Backlash-free low-friction lead screw

Field of the invention

The present technical solution relates to mechanical machine parts for enabling motion and motion transfer – lead screws. The technical solution falls within the engineering field.

Prior art

One way to mechanically convert rotary motion into linear motion is to use screw mechanisms. Presently, one of the options is to use a trapezoidal thread or lead screws comprising rolling elements. The most frequently used are ball screws or trapezoidal threads. With a trapezoidal thread using a nut, the displacement of the nut or the screw is conventionally achieved by a trapezoidal thread connection. A ball screw is a lead screw with a ball (or some other rolling element, such as a cylinder, etc.) that provides for rolling motion between the screw axis and the nut. A representative of such a solution is the lead screw described in the published patent EP 1 373052 B1.

Another lead screw type is a screw with rolling elements arranged in the form of annular rotating elements arranged within the nut in a circular array, wherein each element is offset by the thread pitch for the specific angle and the element is profiled to fit into the thread shape. A representative of such a solution is the lead screw described in the published patents DE 4143020 A1 and EP 0 606509 A1.

Prior art knows solutions using elements embedded in bearings to reduce thread friction during motion in the form of discs, threads or rotating elements arranged eccentrically, without directly solving the rolling action utilizing only the rolling resistance while ensuring constant contact between the nut and the spindle profile. A representative of such a solution is the lead screw described in the published patent EP 0 185301 A1.

There is also an actuator for driving a rear axle of a motor vehicle which comprises a spindle nut with an internal thread in combination with internal gearing. The spindle has an axial arrangement with eccentric housing. The spindle is in contact with part of the circumference of the gearing and at the same time with part of the circumference of the thread. The nut is driven and the spindle moves axially. A representative of such a solution is the utilisation of the lead screw described in the published patent WO 2017202563 A1.

Finally, there is a lead screw design comprising three nuts with threads arranged eccentrically from one another and from the threaded rod, where the inner diameter of the nuts is larger than the diameter of the threaded rod, wherein the threaded rod is alternately engaged with one side of one nut and subsequently with another side of another nut. The contact is only between short arcuate sections of the engaged nut threads and the threaded rod. This solution is characterized by smooth motion of the threaded rod, the friction resistance is small due to the absence of balls between the threaded rod and the nuts and the operation is fluid when respective parts move with respect to one another. The disadvantage of the solution is that it uses six bearings. A representative of such a solution is the lead screw described in the published Japanese patent application JPS 58207562.

Summary of the technical solution

The above disadvantages of solutions known from the prior art are eliminated by the backlash-free low-friction lead screw according to the present technical solution. The kinematic pair of a spindle, as the male member and a nut, as the female member, in each cross section is defined by two principal circles rolling on each other. One is coupled with the spindle and the other with the nut. Theoretically, it is thus possible to create a backlash-free low-friction lead screw by hypocycloids and epicycloids rolling around each other in cross-section resulting in a lower friction coefficient and rolling motion. It is known from the gear theory that a curve generated by a curve rolling on another curve is a cycloid. Mutual position of the rolling circles in this rolling solution produces eccentricity, which can be eliminated structurally. Eccentrically positioned components can be designed as epicycloids or hypocycloids or a combination thereof. The screw can be generated by a specific arrangement of cycloids, which however are more difficult to manufacture. Such an arrangement is advantageous as a transfer between the spindle and the nut, since this arrangement also produces different axial displacement ratios, it generates gear displacement ratio, and the thread pitch of both the spindle and the nut must have the same ratio. In such an arrangement, with suitable choice of rolling circles, it is also possible to achieve mutual rolling of the right and left thread. The most advantageous choice for such solution is to use the epicycloidal principle, because the hypocycloidal solution does not produce eccentricity. However, with this solution it is not possible to achieve contact along the entire circumference. From the point of view of achieving continuous contact around the entire circumference, the most advantageous is the hypocycloidal solution, relative with one hypocycloidal arc smaller. It is known that when a circle rolls within another circle, all points of the inner circle describe hypocycloids. Linear motion performed by the nut and a point on the spindle rolling within a curve is only possible if the point lies on a circle and the circle rolls on another circle. A hypocycloid generated by a circle rolling on another circle corresponds to the nut profile. In the case of a single-start thread, the spindle has the shape of a screw-shaped surface generated by the movement of a circle, the centre of which describes a helix, the sleeve has the shape of a helix with a cycloidal profile generated by the spindle circle. The backlash-free low-friction lead screw with a cycloidal thread profile can also have a two-start or even a multi-start thread. What is import, above all else, is the technological ease of manufacture and the achieved effect. Multi-start screws, e.g. a double-start spindle of such a construction, have a profile symmetric cross-section with semicircles at both ends and the nut has the profile defined by the profile of the double-start spindle rolling on a generatrix cycloid. It is likewise with higher ratios. Relative pitch ratios are defined by mutual movement of the rolling profiles 2:3, 3:4, 4:5, 5:6 etc., wherein in these cases the spindle has one thread less. The rolling hypocycloid, as long as it has one arc less, rolls on a hypocycloid with a higher number of arcs, where the advantage of the one-thread-less arrangement is continuous contact around the circumference. Other ratios of hypocycloid arrangements are also possible, but with these other arrangements it is not possible to achieve a state in which the two components are in contact around their entire circumference. The relation between the pitch of the nut and the spindle must be proportional to the ratio of the number of starts, wherein the number of starts is determined by the shape, i.e. the number of peaks of hypocycloids rolling on each other. For technological reasons, the most suitable profile for the shape of screw surfaces is a circle or a line. For this reason, the most important in terms of ease of manufacture are the ratios 0:1, 1:0, 1:1 or 1:2. Zero pitch can only be achieved in the case of rotating components because the size of the axial displacement of the helix is equal to zero even if the angle changes, which however does not prevent the necessary profile of the rotary surface to be created. However, the ratio of 1:1 or other ratios are also technically usable. Rolling of right and left threads, or other ratios can be used with screw differentials.

To create the necessary profile of surfaces rolling on each other, it is necessary to start with rolling of circles generating a cycloid. The ratio of rolling circles corresponds to pitch ratio, that is, if the pitch ratio is 1:1 circle radii are the same. In the case of other ratios, namely the ratio of 1:2, the ratio of the circle radii is one to two, wherein the distance between the circle centres defines the necessary eccentricity, depending on the solution – hypocycloidal inner, epicycloidal outer. The shape of the nut is defined by the cycloid generated by the rolling of the circles. The spindle corresponds to the shape of the cycloid with the number of arcs equal to the pitch ratio, i.e. if the pitch ratio is 1:0, theoretically speaking, the spindle is a circle and the nut is a point. If the pitch ratio is 0:1, in this case the spindle is a point and the nut is a circle. If the pitch ratio is 1:2, the spindle is a point and the nut is a line. With epicycloidal solutions mainly the ratios of 1:1 or 1:-1 are utilised, in which case the nut is a cardioid and the spindle is a circle. With the pitch ratio of 1:-2, the spindle is a circle and the nut is an ellipse. It is similar also for other pitch ratios, and cycloids rolling on one another. This is how the necessary shapes of meshing cycloids are defined, wherein the number of starts determines the cycloid shape by defining the number of arcs. However, out of all the technological options it is not possible to use theoretical shapes, i.e. it is not possible to produce a point or a line. A profile that is usable from the technological point of view is a curve equidistant, i.e. having equal distance, from generatrix cycloids, which means that the point becomes a circle, the line becomes a curve made of two arcs connected by lines etc., the cardioid becomes an equidistant curve. In this way it is possible for the epicycloidal solution to achieve necessary rigidity for the thread cross-section. With the equidistant curve, the distance is the spindle radius. In the case of use of cycloids with a large number of arcs, i.e. at higher pitch ratios, the most appropriate shape is the theoretical shape, or a combination similarly to that of toothing. In the case of solutions with threads with zero eccentricity, rolling is not possible, and it should be noted that these threads are very advantageous in terms of their strength. An example may be a cardioid connected with a cardioid through its profile.

A single-start spindle comprises, other than in 0:1 ratio, a single-start thread of the spindle, wherein any spindle cross-section is a circle equal to its radius, the centre of any cross-section is offset from the spindle axis by the eccentricity. The spindle surface is formed by simultaneous rotation and axial movement of a sinusoid – a helix. With angular rotation the axial movement of the sinusoid is equal to the pitch.

