Analysis of movement processes occurring under varying load cases for the optimization of wire race bearings

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Research Article

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Analysis of movement processes occurring under varying load cases for the optimization of wire race bearings

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Abstract Rolling bearing technology is used in many areas of mechanical engineering. In order to be able to use and optimize the rolling bearing technology in a meaningful way, a particularly good knowledge of the movement processes in the bearings is required. In this paper the processes in wire race bearings under different loads are considered. In this case the three most common bearing loads, preload, axial load and radial load, were considered. For this purpose, preliminary considerations, simulations and tests were carried out and evaluated. The results of the simulation provide information on how the rolling process, load distribution and contact angle change takes place in the bearing. In the tests, the contact angle change in the bearing was investigated. The results of the preliminary considerations, the simulation and the tests based on these results are used to explain speed changes that occur under different types and intensities of load.

Keywords: Contact angle change; Roller bearing; Roller bearing loadzones; Roller bearing slip; Testing

1. Introduction

Roller bearings are used in many machines and areas of daily life, for example medical technology, shipping, automotive industry and power generation. It is hard to imagine life without them. Roller bearings exist in all conceivable shapes and sizes. They are often used but not sufficiently researched.

The more applications roller bearings could be used in, the higher the requirements for performance and accuracy have become. In order to ensure optimization and innovation in the field of roller bearing technology, a closer look must be taken at the processes within the roller bearing.

In the following, the change in slip and contact angle in wire race bearings will be considered. This is necessary to describe the movement processes in the wire race bearings. Different load conditions are considered. With the knowledge of the movement processes, the wire race bearings can be optimized.

In order to describe the movement processes, simulations and tests are performed. The simulations provide information about the relative movements in the bearing, while the tests are used to measure the rollover frequency. With this rollover frequency, the movement processes in the bearing can be deduced, taking into account preliminary considerations.

2. State of the Art

Roller bearings generally consist of an outer bearing ring and an inner bearing ring. The rolling elements move between these rings. [1][2][3][4]

The wire race bearings of Franke GmbH are a special form of the four-point contact bearings. A four-point contact bearing differs in various aspects from other roller bearing types. [5]

The raceways on the inner and outer ring are in the shape of a circular arc. The degrees of curvature are selected so that a pointed arc is created when the raceways meet. Due to this pointed arc shape, the rolling elements contact the raceways at four points under radial load. In order to be able to fill the bearing with the spherical rolling elements, it is necessary to manufacture either the inner ring or the outer ring in split form. The inner bearing ring is usually selected for this purpose. [6][7]

This type of bearing also has the special feature that this four-point bearing can be subjected to both axial forces F_a and radial forces F_r. The contact angle occurring in this bearing is relatively large at approx. $\alpha = 35°$.. If loads act on the bearing, the contact angle changes due to the load-induced deformation processes in the bearing. [6][7][8][9]

In wire race bearings, the inner and outer ring of the four-point contact bearing is replaced by four wires (Fig. 1.). This is possible because there is a maximum of four contact points, which results in four contact lines on the inner and outer bearing rings due to the rotational motion of the wire race bearing. The positioning of the bearing rings is done directly by the surrounding construction. This flexibility allows many variations of the surrounding construction. In contrast to a four-point contact bearing, the contact angle in the wire race bearing is $\alpha = 45°$. [10]

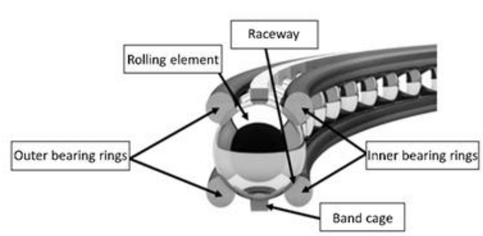

Fig. 1. Construction of a wire race bearing of the company Franke [11]

2.1 Slip in roller bearings

Slip is the deviation of the theoretical angular velocity from the actual measured angular velocity. Slip always occurs when the rolling elements do not move in a pure rolling motion. [12]

As the lubricant film is partially interrupted when slip occurs, high wear often appears. Slip is very likely to occur at low loads. To avoid slippage, the minimum loads should therefore be taken into account. [13]

The company BestSens has developed systems to measure the slippage in roller bearings. Thereby acoustic surface waves are used which are generated by special sensors. These waves spread in the outer bearing ring of the roller bearing and form a standing wave. If a rolling element moves between these sensor heads, the boundary conditions and the acoustic properties of the transmission path change. Since these changes occur periodically due to the rolling elements, the periodic components can be extracted from the received signals. The rollover frequency of the rolling elements and the cage speed can be determined from these signals by a frequency analysis. By comparing these results with the theoretical cage speed, a statement can be made about the amount of slip. [14]

2.2 Contact angle change in roller bearings

The load-dependent contact angle change within a roller bearing is simulated in simulation programs such as ANSYS. The contact angle change can be made visible in the corresponding sectional view of the simulation. In addition, the contact angle change can be made visible by computer tomography. For this purpose, the roller bearing is transilluminated with an X-ray cone beam and the shadow cast is detected. The bearing is X-rayed in different positions and can then be displayed on the computer in different sectional planes. The contact angle can thus be measured in these plains.

