A progressive method of mounting machine parts on the shaft

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Abstract. In mechanical engineering, various methods of fastening the hub to the shaft for the transmission of torque are widely used. However, the methods used are not devoid of a number of disadvantages inherent in varying degrees for each of them. The authors proposed a constructive solution for reliable mounting of the hub on the shaft, which provides operational control of the axial and angular position of the part, and also developed a software application that allows the calculation of the tightening force depending on the connection parameters.

1. Introduction
The main task of the shaft-hub connections (hereinafter referred to as SHC) is, as a rule, the transfer of torque, which can be carried out in two ways - rigid and friction. In the first method, this problem is solved through the use of rigid elements working on shear, collapse or bending. This method is implemented in the form of keyed, slotted, prismatic, profile, pin, flange connections. In the second (friction) method, the torque from the shaft to the hub (or vice versa) is transmitted due to the friction forces generated on the cylindrical, conical or end surfaces of the shaft. These include connections with tension, tapered, with spring-loaded clamping rings, terminal. Sometimes a combination of both methods is used, in which for rigid joints the load capacity is increased due to friction forces created by axial or radial-axial tightening, and for friction joints in order to prevent relative turning or fixing of a certain angular position of the part on the shaft, rigid elements (keys, pins, etc.) are inserted [1-10].

2. Structural analysis of existing methods
Each type of SHC has its own characteristics and, in comparison with another type, has a set of certain advantages and disadvantages. Comparative evaluation of compounds of various types when choosing one of them for use in a projected unit or mechanism can be carried out in many ways, namely:
- load capacity limiting the amount of transmitted torque;
- reliability in work;
- dimensions;
- manufacturability;
- the cost;
- the possibility of limiting the value of the transmitted maximum torque and using the connection, along with the main purpose, as a safety device;
- the degree of alignment of the fixed part with the shaft;
- axially fixing the mounted part on the shaft;
• possibility, simplicity and mobility of regulation of the axial and angular position of the part on the shaft;
• working conditions;
• serial production.

Considering a specific type of SHC for each of the above indicators, it is possible to determine its place among others according to the degree of satisfaction of a particular requirement, or to exclude it altogether from the list suitable for the designed mechanism.

Among mechanical gears, which are widely used in mechanical engineering and, in particular, in machine-tool construction, many require, during installation, strict compliance with the axial, and sometimes angular, position of the parts that make up the kinematic pair. As an example, the drive gear and the driven wheel in a bevel gear, a worm and a worm gear in a worm gear, chain sprockets and belt gear pulleys, as well as elements of some other mechanisms can be mentioned [11-14].

Consider further different types of connections according to the criterion of the possibility of regulating the axial position of the part on the shaft with an assessment of the simplicity and efficiency of this operation, as well as taking into account that they meet other requirements, based on the list of the above criteria for comparative evaluation of connections.

From these positions, the types of SHC used in mechanical engineering can be divided into the following groups.

1. Fastening the part on a cylindrical or conical shaft section using a key, spline or profile connection to transfer torque and stop the hub into the collar on the shaft. The hub is pressed against the shoulder sleeve, nut or washer from the other end [1-10].

Compounds of this type are characterized by high load capacity and reliability. However, adjustment of the axial position of the part relative to the shaft is not possible.

2. Fastening the part on the cylindrical section of the shaft using a key, spline or profile connection and placing an adjusting ring between the end of the hub and the shaft shoulder to which the part is pressed through this ring to prevent axial displacement. The axial position of the mounted part determines the thickness of the adjusting ring [15].

This type of SHC preserves the advantages of the connections of the previous group and, at the same time, allows adjustment of the axial position of the part independently of the shaft. However, this operation, being associated with the need to dismantle the part itself, mounted on the shaft, is quite lengthy and time consuming. To reduce the adjustment time, the ring is replaced by two half rings, which eliminates the need to dismantle the part and requires only a small axial displacement of it to extract the half rings from the bore in the hub.

3. Connections in which the regulation of the axial position of the part is carried out using a set of thin metal gaskets installed between the flanges of the bearing caps and the housing.

Here, according to the principle of regulation of the axial position of the part, can be attributed a method of mounting pulleys and sprockets on the glass, made together with the bearing cap [15], in order to unload the shaft console from the forces acting in a belt or chain drive (figure 1).

This adjustment method allows to ensure high accuracy of the position of the part in the axial direction, and the duration of the operation can be reduced by replacing thin metal gaskets with a set of gaskets of various specific thickness.

SHC in the following groups (4-7) combines the use in their structures of two contacting (internal and external) conical surfaces, moving towards each other.

4. Connections that use wedge keys, which make it possible to easily and quickly change the axial position of the part, regardless of the shaft, but not providing it with precise centering.

5. Structural solutions for SHC using a pair or a set of paired elastic conical rings, which are shifted between themselves and located in the end bore or in the annular gap between the hub and the shaft [15].
6. Compounds in which a split elastic sleeve with an outer conical and cylindrical inner surface is used to fasten the hub to the shaft. This sleeve is tightened into the annular gap between the hub and the shaft [15].

