Asymmetries in Planetary Touch-Down Bearings

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Abstract

For certain applications, magnetic bearings are preferred over rolling element bearings, for example, due to the absence of mechanical friction leading to high efficiency and low maintenance needs. However, they also require touch-down bearings (TDB) to bear thpe rotor in case of a malfunction or overload. For vertical systems with high DN numbers, like outer rotor flywheels, the design of the TDB becomes a challenging task. For such systems, the planetary TDB can be applied. The suitability of this design has already been shown in the literature (Quurck et al., 2017; Quurck et al., 2018). However, there are multiple parameters influencing the performance of the planetary TDB. For example, if an asymmetric planetary TDB should be preferred over a symmetric one, and if this is the case which asymmetries increase the performance of the planetary TDB. Therefore, this paper investigates asymmetries in planetary TDB in a simulation study performed with the Matlab-based simulation environment ANEAS. The results of this study indicate that the performance of planetary TDB can be increased when the air gap of the individual bearing units differs. If the air gap from one bearing unit is reduced by 20 % the maximum force acting on the TDB was reduced, in the best case up to 52 %.

Keywords: *touch-down bearing; backup bearing; safety bearing; drop-down; simulation*

1. Introduction

Magnetic bearings have many advantages over conventional bearings like no mechanical friction and lower maintenance needs; hence they are preferred for some applications. However, they always need a mechanical bearing that bears the rotor at standstill or in case of malfunction of the magnetic bearing. Conventional touch-down bearings (TDB) for inner rotor systems consist of plain or rolling element bearings with a slightly greater diameter than the rotor diameter. Hence, in normal operation, there is a gap between the rotor and the TDB. To prevent a destructive, friction-induced backward whirling of the rotor in the TDB, rolling element bearings are preferred especially for vertical systems. If the product of the diameter and the rotational speed (DN number) reaches high values, conventional rolling element bearings can no longer be used, because the bearings cannot withstand the high centrifugal forces under rotation. Such high DN numbers are reached for example in outer rotor flywheels, where the rotor is a hollow cylinder mainly made of fiber-reinforced plastic. For such systems with high DN numbers (Penfield JR. and Rodwell, 2000) proposed using the planetary TDB. Similar designs are given in (Fonseca, et al., 2015) and (Lahriri and Santos, 2013). In the planetary TDB proposed by (Quurck et al., 2017), which is also the design under investigation in this paper, multiple small bearing units are distributed circumferentially around the stator. Figure 1 shows on the left a partial section view of a planetary TDB. Each TDB unit consists of a roller that gets in contact with the rotor in case of a drop-down and two rolling element bearings on the upper and lower end of the roller. The right of Figure 1 shows a schematic representation of the clearance of the planetary TDB and how it arises. The clearance of the planetary TDB is polygonal shaped and the number of corners depends on the number of TDB units in the planetary TDB. The boundary of the clearance is defined by the herpolhodes of the rotor rolling on the different TDB units.

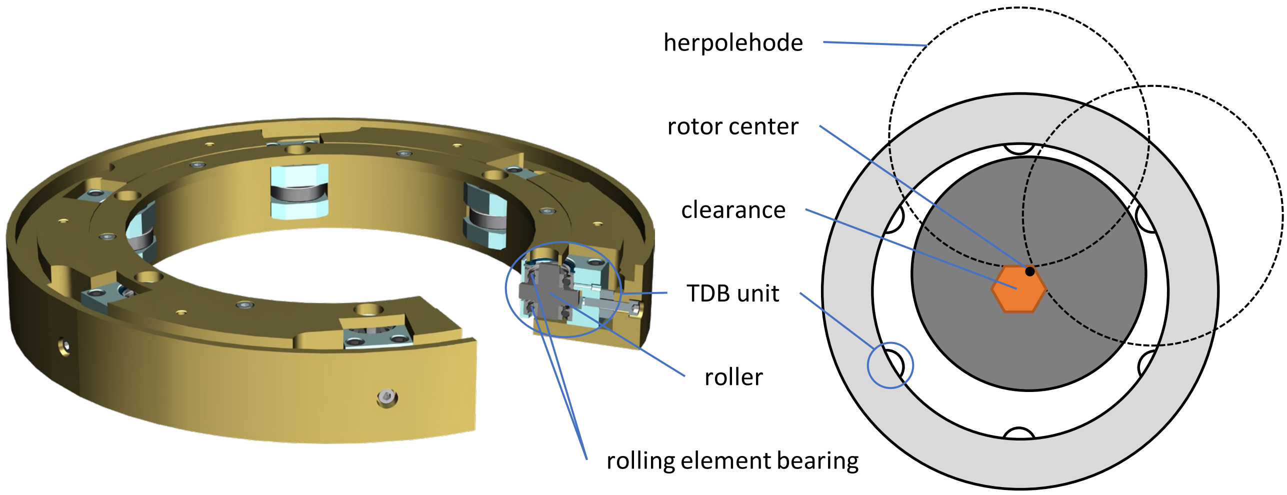

Figure 1 Left: planetary TDB of the TDB test rig with partial section of one TDB unit; right: schematic top view on planetary TDB with clearance of the rotor in the planetary TDB (not true to scale)