3. Method of detecting rollover frequencies

The following tests are carried out to determine the rollover frequency. The aim of the tests is to find out how an occurring load affects the contact angle and slip. Different types of load will be investigated. On the one hand an increasing preload and on the other hand increasing axial and radial loads.

In order to interpret and qualitatively predict the expected test results, preliminary considerations were made. The various loads are considered with regard to their effect on the bearing. Special attention is paid to the formation of load zones, slip changes and contact angle changes.

3.1 Signal generation

In order to make the movements in the bearing measurable, an induction sensor is inserted into the outer housing through a radial through-hole, thus being close enough to the rolling elements to detect them during movement. Since the rolling elements are located inside a band cage, there is one rolling element space between the rolling elements p_a that is different from the others p_n (Fig. 2.). This indicates when the cage has rotated once. Instead of the induction sensor, an acceleration sensor could also be installed. However, in addition to the structure-borne noise that the rolling elements cause when rolling over the bearing ring gap, this sensor also detects vibrations from the environment, which would then have to be filtered out. For this reason an induction sensor is more suitable for this application.

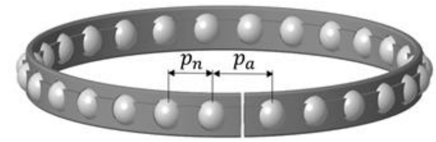

Fig. 2. Cage with rolling element divisions

To calculate the signal, the rollover frequency on the outer bearing ring $f_{üa}$ and the inner bearing ring $f_{üi}$ must be determined. [15] [16]

$$f_{üa} = \frac{1}{2} f_{ri} Z \left(1 - \frac{d}{D} \cos(\alpha)\right) \tag{1}$$

$$f_{üi} = \frac{1}{2} f_{ri} Z \left(1 + \frac{d}{D} \cos(\alpha)\right) \tag{2}$$

Here f_{ri} indicates the rotation frequency of the inner bearing ring. Z describes the number of rolling elements, d the rolling element diameter, D the rolling element circle diameter and α the contact angle. Due to the arrangement of the wires of the wire race bearing, the contact angle in unloaded condition can be assumed to be $\alpha = 45°$. [16]

4. Preliminary considerations

In this chapter, the effects on the signal and the rollover frequencies by variation of different load types are considered.

4.1 Preload

Load Zones

If the preload is increased, the load increases equally on each of the four bearing rings. This results in a load zone in each of the four bearing rings. The loaded races are marked red in Fig. 3.

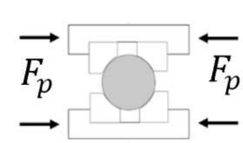

Fig. 3. Bearing cross section under preload F_p with loaded bearing rings

Slip

The slip affects the rollover frequency and must therefore be determined qualitatively. Slip occurs more often in less stressed areas. Since the load zones are formed in the same way in all four bearing rings, the slip that occurs affects each of the bearing rings to the same extent. Since the slip decreases with increased preload of the bearing, a qualitative course similar to that shown in figure 4 will result.

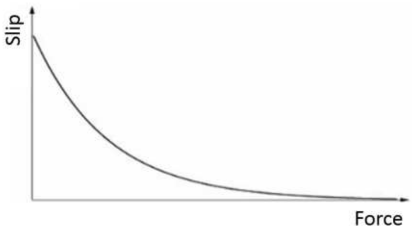

Fig. 4. Slip curve with increasing preload

Contact angle

If preload is applied to the roller bearing, the contact angle will decrease with increasing preload (Figure 5). This is because the outer bearing rings, driven by the preload applied, move upwards along the rolling element curvature. This causes the rolling element to be displaced downwards and pushes the inner bearing ring outwards to a greater extent (Figure 6).

