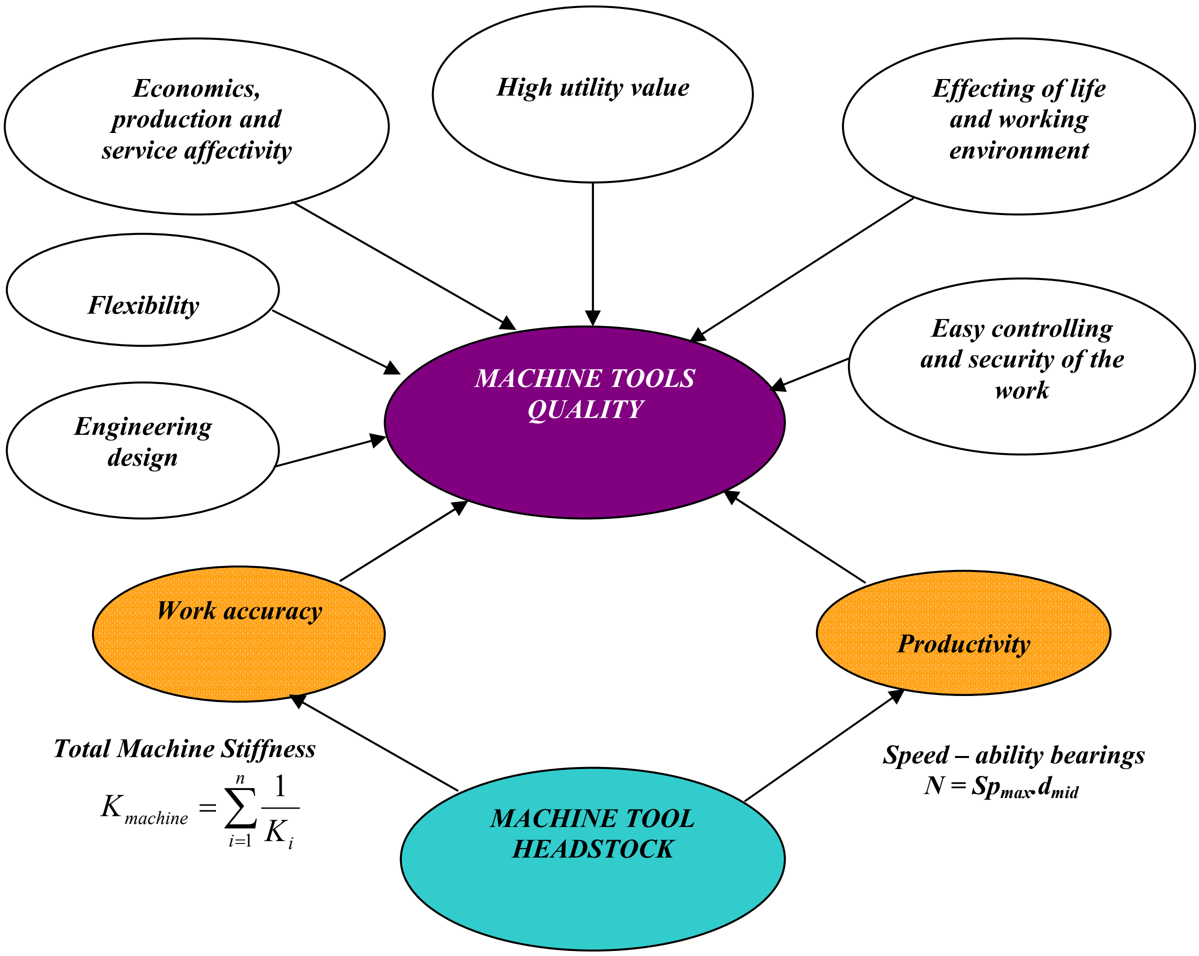

Fig. 1 Factors influence on Quality of Machine Tool, [7].

