The Utilization of Production-Related Defects for Improving Operating Properties of Journal Bearings

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The function of hydrodynamic journal bearings is primarily determined by their lubrication gap geometry. Even small deviations in the bearing geometry can lead to a change in the operating properties and in the worst case to bearing failure. Such deviations of the ideal geometry always occur within production. These can be caused, for example, by clamping in a three-jaw chuck - this typically leads to a three-sided uniform thickness geometry (or three-sided-lobe geometry). In order to ensure safe operation of the journal bearings, the shape tolerances are traditionally selected very precisely, which leads to high manufacturing costs.

In this work we follow an alternative approach. We allow larger form deviation values, but orient these when installing the bearing so that negative effects on the operating properties are minimized. The shape deviation investigated is a three-sided-lobe geometry in circumferential direction.

The influence of the orientation of form deviation of hydrodynamic journal bearings were simulated on the basis of the Reynolds equation and evaluated by a worst-case and best-case investigation.

The investigations show that with knowledge of the production-related effects, negative influences of the form deviation can be negated. In addition, a positive influence on the operating properties can be generated by the correct utilization of the form deviations.

The knowledge about the influence of the shape deviation allows to extend the given tolerance data from the standards and thus to widen the production tolerances.

Keywords: journal bearing, form deviations, shape deviation, shape adaption, operating values

1. Introduction

Production drawings require dimensional, form and position tolerances. In order to define these tolerances, the knowledge about their functional influence is required. The function of journal bearings depends largely on the geometry of their hydrodynamic lubricating gap. Shape deviations may result in an early failure of the bearing due to a reduced lubricating gap height or edge carrying. For the technical implementation, ISO 12129-2 gives the permissible shape deviation for thrust rings and shafts [1]. The standards do not provide any information about the tolerance of shape and position deviation of journal bearings. For this reason ISO 12129-2 is often referred to as the reference for journal bearing tolerance.

Investigations focusing on the macroscopic shape deviation of journal bearings show the influence of multi-lobe bearings on the operating values [2]. As a result, these journal bearing forms have been used in industrial practice for a long period of time. Also shape deviations in the microscopic range show a change in operating values [3], [4], [5]. As a result, specific microscopic geometric form deviations were investigated, which had advantages for the operation. These include hyperboloid journal bearings, which are particularly effective against edge-carrying on tilted shafts [6]. Likewise, out-of-roundness deviations show a reduction in wear in journal bearings [7], [8]. If inaccuracies in the manufacturing process are considered, wavy surfaces are a common result. The waviness influence on a rectangular slider bearing [9] and on a hydrodynamic journal bearing [10] can increase the load-carrying capacity depending on the number of waves. The waviness of the journal bearing corresponds to a multi-lobe bearing in the microscopic scale. While the previous works consider the geometric deviation of the cylindrical journal bearing, the geometric orientation was not taken into account. The orientation shows in [11] and [12] an additional influence.

The standards do not define the effects of shape deviations of the bush geometry on the operating values of journal bearings. Therefore, a worst-case analysis is usually carried out for the application. This analysis assumes the form deviation and orientation, which reduces the lubrication gap height the most. For the application, the tolerance zone for the journal bearing is typically derived from the tolerance zone of the shaft from ISO 12129-2. The aim of this work is to eliminate uncertainties regarding the form deviation of journal bearings and to optimize the bearing geometry for operation. For this purpose, a best-case analysis is used to orient the form deviation in such a way that the largest possible lubrication gap height for the operating point is achieved. This work is an extension of the results obtained in [13] and [14].

2. State of the art

The investigations carried out so far show that form deviations have an influence on the operating values of the bearing. The form deviations are caused by inaccuracies in the manufacturing process.

For the practical application, a safe function of the journal bearing is necessary. During operation, it is necessary that some operating values such as the lubrication gap height, which represents the load-carrying capacity, do not fall below specific limit values. In order to guarantee a safe operation of the journal bearing, in any situation, it is required to cover any misalignment of the bearing form deviation that may occur as a result of the manufacturing or assembly process.

Usually, the manufacturing accuracy is therefore increased that a form deviation is kept at a minimum for operation. A misalignment of bearings with a larger form deviation can lead to the limit lubrication gap height being undercut. This means that the bearing operates permanently in the mixed friction area during operation. The wear in the bearing is greatly increased and a failure of the machine element is the consequence.

