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Technical Note

Sub-miniature rolling thrust micro-bearing

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Abstract

The original design of the smallest two-way rolling thrust micro-bearing with sub-millimeter dimensions is presented. The bearing is self-contained and is capable of transmitting thrust load up to about 8 N in two directions, as well as radial loads up to about 0.4 N. Thanks to special design of the raceways, operation without lubrication is possible. The scope of experimental study is discussed, and preliminary experimental results are reported. Ways of further miniaturization are suggested.

Supplementary material for this article is available online

Keywords: rolling bearing, ball bearing, thrust bearing, axial bearing, sub-miniature bearing

1. Introduction

The smallest ball bearing in the world that has been described had the following characteristic dimensions: internal diameter 0.5 mm, external diameter 1.5 mm, width 0.65 mm, with balls having diameter of ca. 0.2 mm [1]. Besides that, the smallest bearing balls made of steel that are commercially available have diameter of 0.397 mm (1/64″) [2]. There are also non-standard subminiature angular contact self-aligning ball bearings (without cage and inner ring) [3]. The smallest bearing of this type is presented in figure 1 and features the external diameter D $\geqslant$ 1.0 mm [4].

Designs of rolling micro-bearing fabricated in MEMS technology were also presented [5–7]. While operating under thrust load, these bearings did not feature reasonable durability due to technological problems related to fabrication of the rolling elements keeping appropriate accuracy, which determines their possible spins. For example, should balls with diameters that differ by 2 μm be used in a thrust ball bearing, rotating at the speed of 500 rpm, their linear travel on the raceways might differ up to 10 mm within 1 min only.

Among other applications like precision mechanical measurement instruments, miniature ball bearings found their application in clockworks [1] of exclusive wrist watches, for example ones manufactured by Eterna. So far, two members have been equipped with such ball bearings: the rotor of the self-winding unit [8] and the going barrel [9]; in the second case, a non-standard bearing with 3 rings and 2 sets of balls is used, which, allows suspension between 3 components.

It seems that there are still other application fields, where miniature rolling bearings would be a desired element providing support and ensuring small resistance to motion, especially in the case of rotary and linear micro-actuators, presented in [10, 11] or biomedical applications, such as a micro-robotic joint that could lead to a steerable catheter, an orientable micro-pointer, micro-clamps actuator, micro-shredder swarm,

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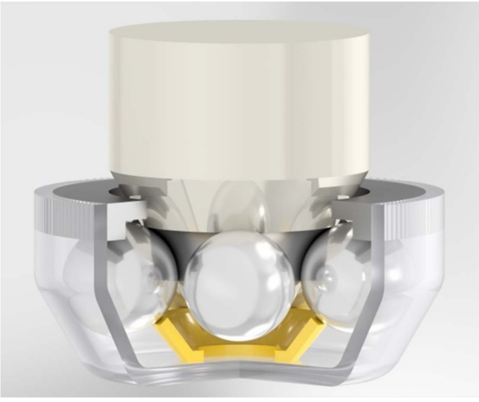

Figure 1. Design of the smallest sub-miniature ball bearing.

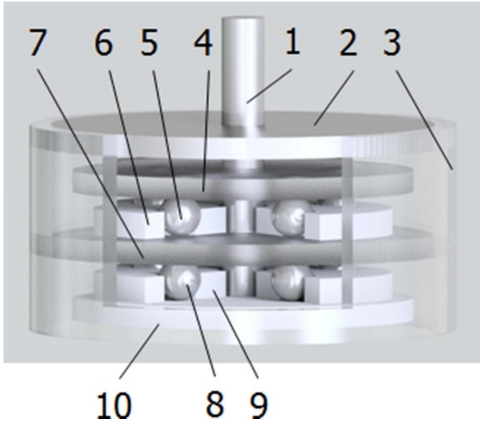

Figure 2. The smallest two-way thrust micro-bearing (elements 3, 6, 9 are show in cutaway view). 1—middle shaft, 2—upper cap—part of the housing, 3—outer cylinder—part of the housing, 4&10—bearing disk rotating, 5&8—rolling elements, 6&9—cage, 7—stationary disk.

self-propelled microcapsules, eye lens adjuster or localized drug delivery capsule [12–16]. All of these devices could diminish collateral damage during many surgeries, such as e.g. atherectomies.

Since ball bearings, especially angular bearings such as the one presented in figure 1, are usually capable of transmitting both radial as well as axial load, the smallest commercial thrust bearings are relatively large, with the external diameter of 6 mm and balls with diameter over 1 mm.