The advantage of the planetary TDB design is, that the rolling element bearing diameter is decoupled from the rotor diameter and hence, the planetary TDB is suited for high DN numbers. A further advantage is a whirl suppressing characteristic of the planetary TDB, which is shown with plain bearings in (Lahriri and Santos, 2013) and with rolling element bearings in (Schüßler et al., 2022). However, the rolling element bearings in the planetary TDB units are comparatively small to the overall system, which is why the forces may exceed the static load rating of the bearing. Hence, the planetary TDB must be carefully designed to withstand multiple drop-downs. In literature, the influence of different designs on the TDB loads is rarely investigated. Only a few guidelines are given on how the planetary TDB should be designed. For example, in (Simon, 2002) and (Schüßler et al., 2022) the number of elements in a planetary-like arrangement is investigated both in simulations and in experiments. In (Zülow and Liebich, 2009) a further planetary design is investigated theoretically for a horizontal rotor system. The investigated TDB configurations contain even a geometrically asymmetrical TDB design. The results show that the rotor run-out in the bottom of the clearance in the asymmetric configuration is more unsteady and therefore not preferred for the investigated horizontal system. In comparison to the investigations in the literature, this paper focuses on vertical systems. In addition, it investigates further asymmetries and analyses how they affect the TDB loads.

2. Method

The investigation of different asymmetries in planetary TDB is performed as a simulation study. The system chosen for the modeling and consequently for the investigation is the TDB test rig, with which multiple drop-down experiments for symmetric planetary TDB have already been performed (Quurck et al., 2018; Quurck, 2019). The principal behavior of these drop-down experiments at the TDB test rig can already be simulated with the MATLAB-based simulation tool ANEAS (Quurck, 2019). Due to this validation, this simulation tool is used for the present investigation, too. A short overview of the simulation software ANEAS is given and essential ideas of the modeling are shown. Afterward, two severity indicators are introduced, to compare the different simulation results of the conducted investigation. Figure 2 shows an overview of the asymmetries investigated in simulations. These asymmetries can either be geometric or they can be asymmetries in the stiffness and damping between the different TDB units.

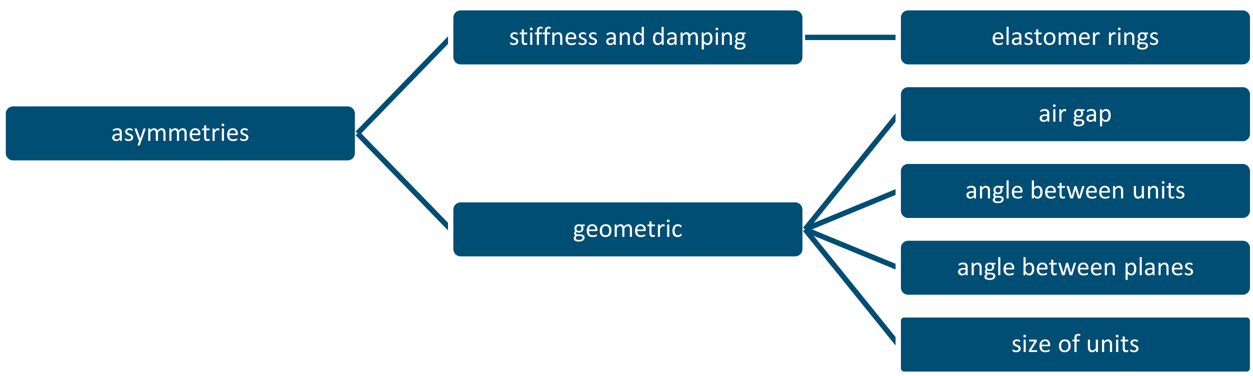

Figure 2 Investigated asymmetries.

In the real TDB, there are different possibilities to vary the stiffness and damping, one is the use of elastomer rings (ER). As shown by (Schüßler et al., 2021) the effectiveness of the elastomer rings is heavily influenced by their properties: on the one hand by the material on the other hand by the geometric properties. Hence, the investigation in this paper is based on the modeling and the results in (Schüßler et al., 2021). Based on this previous investigation the model parameters of fluorocarbon rubber (FKM) are used for the modeling of the elastomer rings. The geometric asymmetries are the size of the air gap, the distance or angle between the different TDB units around the stator, the angle between the two polygonal-shaped clearances of the two TDB planes, and the size of the TDB units. Figure 3 shows, how the different geometric asymmetries affect the TDB clearance.