It is therefore important to keep the lubrication gap height as high as possible.

The problem results from the fact that form deviations must be defined more and more precisely in order to compensate errors in the production and mounting process. These more precise tolerance zones allow the required operating values to be maintained.

This lead to increased costs of the bearing manufacturing process. There is a lack of studies on acceptable form deviations and how the operating values can be ensured without selecting the tolerance zone of the form deviation too small.

ISO 12129-2 includes guidelines for defining form and position tolerances of thrust rings and shafts in journal bearing systems. For a hydrodynamic radial journal bearing made of shaft and bushing, the roundness, straightness and parallelism tolerances are especially critical.

These form deviations can be seen in Figure 1, with the corresponding symbols from the Geometrical Product Specification (GPS) System. The size of the form deviations is described in the figure for the roundness, straightness and parallelism deviation with the parameters t_1, t_2 and t_3.

These form deviations can result in different bearing geometries that deviate from an ideal cylindrical bearing geometry. Each of these geometries affects the convergent lubrication gap and thus the operating parameters compared to an ideal cylindrical bearing geometry. In addition, mixed forms can occur in which, for example, a roundness deviation with a straightness deviation creates a geometry.

In order to investigate the influence of form deviations on the operating values, this work will mainly focus on a roundness deviation (t_1).

The permissible form deviations for journal bearings are derived in this study from ISO 12129-2. However, these specifications only apply to thrust rings and shafts, but not specifically to bearing bushes.

Table 1 shows the acceptable deviation values of t_1, t_2 and t_3 for the form deviations as a function of the lubricating gap height according to ISO 12129-2. This information serves as an orientation for the investigation. The critical case of a lubrication gap height between 5 and 10 µm is assumed.

The exclusion of possible errors in manufacturing and mounting processes, such as a larger form deviation of the bearing running surface or an unfortunate mounting position of this form deviation, requires a larger cost input. By allowing a higher form deviation tolerance zone and a precise definition of the mounting position costs can be cut, but only with knowledge about the influence on the operating values. The aim of the work is to investigate the relationship between a specific form deviation on a journal bearing and its mounting position in order to obtain the best possible operating values.

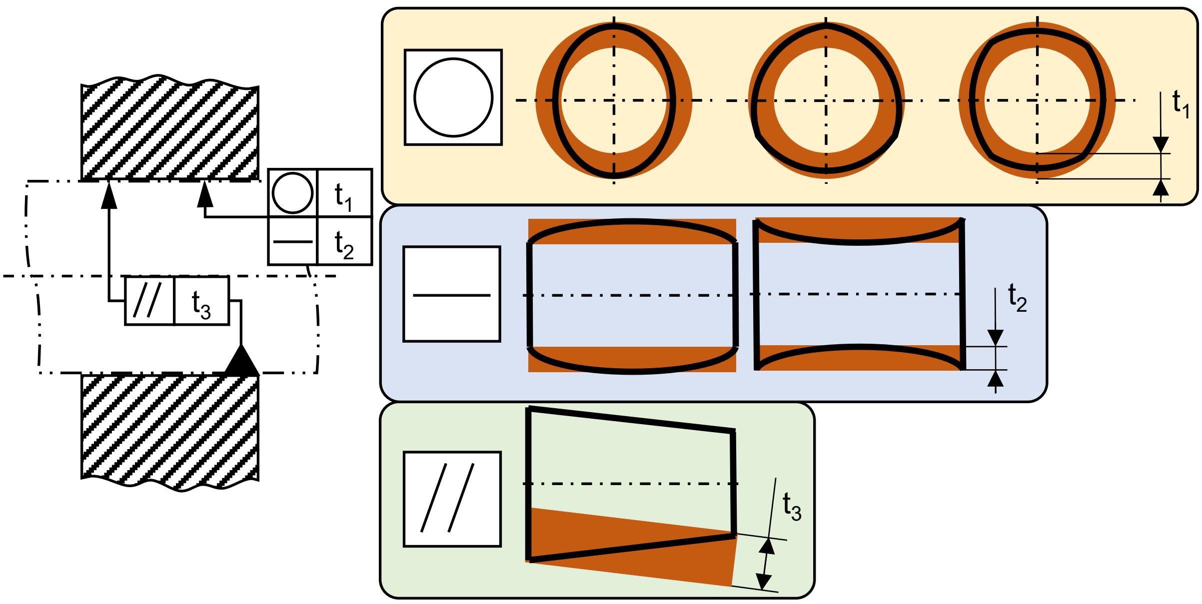

Figure 1: Resulting geometric shapes of journal bearings through form deviation

Table 1: Tolerance values according to ISO 12129-2 [1]