2. QUALITY OF THE DESIGN PROCESS OF MACHINE TOOLS

Each factor wich has influence on machine tools quality depends on large number carracteristies. Because the subject of this paper is engineering design, 3. aspect (designing) subaspect: methods for calculations and analyse, for machine tools headstocks autor proposes extended model of quality (figure 2) based on [16]. Dominant influence has the quality of machine tools elements. This part of quality is specialy important for headstock of machine tools (weight w_{13}). Stiffness has significant weight on second level (w_{131}). This is reason for carefull and precise static analysis and calculations of headstoch stiffness.

2.1 Primary static analysis

The calculation of the headstock ultimate revolving frequency is relatively simple. The ultimate revolution frequency of the bearing arrangement is calculated on the basis of ultimate revolving frequency of one bearing by multiplying this frequency by various coefficients reflecting the influence of bearings in bearing arrangement, bearing precision, preload value, lubrication and cooling conditions. But the problem is how quickly and with sufficient precision calculates headstock stiffness.

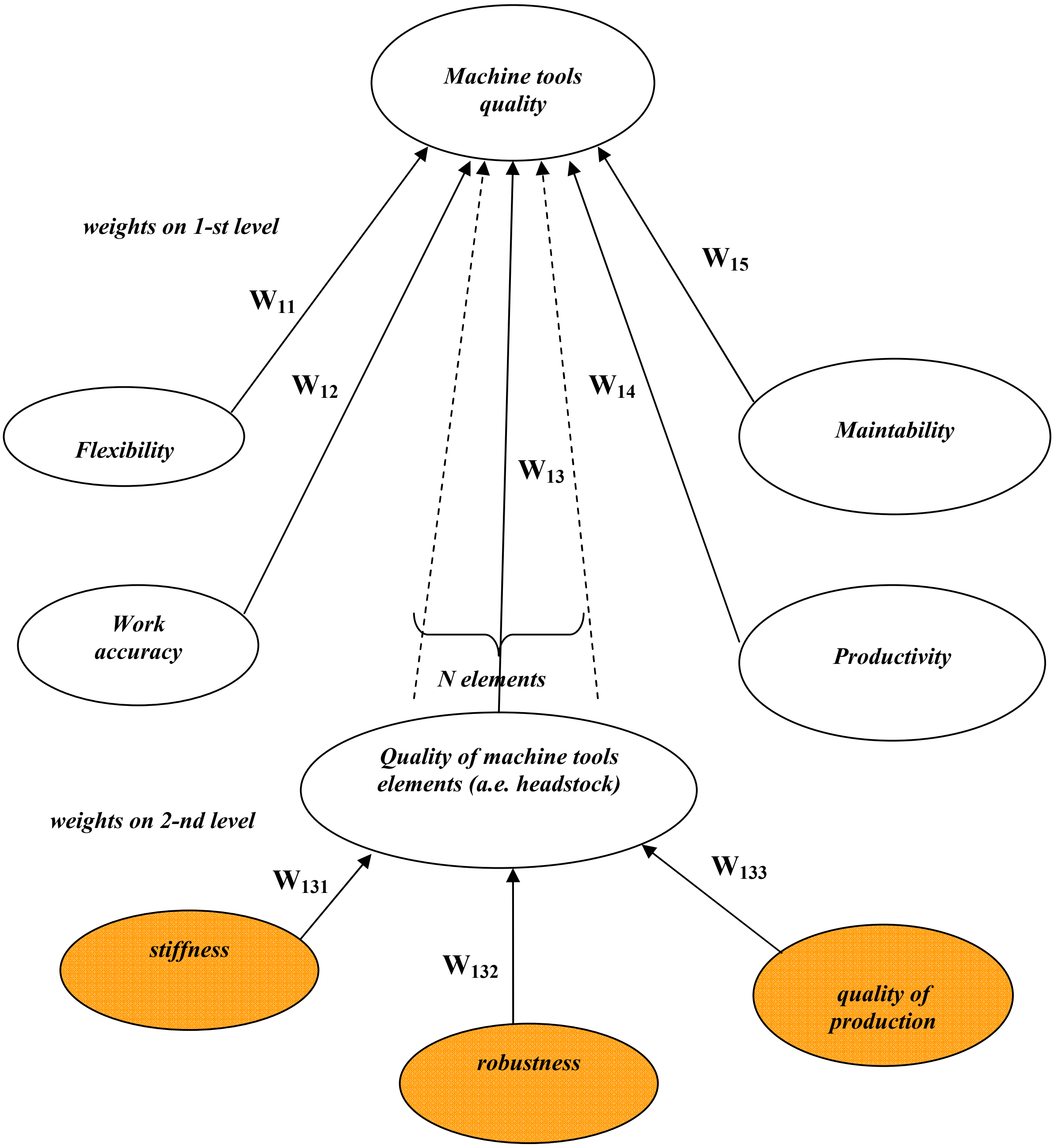

Fig. 2 Extended model of quality

The headstock stiffness must be calculated in accordance to deformation of the front spindle end, because the deformation at this point has direct relationship to precision of the production. The deformation of the front spindle end is summation of various more or less important partial deflections. Resulting radial deformation y_{rc} of front spindle end is shown at Fig. 4.