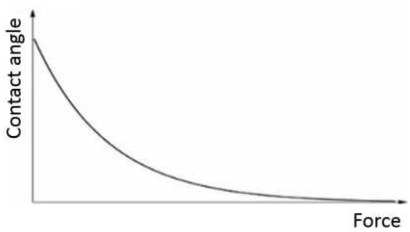

Fig. 5. Contact angle with increasing preload

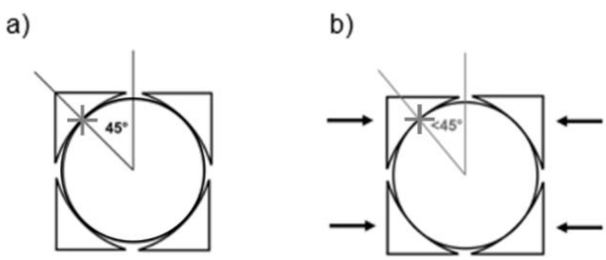

Fig. 6. Bearings under preload Fp a) before contact angle change b) after contact angle change

4.2 Axial Load

Load Zones

Under axial load, load zones are only formed in two aslant opposite bearing rings. One of these bearing rings is an inner bearing ring and the other an outer bearing ring (Figure 7). In which bearing rings the load zone is formed depends on the orientation of the axial load.

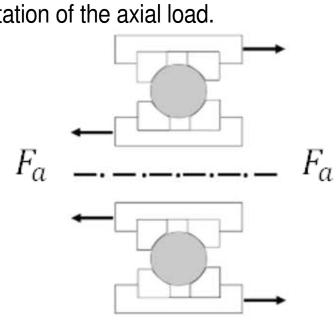

Fig. 7. Bearing cross section under axial load F_a with loaded bearing rings

Slip

Theoretically, under axial load, there is less slippage on the bearing ring in the load zones than on unloaded bearing rings (Figure 8). Since in the case of four-point bearings it is assumed that under axial load the rolling element only touches the raceways at two points, this idealization is also applied here. Here the lower slip at the loaded bearing rings dominates. [3]

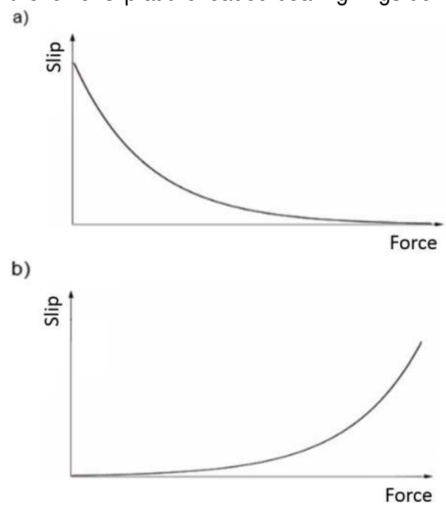

Fig. 8. Slip curve with increasing axial load in a) loaded bearing rings, b) unloaded bearing rings

Contact angle

Under axial load it can be assumed that the contact angle tends to increase, since the rolling element is pushed by the loaded outer bearing ring onto the loaded inner bearing ring and will move upwards along the bearing ring curvature (Figure 9 and Figure 10).

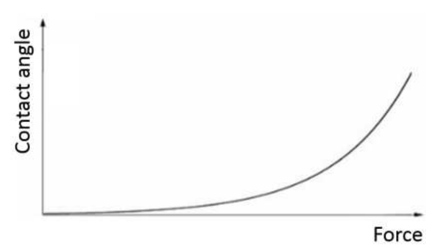

Fig. 9. Contact angle with increasing axial load

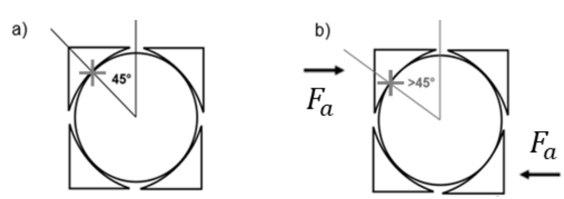

Fig. 10. Bearing under axial load F_a a) before contact angle change b) after contact angle change

4.3 Radial Load

Load zones

Under radial load, the load zones form uneven over each bearing ring (Figure 11). Since the force is introduced close to the outer bearing ring, a load zone is formed in the upper part of the bearing. This load zone extends over all four bearing rings in the upper part of the bearing. In the lower part of the bearing, the four bearing rings are almost unloaded. The position of the load zone in the bearing depends on the orientation of the radial load.