Feature / parameter on drawing			Accuracy grade			
			5	10	20	30
Lubrication film thickness		h_0 in µm	$5 \leq h_0 < 10$	$10 \leq h_0 < 20$	$20 \leq h_0 < 30$	$h_0 \geq 30$
Cylindrical form	Roundness tolerance	t_1 in mm	0,004	0,006	0,01	0,015
	Straightness tolerance	t_2 in mm	0,005	0,01	0,015	0,02
	Parallelism tolerance	t_3 in mm	0,015	0,02	0,03	0,04
Surface roughness		Ra in µm	0,4	0,4	0,63	0,8
		Rz in µm	2,5	4	5	6,3

In order to achieve these goals, a worst-case analysis is first carried out. This can determine how critical a large form deviation and an inaccurate mounting position can be. It is shown that the consideration is necessary, due to the significantly decreasing lubrication gap height.

Additional, a best-case investigation is carried out. This analysis proves that it is worth considering the orientation of the bearing for the operating parameters.

Nevertheless, it must be determined whether the best-case orientation is able to keep the lubrication gap height above a limit value.

Based on these results, the influence of the orientation on the lubrication gap height is investigated, to find a mounting positions, where a safe operation can be guaranteed, even if larger form deviation occurs. Thus, if the shape deviation is known, a mounting position could be defined, which generates a sufficient lubricating gap height even in case of slight angular errors in the mounting process and thus increases the service life of the bearing.

3. Simulation Set up

For the investigation of the roundness deviation a three-sided-lobe geometry is examined by means of simulations. This is one of the most common roundness deviations.

To describe the three-lobe bearing a H3 Polygon according to DIN 32711-1 [15] was used.

Object of investigation is a journal bearing with 30 mm diameter and a B/D-ratio of 0.5. The relative bearing clearance ψ is 2 ‰. The hydrodynamic simulations were carried out with the program ALP3T. A field of 256 points in circumferential direction and 34 points in axial direction describe the geometry of the journal bearing to be simulated, which is the maximum field size that is possible in the standard programme.

Thereby, the degree of deformation is varied. It is assumed, that the form deviation always occupies the maximum space within the tolerance zone. Figure 2 shows a three-sided-lobe shape in the tolerance zone defined by the value of the roundness deviation t_1. The dimension of the value t_1 describes the size of the tolerance zone. In the simulations, the tolerance zone was increased in 0.5 µm steps, starting at 0 µm.

In practical applications, production accuracy of 1µm is already very complex and associated with high costs. A finer definition of the tolerance zone with an accuracy of less than 1µm is economically useful for high-precision applications. For journal bearings, smaller accuracies can achieved with higher production costs. For a more precise resolution within the investigations, a step width of 0.5 µm was therefore chosen. For bearings with a diameter far greater than 30 mm or taller lubrication gap heights as assumed in this study (see Table 1) and used for standard applications, a lower resolution, e.g. in steps of 1 µm, can also be selected.

Additional, the shape orientation have to vary in the simulations. Therefore one peak point is the reference for the orientation. The start position is defined with a peak point along the load direction, the tilt angle φ is zero. The orientation is changed counterclockwise in 86 steps of 1.41° each, until the tilting angle reaches 120° (see Figure 2). Due to the three-sided-lobe geometry, the angular position of 120° corresponds to the geometry at the angular position of 0°.

The angular steps of the investigation are based on the resolution of ALP3T. A maximum of 256 points can be defined in the programme in the circumferential direction. So each field point represents, at a circumferential angle of 360°, an angle of about 1,41° $(360°/256 = 1{,}40625°)$. Since every 120° the shape of the same thickness is identical again, 86 steps $(120°/1{,}40652° = 85{,}333)$ are needed to examine each orientation of the bearing.

In the simulations, elastic or thermo-elastic deformations were neglected. The bearing bushing was therefore assumed to be rigid.

