NEW METHOD FOR MACHINING OF LOW-RIGIDITY SHAFTS

Antoni Świć, Victor Taranenko, Dariusz Wołos

S u m m a r y

Achieving the technological reliability of machining low rigid shafts is essential problem in machine industry. Therefore studies on theoretical and experimental bases of controlling the elastic deformable state of elements during the technological process is very important. The definition of technological reliability of processing low rigid shafts was introduced and also the classification of structural and technological methods of increasing the technological reliability was worked out. The important scientific question of increasing the technological processing reliability of low rigid shafts was solved basing on the system analysis of cause - effect relations between precision and reliability of low rigid shafts processing. Several construction of lathes' tailstocks were designed in order to achieve the suitable reliability of technological processing of low rigid shafts by producing elastic deformable state.

The credibility of basic results was confirmed during designing and experimental research on structural and technological methods of increasing the technological reliability.

Keywords: Machining, low rigid shafts

Nowy sposób obróbki mechanicznej wałków o małej sztywności

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Introduction

Approximately one half of all machine parts are revolving parts, out of which shafts account for up to 40%. Shafts are classified in various ways, some of which take the rigidity of the parts into account. As follows from an analysis of products of various branches of industry, low-rigidity shafts may constitute even 40% of all shafts. They are applied, among others, in the aerospace industry, in precision mechanics, in tool-making industry, in motor industry, etc. [1].

A highly important, and at the same a complex problem is the process reliability of machining of parts of this type.

The concept of process reliability of machining of low-rigidity shafts is understood as the achievement of the required accuracy of form, dimensions, and surface quality of parts produced under conditions of stable functioning of the technological system. Stability of technological system precludes the occurrence of dangerous and detrimental production factors, leading to the appearance of breakdown or emergency situations and to a lowering of the level of production safety.

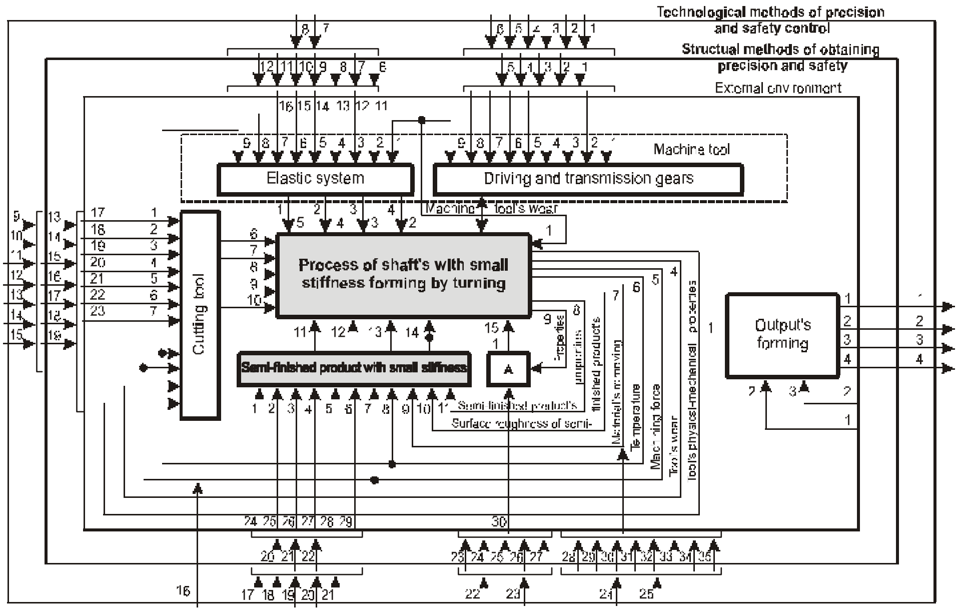
It is generally known that the problem of reliability should be considered in machine technology in a comprehensive manner, with relation to the whole technological process, as errors depend not only on the variant of the technological system but are also determined by the effect of a considerable number of systemic and incidental factors on the technological process, such as inaccuracy of the technological system, its deformations due to the effect of force factors and temperature, inaccurate positioning and wear of tools, measurement errors, etc.

Classification of methods of achieving technological reliability of machining of low-rigidity shafts

Examination of the mutual effect of particular factors on machining reliability is a problem of multi-criterion analysis that can be presented in the form of a hierarchical structure as shown in Fig. 1 [2-9].