In the case of 1:1 pitch ratio in the hypocycloidal solution, a screw connection with a very advantageous technological profile is created where both parts, the nut and the spindle have a circular cross-section, but with this type of connection it is not possible to achieve mutual rolling, because the rolling circles share the same centre, thus forming a simple screw joint. The spindle has the same surface geometry as the nut, with the screw faces being identical and coaxial in this case. However, what stands out in this solution is a technologically advantageous shape for machining both parts. Such a connection can be substitute for a conventional thread because depending on the pitch it has properties combining metric, trapezoidal and round thread. Again, applicable is the epicycloidal solution, wherein the nut profile curve is an equidistant of the cardioid formed by mutual rolling of identical circles with the radius equal to the spindle eccentricity, wherein the distance of the equidistant equals to the radius of the eccentrically offset circle generating the spindle profile.

The kinematic ratio of 1:2 is a single-start circular cross-section spindle and a two-start nut with symmetrical cross-section having semicircles at both ends connected by line segments.

The single-start backlash-free low-friction lead screw structurally comprises a spindle thread that rotates together with the nut as a sleeve. The nut comprises a nut casing, sleeves and a spring. The spindle surface is generated by simultaneous rotation and axial movement of a sinusoid, a helix. With angular rotation the axial movement of the sinusoid is equal to the pitch. The sleeve is a cylinder with a profiled inner surface in the shape corresponding to the pitch ratio.

The pitch of the screw surface of the sleeve is a multiple of the spindle pitch. The sleeve is positioned in the nut housing in a position offset by eccentricity, thereby achieving rotation of the sleeve together with the whole body of the nut around the spindle centre. The sum of the eccentricities of the nut and the spindle member is the same, the axis of the nut as a whole and the axis of the spindle are coaxial. The axis of the threaded surface of the sleeve is eccentric with respect to the nut housing axis. This means that when rotating the spindle attempts to move out of the sleeve or to push the sleeve in the direction of the motion. The actual nut is made of a plurality of sleeves to prevent the spindle from falling out of the sleeve profile, to prevent such falling out or undesired slippage it is sufficient to have two sleeves rotated by 180° from each other, each of them offset by the eccentricity in the direction opposite to the other sleeve. It is also possible to have a solution with multiple sleeves offset by different angles of rotation. The sleeves must be mutually secured against angular displacement, and such mutual displacement within the nut housing can be achieved by using a key, splining or other methods allowing for mutual linear movement. Such secured sleeves are sliding fit within the body of the nut housing. Between the sleeves is a spring pushing the sleeves away from each other and pressing them against the surface of the spindle, thus generating a prestress. This makes the lead screw backlash-free. The prestress can also be generated by various other arrangements of springs and sleeves. It can also be generated without the use of springs by mutual linear or angular offset of the sleeves with respect to the spindle and the nut as a whole by elasticity of individual components. In this case, demands for the nut casing are reduced. In the case of achieving the nut and spindle prestressing by elasticity of individual components, the sleeve becomes the actual nut casing, which greatly simplifies its production, and the sleeves can be produced as one piece, to achieve this it suffices to ensure small structural angular offset or a small linear offset in the geometry, so as to achieve prestressing. Such combined sleeve can be assembled by elastic stressing of the spindle by torque. By rotating the spindle, the nut also rotates and that is why the nut housing is seated in bearings which are fitted to the bearing blocks of the moved component. Zero backlash thus depends mostly on the properties of bearings, with tapered or pre-stressed bearings the arrangement is guaranteed to be backlash-free. The nut and the spindle may be mutually interchangeable with respect to the application of torque, either the spindle or the nut may be turned.

Technologically very advantageous is the ratio of 0:1, i.e. a single-start nut, it is a cylinder with a profiled inner surface with a single thread, the profile of which is circular in cross-section and equal to the radius. The centre of any cross-section is offset from the nut axis by eccentricity. The nut surface is formed by simultaneous rotation and axial movement of a sinusoid, a helix. With angular rotation the axial movement of the sinusoid is equal to the pitch. Its geometry is formed by an eccentrically positioned circle pulled along a helix. In the case of this ratio, the spindle is formed by a rotated profile of a near-sinusoid or near-cycloid curve, in the longitudinal direction, the shape of which is defined by continuous contact and allows for mutual rolling of both surfaces and it is also circular in the cross-section. In the cross-section, the surface is defined by the contact circle, gradually changing its radius with respect to the axis of the nut, circle of the threaded surface of the nut, i.e. the spindle is not formed by the thread surface. Gradual rolling of the rotary part on the spindle is such that the changing diameter of the spindle with respect to the rolling nut is at the contact point of the nut circle opposite the centre of the nut circle and it is located at the line connecting the spindle centre and the centre of the generatrix circle of the thread surface of the nut. The contact of the rotary surface is at its maximum value equal to the radius of the nut circle. At its minimum value, the contact at the lowest point of the sinusoid of the longitudinal section is generated by the screw surface of the nut. The spindle diameter is defined by the formula:

$$d = D - 2e$$

where: d – spindle diameter

D – diameter of the outer profile surface of the nut sleeve

e – eccentricity of the axes of epicycloidal or hypocycloidal profiles of the meshing surfaces of the nut sleeve relative to the nut axis, wherein it is defined by the difference between locations of the centres of circles rolling on each other and generating an epicycloidal or hypocycloidal profile of the meshing surfaces.

However, technologically the easiest to manufacture is the inverse ratio of 1:0, it has inverted properties to the ratio of 0:1, i.e. the spindle has a single single-start thread, the cross-section of the profile of which is circular, its geometry is identical to the geometry of the surface, formed by an eccentrically offset circle pulled along a helix, similarly to the nut in the ratio of 0:1. But the nut is generated by a rotated profile of a near-sinusoid or a near-cycloid, in the longitudinal direction, the shape of which is defined by continuous contact and allows for mutual rolling of both surfaces and it is also circular in the cross-section, in the cross-section the nut surface is defined by a contact rolling circle gradually changing its diameter with respect to the body axis, to the circle of the thread surface of the spindle in the cross-section, generating the profile of the contact circles successively, i.e. the nut is not formed by a thread surface. The generation of the nut contact curve with respect to the rolling spindle is at the nut contact point, which is located on the line connecting the centre of the spindle with the axis of the generatrix surface of the sleeve when offset by the eccentricity on the side adjacent to the spindle circle. The generatrix surface of the sleeve is generated by circles having their centres in eccentricity and the radius from the sleeve axis to the contact point. The contact of the rotary surface of the nut at its minimum value is equal to the spindle radius. Zero backlash and securing against falling out of the profile is achieved by multiple sleeves and their respective positions. Similarly, the nut axis is aligned with the eccentric positions of the sleeves relative to the spindle axis. Conversion of rotary to linear movement is possible by applying torque to both the spindle and the nut, the nut is an eccentrically housed rotary surface, mutual rolling needs to be ensured by bearings.

Technical solution of the ratio of 1:-1 is again a epicycloidal solution, wherein the nut profile curve is an equidistant of the cardioid generated by mutual rolling of identical circles with the radius equal to the spindle eccentricity, wherein the distance of the equidistant equals to the radius of the eccentrically offset circle generating the spindle profile, the structural design of which is similar to the above cases.

With sufficient manufacturing precision and the nut and spindle rigidity, the backlash-free low-friction lead screw can be used directly as a linear guide. With two backlash-free low-friction lead screws arranged in parallel in a single plane, if both nuts are attached to a sliding member, with sufficient rigidity connected by a mutually coupled gear, it is possible to replace the linear guide, this also applies to the assembly of nuts mutually coupled by gear, as both of these assemblies can be stress loaded. The assembly of two backlash-free, low-friction lead screws can also be used without mutual coupling by a gear in such a way that one spindle and the nut will be freely housed in bearings, in this way it is possible to replace a sliding bushing. Application depends on whether or not the mutual arrangement is self-locking or how the assemblies are combined, based on the pitch used, this determines any need for mutual gearing, thereby reducing the cost of using multiple components.

Mutual sealing of the nut and the spindle components of the backlash-free low-friction lead screw is very convenient due to the circular shape of the spindle.