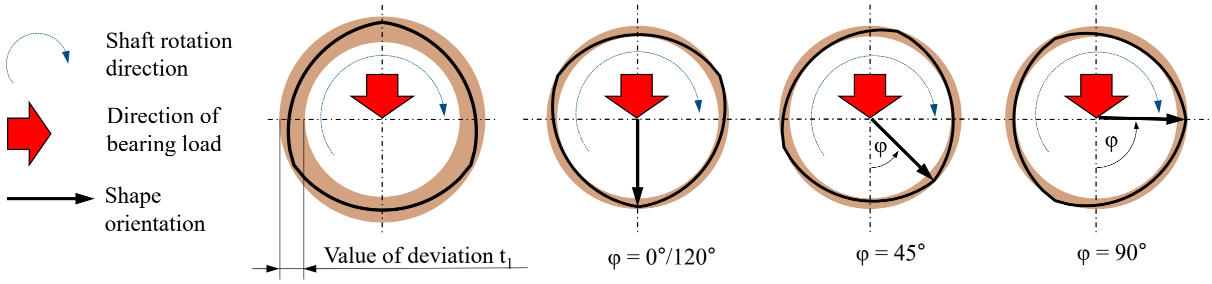

Figure 2: Value of deviation and orientation of the geometric shape

4. Simulations

In the first step of the methodical procedure, a worst-case analysis is carried out. The orientation of the respective form deviation is assumed, which reduces the lubrication gap height most. In the second step, a best-case analysis is carried out, in which the orientation is assumed to be the one that provides the largest lubrication gap height. In the third step, the lubrication gap height is then shown as a function of the angle of rotation for a specific operating condition.

The investigations concentrated on the minimum lubrication gap height. For the examined bearings with a bearing diameter of 30 mm, this is the critical parameter due to the lower relative speed.

Failure due to excessive local pressure occurs mainly in hydrodynamic operation. However, as long as no sufficient lubricating film can be formed, the bearing is still in the mixed friction area and the bearing load is additionally transmitted by the solid contacts between shaft and bushing. Therefore the lubricating gap height at this moment is more critical than the maximum local pressure, due to increased wear.

In comparison to bearings with larger diameters, smaller bearings have a higher heat dissipation, so that thermal failure is less frequent.

Due to the lower relative speed of bearings with smaller diameters, the load-carrying capacity of the bearing is lower, so that the lubrication gap height is in general smaller, compared to larger diameters. This means that there is a greater risk of driving in the critical area of mixed friction.

The influence of form deviation on parameters such as temperature, pressure and stiffness were therefore neglected.

The following results only applies to bearings with a diameter of 30 mm. The influence on the lubrication gap height is given as a percentage change to the lubrication gap height of an ideal cylindrical journal bearing.

4.1. Worst-Case analysis

Object of research is a lubrication gap height between 5 and 10 µm, as this is where wear is most likely to occur due to possible mixed friction. According to ISO 12129 - 2 the maximum allowed roundness tolerance value t_l is 4 µm. In the simulation, the roundness deviation is varied, while the straightness (t_2) and parallelism (t_3) deviations are neglected and kept at 0 µm.

The simulations were made with three different specific loads p of 0.9 MPa, 1.8 MPa and 2.7 MPa. Each specific load was simulated at five different speeds n, beginning from 2000 rpm to 10000 rpm, in steps of 2000 rpm. Figure 3 shows the minimum lubrication gap heights for a worst-case orientation for p equal to 0.9 MPa, 1.8 MPa and 2.7 MPa, for each value of t_l from 0 to 10 µm in steps of 0.5 µm.

The results in Figure 3 show, that a worst-case orientation of the form deviation can reduce the lubrication gap height by about 25 %, within the given tolerance zone of 4 µm of roundness deviation, according to the results for 2.7 MPa. At 1.8 MPa and 0.9 MPa and a roundness deviation of 4 µm the reduction of the lubricating gap height is still 20% of the original lubricating gap height of a cylindrical geometry.

With increasing roundness deviation over the given 4 µm, the minimum lubrication gap height decreases further. With a form deviation of more than 8 µm, the lubrication gap height of the bearing under investigation is less than 50% of the cylindrical reference bearing.