The radial headstock stiffness we can calculated

$$K_{rc} = \frac{F_r}{y_{rc}} \qquad (1)$$

then "F_r" is tangential Force (Fig. 5).
The calculation of front-end spindle deflection which could take into consideration all important parameters can be done only using powerful computers. The analysis can be realized by standard or special (fit to problem) software programs. The calculations of many combinations

are very demanding on time and money. The stiffness analysis by standard programs depends on engineers experiences. The results can be very disputing although when suitable mathematical method is used (finite elements method, boundary elements method, Castilian theorem,). This can be caused by the fact that headstock box, bearings or bearings arrangement are statically indefinite systems with nonlinear deformation of the node under the load. Special software's are very expensive. They are developed using the up to date theoretical and practical knowledge. These programs were particularly developed by research institutions and bearings producers and possibility use such programs significantly influences their position on the spindle-bearing systems market.

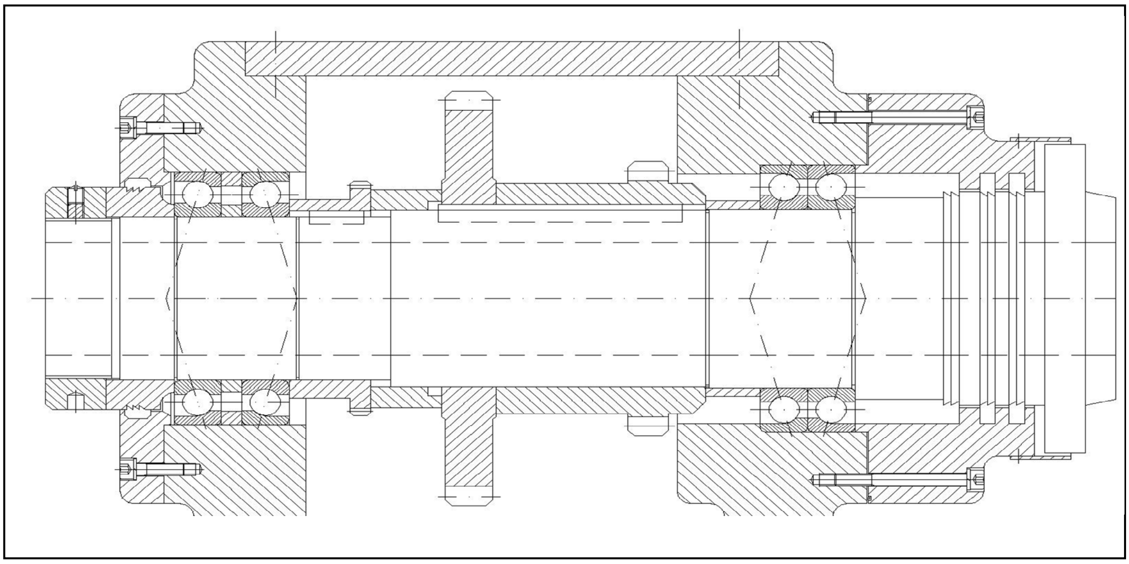

Fig. 3 The Headstock of the precision boring machine DB24 by Eislinger, [6]