When the spindle and the nut rotate, the cross-section of the sealing element is always rotary, as long as the spindle is not a rotary member but rather a screw surface, by placing it on the nut, the relative position of the rotary cross-section during linear motion does not change. This is problematic for the ratio of 0:1 or other ratios. In other ratios, the cross-sectional shape is identical to the spindle shape. Thanks to a highly preferred profile of the nut and the spindle, the backlash-free low-friction lead screw can be produced at a price similar to that of a trapezoidal thread with properties similar to that of a ball screw, as the problem with the ball screw is to produce a costly nut of a complex shape, the guide tracks of the rolling elements. A technology suited for the production of both nuts and spindles of the backlash-free low-friction lead screw is pressure casting, the spindle profile can be produced directly by turning, using a profiled knife as when producing a trapezoidal thread, or by rolling. If the nut is made of plastic, it can be produced by pressing. The spindle and the nut profile can also be ground, which guarantees high production precision. Nut sleeves can also be split longitudinally and produced by CNC machining and subsequently aligned and joined together. The movement of the nut and spindle is achieved by contact surfaces rolling on each other, which ensures high resistance to wear allowing for a long service life. At the same time, the mutual contact of both surfaces is curved, continuous, which again impacts service life. Another advantage is that with the backlash-free low-friction lead screw, depending on the choice of pitch size, it is possible to achieve self-locking or non-locking of the nut and spindle. In the self-locking case, the energy demand is reduced, because the requirement for the motor torque to maintain the screw in position is no longer necessary. A disadvantage of the backlash-free low-friction lead screw is the need to house both the nut and the spindle in bearings to ensure that the surfaces of both components roll on each other and the need to balance the parts for high speeds to reduce vibration.

Advantages of the backlash-free low-friction lead screw according the present technical solution are apparent from its effects exhibited externally. Generally, it can be noted that the originality of the presented backlash-free low-friction lead screw, the spindle or the nut of which is directly or via a gearbox connected to a motor, lies in the fact that mutual rolling – rotation of the nut and the spindle converts to linear motion capable of transferring a torque higher than with ball screws. Such conversion can be utilised for machine parts such as sliding tables for CNC machines – a replacement for ball screws and trapezoidal threads. The backlash-free low-friction lead screw can be utilised for converting rotary motion to linear motion. The backlash-free low-friction lead screw is a spatial arrangement of circles rolling on each other and forming the surfaces of the nut and the spindle. The cross-section of such surfaces is epicycloidal or hypocycloidal. This arrangement does not require any intermediate member, i.e. a third part enabling the rolling. Zero backlash of the low-friction lead screw is achieved by flexibility and/or prestressing of individual components. To prevent mutual slippage and misalignment with the axis, the nut must be comprised of a multitude of components angularly offset from one another and their eccentricity must be arranged so as to ensure axial alignment. Such an arrangement allows for creating zero backlash. Two backlash-free low-friction lead screws arranged in parallel in a single plane, if both nuts are attached to a sliding member, with sufficient rigidity connected or not connected by a mutually coupled gear, create a replacement for linear guides, as this assembly can be stress loaded. This arrangement can be used as a common function of a linear guide and a lead screw, usable in machines. The backlash-free low-friction lead screw can also be used for reverse conversion of linear motion to rotary motion, depending on the pitch and self-locking properties of such an assembly. There is a variability in pitch ratios of epicycloidal or hypocycloidal profiles of the meshing surfaces of the spindle and the nut sleeve in values of 1:1, 1:0, 0:1 or 1:-1. Technologically the easiest to manufacture is the 1:0 ratio. For these two ratios, either the nut or the spindle is formed as a rotary body or an eccentrically fitted rotary body. In the case of 1:0 or 0:1 ratios, the cross-section of the generatrix surfaces is circular.

Brief description of drawings

The backlash-free low-friction lead screw will be shown in several embodiments on drawings where Fig. 1 shows the A-A section of the spindle profile with marked out eccentricity of the centre of the radius of the generatrix circle and helix pitch ratio of 1:0 or 1:2. Fig. 2 shows individual spindle and sleeve profiles at peak contact points at a distance in the split sleeve design and prestressing achieved by springs with the ratio of 1:2. Fig. 3 shows a cross section of a possible embodiment in which the prestressing is achieved by mutual elasticity of individual components, where the nut is made of a single piece and the ratio is 1:2. Fig. 4 shows a longitudinal section of a backlash-free low-friction lead screw with the pitch ratio of 0:1. On the right is an example of a nut design with three sleeves offset by a certain angle along with the spindle as the rotary component. The spindle and the nut are coaxial. The section view also shows the longitudinal profile of the generatrix curve. On the left is a spindle shown as the rotary part in a three-dimensional view. Fig. 5 shows a cross section of a backlash-free low-friction lead screw with the pitch ratio of 0:1. The cross section shows a gradual rolling along the spindle of the rotary part and the method of generating the spindle contact curve with respect to the rolling nut. The spindle contact point is located at the line connecting the centre of the spindle and the generatrix circle of the nut on the side opposite to the spindle circle. Cross sections follow one another in the first thread during the contact of the nut and the spindle, the section planes are not shown for clarity. Fig. 6 shows a longitudinal section of a backlash-free low-friction lead screw with the pitch ratio of 1:0, where the nut (is fitted with?) two sleeves angularly offset from each other, with the nut as a rotary component. The spindle and the nut are coaxial, but the profile of the sleeves is offset by eccentricity. The section view also shows the longitudinal profile of the generatrix curve. Fig. 7 shows a cross section of a backlash-free low-friction lead screw – with the pitch ratio of 1:0. Cross sections follow one another in the first thread during the contact of the nut and the spindle, the section planes are not shown for clarity. The cross sections show gradual rolling along the spindle and generating of the nut contact curve with respect to the rolling spindle, the contact point of the nut is located on the line connecting the centre of the spindle with the axis of the generatrix surface of the sleeve when offset by the eccentricity on the side adjacent to the spindle circle. The generatrix surface of the sleeve is generated by circles having their centres in the eccentricity and the radius from the eccentricity centre to the contact point. Fig. 8 show a section of the longitudinal profile of sleeves as rotary components with marked eccentricity and a longitudinal section of the nut at the pitch ratio of 1:0. Fig. 9 shows an example of a spindle and sleeve profile for a design with the pitch ratio of 1:1, indicated is the method of generating an epicycloid by means of two identical circles rolling on each other and a sleeve profile as an equidistant with a spindle radius and shown spindle circle of this solution with marked eccentricity. The top part shows the spindle and nut surfaces rolling on each other. Fig. 10 shows examples of possible spindle and sleeve profiles in multi-start screws with various pitch ratios and number of starts in a hypocycloidal solution with marked eccentricity.

Description of the preferred embodiments

Example 1

This example of a particular embodiment describes a backlash-free low-friction lead screw with the technologically easiest to manufacture ratio of 1:0. Fig. 1 shows the A-A cross section of a spindle 1 profile with marked eccentricity e of the centre of the radius of the generatrix circle and helix pitch t ratio of 1:0. This means that the spindle 1 is a single single-start thread, the cross section of the hypocycloidal profile of which is circular. Its geometry is identical to the geometry generated by a circle positioned eccentrically and pulled along a helix. The nut is generated by a profile of a near-sinusoid or near-cycloid curve rotated in the longitudinal direction, the shape of which is defined by continuous contact and allows for rolling of both surfaces on each other. In its cross-section it is also circular. In the cross section the nut surface is defined by a contact rolling circle gradually changing its radius with respect to the body axis. It gradually links to the circle of the thread surface of the spindle 1 in the cross-section, generating the profile of the contact circles, i.e. the nut is not generated by a thread surface. The generation of the nut contact curve with respect to the rolling spindle 1 is at the nut contact point, which is located on the line connecting the centre of the spindle with the axis of the generatrix surface of the sleeve when offset by the eccentricity e on the side adjacent to the spindle 1 circle. The generatrix surface of the sleeve is generated by circles having their centres in eccentricity and the radius from the sleeve axis to the contact point. The contact of the rotary surface of the nut at its minimum value is equal to the spindle 1 radius.