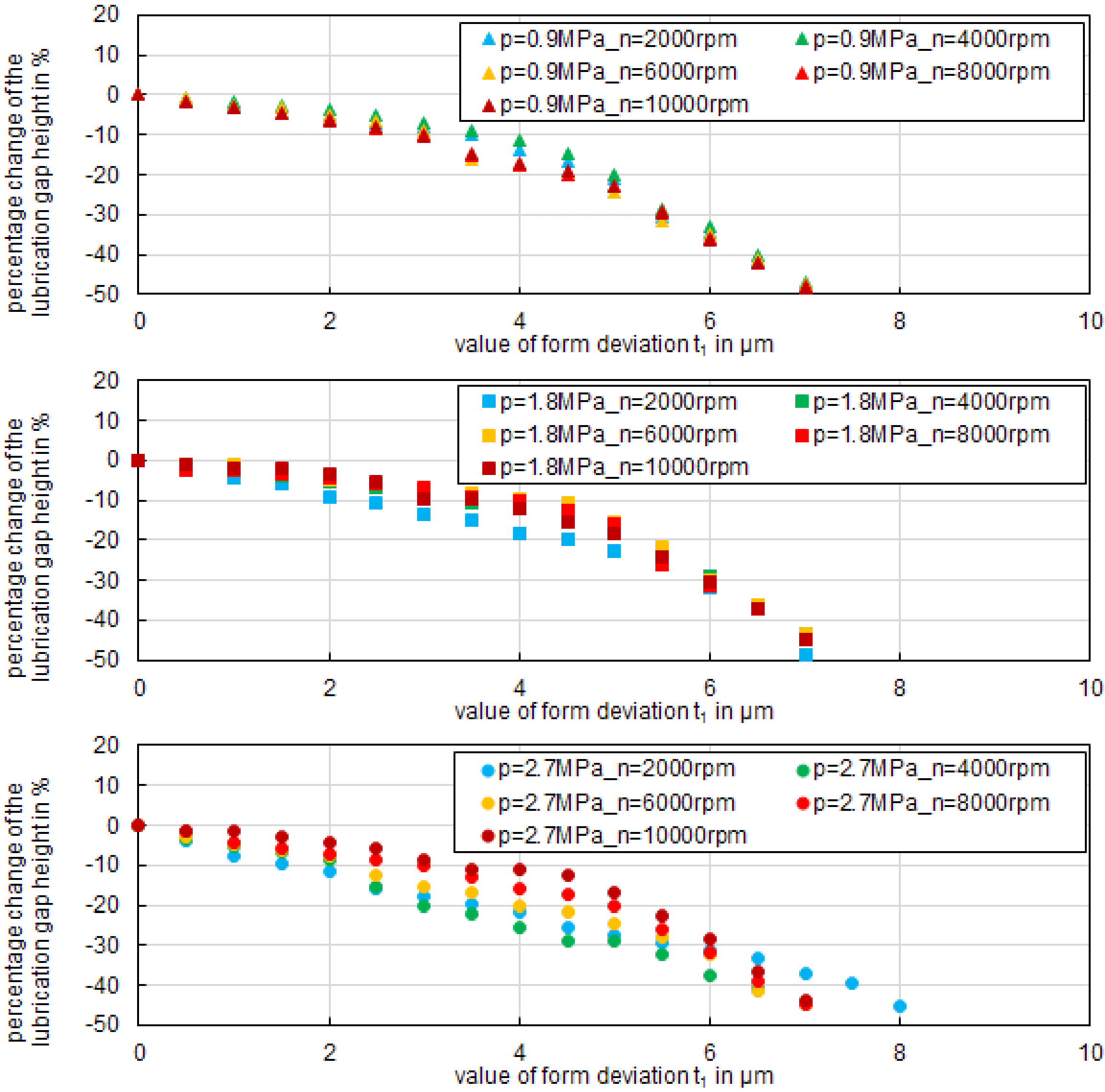

Figure 3: Minimum lubrication gap height of a three-sided-lobe bush at different form deviations in a worst-case orientation scenario for a journal bearing with diameter d=30 mm, wide-to-diameter ratio b/d=0.5 and a relative bearing clearance of ψ = 2 ‰

4.2. Best-Case analysis

Figure 4 shows the best-case analysis with the largest possible minimum lubrication gap heights. The shape deviation was again increased from 0 to 10 µm. For each value of the form deviation, the highest lubrication gap height was selected, which resulted from the best possible orientation of the bushing. A form deviation was aimed for in which the lubricating gap height in the best-case orientation achieves the same 25% reduction as shown in Figure 3 for 2.7 MPa in the worst-case analysis.