On the highest level there are the stages of the whole technological process (including the "Shaping of surface"). Listed below are the technological processes applied (in this case only one method is considered – that of "Machining"). Level III presents the areas of appearance of dangerous and detrimental production factors, level IV – the causes of their appearance, level V – their effects, and at the bottom of the structure we have listed the design and technological methods for the improvement of technological reliability, indicating the methods and factors that lie in the focus of research interest of the authors.

Based on a review of the available literature, a proprietary system has been developed for the attainment of reliability of machining of low-rigidity shafts, demonstrated in Fig. 2. Numbers from 1 to 35 symbolise the input and output parameters of the individual subsystems. As an example, in the case of the subsystem “Semi-finished product of low rigidity” these can be the weight, rigidity, dimensions, surface roughness, etc.



A - Cutting fluid

Fig. 2 System’s structure of shafts’ precision and quality parameters and machining safety

For the purpose of improving the level of technological reliability of machining of low-rigidity shafts methods are also used that are not included in any classification existing so far. Based on our review of the literature concerning studies on machining accuracy and on a cause-and-effect analysis, we have developed our own classification (Fig. 3), in which we have indicated areas directly related with our research activity.

Based on the existing knowledge we can state that machining accuracy largely depends on the convergence between shaft rigidity and machine tool rigidity and may vary within a broad range [10-12].

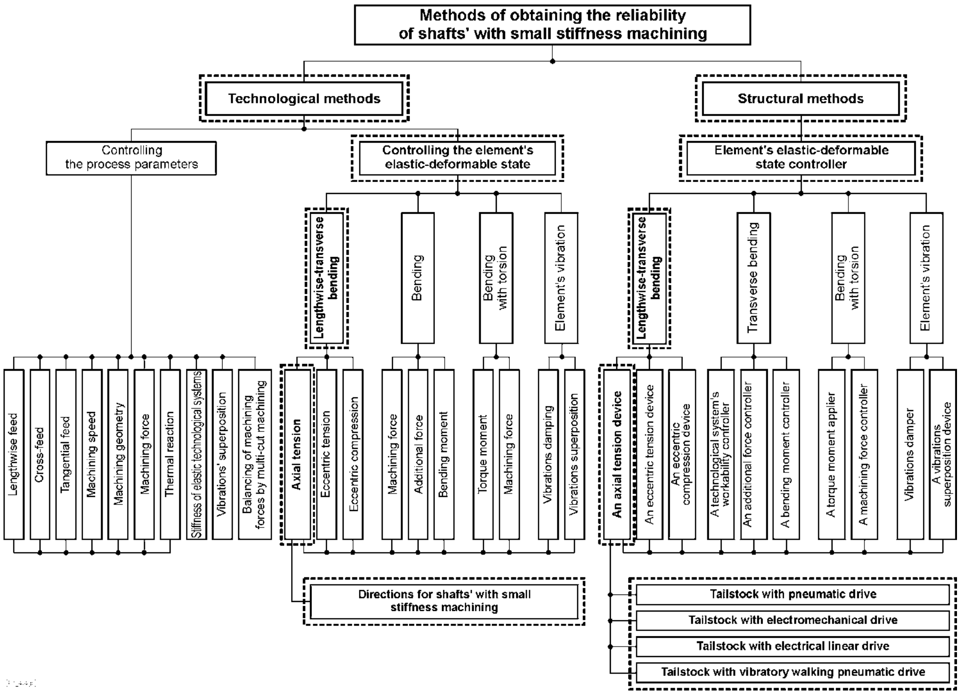


Fig. 3. Classification of methods of attaining the hafts' with small stiffness machining reliability

Modelling of elastic deformations of shafts

We developed mathematical models of elastic deformations of shafts in steady state under various conditions of fixing and loading. In the study and in the development of the models we assumed that the technological process is continuous and stable and that the machining parameters and the cutting power of the tool are invariable during the machining of a single part. The initial conditions are defined at the moment of contact between the cutting tool and the part; the technological system is limited by the section: fixed headstock-shaft-tailstock (tail centre or grip).

In solving the modelling problem two stages were identified:

Stage I – development of mathematical model permitting analytical determination of the effect of the set of factors on the accuracy.