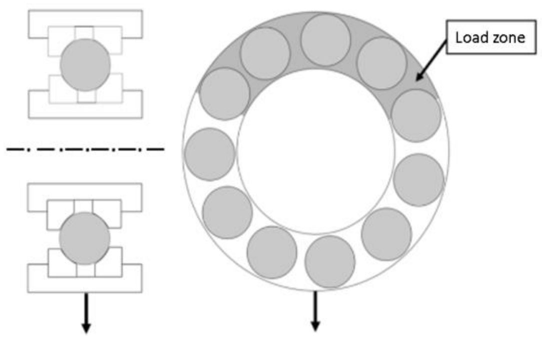

Fig. 11. Bearing cross section under radial F_r load with a) loaded bearing rings b) load zone

Slip

The slip occurring under radial load changes over the circumference of each bearing ring. The slip decreases in the load area, while it increases again in the unloaded areas outside the load zone (Figure 12). Here too, the slip decrease in the loaded area is dominant, since this determines the speed of the entire cage.

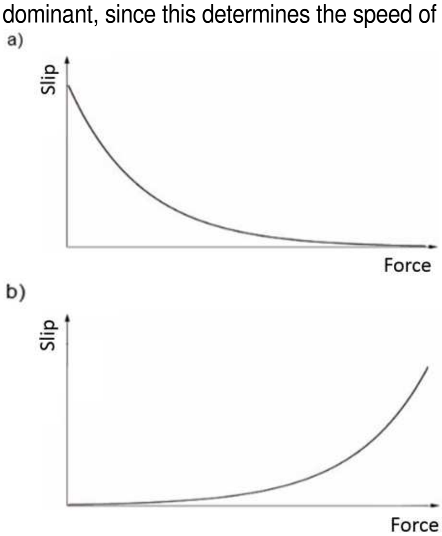

Fig. 12. Slip curve with increasing radial load in a) loaded area b) unloaded area

Contact angle

For the area of the wire race bearing which is located within the load zone, it can be assumed that the contact angle decreases with increasing radial load (Figure 13). This is due to the fact that the radial force presses the outer bearing rings more strongly onto the rolling element (Figure 14). The rolling element tends to move downwards, while the outer bearing ring tend to move downwards along the rolling element curvature. For the area of the bearing that is outside the load zone, it can be assumed that the contact between the rolling element and bearing ring will begin to loosen under radial load.

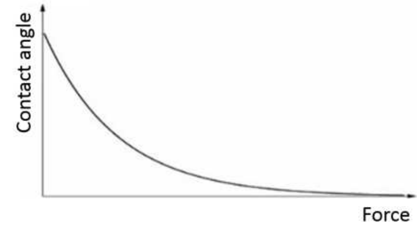

Fig. 13. Contact angle with increasing radial load

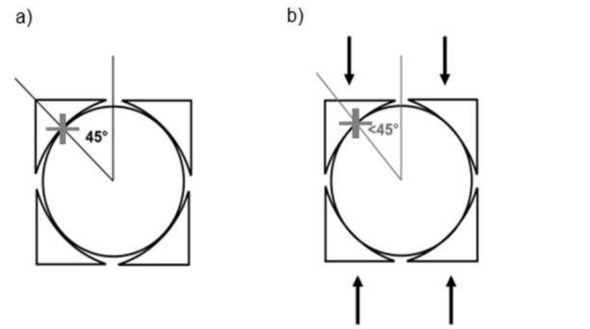

Fig. 14. Bearing under radial F_r load a) before contact angle change b) after contact angle change

4.4 Contact angle change

If the contact angle change is considered, it can be assumed that the contact angle changes significantly at the beginning of a load increase. This may be due to the fact that only the softness of the bearing loosens and the bearing rings are shifted so that the clearance disappears (Figure 15). If the load is increased further, the contact angle change will continue to decrease. Now deformation mechanisms are at work. The bearing rings and the housing are deformed. If the load is now increased further, the contact angle change will approach zero, as the bearing is now in the overload range. The wire race bearing is now completely braced.

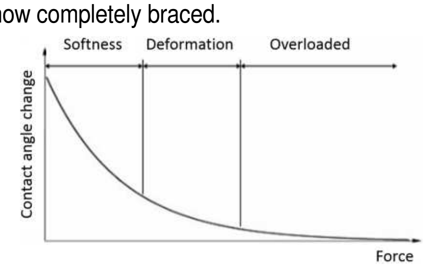

Fig. 15. Contact angle change with increasing load

4.5 Possible curves of the rollover frequency

Slip

If the slip increases, this means that the difference between the theoretical rollover frequency and the actual measured rollover frequency increases. Thus, an increase in slip means a reduction of the rollover frequency, with the same boundary conditions. A reduction of the slip has the opposite effect.

Contact angle

A change in contact angle affects the rolling radius of the rolling element. The larger the rolling radius of a rolling element, the greater its circumferential speed. If the contact angle increases, the rolling radius and thus the circumferential speed of the rolling elements is reduced at this point. This reduction results in an increase in the overrolling frequency. If the contact angle becomes smaller, the rolling radius increases and the path speed increases, resulting in a reduction in the overrolling frequency.