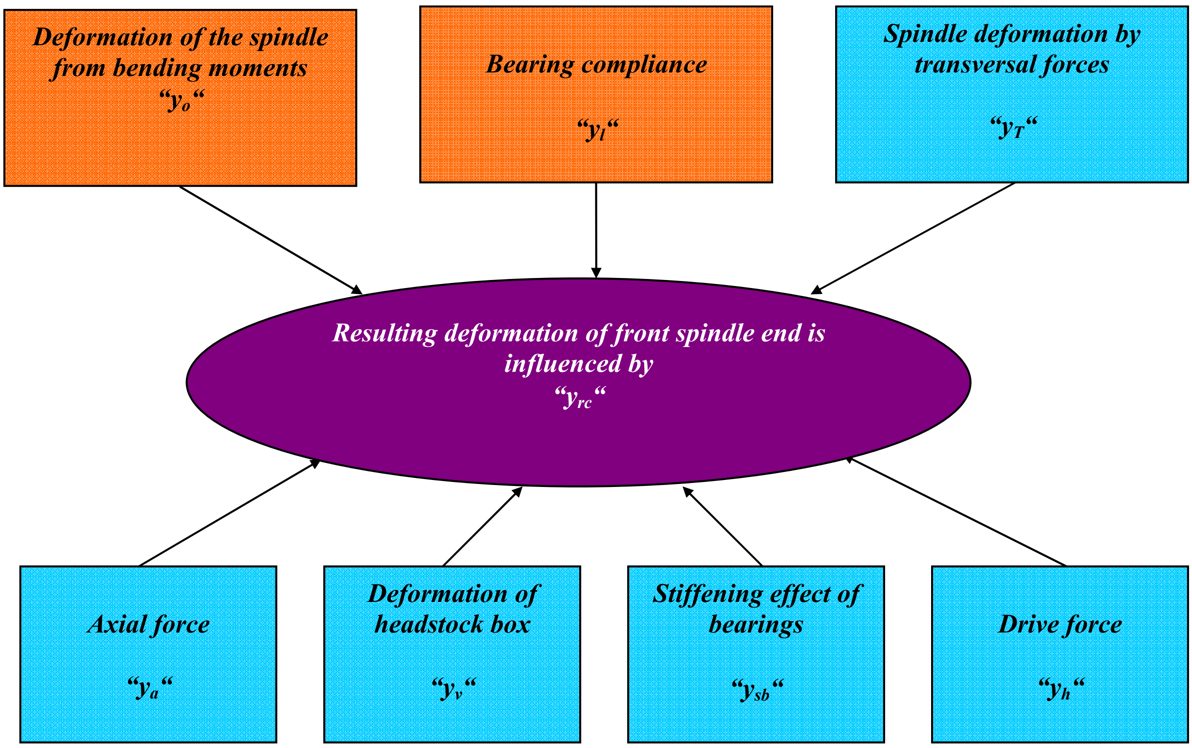

Fig.4 Factors influencing resulting deformation

Taking into the consideration facts mentioned above engineer would appreciate the existence of the methodology of simplified static analysis. Such a methodology will enable the engineer in the preliminary design stage reduce the number of possible spindle-bearing variants and determine the direction which will lead to optimal spindle-bearing system design, [6].

2.2 Simplified Method of calculation

The experiences showed that whatever mathematical method and software is used, the spindle deflection caused by bending moments and by bearing compliances have the greatest influences to resulting front end spindle deflection. The ratio of these two partial deflections is always greater than 90 % from resulting deflection. If the methodology is simplified it is sufficient to pay attention only to these two partial deflections, [1], [7], [10].