Example 2

This example of a particular embodiment describes a backlash-free low-friction lead screw in an embodiment with two split sleeves 2 positioned axially after one another, with spindle 1 passing through them. The spindle 1 is prestressed by means of a spring 5 inserted between the sleeves 2 in a technological gap 6 which may be omitted from the structural point of view if the pitch ratio is 1:2 as shown in Fig. 2. The C-C section shows individual profiles of the spindle 1 and sleeve 2 at their peak contact points. The two sleeves 2 are housed in the nut housing 4 with bearings 3. The sleeves 2 of the nut and the spindle 1 have hypocycloidal profiles of meshing surfaces which are eccentrically offset with respect to each other by the eccentricity e, wherein the diameter d of the spindle 1 is equal to the diameter D of the outer profile surface of the nut sleeve 2 reduced by twice the eccentricity e of hypocycloidal profile axes of the meshing surfaces of the nut sleeve 2 with respect to the nut axis, wherein the eccentricity e is determined by the difference in the position of the centres of circles rolling on each other generating the hypocycloidal profile of meshing surfaces.

Example 3

This example of a particular embodiment describes a backlash-free low-friction lead screw in an embodiment with a one-piece nut with two coupled sleeves 2 positioned axially after one another, with spindle 1 passing through them, with the pitch ratio of 1:2, with mutual prestressing generated by mutual flexibility of individual components as shown in Fig. 3 in the D-D section including individual profiles of the spindle 1 and the sleeves 2 at peak contact points. Both sleeves 2 and also the technological gap 6, which from the structural point of view may be omitted, form a monolithic structure of the one-piece nut housed in the housing 4 of the nut with bearings 3. The sleeves 2 of the nut and the spindle 1 have hypocycloidal profiles of meshing surfaces which are eccentrically offset with respect to each other by eccentricity e, wherein the diameter d of the spindle 1 is equal to the diameter D of the outer profile surface of the nut sleeve 2 reduced by twice the eccentricity e of hypocycloidal profile axes of the meshing surfaces of the nut sleeve 2 with respect to the nut axis, wherein the eccentricity e is determined by the difference in the position of the centres of circles rolling on each other generating the hypocycloidal profile of meshing surfaces. The prestressing generated by mutual elasticity of individual components is achieved by the epicycloidal or hypocycloidal profiles of the meshing surfaces of adjacent nut sleeves 2 of the monolithic housing 4 being angularly offset from each other, or alternatively, by being axially offset.

Example 4

This example of a particular embodiment describes a backlash-free low-friction lead screw in an embodiment with a one-piece nut with three sleeves 2 with mutual prestressing generated by an angular offset, with the pitch ratio of 0:1, as shown in Fig. 4 including individual profiles of the spindle 1 and the sleeves 2 at peak contact points. Section G-G also shows the longitudinal profile of the generatrix curve. On the left is a spindle 1 shown as the rotary part in a three-dimensional view. Fig. 5 shows cross sections showing gradual rolling along the spindle 1 of the rotary part and the method of generating the spindle 1 contact curve with respect to the rolling nut. The spindle 1 contact point is located at the line connecting the centre of the spindle 1 and the generatrix circle of the nut on the side opposite to the spindle circle. Cross sections follow one another in the first thread during the contact of the nut and the spindle 1, the section planes are not shown for clarity. Spindle 1 has hypocycloidal profiles of meshing surfaces with zero pitch. The sleeves 2 of the nut have hypocycloidal profiles of meshing surfaces which are alternately eccentrically offset with respect to each other by eccentricity e, wherein the diameter d of the spindle 1 is equal to the diameter D of the outer profile surface of the nut sleeve 2 reduced by twice the eccentricity e of epicycloidal profile axes of the meshing surfaces of the nut sleeve 2 with respect to the nut axis, wherein the eccentricity e is determined by the difference in the position of the centres of circles rolling on each other generating the hypocycloidal profile of meshing surfaces.

Example 5

This example of a particular embodiment describes a backlash-free low-friction lead screw in an embodiment with a one-piece nut with two sleeves 2 angularly offset from one another with mutual prestressing, with the pitch ratio of 1:0, as shown in Fig. 6 including individual profiles of the spindle 1 and the sleeve 2 at peak contact points.

The spindle 1 and the nut are coaxial, but the profile of sleeves 2 is offset by the eccentricity e. Sleeves 2 have hypocycloidal profiles of meshing surfaces with zero pitch. Section H-H also shows the longitudinal profile of the generatrix curve. Fig. 7 shows cross sections of a backlash-free low-friction lead screw – with the pitch ratio of 1:0, i.e. the sleeves 2 have zero pitch. Cross sections follow one another in the first thread during the contact of the nut and the spindle 1, the section planes are not shown for clarity. The cross sections show gradual rolling along the spindle 1 and the method of generating the nut contact curve with respect to the rolling spindle 1. The nut contact point is located on the line connecting the centre of the spindle 1 with the axis of the generatrix surface of the sleeve 2 when offset by the eccentricity e on the side adjacent to the spindle 1 circle. The generatrix surface of the sleeve 2 is generated by circles having their centres in the eccentricity e and the radius from the eccentricity e centre to the contact point. Fig. 8 show a section of the longitudinal profile of sleeves 2 as rotary components with marked eccentricity e and a longitudinal section of the nut at the pitch ratio of 1:0.

Example 6

This example of a particular embodiment describes a backlash-free low-friction lead screw in an embodiment with a one-piece nut with two sleeves 2 with mutual prestressing, with the pitch ratio of 1:-1, as shown in Fig. 9. They are produced by the method of generating an epicycloid by means of two identical circles rolling on each other and a sleeve 2 profile as an equidistant with a spindle 1 radius r and shown spindle 1 circle of this solution with marked eccentricity e. The top part shows the spindle 1 and nut surfaces rolling on each other. The sleeves 2 of the nut and the spindle 1 have epicycloidal profiles of meshing surfaces which are eccentrically offset with respect to each other by the eccentricity e.

Industrial applicability

The backlash-free low-friction lead screw can be utilised for converting rotary motion to linear motion. The spindle or the nut is directly or via a gearbox connected to the motor. Mutual rolling – rotation of the nut and the spindle translates into linear motion. Such conversion can be utilised for machine parts such as sliding tables for CNC machines – a replacement for ball screws and trapezoidal threads. Two backlash-free low-friction lead screws arranged in parallel in a single plane, if both nuts are attached to a sliding member, with sufficient stiffness connected or not connected by a mutually coupled gear, create a replacement for linear guides, as this assembly can be stress loaded. This arrangement can be used as a common function of a linear guide and a lead screw, usable in machines. The backlash-free low-friction lead screw can also be used for reverse conversion of linear motion to rotary motion, depending on the pitch and self-locking properties of such an assembly. It can also be used for screw differentials.

CLAIMS

1. A backlash-free low-friction lead screw comprising a nut housing with bearings, a spindle housed in the nut, where the nut is made of at least two sleeves mounted axially in series, wherein the profiles of their meshing surfaces are eccentrically offset with respect to one another, **characterized in that** the sleeves (2) of the nut and the spindle (1) have epicycloidal or hypocycloidal profiles of their meshing components, wherein the diameter (d) of the spindle (1) is defined by the formula:

$$d = D - 2e$$

where: d – spindle diameter

D – diameter of the outer profile surface of the nut sleeve

e – eccentricity of the axes of epicycloidal or hypocycloidal profiles of the meshing surfaces of the nut sleeve relative to the nut axis, wherein it is defined by the difference between the locations of the centres of circles rolling along each other and generating an epicycloidal or hypocycloidal profile of the meshing surfaces.

2. A backlash-free low-friction lead screw according to Claim 1, **characterized in that** the spindle (1) has a backlash-free prestressed housing in the nut sleeves (2).
3. A backlash-free low-friction lead screw according to Claim 2, **characterized in that** there is at least one spring (5) inserted between the nut sleeves (2).
4. A backlash-free low-friction lead screw according to Claim 2, **characterised in that** the nut sleeves (2) are a monolithic nut casing (4) with a technological gap (6) between them, wherein the epicycloidal or hypocycloidal profiles of

the meshing surfaces of adjacent nut sleeves (2) of the monolithic casing (4) are angularly offset or axially offset from each other.