This correlation can be explained by the opposing behavior of the bearing rings when the contact angle is changed. In order for the contact angle in the roller bearing to decrease, the outer bearing ring must move upwards along the rolling element curvature, while the inner bearing ring moves downwards along this curvature. This results in an increase in raceway length on the outer bearing rings and a reduction on the inner bearing rings. Thus, one circuit on the outer bearing ring will take longer than before the contact angle change and therefore the overrolling frequency on the outer bearing rings is reduced. The opposite is true for the overrolling frequency on the inner bearing rings. This fact is decisive for the evaluation and interpretation of the measured data. Since the induction sensor is located at the outer bearing rings in the test set-up explained later, the behavior of the rollover frequency at the outer bearing rings must be used for evaluation.

In conclusion the behavior of the rollover frequency on the outer bearing rings:

Reduced contact angle → reduced rollover frequency
Increased contact angle → increased rollover frequency

Possible curves under preload

If the force on the wire race bearing is increased, the softness and displacements are first released from the bearing (Figure 16). During this process the contact angle changes. In this case the contact angle becomes smaller and therefore the rollover frequency is reduced. When all softness and displacements in the bearing have disappeared, the slippage overlaps the contact angle change. As the slip decreases with increasing load because the bearing becomes more and more jammed, the rollover frequency increases. When the change in slip and contact angle is complete, the wire race bearing is braced and the rollover frequency no longer changes.

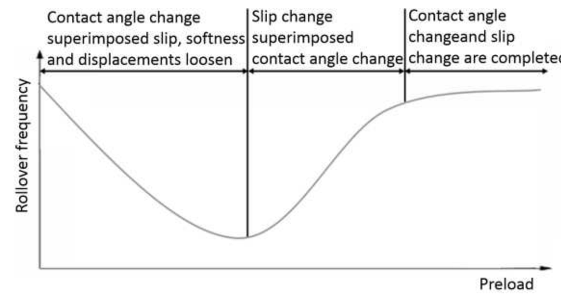

Fig. 16. Possible curves of the rollover frequency under preload

Possible curves under axial load

If an axial load is applied to the wire race bearing, the contact angle increases, since the softness and displacements in the bearing are released first (Figure 17). Subsequently, the change in slip superimposes the change in contact angle, as all softness in the bearing is released. Also in this case the low slip in the loaded bearing rings dominates and the rollover frequency continues to increase. Once the change in contact angle and the change in slip are complete, two further mechanisms take effect. It can be assumed that friction increases under axial load, since the load is now distributed over two instead of four bearing rings. Similarly, the increased load on both loaded bearing rings can cause an increase in the pressure ellipse. As a result, the increased leading and lagging areas result in a higher loss. These two mechanisms reduce the rollover frequency due to their losses.

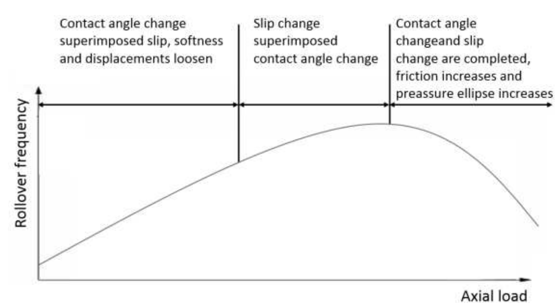

Fig. 17. Possible curves of the rollover frequency under axial load

Possible curves under radial load

If a radial force is applied to the wire race bearing, the soft spots and displacements are first released from the bearing (Figure 18). This process does not only reduce the contact angle but also reduces the rollover frequency. When all softness and displacements in the bearing have disappeared, the slippage overlaps the change in contact angle. Since the slip decreases with increasing load, because the bearing jams more, the rollover frequency increases. When the change in slip and contact angle is complete, the wire race bearing is braced and the rollover frequency no longer changes.

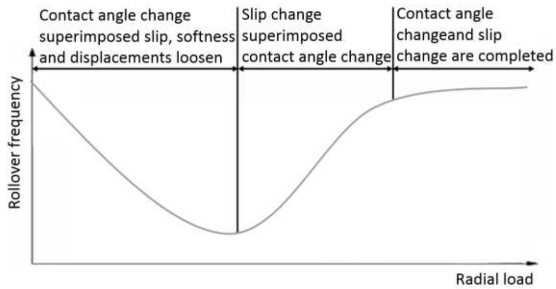

Fig. 18. Possible curves of the rollover frequency under radial load

5. Simulation of the processes in the wire race bearing

In order to be able to make further predictions about the tests, a simulation model of a bearing section is created. This geometry is loaded into ANSYS and is assigned to corresponding materials. Afterwards a mesh is laid over the geometry. Then the individual components are supported appropriately and the surfaces are loaded with forces according to the examined load case.