Then $y_{rc} = y_0 + y_l$ (2)

where the deflection caused by bending moments is as follows:

$$y_o = \frac{F_r a^2}{3E}\left[\frac{a}{J_a} + \frac{L}{J_L}\right] \quad (3)$$

and the deflection caused by bearing compliance is as follows:

$$y_l = \frac{F_r}{L^2}\left[\frac{a^2}{K_B} + \frac{(L+a)^2}{K_A}\right] \quad (4)$$

Increasing moments of inertia *"J_a", "J_L"* we calculated

$$J_a = \frac{\pi}{64}\left[D_a^4 - d_a^4\right] \text{ and } J_L = \frac{\pi}{64}\left[D_L^4 - d_L^4\right] \quad (5)$$

The definition of the quantities is shown at Fig. 5.

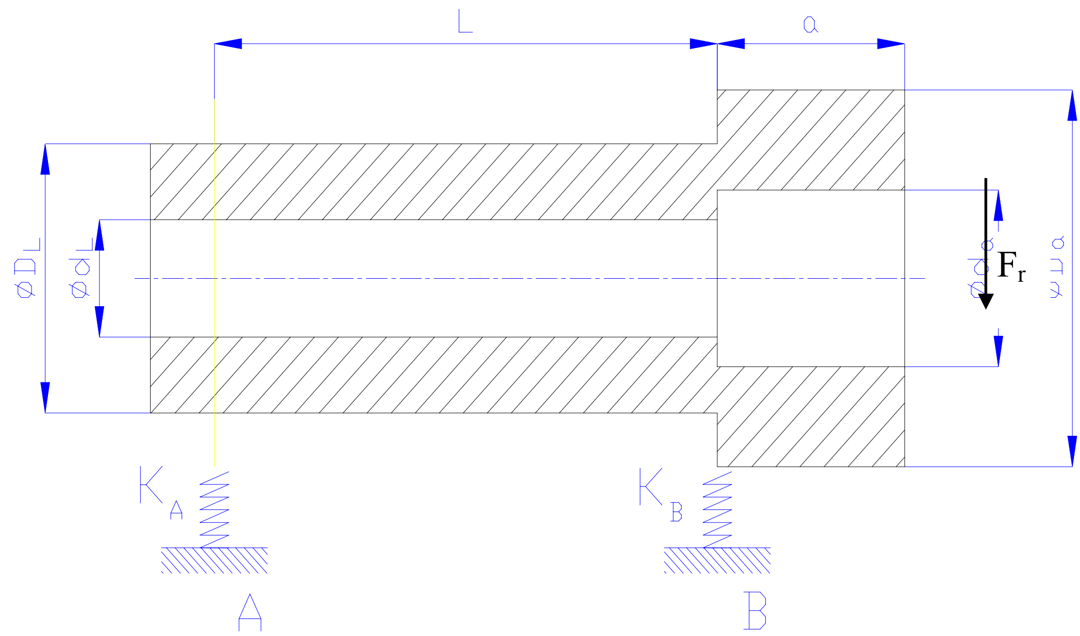

Fig.5 Replace scheme of the spindle-bearing system

The individual headstock parts (spindle, bearing arrangement,) create serial springs arrangement and it is evident than resulting stiffness K_{rc} is limited by stiffness of the weakest part, [9]. The expert can see which part should be improved, which from partial deflections should be decreased.

The parameters *"F_r", "a", "L"* influence at the same time the value of both deflections. The spindle deflection caused by bending moments can be decreased also by as follows:

- increasing of material modulus of elasticity *"E"*,
- increasing moments of inertia *"J_a", "J_L"* by change of spindle diameters *"D_a", "D_L", "d_a", "d_L"*.

The stiffness of the bearing arrangement (K_A, K_B) is the specific parameter which has influence on resulting spindle deflection. The simplified mathematical model for calculation of stiffness of bearing arrangement on journal angular ball bearings [8] can be expressed in form of the following equation:

$$K_{A,B} = \frac{3}{4}.2{,}3.t_1^{2/3}.z^{2/3}.d_w^{1/3}.F_p^{1/3}.\frac{\cos^2\alpha_1}{\sin^{1/3}\alpha_1}\left[1+\frac{t_2^{2/3}.\cos^2\alpha_2.\sin^{1/3}\alpha_1}{t_1^{2/3}.\cos^2\alpha_1.\sin^{1/3}\alpha_2}\right] \tag{6}$$

Taking to the consideration equation (6) it is evident that stiffness of bearing arrangement depends on number of bearings (t_1 and t_2) in arrangement, dimensions of the bearings (z_1, d_{w1} and z_2, d_{w2}), contact angle (α_1 and α_2) and preload value F_p.