5. A backlash-free low-friction lead screw according to Claim 2, **characterised in that** the nut sleeves (2) are a monolithic nut casing (4) and they follow each other back-to-back, wherein the epicycloidal or hypocycloidal profiles of the meshing surfaces of adjacent nut sleeves (2) of the monolithic casing (4) are angularly offset or axially offset from each other.
6. A backlash-free low-friction lead screw according to any of the Claims 1 to 5, **characterised in that** the epicycloidal or hypocycloidal profiles of meshing surfaces of the spindle (1) and the nut sleeve (2) have the pitch ratio of 1:2 with the meshing profile of a circle and an equidistant of a line.
7. A backlash-free low-friction lead screw according to any of the Claims 1 to 5, **characterised in that** the epicycloidal or hypocycloidal profiles of meshing surfaces of the spindle (1) and the nut sleeve (2) have the pitch ratio of 1:0 with the meshing profile of circles.
8. A backlash-free low-friction lead screw according to any of the Claims 1 to 5, **characterised in that** the epicycloidal or hypocycloidal profiles of meshing surfaces of the spindle (1) and the nut sleeve (2) have the pitch ratio of 0:1 with the meshing profile of circles.
9. A backlash-free low-friction lead screw according to any of the Claims 1 to 5, **characterised in that** the epicycloidal profiles of meshing surfaces of the spindle (1) and the nut sleeve (2) have the pitch ratio of 1:-1 with the meshing profile of a circle and an equidistant of an epicycloid.
10. A backlash-free low-friction lead screw according to any of the Claims 1 to 9, **characterised in that** the epicycloidal or hypocycloidal profiles of meshing surfaces of the spindle (1) and the nut sleeve (2) are multi-start, wherein the meshing profile is a cycloid with an integral number of cycloid arcs on the

spindle (1) together with a cycloid with an integral number of cycloid arcs on the nut sleeve (2).

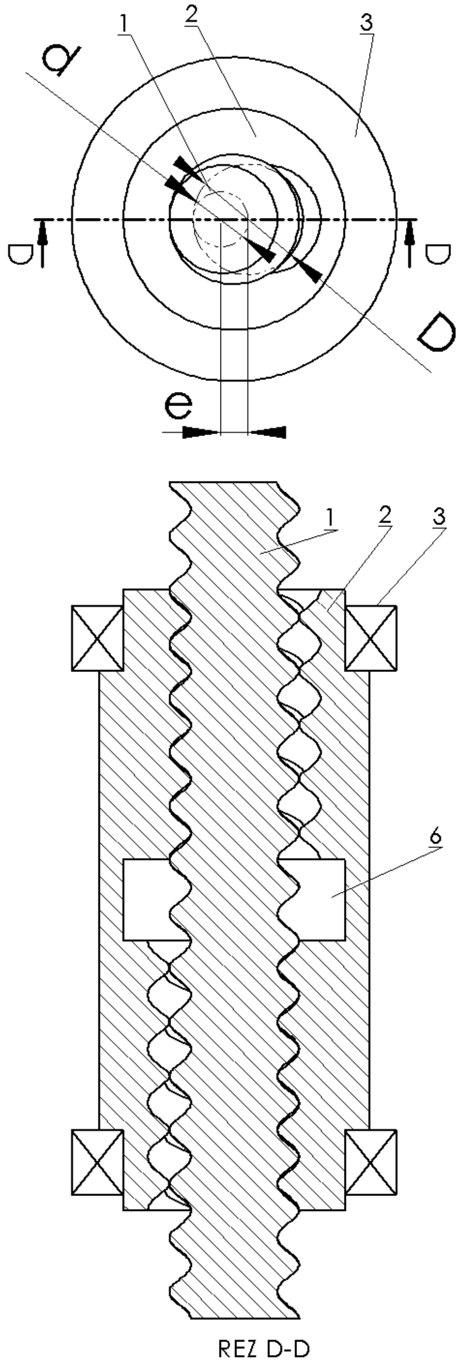
Abstract of disclosure

Title of the technical solution:

Backlash-free low-friction lead screw

The technical solution addresses geometry of mutually rolling nuts and spindles without the use of any intermediate members while simultaneously achieving zero backlash of such an arrangement by means of pre-stressing achieved by mutual elasticity of individual components. It is applicable to conversion of rotary movement to linear movement and vice versa, provided that the individual components are rigid it is a possible substitute for lead screw and linear guide assembly. Nut sleeves (2) and a spindle (1) are directly housed in bearings (3). With simultaneous rotary motion, the geometry alone ensures that the surfaces roll on each other, thus generating linear motion. The nut sleeves (2) and the spindle (1) have epicycloidal or hypocycloidal profiles of meshing surfaces, wherein the eccentricity e of the axes of epicycloidal or hypocycloidal profiles of meshing surfaces is defined by the difference between the locations of the centres of circles rolling on each other and generating the epicycloidal or hypocycloidal profile of the meshing surfaces.