From the results, it can be seen that at 8 µm roundness deviation a reduction of 25% is achieved for the first time, with a best-case orientation at 2.7 MPa.

At 1.8 MPa and 0.9 MPa, the reduction at 8µm is about 20%, which is on the same level as in the worst-case analysis at 4µm.

Above a form deviation of 8 µm, the reduction of the lubrication gap height is lower due to the best-case orientation.

Furthermore, it is shown that the roundness deviation does not necessarily have a negative influence on the lubrication gap height. At slower speeds with small roundness deviations (of 0 to 4 µm) the best-case orientation can increase the lubrication gap height above the initial value. At higher speeds this is not the case. The positive effect of the form deviation is therefore not only dependent on the orientation but also on the operating point.

With the best-case orientation, the same lubrication gap heights can be assumed for a three-sided-lobe geometry and larger form deviations (of 8 µm) as in the worst-case analysis with smaller form deviations (of 4 µm).

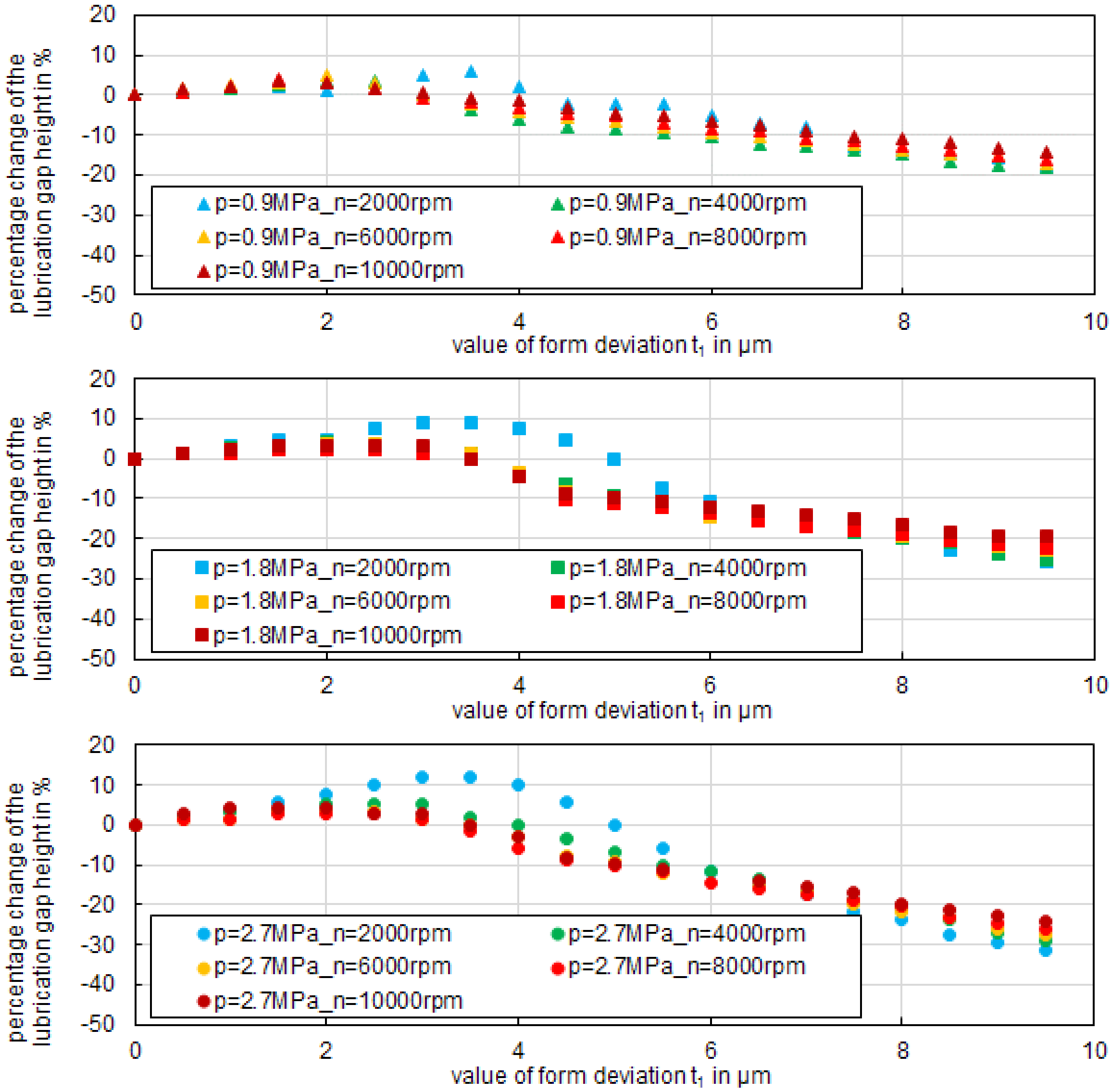

Figure 4: Minimum lubrication gap height of a three-sided-lobe bush at different form deviations in a best-case orientation scenario for a journal bearing with diameter d = 30 mm, wide-to-diameter ratio b/d = 0.5 and a relative bearing clearance of ψ = 2 ‰

4.3. Orientation analysis