Stage II – formulation, based on methods of optimisation, of algorithms of control of the elastic-deformable state of the shaft, accounting for real relations, and development of new methods of controlling the technological reliability of machining.

Based on the adopted assumptions, seven steady-state mathematical models were developed. Examples of schematics of fixing and loading, together with the corresponding functions of deformation, are given in Table 1 [13].

Examination of shaft deformations in steady state (Fig. 4) proceeded as follows. The cross slide was pushed in by a model spring dynamometer – the shaft was loaded by the radial component force of machining.

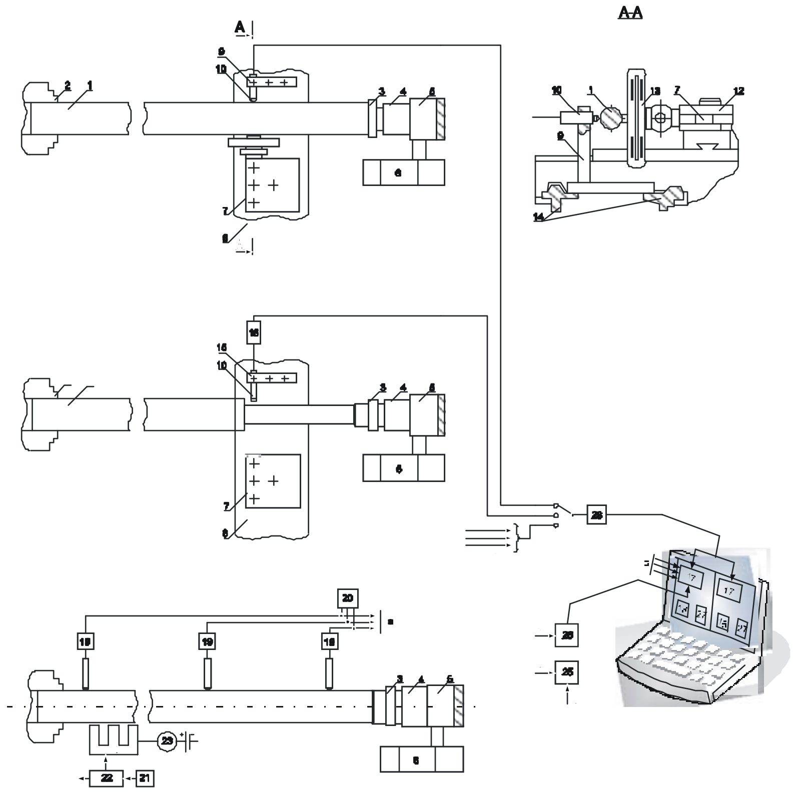


Fig. 4. Schematic of experimental station for testing of elastic deformations of shafts under the application of tensile force to the part

The shaft was fixed by one end in the grip of the fixed stock, and by the other in the grip sleeve of the tailstock of the lathe. Elastic deformations were measured with a displacement gauge and recorded on a computer. The results of shaft tests are presented in Fig. 5, where the curves obtained experimentally under fixing and loading conditions conforming to model 3.3 are designated as 3.5. The differences between elastic deformations, experimental as well as modelled, did not exceed 12%.

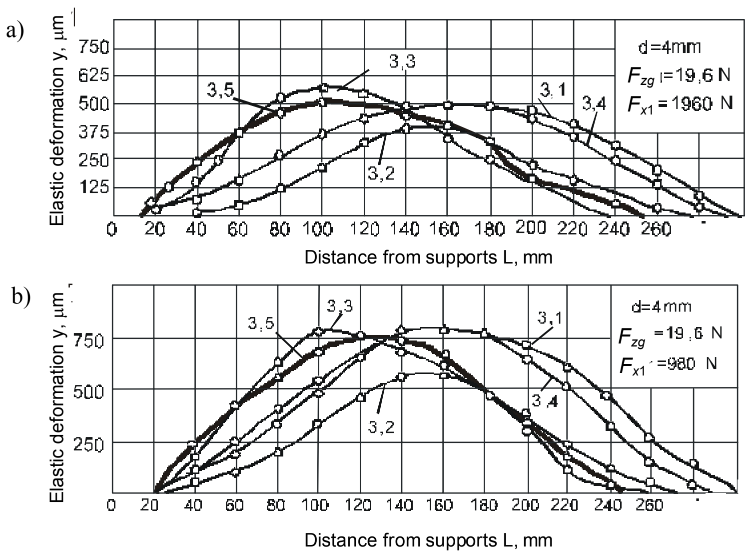


Fig. 5. Functions of changes in elastic deformation of shafts at ($x = a$), $d = 4$ mm: a) $F_{x1} = 1960$ N, b) $F_{x1} = 980$ N. 3.5 – curve obtained experimentally in accordance with model 3.3