Aiming to design a micro rolling bearing much smaller than the existing ones, we studied various options and found the original solution to the problem.

2. Design of the micro-bearing

Since it is difficult to create precise raceways in elements having sub-millimeter dimension, a thrust bearing is a reasonable solution, since it does not require raceways in a form of typical groves having curvilinear surface: a flat surface of the plates would be satisfactory in this case. Another problem concerns the rolling elements, which must feature very low tolerance of the diameter, small shape deviation, high hardness, small surface roughness and good tribological properties (low friction and small wear). As mentioned above, the smallest bearing balls made of steel have a diameter of 0.397 mm, so they are relatively large with respect to the sub-millimeter external diameter of the designed bearing. It seems that the only reasonable way to obtain suitable balls for building a micro-bearing is to apply glass balls manufactured for optical elements (microlenses). The following diameters of micro glass balls are commercially available: 30, 40, 50, 100 μm. The used material is e.g. soda-lime glass [17].

The mechanical structure of the designed micro-bearing is a subject of the patent pending [18] and is presented in figure 2.

Completely flat disks 4 and 10 are permanently attached to the steel input shaft 1 having diameter of 100 μm, whereas the flat disk 7 located between the disks 4 and 10, as well as the upper cap 2, are permanently attached to the sleeve-shaped housing 3 having diameter of 1 mm. Cages 6 and 9, as well as the disk 7 and the cap 2, can freely rotate on the shaft 1 owing to a clearance fit of their diameters.

Sets of rolling elements 5 and 8 having diameter of 100 μm are seated in the holes created in the cages 6 and 9. There are two sets of seven balls illustrated in figure 2, however each set may consist of a different ball number, provided no lesser than three.

The disks 4, 7 and 10 are made of steel and their thickness is of 50 μm. Owing to the fact that their raceways are flat, it is relatively easy to fabricate such disks on a micro-scale, e.g. through a one-step LIGA process or by laser cutting directly out of a rolled sheet.

Moreover, bearing shaft 1 ensures alignment of the disks and cages, what reduces assembly problems related to positioning accuracy in micro-scale.

Cages 6 and 9 are also made of steel. Several experiments have been conducted with their surface coated with silver, gold or copper, as well as their entire mass made of silver or copper by electrodeposition. So far, however, no significant improvement in bearing performance has been observed.

The balls are made of soda-lime glass. Although it is not as easy to make a wide selection of materials for rolling bearings as it is for sliding bearings, such as various polymers [19], other types of materials have been tested: borosilicate glass, titanium, zirconium, barrium titanate, however since such balls were found to have higher sliding friction coefficient, they were not used.

2.1. Radial loads

Due to the special design, the bearing is capable of transmitting not only thrust load but radial load as well. In the case when a radial load appears, the bearing operates as a typical sliding support. The input shaft 1 is then supported in two cylindrical bearing sleeves: the first in the cap 2, and the second in the disk 7. Fits between shaft 1 and the adjacent plates are illustrated in figure 3.

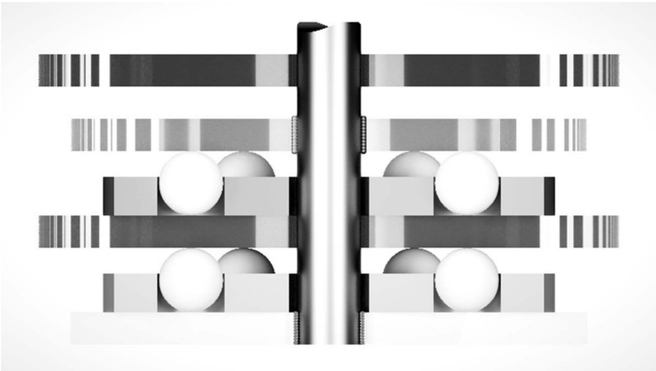

Figure 3. Fits between the shaft and the holes of the adjacent members.

However, depending on the initial position of the input shaft 1 with respect to the housing 3 and on the distance between a radial force and the housing 3, it may be the case that no sliding friction will occur, since the torque generated by the radial force will be transmitted by the two layers of the balls: one half of each layer will be squeezed by the disk 4 or 10, respectively. The occurrence of a mixture of such rolling friction and sliding friction is even more probable.

2.2. Elimination of lubrication

Generally, in the case of any rolling bearing, the two are unavoidable: a spin of the rolling elements with respect to the raceways and to the cage. Both result from the fact that the cage makes the rolling elements circulate with the same angular velocity, whereas each of them features slightly different diameter (because of fabrication tolerances and variable deformation due to individual load).