Figures for the abstract: Fig. 3



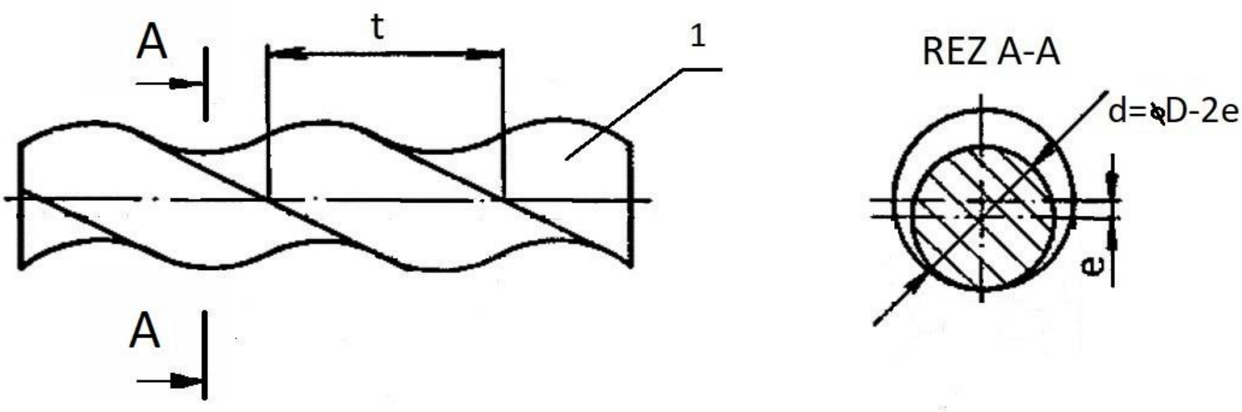


Fig. 1

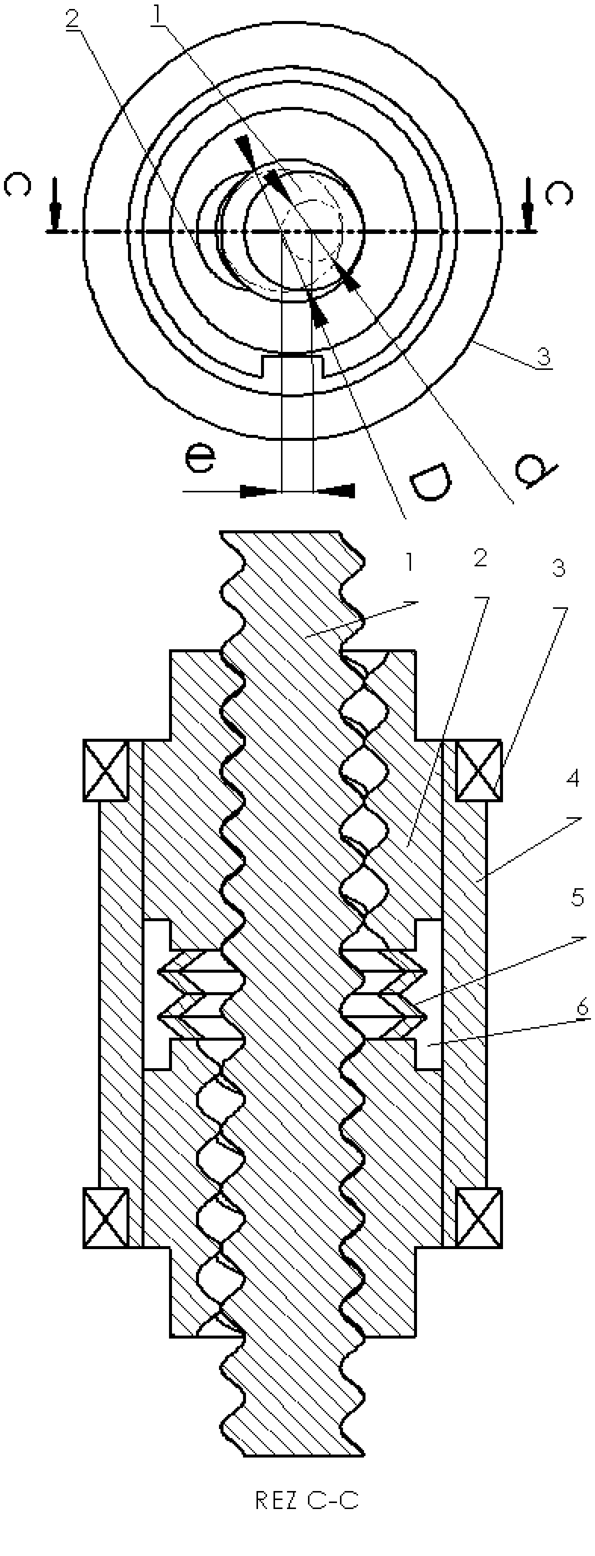


Fig. 2

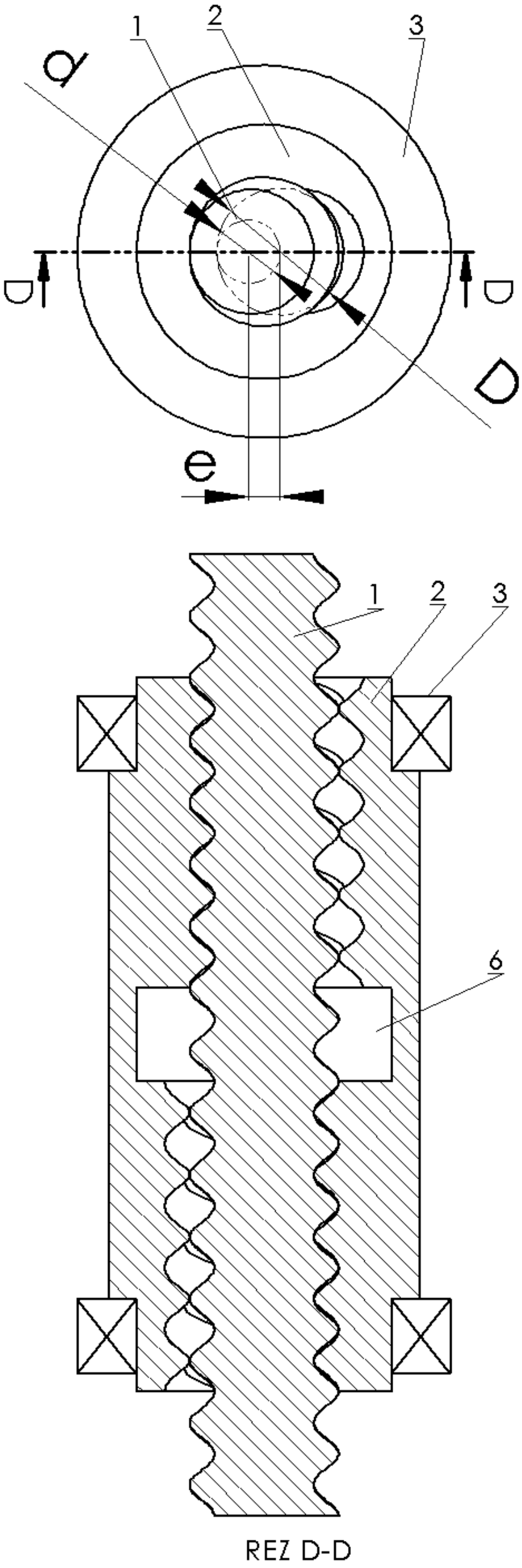