Preload

The comparative stresses (Figure 19) show that the load increases on all four bearing rings. The outer bearing rings are loaded slightly more than the inner ones because they are closer to the area of influence of the forces. If a factor of 20 is applied to the equivalent stress and the change in stress is shown as a sequence, it can be seen that the rolling element is displaced downwards by the preload. On closer inspection of the contact angle, it can be seen that the contact angle tends to decrease with increasing preload.

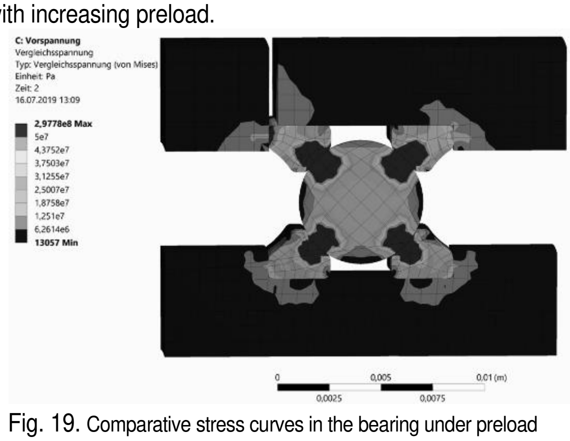

Fig. 19. Comparative stress curves in the bearing under preload

Axial load

The comparative stress curves are shown in Figure 20. The comparative stress shows that the load increases in the left outer and right inner bearing ring. In the immediate vicinity of these bearing rings, the adjacent housing parts are also loaded. In the rolling element, the area of the highest load runs diagonally downwards from contact with the left outer bearing ring to contact with the right inner bearing ring. If the direction of the axial force were reversed, the previously unloaded bearing ring would be loaded.

The evaluation of the increased movement of the rolling element shows that the contact angle grows with increasing axial load. This increase is due to the fact that the outer left bearing ring is pushed upwards along the rolling element curvature. This means that the rolling element runs up against the right-hand inner bearing ring and also moves upwards along the bearing ring curvature. As a result of this upward movement, the contact point between the rolling element and bearing ring on the raceway is also shifted upwards. As a result, the contact angle increases.

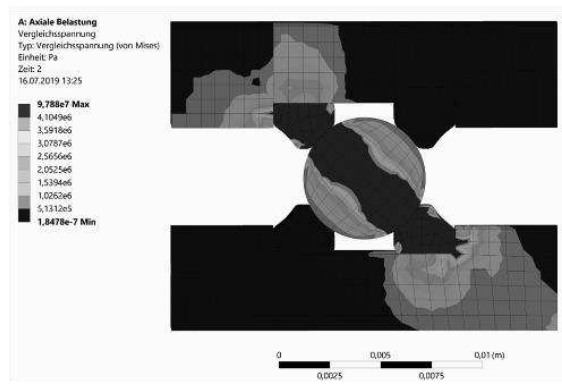

Fig. 20. Comparative stress curves in the bearing under axial load

Radial load

If we now look at the comparative stress from Figure 21, we can see from this diagram that the load increases in all four bearing rings. If a factor of 20 is applied to the comparative stress and the stress development is shown as a sequence, it can be seen that the rolling element is pushed down by the radial force.

With regard to the contact angle, it can be seen that the contact angle tends to decrease with increasing radial load. This reduction occurs because a radial load equally compresses that part of the wire race bearing which is located within the load zone.

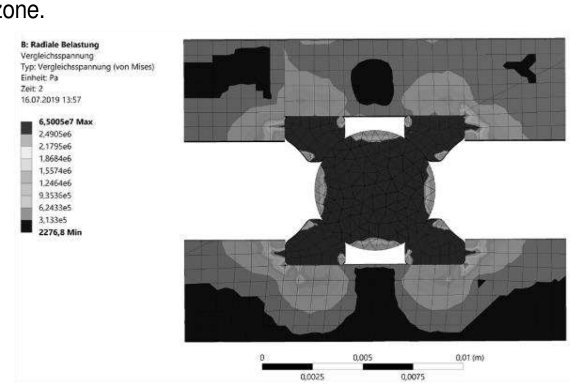

Fig. 21. Comparative stress curves in the bearing under radial load

6. Tests

In order to check the results of the preliminary considerations and the simulation, tests are now being carried out.