As results from the specific character of manufacturing shafts of low rigidity and from analysis of theoretical and experimental studies, one of effective approaches to the improvement of reliability of machining of such shafts is increasing their rigidity through controlled change of their elastic-deformable state by applying a tensile force that creates, together with the machining force, a longitudinal-lateral (axial-radial) load.

In the example presented in Fig. 6, deformations in conventional machining exceed 120 µm. Such a level of deformations practically renders machining impossible (e.g. due to vibrations, damage to the cutting tool edge etc.).

We performed also modelling of shaft deformations with eccentric tension. Fig. 7 presents a general view of the surface of objective function values response with technological limitations in the form of $F_{x1\max}$, $e_{\max}$, that has an extreme at point F. In many cases there is no need to find an extreme, as it is enough to adopt the limitation to a certain required value of $y_{sk.zad}$, adopted in prior. The cutting planes $O_1A_1C_1D_1$ and $O_2A_2C_2D_2$ correspond to the adopted deformation values $y'_{sk.zad.}$ and $y''_{sk.zad.}$, relative to which the search for the optimum set of values F_{x1} and e is conducted.

Comparison of modelled elastic deformations on the example of a shaft with 6 mm in diameter and 240 mm long, at various states of loading, is presented in Fig. 8.

The values of maximum elastic deformations at axial tension are ca. 2.2-fold lower, and at eccentric tension ca. 18-fold lower than in conventional machining.

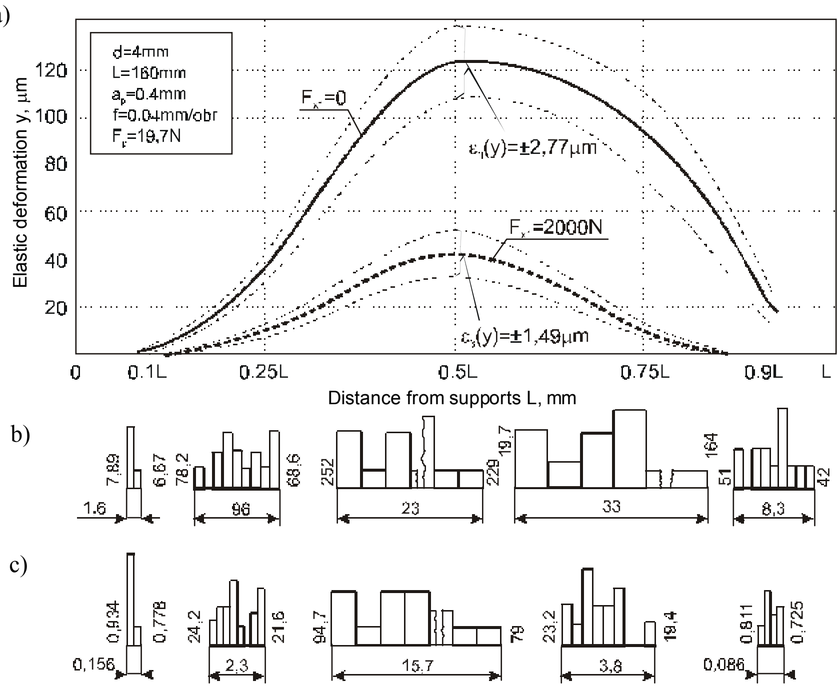


Fig. 6. Function of changes in elastic deformations during the turning of a shaft with d = 4 mm: a) functions of changes in elastic deformations with intervals of confidence, b) histograms of distribution of dimensions in turning without the elastic-deformable state, c) in the elastic-deformable state