The results of the worst-case and best-case analysis do not provide information about the orientation of the geometry. Therefore, Figure 5 shows the percentage changes of the lubrication gap height over the rotation angle φ for the three specific loads of p equal to 0.9 MPa, 1.8 MPa and 2.7 MPa for different form deviations t_1 at a speed n equal 2000 rpm each. Due to the amount of data, the load case with n equal 2000 rpm was chosen to be displayed in the diagram, as this case is the most critical due to the low rotational speed. In addition, only the form deviations of 0, 2, 4, 6 and 8 µm were displayed. The form deviation at 0 µm corresponds to the ideal cylindrical journal bearing.

It can be seen that with an installation angle of φ = 60° - 70° the greatest reduction of the lubricating gap height is achieved. This orientation therefore corresponds to the worst-case orientation. In this installation position, the lubricating gap height is significantly reduced and mixed friction is most likely to occur.

With a mounting position of φ = 30° - 50°, the smallest reduction in the lubricating gap height is shown with the form deviations of 6 to 8 µm. The installation area therefore shows the favorable conditions to ensure reliable operation at higher form deviation (6 to 8 µm). In this mounting position, the negative effect on the lubricating gap height can be reduced for higher form deviations.

With a form deviation of 2 to 4 µm, for this bearing geometry and the corresponding load, there is an improvement in the lubricating gap heights in a range from 0° - 10° and from 110° - 120°. The increase in the lubricating gap height is more noticeable with a higher bearing load. Even with higher form deviations (6 to 8 µm), the reduction of the minimum lubricating gap height is comparatively small in this angular range.