The aim of these tests is to measure the rollover frequency and to show how it changes with increasing load. Subsequently, the resulting curve should enable statements to be made about the correctness of the preliminary considerations made in this thesis.

In order to prevent a change in the viscosity of the grease lubrication during the measurements, a warm-up phase of 10 minutes at 700 rpm was observed before the tests. In order to check the quality of each individual measurement and to keep the effect of individual errors as small as possible, fifty tests are carried out with each test setting. In addition, a high number of tests enables a statement to be made about the scattering of results.

The recording time for each test is 20 seconds. In order to be able to assess the statistical errors and the test scatter, it is necessary to prevent the frequencies from leveling out over the fifty tests with the same test setting. This is achieved by increasing the test speed by 100 revolutions per minute after each test and then reducing it to the test speed after this new speed is reached.

For each test, the speed range from 100 rpm to 800 rpm is considered. The speed is increased step by step by 100 rpm. For the tests on axial and radial loads, it is also important to ensure that a waiting time is observed. During this waiting period the rope system can come to rest. While evaluating the measurements, it occurred that in the speed range from 700 rpm to 800 rpm, the structure-borne noise of the bearing generates a vibration resonance which disturbs the measurement. This must also be taken into account when evaluating the measurement results.

Tests are now carried out for the different load conditions according to this pattern. The loads caused by preload, axial load and radial load are investigated. In order to investigate the effects of increasing preload, it is successively increased. For this purpose, shims are installed in the bearing. The thicker the layer of fitted shims, the lower the preload. Since the preload cannot be calculated, the thickness of the shims is used as a reference. The preload is increased in 0.025 mm steps from 0.950 mm to 1.075 mm. For the axial load, the range from 0 N to 1000 N is examined in steps of 100 N each. These test parameters for axial load also apply to the investigation of radial load. In order to allow different forces to act on the bearing, different masses are attached to the rope construction.

These tests result in eight diagrams each with characteristic curves of the rollover frequencies. One of these characteristic curves is compared with the curves from the preliminary considerations.

7. Results

If the results of the preliminary considerations, simulations and tests are compared, it can be seen that there is agreement when considering the change in contact angle. This results in similarities of the rollover frequency characteristics. These similarities of the curves are examined in detail in the following.

The preliminary considerations have shown that a reduction of the contact angle also results in a reduction of the rollover frequency. Accordingly, an increase in the contact angle results in an increase in the rollover frequency. However, this only applies to a measurement of the rollover frequency on the outer bearing rings, as is the case with the test rig used. For a measurement on the inner bearing rings, an increase in the contact angle would result in a reduction of the rollover frequency.

Preload

With increasing preload, the contact angle is reduced according to the preliminary considerations. This effect was confirmed by the simulations carried out. By reducing the contact angle, the rollover frequency is also reduced. In addition, it can be shown that when the roller bearing is subjected to a preload, load zones are formed in all four bearing rings equally. If the results of the preliminary considerations and the simulations are compared with the test results, it can be seen that the first part of the rollover frequency curve can be explained by the preliminary considerations (Figure 16 and Figure 22). Only the second part of the oscillation from 1,05 mm upwards cannot be explained by this. Further influencing factors must be determined for this explanation.

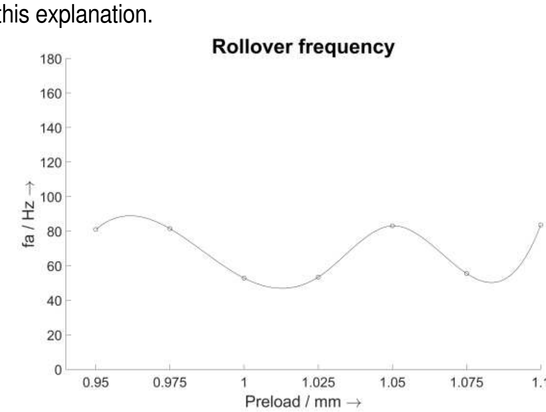

Fig. 22. Curve of the rollover frequency under preload

Axial load

If the roller bearing is considered under axial load, a contact angle increase is to be expected according to the preliminary considerations. This increases the rollover frequency. (Figure 17 and Figure 23). This can be confirmed by the simulations. Furthermore, the simulations show that under axial load a load zone is formed in each of two obliquely opposite bearing rings. Here the lower slip in the loaded bearing rings dominates and the rollover frequency is reduced. If the preliminary considerations, simulations and tests are compared, it can be seen that the preliminary considerations clearly illustrate and explain the test results. It can be assumed that the drop in the rollover frequency in the rear section of the track is due to increased friction and an enlarged pressure ellipse. This change in friction and pressure ellipse is caused by the redistribution of the load from four to two bearing rings.