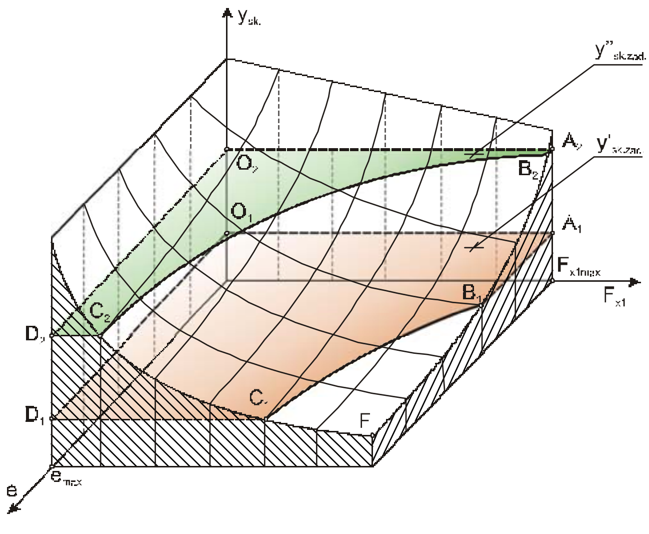


Fig. 7. The general view of the surface of objective function values response

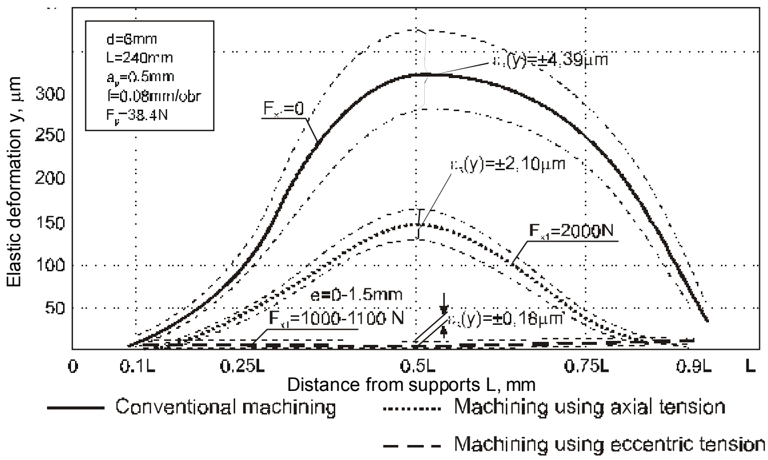


Fig. 8. Functions of changes in elastic deformations with intervals of confidence in shaft turning (*HB* = 140 – 240)

Based on the theoretical and experimental studies, we developed a method for the machining of low-rigidity shafts that guarantees the attainment of technological reliability in the course of turning and that permits control of the elastic-deformable state of shafts [14, 15]. A schematic of a device for the realization of machining of low-rigidity shafts is given in Fig. 9. The mechanism

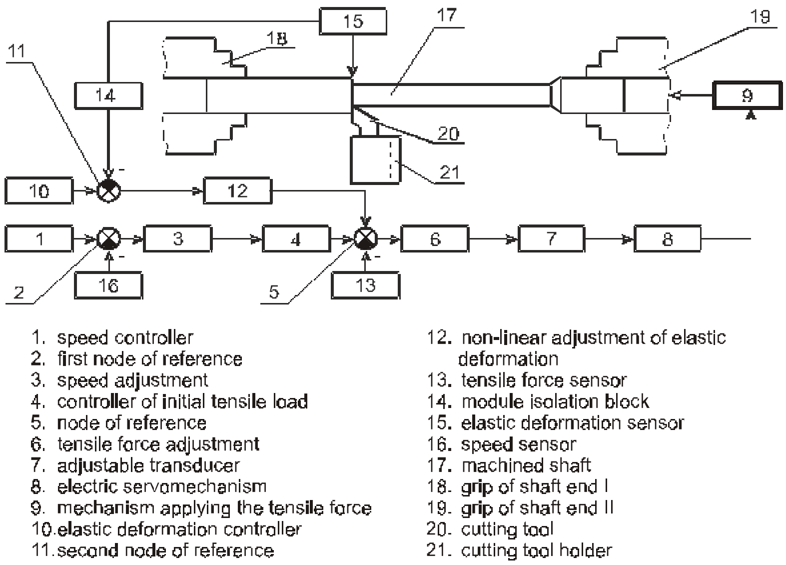


Fig. 9. Schematic diagram of the device for the realization of machining of low-rigidity shafts

applying the tensile force is marked as item 9. In order to allow shafts to be fixed in such mechanisms it is necessary to make alternative technological alignment datums, examples of which are shown in Fig. 10 [13].