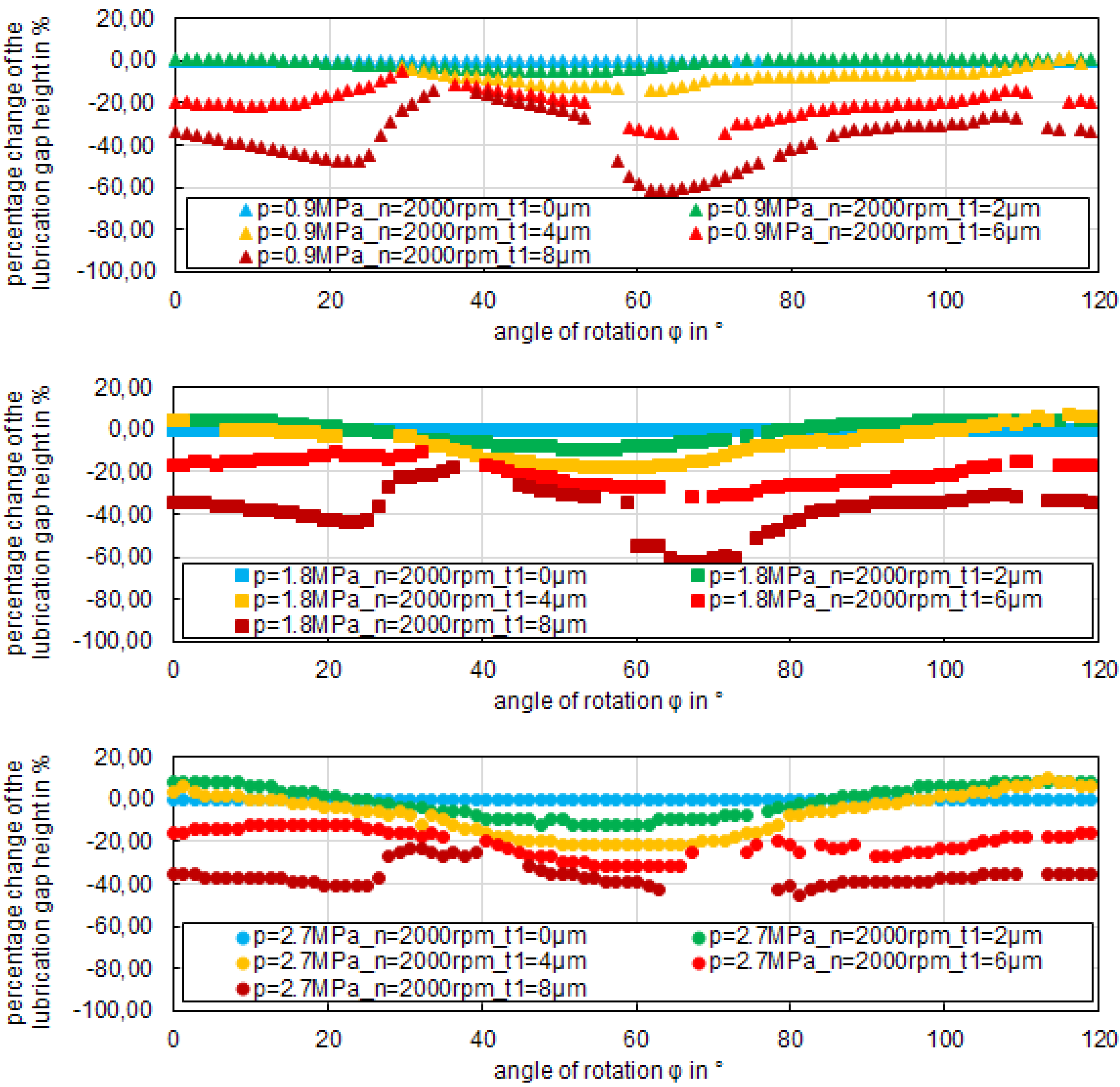

Figure 5: Minimum lubrication gap height of a three-sided-lobe bush at different form deviation values t_l at different rotation angles φ or a journal bearing with diameter d= 30 mm, wide-to-diameter ratio b/d = 0.5 and a relative bearing clearance of ψ = 2 ‰

5. Conclusions

If the form deviation of the bearing and its orientation is not known, the worst operating condition must be assumed, in which the minimum lubrication gap height is reduced the most. However, if the form deviation is known, the negative influence on the lubricating gap height can be reduced due to its orientation during the mounting process. With a suitable dimension of the form deviation, the lubricating gap height can even be improved compared to circular cylindrical bearing geometries.

Depending on the operating point considered, a best-case analysis can increase the minimum lubricating gap height of the bearings observed by up to 10% with the same utilisation of the tolerance.

Furthermore, in certain load cases, the tolerances from ISO 12129-2 can be extended to 200% (from 4 µm to 8 µm) with a constant lubricating gap height by changing from a worst-case to a best-case installation position.

The following conclusions can be derived from the work:

- Form deviations influence the lubrication gap geometry, whether they have a negative or positive effect on the operating conditions cannot be generally stated;
- Without precise knowledge of the type of form deviation and without knowledge of how the form deviation is oriented in the installation, it must be assumed to be negative;
- For a roundness deviation in the form of a three-sided-lobe shape, an orientation can be selected which improves or only slightly reduces the lubrication gap height.

At this point, it must be made clear that the results only apply to bearings with a bearing diameter of 30 mm, which also have a pure form deviation of a three-sided lobe.

Further investigations must show how other form deviations affect the operating values, like elliptical or multi-lobe roundness deviations, which do not necessarily come from a three-jaw chuck.

In addition, the influences of straightness and parallelism form deviations must be investigated and to what extent the combination of different form deviations can change these operating values.

In further investigations the influence on the operating values temperature and pressure must also be considered.

With the exact knowledge of the form deviation on the running surface of the journal bearing, an orientation can be selected which provides optimal operating conditions.

With a specific geometry in the micrometer range, which cannot be assigned to any conventional geometry, the operating values of the journal bearing can be improved compared to a cylindrical bearing. For this reason it is assumed that for each operating condition the bearing geometry would have to be specifically adapted in order to achieve optimum operating results.

Acknowledgment

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