This new equation (6) for middle stiffness of the bearing arrangement "K_r" calculation was experimental verified, [7]. At figure 6 we have been compared experimental measure stiffness, exactly and middle calculated radial stiffness of the bearing arrangement B7216 AATB P4 O UL. Results are very good

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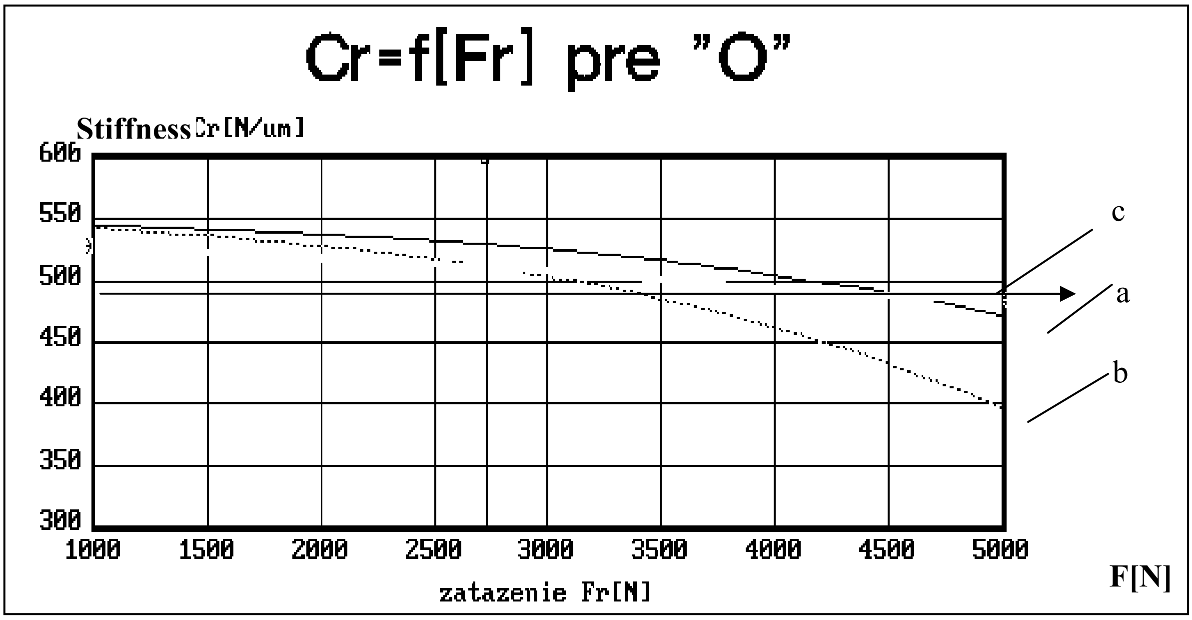

Fig.6 Radial stiffness of the bearing arrangement B7216 AATB P4 O UL, a - experimental, b - exactly, c - middle

The variation of the stiffness of the bearing arrangement B7216 CATB P4 O UL is shown at Fig. 7. The stiffness variation was studied at the change of the parameter by 25 %. Nominal valued of bearing arrangements: z_1, z_2= 14, d_{w1}, d_{w2} = 19,05 mm, α_1, α_2 = 12°, F_p=340 N.