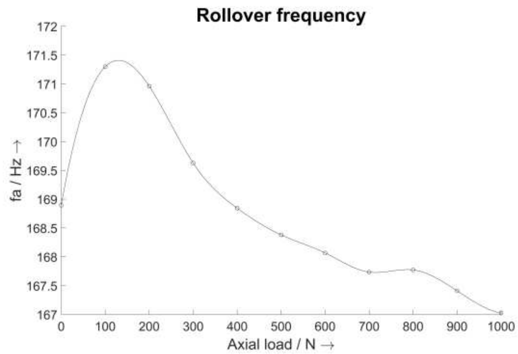

Fig. 23. Curve of the rollover frequency under axial load

Radial load

If a radial load is applied to the roller bearing, the contact angle within the load zone will decrease according to the preliminary considerations and the rollover frequency will be reduced (Figure 18 and Figure 24). Outside this load zone the contact angle will start to loosen. This could be proven by the simulations. The low slip within the load zone dominates. Thus the rollover frequency increases as soon as the contact angle change is completed. If figure 18 and 24 are compared, it can be seen that the preliminary considerations largely confirm the test results. Only the pendulum movement at the rear of the curve cannot be explained with this approach. In order to explain this movement, further influencing factors must be determined and checked.

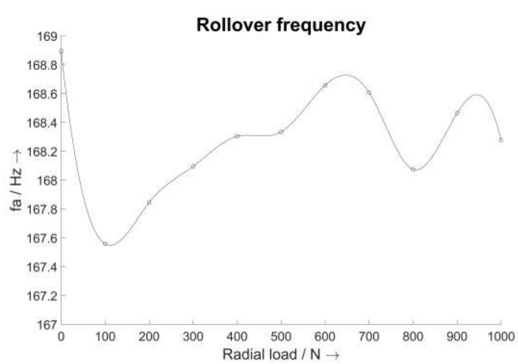

Fig. 24. Curve of the rollover frequency under radial load

8. Conclusion statement

With the considerations, simulations and tests carried out, an impression of the rollover frequency in the wire race bearing is obtained. The factors considered, such as slip, contact angle and load zones, have a significant influence on the rollover frequency. With these findings, different processes in roller bearings can be described and explained more precisely in the future.

By the totality of these tests and their evaluation it is possible to explain and predict movement processes in roller bearings more precisely in the future. This will allow further optimizations of wire race bearings, such as design improvements and changes in material selection. In addition, the processing of the surfaces can be adapted to the corresponding load case and lubricants can be selected exactly. Furthermore, damage patterns can be classified more precisely and further steps towards predictive maintenance can be taken. The sensor position is important here [17]. Since in real use of roller bearings often no pure axial or radial load occurs but a mixed form, a superposition of the loads can be investigated as a further step.

Likewise, the type of load can be determined by recording the rollover frequency of a bearing. If further test series are carried out, conclusions could also be possibly drawn about the amount of force. The inductive sensor could be used to map a virtual sensor. In order to develop such a smart sensor system, it is extremely important to know the motion sequences in the rolling bearing.

If, in addition to the load, other external influencing factors have to be considered, further measurements can be carried out. Of particular interest here is the consideration of the temperature influence. Due to the friction in the bearing, the temperature increases continuously during the measuring process, whereby an expansion of the components can cause additional tension in the roller bearing. In order to be able to estimate the magnitude of this influence, it is advisable to carry out further investigations.

Nomenclature

α	: Contact angle
F_a	: Axial Forces
F_r	: Radial Forces
f_{ri}	: inner bearing ring rotation frequency
$f_{üa}$	: Outer bearing ring rollover frequency
$f_{üi}$	: Inner bearing ring rollover frequency
p_a	: Differing rolling element space
p_n	: Usual rolling element space
Z	: Number of rolling elements
d	: Rolling element diameter
D	: Rolling element circle diameter

Declarations

The corresponding author declares on behalf of all authors that there is no conflict of interest.

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests

There are no competing interests.

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Authors' contributions

Bauer had the initial idea of this research topic. He take the decision of using a test rig for initial tests and was a major contributor in writing the manuscript.

Rappold has managed the whole project and was a major contributor in analyzing the data sets.

Kley supervised the whole project.

All authors read and approved the final manuscript.

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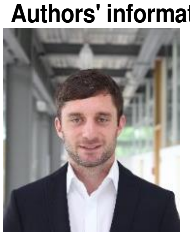
Authors' information



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