In the case of thrust bearings, all the rolling elements are axially loaded, so compensation of the path traveled by the balls, whose diameter always slightly differs, must occur as a result of ball slip with respect to the raceway. For the slip to occur, the orthogonal force of the ball acting upon the cage must increase to a value that exceeds the sliding friction force between the ball and the raceway. In this case, the necessary factor to guarantee a correct operation is adequate lubrication of the bearing, reducing the coefficient of friction between the mating elements. In bearings with an outer diameter of less than 1 mm, the lack of adequate lubrication is a major factor in the wear of the cage, the balls and the raceways.

Employing a novel concept developed previously for standard ball bearings [20], which made it possible to eliminate lubrication, it was proposed to create a special lateral grove 11 over the raceways of the disk 4 (and 10 as well), as illustrated in figure 4.

Lateral groove 11, created for example by laser cutting of the raceway, allows the ball 5 to be temporarily unloaded and not to mate with the raceways. As a result, the orthogonal force of interaction between ball 5 and cage 6 (caused by slightly different diameter of the balls and their uneven load) significantly decreases. The rotating cage 6 slides on the surface of

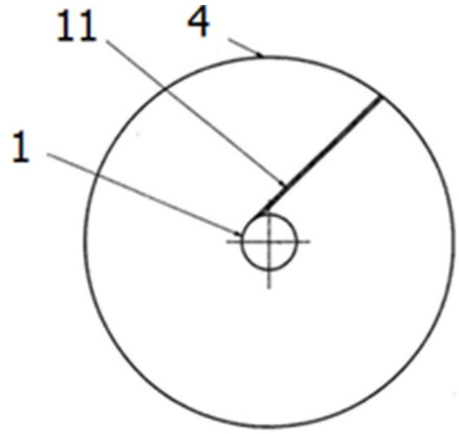

Figure 4. Arrangement of the special lateral groove. 1—middle shaft, 4—rotary bearing disk, 11—lateral groove.

the stationary disk 7 or is lifted upward by the forces occurring between the disk 7 and the balls 5.

The groove 11 eliminates slip of the balls with respect to the raceways, therefore the bearing does not require lubrication, and wear in the bearing is significantly reduced because spin of the balls with respect to the cage occurs at a much lower frictional force.

It is worth noting that the lateral groove reduces effects resulting from sliding friction, and at the same time does not impact the heat transfer, corrosion resistance or protection from dust particles, which are additional benefits of lubrication.

2.3. Assembly of the bearing

The assembly was realized by means of a set of mechanical microgrippers and a set of pneumatic microgrippers (employing thin nozzles connected to a vacuum pump). Various grippers were used for different parts; movement of shaft 1 and housing 3 was performed using a gripper made of tweezers driven by a stepper motor that controlled opening and release of the tweezers. Flat disks and cages were handled using G34 needle with a vacuum pump system, while pick-and-place of balls was performed using a G36 needle. Deposition of the adhesive was realized by wetting a specially prepared dispenser, laser cut probe with a special groove to draw the adhesive into it and afterwards touching the desired elements with the probe with glue. Positioning of the elements was performed by means of a 3-axis linear stage driven by stepper motors.

A prototype of the micro-bearing was assembled in the following way. All the elements were oriented upside down with respect to figure 2. First, shaft 1 (diameter of 0.1 mm) was permanently connected with the upper disk 4 by means of an adhesive, and the middle disk 7 was permanently connected with the housing 3 in the same way. Then, cage 6 was placed on the disk 4 and filled with seven balls 5 (figure 5). Then, the housing 3 connected with the disk 7 was placed on top of the pile. Successively, the cage 9 was placed on the disk 7 and filled with seven balls 8. Then, the disk 10 was placed on top of

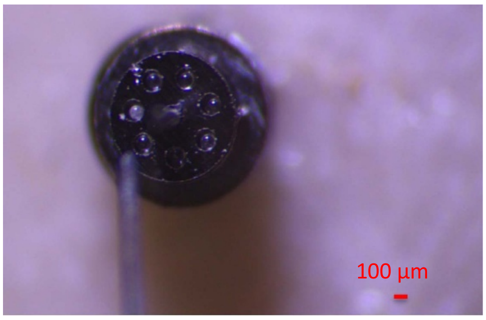

Figure 5. Assembly of the micro-bearing: cage filled with 7 balls along with the vacuum nozzle.

Figure 6. Exemplary rolling micro-bearing on hand.

the pile. The whole pile had been subjected to an initial thrust load, and under that load the disk 10 was permanently connected with the shaft 1 by means of an adhesive. As the final stage, the cover cap 2 was permanently connected with the housing 3. Figure 5 presents a sample bearing while assembled, while figure 6 present bearing after assembly on hand to scale.