7. Connections that are applicable to parts of significant radial dimensions, made using two (outer and inner) biconical split rings, inserted into the end bores on both sides of the hub and unclasped by two side intermediate rings located in the annular gap between the biconical split rings on both sides [15].

All types of SHC, referred to the four last groups, allow operatively, by weakening the mutual conic surfaces, to achieve the possibility of adjusting the position of the part in the axial direction without dismantling it. However, these methods of mounting the hub on the shaft are not without a number of the following disadvantages, which are inherent in varying degrees for each of them:

- limited by the structural dimensions of the part load capacity, i.e. the amount of torque transmitted from the shaft to the part (or vice versa);
- high manufacturing cost;
- centering the hub relative to the shaft on several surfaces;
- numerous details in the design;
- significant radial or axial dimensions.

**Figure 1.** Fastening the pulley on the glass with the unloading of the shaft from the forces acting in the belt drive
3. Description of the new method

The analysis of the features of the above-considered compounds allowed the authors to conclude that it is necessary to develop a reliable and simple design for securing the part to the shaft, which ensures the operational control of the axial and angular position of the part independently of the shaft. The result of the research is the progressive method of mounting the part on the shaft, proposed by the authors, for which patents were obtained for the useful model “Shaft coupling with hub” and “Shaft-hub connection” [16, 17] (figure 2). This method consists in the use of two identical sleeves, integral or consisting of two halves (figure 3), with a conical outer and cylindrical inner surface, with end grooves alternating in direction to ensure the elasticity of the sleeves. The bushings are interconnected in the space between the shaft and the two conical holes in the hub with screws of an even number [15]. For this purpose, in the sleeves, alternately alternating, holes of two types are made: threaded and smooth - for the rods of screws [15]. Two sleeves, by turning at a certain angle around its axis, are placed when mounting the connection relative to each other so that the threaded holes in one of them become coaxial with the holes for the rods of the screws of the other. In case of difficult access to the screws from both sides, the design of the sleeves may differ. Only threaded holes can be made in one sleeve, and only holes for the rods of screws in the other.

**Figure 2.** Constructive scheme of mounting parts on the shaft using two bushings with an outer conical surface

**Figure 3.** (a) The design of the solid sleeve and (b) the design of the sleeve consisting of two halves

In order to ensure a high degree of alignment of the two conical holes in the hub between them, a narrow cylindrical hole bore simultaneously with one of the conical holes is provided (figure 2), which
is designed to perform the function of the base when processing the second conical hole on the other side of the hub [15].

Fixing the part on the shaft after installing it in the required axial and angular position is performed by tightening the two bushings together by tightening all the screws with a tightening force limited by the tensile strength of the screws. Tightening is necessary to create sufficient external pressure on the external conical and internal cylindrical surfaces of the bushings, ensuring that the connection from the shaft to the hub (or vice versa) of a torque $T$ (N\(\cdot\)m) of a given value with the introduction of a safety factor corresponding to the purpose of the mechanism.

The relationship of these parameters establishes the following dependence:

$$T = 10^3 \pi d_{av}^2 l_{act} p f,$$

where $d_{av} = \frac{d_2 + d_1}{2}$ (mm) – average diameter of sleeves with larger $d_2$ and smaller $d_1$ diameter; $l_{act}$ (mm) – the active length of each sleeve (in calculations it can be taken equal to the length of the sleeve $l$); $p$ (MPa) – pressure on the outer conical surfaces of the sleeves. Permitted value for steel parts $[p] = 200…250$ MPa; $f$ – coefficient of friction (average calculated value for steel parts $f = 0.1…0.12$).

From here, the pressure $p$ (MPa), necessary for the transmission of torque $T$ (N\(\cdot\)m) on the outer surfaces of the bushings, which determines the carrying capacity of the connection, can be found:

$$p = \frac{10^3 \pi T}{\pi d_{av} l f},$$

The pressure $p$ is created due to the convergence of 2 sleeves inside the hub mounted on the shaft of the part with a force $F_{ax}$ (N), acting on each sleeve from the outside:

$$F_{ax} = p \pi d_{av} l \cdot \tan \alpha,$$

where $\alpha$ - half the central angle of the cone, at that $\alpha = \arctg(0.5K)$, and $K = \frac{d_2 - d_1}{l}$ – the taper of the outer surfaces of the sleeves.

Substituting the value from equation (1) into expression (3), we obtain the following dependence of the required axial force $F_{ax}$ (N) on the transmitted torque $T$:

$$F_{ax} = \frac{10^3 \cdot T \cdot \tan \alpha}{d_{av} \cdot f} = \frac{10^3 \cdot T \cdot K}{2 \cdot d_{av} \cdot f}.$$

This force is realized when mounting the SHC by tightening half the total number of screws $z$ in each of the sleeves on both sides of the hub. Usually for small sleeves, $z$ is 4 or 6. It is preferable to tighten all screws with the same force $F_{sig} = \frac{2F_{ax}}{z}$ using a torque wrench. It should be borne in mind that when tightening the screws, a slightly larger than $F_{sig}$, force, since, in addition to creating the necessary pressure on the radial surfaces of the sleeves, friction on the inner and outer surfaces of the sleeves and in the thread itself is additionally overcome. This circumstance makes it necessary in calculations for the strength of the screws of this design to introduce a certain safety factor when choosing the permissible tensile stress: $[\sigma]_p = \frac{\sigma_f}{k_{saf}}$. Recommended $k_{saf} = 1.8$.