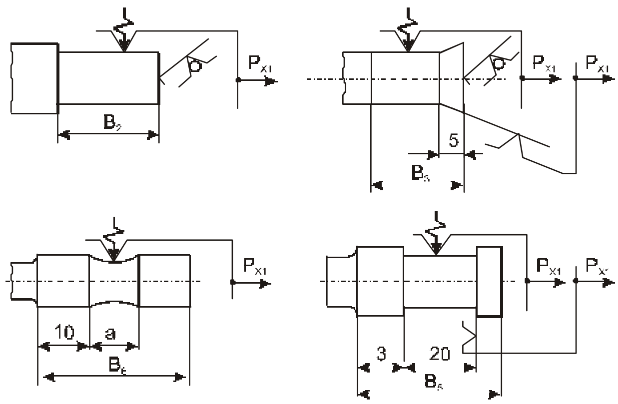


Fig. 10. Example schematics of alignment of shaft end in machining with application of tensile force. Dimension *B* depends on the diameter of the shaft

Designs of lathe tail stocks for machining of low-rigidity shafts

Within the scope of the study we also developed several designs of special lathe tail stocks [16-20]. A design with pneumatic drive, meant for batch and mass production, is presented in Fig. 11. The tensile force is generated by a pneumatic muscle, designated in the drawing as item 1.

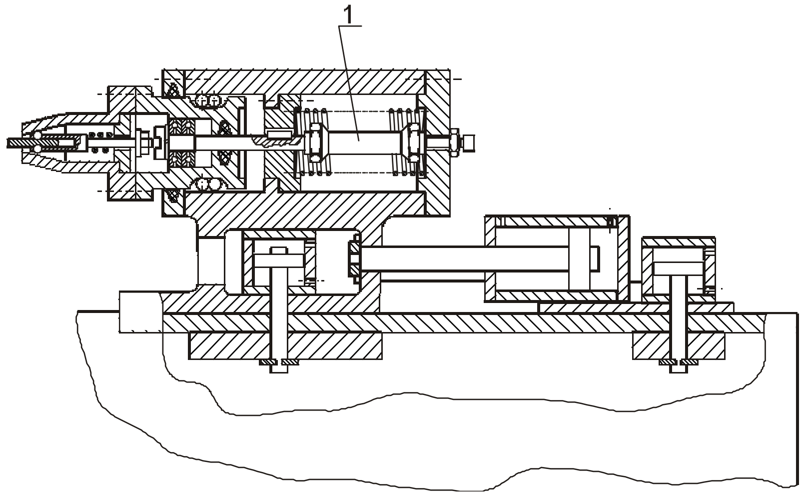


Fig. 11. Design of lathe tail stock with a pneumatic muscle

An example of a simple and inexpensive design based on the use of a set of springs is presented in Fig. 12. This design can be applied in unit production, repeatable unit production, or in small-batch production.

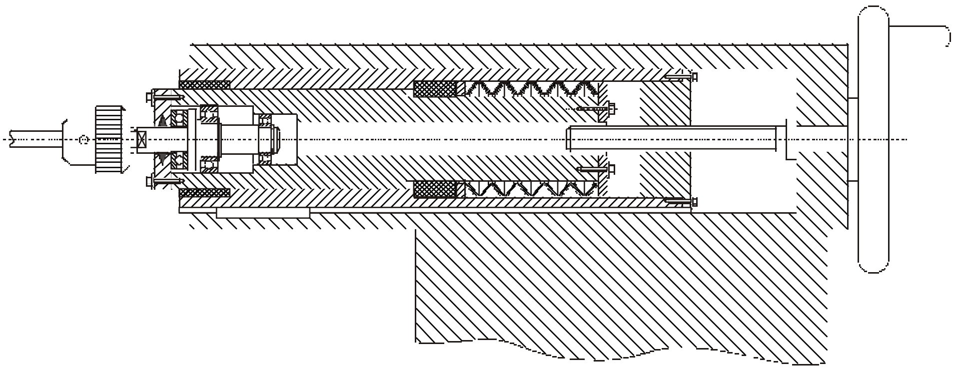


Fig. 12. Design of lathe tail stock with the use of disk springs

Conclusions

Based on the theoretical and experimental studies it was found that:

• It is possible to reduce the elastic deformations of low-rigidity shafts by a factor from 2 to 18, depending on their dimensions, fixing and loading conditions, and machining parameters.