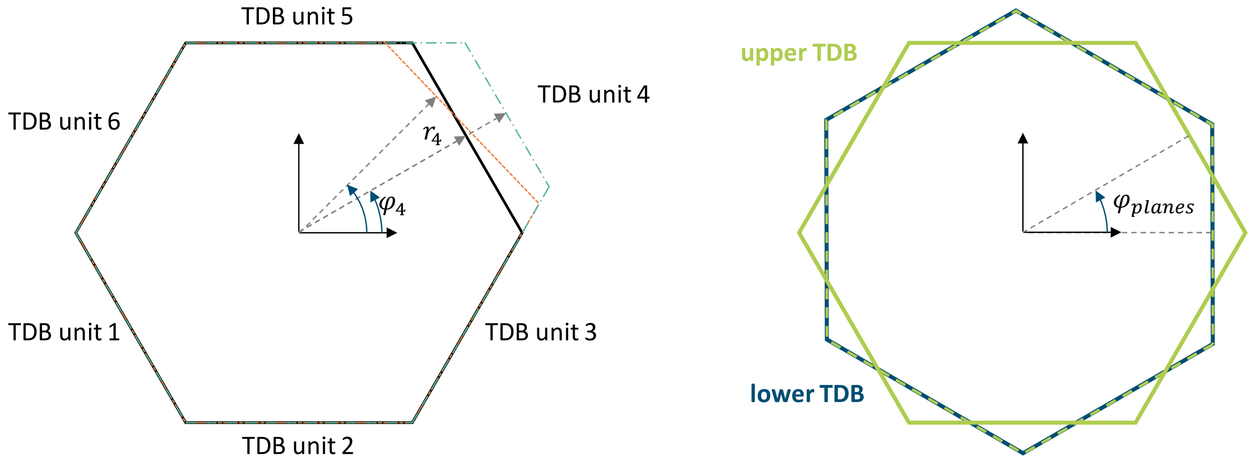

Figure 3 Change of the clearance of the planetary TDB resulting from the different asymmetries. Left: change due to air gap (cyan dashed-dotted line) and angle between TDB units (orange dashed line); Right: change due to angle between TDB planes (green: changed clearance of upper TDB plane compared to blue lower TDB plane)

The size of the TDB units affects the TDB clearance only slightly. The clearance boundaries are based on the herpolhodes of the rotor rolling on the TDB units as it is shown in Figure 1. If the size of the roller is changed, also the radius of the herpolehode changes, and hence, the clearance boundary changes as well. However, the radius is much bigger than the clearance. Therefore, the change of curvature is not seen in the clearance if the size of the roller is changed in a physically reasonable range.

In this investigation, simulations were conducted for TDB with 3, 4, 5, and 6 TDB units per TDB plane. A higher number of TDB units were investigated, neither for symmetric TDB nor for asymmetric TDB because it was shown in (Schüßler et al., 2022), that 6 TDB units are preferred over 8 TDB units. The investigation of asymmetries was conducted in two steps. First, the single simulations were conducted for a broad range of asymmetries to investigate the influence of the asymmetries in principle. Afterward, the promising asymmetries were deeper investigated in a parameter study, in which for the same asymmetry the simulation was conducted six times with different model parameters. In this way, a profound decision on the asymmetries is found.

3. Modeling

The simulation study is based on the simulation environment ANEAS. The software was originally developed by (Orth and Nordmann, 2002) for the investigation of magnetically levitated magnetic bearing systems, especially for the case of drop-down simulations in conventional TDB. Later it was extended by (Quurck et al., 2017) for simulating drop-downs in symmetric planetary TDB, too. In the present investigation, the model was adjusted for asymmetric planetary TDB. The model in ANEAS is based on the equations of motion for the rotor and the stator, which are coupled by the contact forces in case of a drop-down. The rotor and stator models are finite element models based on Timoshenko beam elements. The behavior in the axial direction is not modeled, in the investigated drop-downs only the radial contact and movements are of interest. The general equation of motion for the rotor and stator model is shown in (1). The systems are described by the rotational speed Ω, the mass matrix $\boldsymbol{M}$, the matrixes for the inner and outer damping $\boldsymbol{D}_{in}$, $\boldsymbol{D}_{in}$ and $\boldsymbol{D}_{out}$, the gyroscopic matrix $\Omega\,\boldsymbol{G}$ and the stiffness matrix $\boldsymbol{K}$. The displacements and tilting angles are described by $\boldsymbol{q}$. The external force vector $\boldsymbol{f}$ on the right side of the equation of motion contains for example the contact forces.