Fig. 3

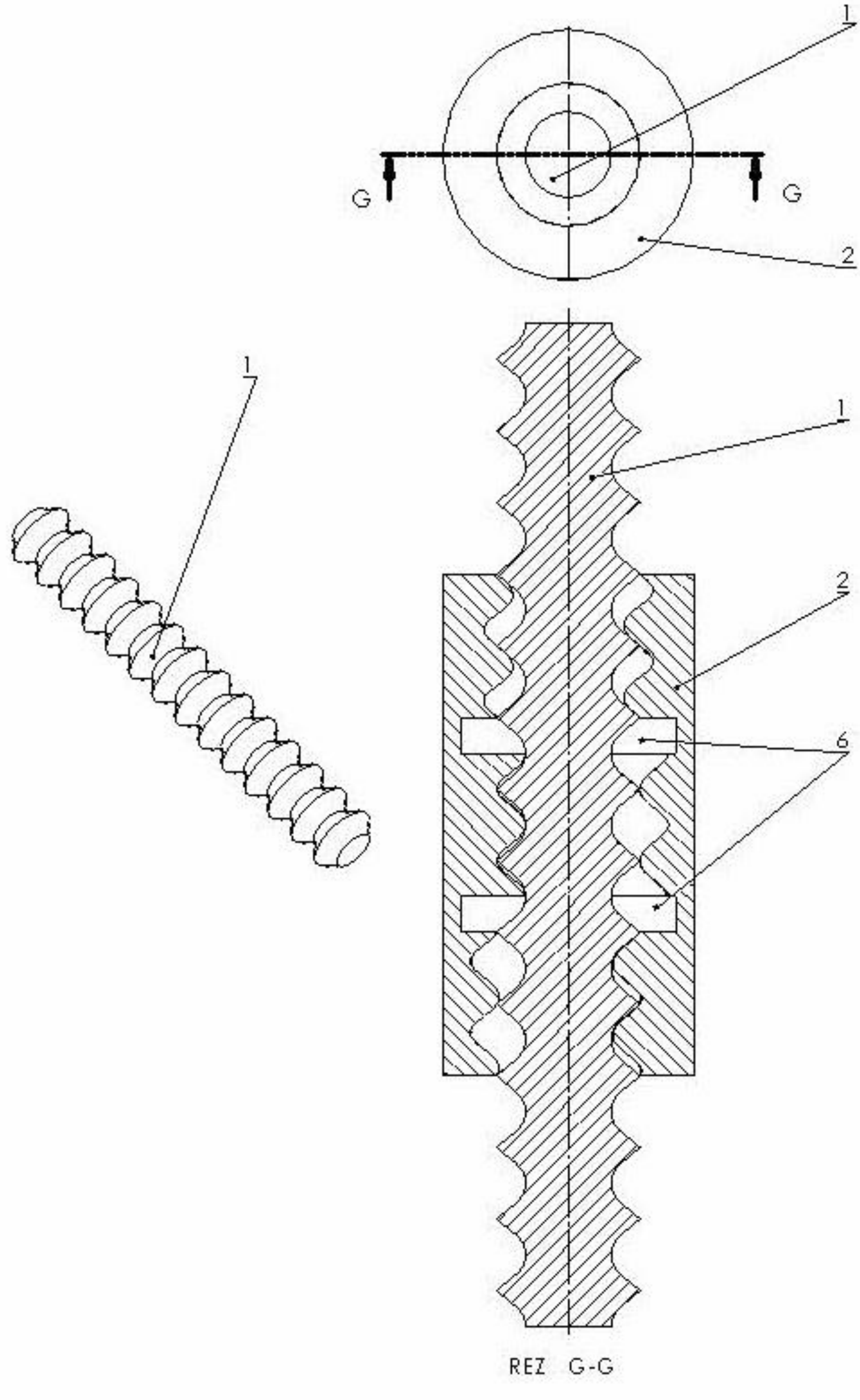


Fig. 4

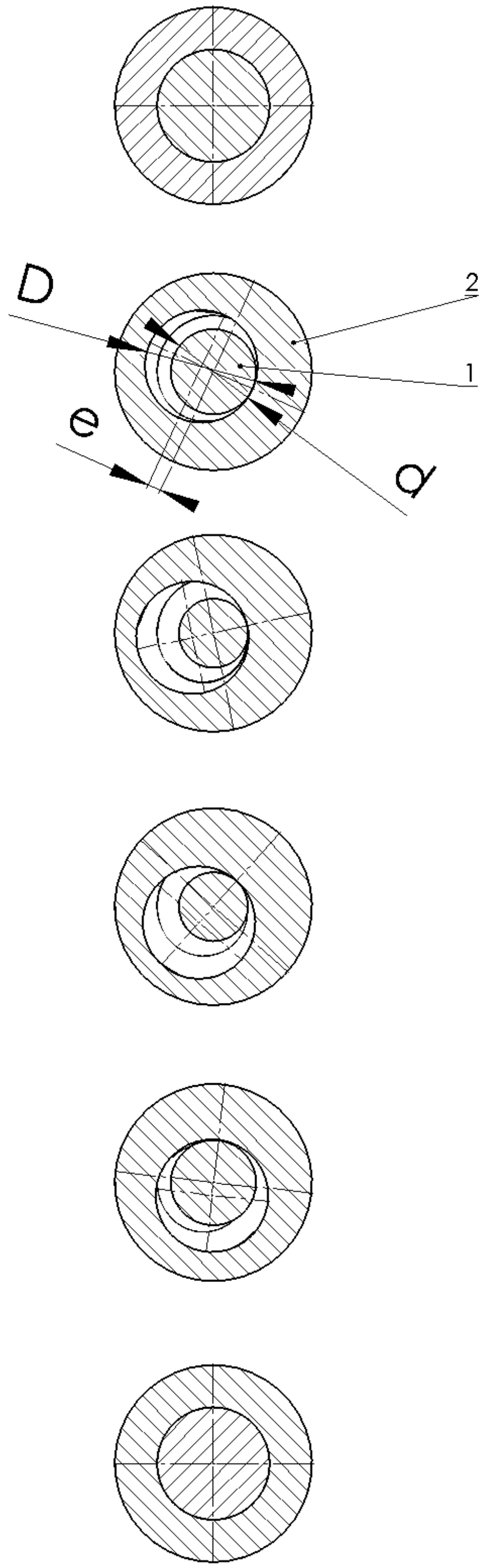


Fig. 5

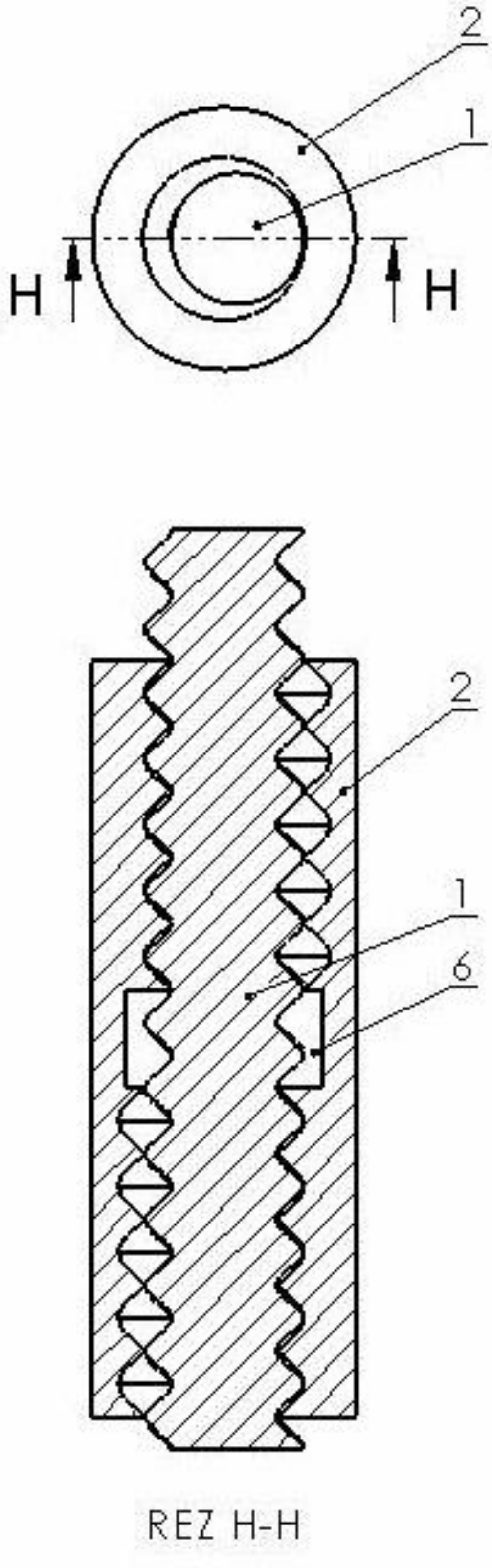


Fig. 6