The force $F_{sig}$ calculated in accordance with formula (4) in the design calculation selects the appropriate thread diameter of the screws for a given material, and in the test calculation they find the
actual tensile stress in the cross section of the screw stem according to the internal diameter of the thread.

The authors, using modern information technologies, developed a software application for which a certificate was received on the state registration of the computer program “Calculation of shaft-hub connection parameters “Shaft-HubJoining”. The application is designed to automate the calculation of the tightening force depending on the following variable connection parameters: transmitted torque, diameters and lengths of the sleeves, friction coefficient (when selecting the appropriate structural materials).

If there are dangers of slipping of the sleeves relative to the shaft along a smooth inner cylindrical surface (in cases when the torque from the shaft to the bushings (or vice versa) is transmitted due to friction forces during the elastic compression of the bushings), the frictional connection of the bush with the shaft can be replaced by a keyed, slotted or shaped connection. Such a replacement will not affect the ability to quickly regulate the axial and angular position of the part on the shaft.

4. Conclusions
The design scheme developed by the authors for fastening parts on the shaft has a whole set of advantages in comparison with other known methods, namely:

- simplicity of design;
- low manufacturing cost;
- high load capacity, limited essentially only by the strength of the thread of the screws, and the proposed design allows the use of screws of significant diameter;
- simplicity and efficiency of regulation of the axial and angular position of the part on the shaft;
- compact design of the SHC design that does not require (as a rule) an increase in the radial and axial dimensions of the part fixed on the shaft;
- the possibility (if necessary) to use this method of fastening the part on the shaft as a safety device, since the design allows you to adjust the allowable amount of torque transmitted by the SHC due to the change in the screw tightening force with a torque wrench and, therefore, set the maximum torque for this mechanism.

Thus, the proposed progressive method of fastening parts on the shaft, due to its advantages, can be recommended for use in machine-building industries and, in particular, in machine-tool construction.

References
[1] Orlov P I 1988 Basics of construction: a methodical manual (Moscow: Mashinostroenie) p 560
[2] Dunaev P F and Lelikov O P 2008 Design of units and parts of machines: studies (Moscow: Academy) p 496
[3] Kurmaz L V 2004 Machine parts. Design (Moscow: Vysshaya shkola) p 300
[4] Guzenkov P G 1986 Machine parts: Training for universities (Moscow: Vysshaya shkola) p 359
[5] Grechishnikov V A and Yashkov V A 2016 Creating a formal mathematical model of the quality of machine parts The II International Youth Scientific and Technical Conference 1 119-23
[6] Grechishnikov V A, Kasyanov S V Yurasova O I and Romanov V B 2016 The competitiveness of enterprises by improving the profitability of the project training production and release autocomponents Vestnik MGTU “Stankin” 37 128-32
[7] Kudryavtsev V N 1980 Machine parts: a textbook for students of engineering specialties universities (Moscow: Mashinostroenie) p 464
[8] Reshetov D N 1988 Reliability of machines (Moscow: Vysshaya shkola) p 238
[9] Bazrov B M 2005 The basics of engineering technology (Moscow: Mashinostroenie) p 736
[10] Birger I A 1993 Calculation of the strength of ma-chine parts (Moscow: Mashinostroenie) p 702
[11] Nekrasov A Ya, Arbuzov M O and Sobolev A N 2015 Automatic Control of the Static Loads in
Multicontact Mechanical Systems *Russian Engineering Research* **35** 442-6

[12] Sobolev A N and Nekrasov A Ya 2016 CAD/CAE Modeling of Maltese Cross Mechanisms in Machine Tools *Russian Engineering Research* **36** 300-2

[13] Chekanin V A and Chekanin A V 2014 Multilevel linked data structure for the multidimensional orthogonal packing problem *Applied Mechanics and Materials* **598** 387–91.

[14] Brovkina Y I, Sobolev A N and Nekrasov A Ya 2018 Research of Characteristics and Parameters of Cycloidal Gear *ICIE 2018* 1169-79

[15] Arbuzov M O, Nekrasov A Y, Sobolev A N and Serebryakov K E 2018 Progressive methods of mounting pulleys and sprockets on shafts *Vestnik MGTU “Stankin”* **45** 15-20

[16] Arbuzov M O, Nekrasov A Ya, and Sobolev A N 2017 Shaft coupling with hub. Application No. 2017118183. Patent for utility model number 177902 *Rospatent*

[17] Arbuzov M O, Nekrasov A Ya and Sobolev A N 2018 Shaft-hub connection. Application No. 2017118184. Patent for utility model number 183767 *Rospatent*