Video of the bearing while rotating, actuated by an external magnetic field is available as the supplementary material. In order to improve the clarity of the video, the housing 3 and the upper cap 2 were removed, while the bearing was held by additional arms added to disk 7.

3. Scope of the experimental study

So far, few types of experimental tests have been carried out, yielding some preliminary results. In our study bearings with seven balls were tested.

3.1. Wear tests

In order to determine the wear of the micro-bearing a special test rig was built, presented in figure 7. Its main components were a precise jeweler's scale, a precise inductive gauge of linear displacement and a driving unit. The scale was used to measure the axial load of the bearing, and the gauge was employed to determine decrease of the bearing height Δh as a measure of wear.

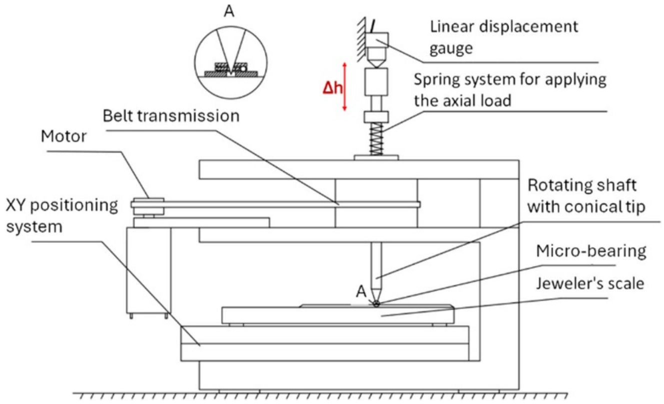

Figure 7. Schematic of the measurement rig for linear displacement Δh as a measure of wear.

Twenty seven pieces of the bearing were tested at the angular speed of about 140 rpm while loaded with axial force in the range of 0.25–0.80 N. The following parameters were recorded: wear (decrease of the bearing height) in the range of 1.2–50.0 μm within operation time from 11 to 112 h.

Most of the tested pieces had a steel cage with thickness of 50 μm and the raceways without a groove. However, 5 pieces had the cage coated, 8 pieces had the cage thicker (60 or 70 μm), 3 pieces had the cage thinner (30 or 40 μm) and one third of the tested bearings had the special groove cut.

The tests proved that in most of the cases the groove extends the operation time of the bearing. Exemplary comparison between bearings with the grove and without it, are presented in figure 8. As aforementioned, the wear was evaluated on the basis of a decrease of the bearing height Δh, whose average value is illustrated by the continuous line, whereas the colored background represents the spread of the measurements.

As can be clearly observed, the bearing with the grove revealed resistance to wear approximately 3 times higher than the one without the grove.

3.2. Determination of the bearing capacity

It was decided to express the bearing capacity in terms of a permissible static axial and radial force that may act upon the bearing, since determination of standard specific dynamic and static capacity is too difficult at this stage.

The permissible axial force was determined in the following way. First, we experimentally determined the minimal value of a static force that caused permanent damage to a single ball. Then we assumed on the basis of FEM simulations that only about 40% of the balls will transmit most of the axial load (due to the diameter deviations). So, in our case (7 balls) at least 3 balls will be loaded. This time the test rig consisted of a linear actuator (to apply the axial force acting upon the tested ball), a jeweler's scale (to determine value of the axial

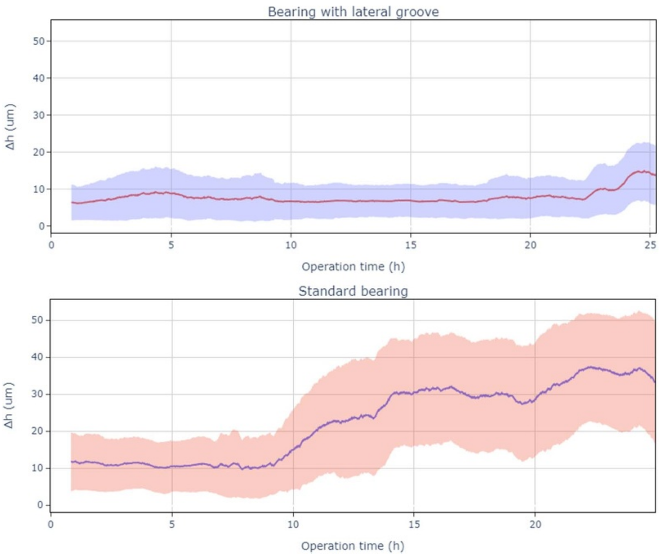

Figure 8. Example measurements of displacement during bearing operation showing resistance to wear: the chart on the top presents the bearing with the groove, while on the bottom the standard bearing.