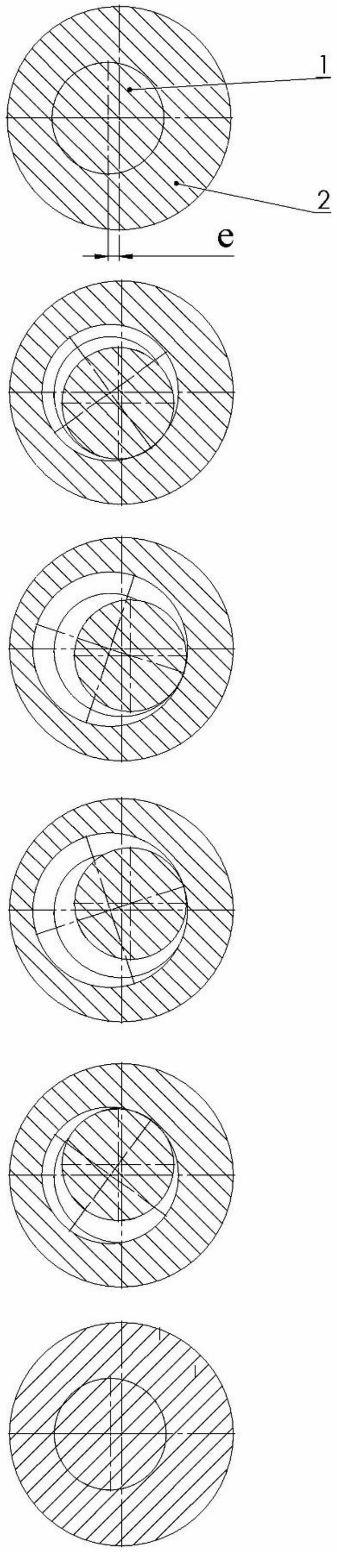


Fig. 7

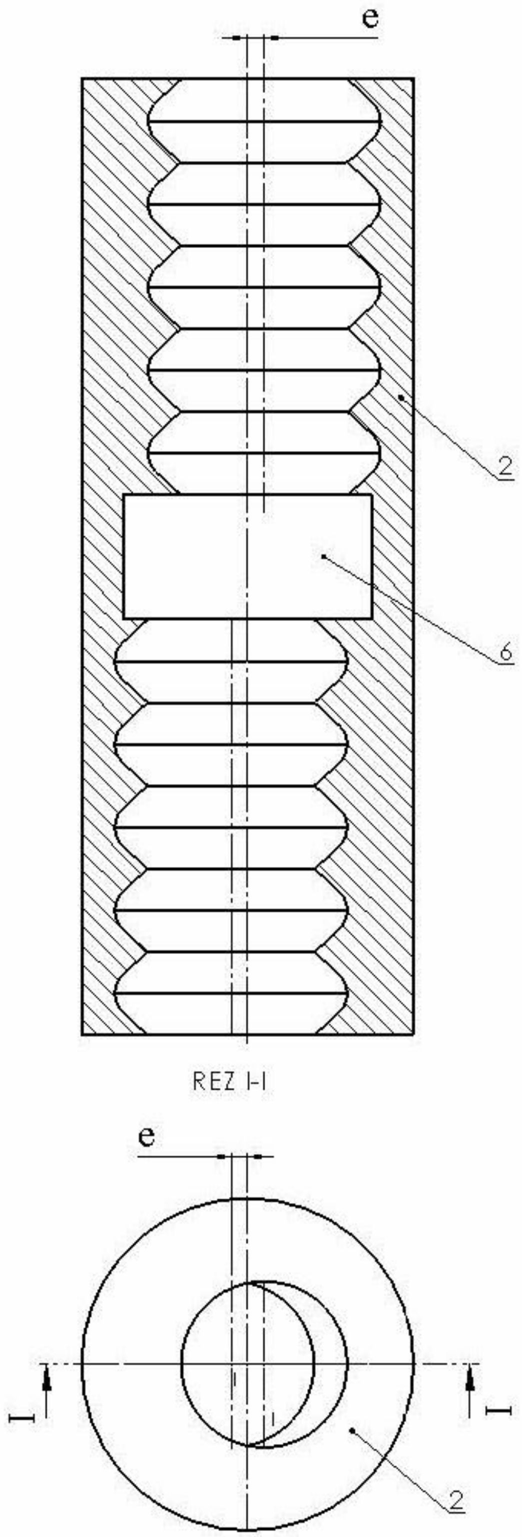


Fig. 8

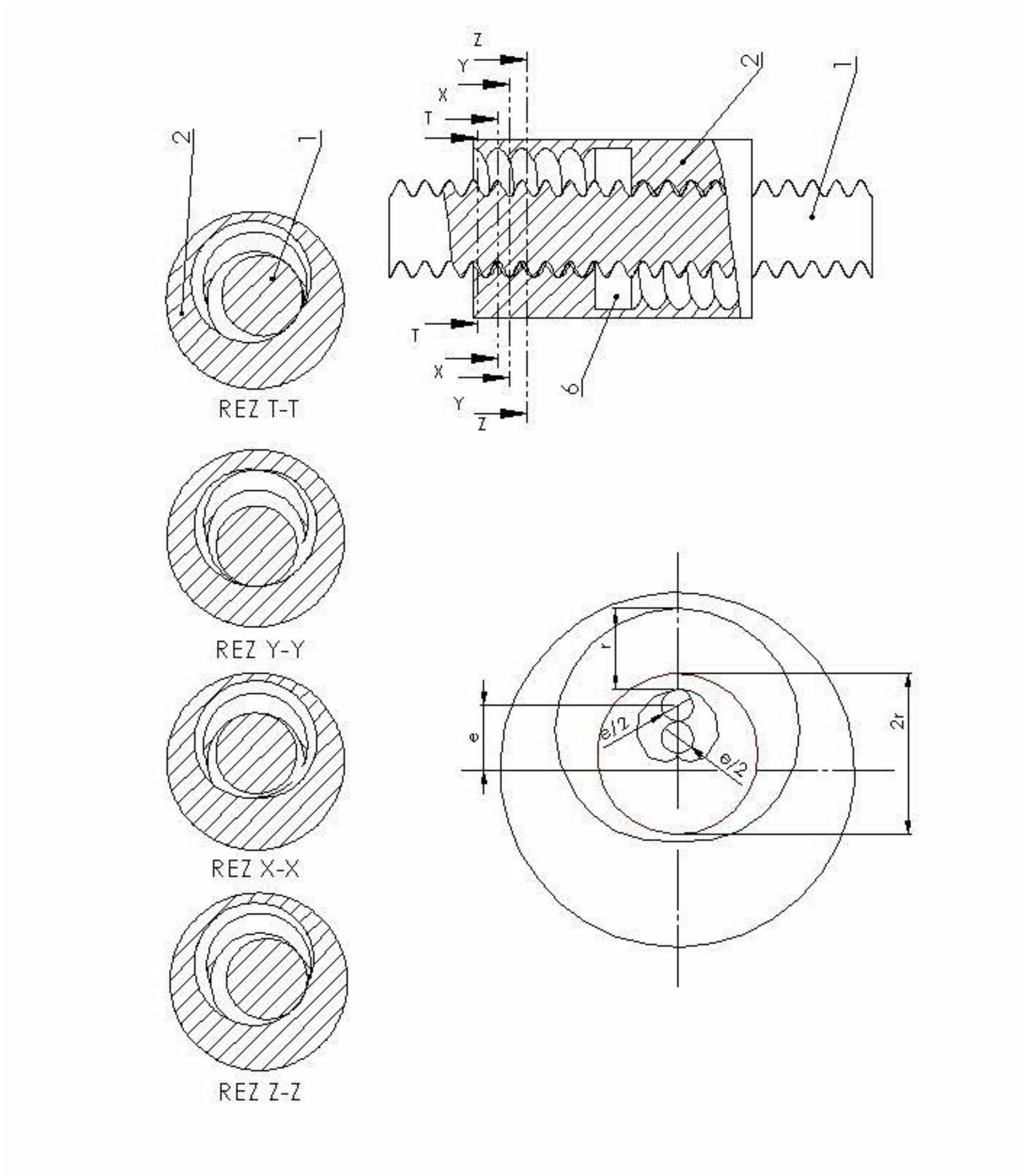


Fig. 9

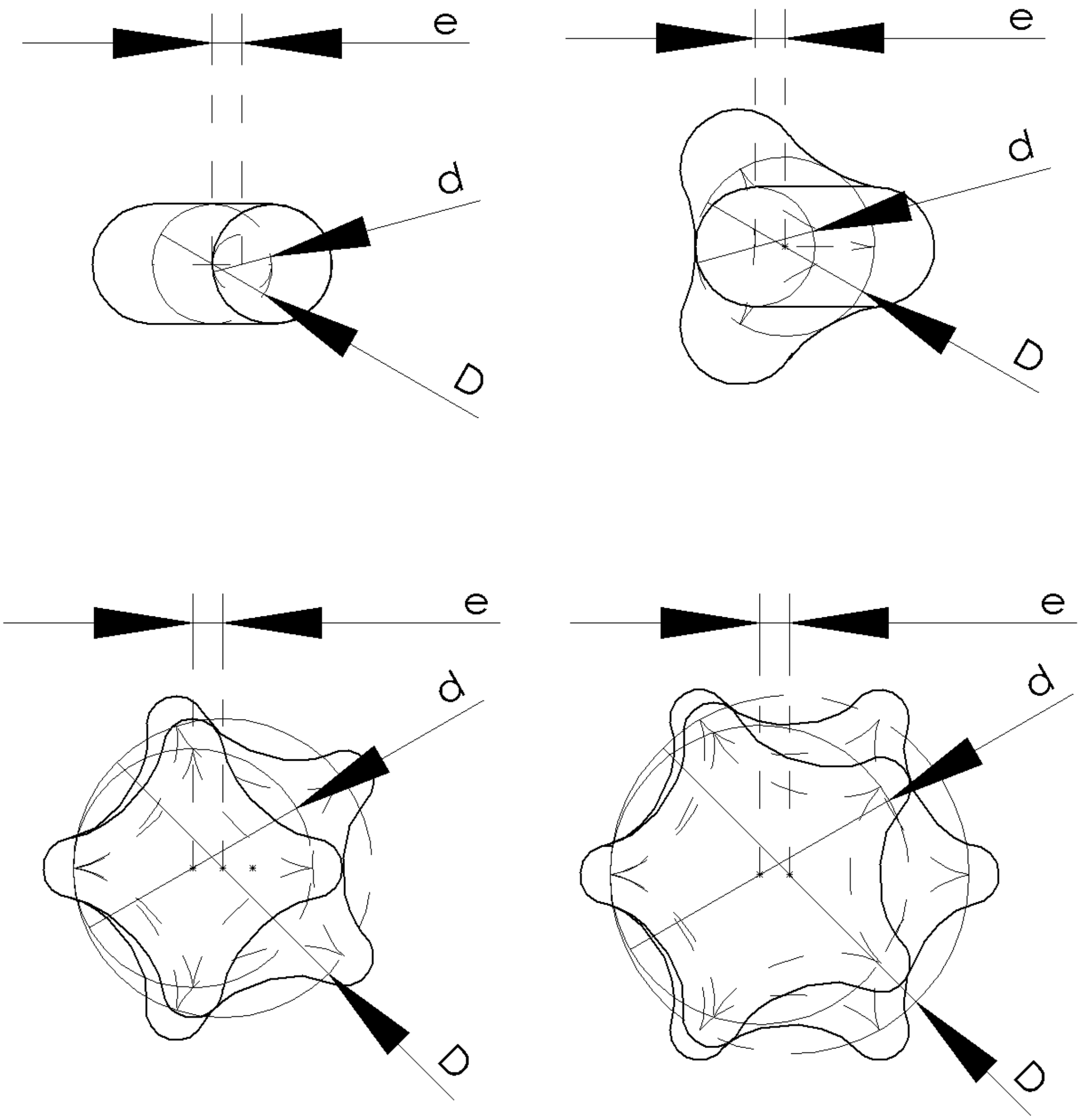


Fig. 10