3. CONCLUSIONS OF THE ANALYSIS

The conclusions of the analysis [3] are as follows:

- The radial stiffness is proportionally increasing with increasing *"z"*, *"d_w"*, *"t"*, *"F_p"* values and is decreased when *"a"* is prolonged.
- The parameters *"z"* and *"d_w"* must be evaluated in mutual interaction because they characterise size and dimensions of the bearings. The increasing of both these parameters and consecutive increasing of stiffness of bearing arrangement can be reached by increasing of inner bearing diameter. The disadvantage is that ultimate revolving frequencies will be decreased. The more suitable solution is to decrease the width of the bearing, e.g. from B72 to B70. In this case the number of rolling elements "*z*" will be increase and their diameter *"d_w"* will be smaller.
- Assuming equation (6), it is evident that *"z"* has more important influence on stiffness increase than *"dw"*. If the diameter of the rolling elements is smaller, their weight will be also decreased and this fact will enable increase ultimate revolving frequencies.
- The number of bearings in bearing arrangement *"t"* is the significant factor which cans favourable influence the stiffness. But the increasing number of bearings will drop ultimate revolving frequencies and therefore it is possible to use this way only for low speed spindle-bearing systems.
- The preload has relatively small effect on stiffness of bearing arrangement. The preload

real value depends also on type of flanges. When fixed flanges are used the preload value can several times exceed nominal value. This fact will cause excessive preload which produce heat and bearing arrangement will be out of order much more sooner as it was supposed.

- The contact angle "α" has significant influence on variation of stiffness of bearing arrangement. When the value of the contact angle is increasing, the radial stiffness and ultimate revolving frequency of the bearing arrangement is decreasing. But on the other side very significantly will be increased axial stiffness of the bearing arrangement.

In this paper was introduced as well simplified mathematical apparatus for evaluation of basic spindle - bearing system parameters as also recommended selection criteria. A designer will get the effective tool for preliminary selection of suitable arrangement by application of computed results. It is first step near analysis various combination spidle - bearings system. By selection optimally spindle - bearings system we achieve asking parameters headstock how necessary presumption for quality assurance machine tool.

4. Literature

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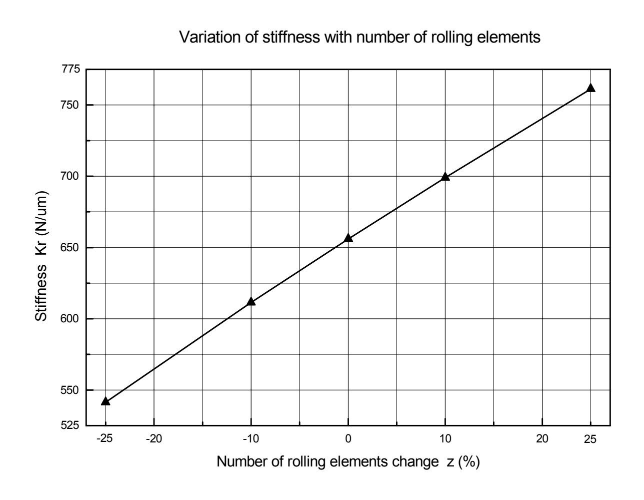
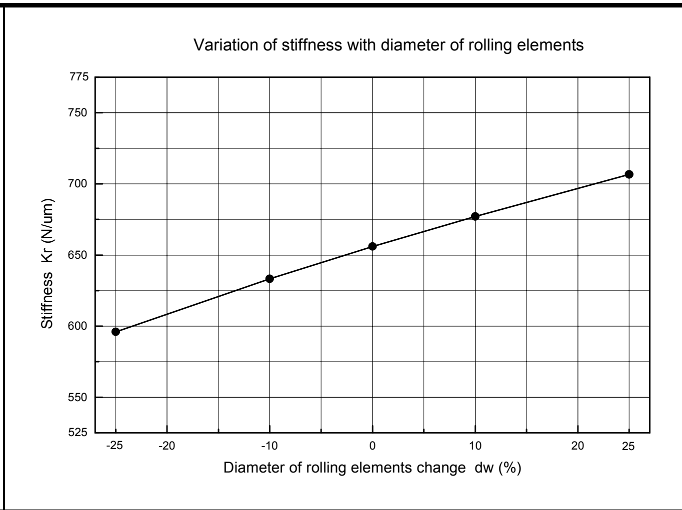
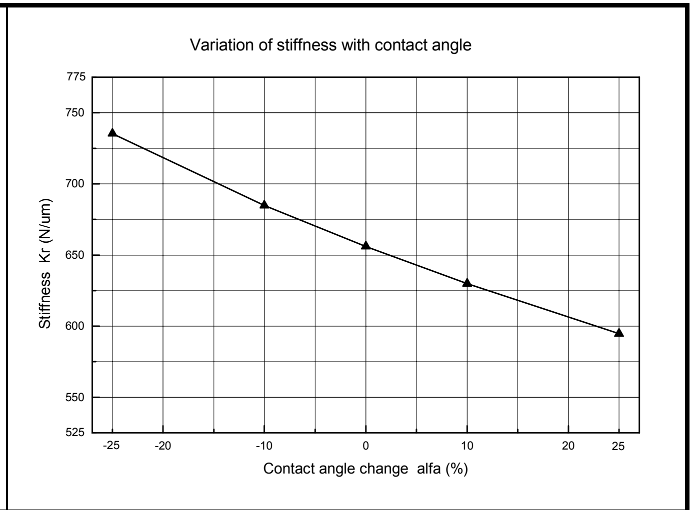