Table 1. Axial force causing a permanent damage of a single ball.

Sample number	Axial force needed to damage a single ball N
1	2.974
2	3.139
3	3.143
4	3.099
5	2.832
6	2.714
7	3.029
8	2.862
9	2.901
10	2.976

force), and a digital microscope integrated with a camera monitoring indication of the balance (to correlate the moment of ball damage with value of the acing force). The recorded values were in the range 2.71–3.14 N, as presented in table 1, so accepting the smallest value, we can state that the bearing is capable of transmitting thrust load up to 8 N in two directions.

In order to determine the permissible radial load, a FEM (figure 9) simulation was performed. It was assumed that a radial force is orthogonal to the axis of the shaft *1* and acts just above the cap 2. Assuming the yield strength of AISI 316 1.4401 as 290 MPa, we determined the value of the force, assuming that it will be counterbalanced by reactions at the holes in the cap 2 and the disk 7. On this basis, we evaluate that the bearing was capable of transmitting radial loads up to 0.4 N (depending on the distance between the force and bearing).

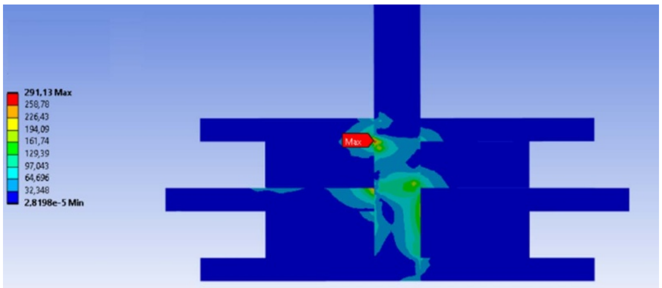

Figure 9. Stress distribution under radial load within the rolling micro-bearing.

3.3. Detection of possible ball spin

In order to detect a possible spin of the balls, we put the bearing in motion and recorded both the rotational speed of the shaft 1 (so, the rotational speed of the disks 4 and 10 as well) and of the cages 6 and 9—whose magnitude is to be 50% smaller [3]. Within the precision of the measurement of the considered rotational speeds, no spin was detected.

3.4. Other tests

The authors previously reported on fabricating special kind of cantilevers for atomic force microscope (AFM), whose tip was made of steel balls [21]. This idea was adopted to fabricate similar cantilevers, where the steel balls were replaced with the considered soda-lime glass balls. Application of AFM equipped with such modified cantilever made it possible to study behavior of the balls made of glass and other materials aforementioned, especially their tribological parameters while subjected to sliding friction [17].

Future tests will be focused on determination of resistance to motion of the bearing. Their results will be helpful while introducing related improvements in the bearing design.

4. Conclusion

(1) Micro-bearing: design benefits
Rolling micro-bearings using micro-spheres made of Si were proposed in [5–7]. However, it results in limiting the range of potential materials and applications of these devices. Besides, the bearings were bigger, using balls with diameter of 300–400 μm instead of 30–100 μm, what in turn increased the size of the whole device. The design we propose leads to a smaller size of the bearing and easier insertion of the bearing cage during assembly.

Since application of liquid lubricants is problematic due to high static friction, large evaporation rate and difficulty in preventing their spreading, the design was oriented on reducing the need for lubrication. The special lateral grove enables operation without any lubricant, what is crucial in some applications e.g. due to purity regime. Results of the experimental study that have been obtained so far are promising. Should the future works result in finding more suitable materials for the disks and the cages, life of the bearing would be much longer and resistance to motion smaller. The special lateral grove can be created on the upper and the lower raceway of disk 7 instead of raceways on disks 4 and 10, or optionally on all the four raceways.

(2) Micro-bearing: potential design changes

The design of the bearing can be simplified by eliminating one stage of the rolling elements, as suggested in [18] (e.g. elements 8, 9 or 5, 6—see figure 2). In this way, height of the bearing can be reduced, however the trust load will be transmitted in one direction only. The presented thrust micro-bearing can be a subject of further miniaturization. Smaller balls (for example 30 μm) made of soda-lime glass can be applied, however the smaller their diameter the bigger the deviations. Therefore, it will be more difficult to select balls of similar diameter for one bearing.

(3) Future works

Experimental study of the earing is still being continued. The results that will have been obtained will be reported in future publications. In the future, extended durability measurements and tests of other possible materials will be performed.

Data availability statement

The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors.

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