• Similar results of machining can be also obtained through the application of multi-pass conventional machining at reduced parameters; however, in such a case the time required for the machining will be considerable extended – even 50-fold.

• In machining of shafts with diameters below 6 mm application of axial tensile force is an effective solution; if the shaft diameters are greater than 6 mm – eccentric tensile force should be applied.

• Four designs of special lathe tail stocks, permitting efficient machining of low-rigidity shafts at various levels and scales of production, have been developed and submitted to the Patent Office.

References

[1] V.È. PUŠ, R. PIGERT, V.L. SOSONKIN: Avtomatičeskie stanočnye sistemy. Mašinostroenie, Moscow 1982.

[2] L. HUDOBIN: Smazočno–ohlaždaûŝie tehnologičeskie sredstva i ih primenenie pri obrabotke rezaniem. Spravočnik. Mašinostroenie, Moscow 2006.

[3] V.A. KARPUŠIN: Issledovanie uprugih progibov nežestkih detalej pri tokarnoj obrabotke s rastâženiem. *Vesci Akademii Navuk Belaruskai SSR, Ser. Fièika–tehnyčnyh navuk,* **1**(1978), 6-9.
[4] M.I. KLUŠIN: Rezanie metallov. Mašgiz, Moscow 1953.
[5] K.S. KOLEV: Točnost' obrabotki i režimy rezaniâ. Mašinostroenie, Moscow 1968.
[6] T.N. LOLADZE: Pročnost' i iznososojkost' režuŝego instrumenta. Mašinostroenie, Moscow 1982.
[7] S.S. KEDROV: Kolebaniâ metallorežuŝih stankov. Mašinostroenie, Moscow 1978.
[8] D. KUMABE et al.: Vibracionnoe rezanie. Mašinostroenie, Moscow 1985.
[9] K. MARCHELEK: Dynamika obrabiarek. WNT, Warszawa 1995.
[10] G. TARANENKO, V. TARANENKO, D. WOLOS: System causal–clause analysis of recision and safety relations by shafts with small stiffness controlling. Proc. Inter. Conf. Mechanical Engineering Technologies. Varna 2006, 80-83.
[11] D. WOŁOS, W. TARANENKO, A. ŚWIĆ: Klasyfikacja metod osiągnięcia niezawodności technologicznej obróbki wałów o małej sztywności. *Przegląd Mechaniczny*, (2007)5, 154-155.
[12] D. WOŁOS: Selected problems of shafts with small stiffness machining reliability. Proc. Inter. Conf. Automation: Problems, Ideas, Decisions. Sevastopol 2007, 53-55.
[13] W. TARANENKO, A. ŚWIĆ: Technologia kształtowania części maszyn o małej sztywności. Wydawnictwo Politechniki Lubelskiej, Lublin 2005.
[14] A. ABAKUMOV et al.: Controlling the dynamical system of machine tools by elastic–deformable shafts machining. Proc. Inter. Conf. Progressivnye Tehnologii i Sistemy Mašinostroeniâ. Doneck 2006, 272-278.
[15] D. WOLOS, V. TARANENKO, A. SWIC: Technological bases of controlling the precision and safety of shafts machining. Proc. Inter. Conf. Automation: Problems, Ideas, Decisions. Sevastopol 2006, 123-124.
[16] V. TARANENKO et al.: Konik obrabiarki. Zgłoszenie wynalazku nr P–384 071. 2007.
[17] V. TARANENKO et al.: Konik obrabiarki. Zgłoszenie wynalazku nr P–384 072. 2007.
[18] V. TARANENKO et al.: Konik obrabiarki. Zgłoszenie wynalazku nr P–387 536. 2008.
[19] V. TARANENKO et al.: Konik obrabiarki. Zgłoszenie wynalazku nr P–387 537. 2008.
[20] D. WOŁOS: Konstrukcja konika tokarki do obróbki wałów w stanie sprężyście--odkształconym. *Przegląd Mechaniczny*, (2006)12, 154-155.

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