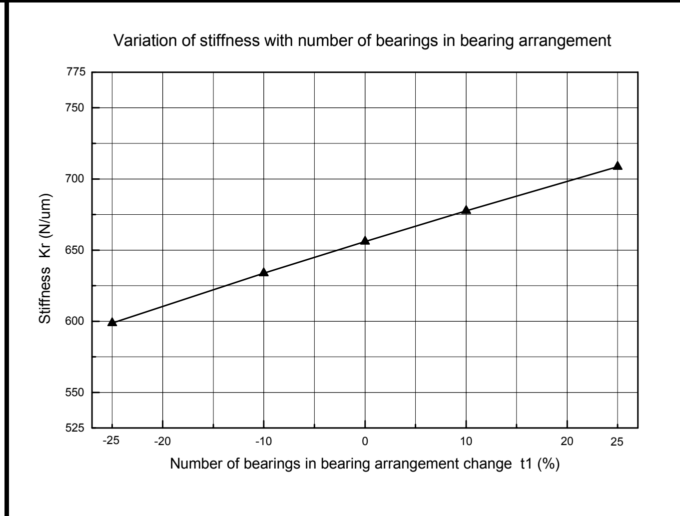
a. Variation of stiffness K_r with number of rolling elements *“z“*



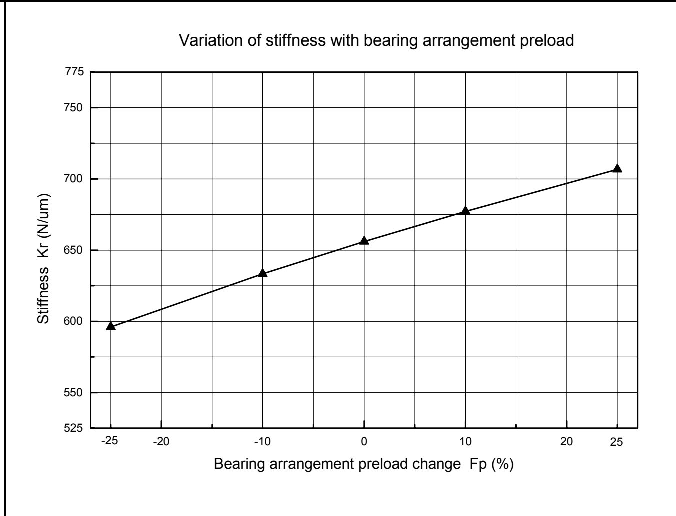
b. Variation of stiffness K_r with diameter of rolling elements *“d_W“*



c. Variation of stiffness K_r with contact angle α “α“



d. Variation of stiffness K_r with bearings in bearing arrangement *“ t_1 “*



e. Variation of stiffness K_r with bearing arrangement preload *“F_p“*

Fig. 7 Variation of stiffness with bearing arrangement parameters