$$\boldsymbol{M}\,\ddot{\boldsymbol{q}} + (\boldsymbol{D}_{out} + \boldsymbol{D}_{in} + \Omega\,\boldsymbol{G})\,\dot{\boldsymbol{q}} + (\boldsymbol{K} + \Omega\,\boldsymbol{D}_{in}^{*})\,\boldsymbol{q} = \boldsymbol{f} \quad (1)$$

For the stator, this general equation of motion is simplified since the axial rotational degree of freedom is neglected, and hence, no gyroscopic effects occur. Because a drop-down in the TDB is a contact problem, the system is nonlinear.

Due to this nonlinearity, the right side of the model has to be evaluated in every time step of the time domain based simulation in ANEAS.

4. Severity Indicators

To compare the different drop-down simulations with each other, severity indicators are used. For planetary TDB the maximum normal force during the drop-down is of high relevance. Because of the small rolling element bearings in the TDB, the maximum force is likely in the range of their static load rating. Hence, one short-term contact can damage the bearing permanently. As a result, the first severity indicator chosen for the evaluation is the static safety S_o as shown in (2). The maximum normal force during the drop-down is expressed by $F_{N,max}$ while $P_{TDB,0}$ is the static load rating of the TDB unit.

$$S_o = \frac{F_{N,max}}{P_{TDB,0}} \quad (2)$$

The second severity indicator used for the evaluation is the bearing service life of the TDB. The TDB consists of multiple TDB units. The service life entire system is the lowest bearing service life of all TDB units $L_{10,h,min}$. The service life of one TDB unit $L_{10,h}$ is calculated according to (3) based on ISO 281 and (Wittel et al., 2009). C is the dynamic load rating of the TDB unit, P_m the average bearing load and n_m the average bearing speed. Neither the bearing load nor the bearing speed are constant during a drop-down and varies in a broad range. The effective values of these are calculated by weighted averaging of bearing speed n and normal force F_N for each time step i. The final time step of the simulation is denoted as ts and the proportion a time step has on the whole simulation time is denoted by a_i. The normal force acting on the TDB unit F_N is divided by the factor of two, because it is assumed that the force is distributed equally on two bearings (see Figure 1).

$$L_{10,h} = \frac{10^6}{60\, n_m}\left(\frac{C}{P_m}\right)^3 \quad \text{with} \quad P_m = \sqrt[3]{\frac{\sum_{i=1}^{ts} a_i n_i \left(\frac{F_{N,i}}{2}\right)^3}{n_m}} \quad \text{and} \quad n_m = \sum_{i=1}^{ts} a_i\, n_i \quad (3)$$

With this second severity indicator, the whole drop-down is taken into account, compared to the first severity indicator S_o where only a single value of a drop-down is considered.

5. Results

The basis for comparing the influence and the benefit of the asymmetries are simulations of symmetric configurations with 4, 5, or 6 bearing units in the TDB. These simulations are conducted without and with ER on all TDB units. These simulations are then compared to simulations where one asymmetry is introduced. When comparing severity indicators of symmetric and asymmetric concepts, the following results are obtained:

- If the angle between the TDB units is changed such that some units are closer to each other, and some are further away from each other, S_o is increased, especially for a high number of TDB units. However, $L_{10,h,min}$ is decreased because the bearing service life of individual bearings becomes lower.
- The second investigated asymmetry is a change in the air gap for individual bearings such that some bearings have greater and others have a smaller air gap to the rotor. In general, the results are similar to the results for the asymmetric angle between the bearing units. For air gap asymmetries $L_{10,h,min}$ varies only slightly, whereas the S_o is increased for all simulations with 5 or 6 bearing units.
- If the stiffness of the individual TDB units within the TDBs is changed, no improvement in S_o and $L_{10,h,min}$ occurs compared to the simulations where all bearing units have the same stiffness.
- Different stiffnesses in the lower and upper TDB plane lead neither to an improvement in $L_{10,h,min}$ nor in S_o.
- If the upper and lower bearing plane a rotated to each other by half of the angle between the TDB units $L_{10,h,min}$ decreases slightly, whereas S_o is increased for 4 and 5 TDB units without ER. Figure 4 shows the results for this asymmetry based on the two severity indicators.
- It was also investigated if it is reasonable to replace the highest loaded bearing unit in the TDB with a bigger one, which has a higher static and dynamic load rating. This led to the result, that another bearing unit in

the TDB became the highest loaded one. Finally, the highest S_o and $L_{10,h,min}$ are reached, if all bearing units are replaced by bigger ones.

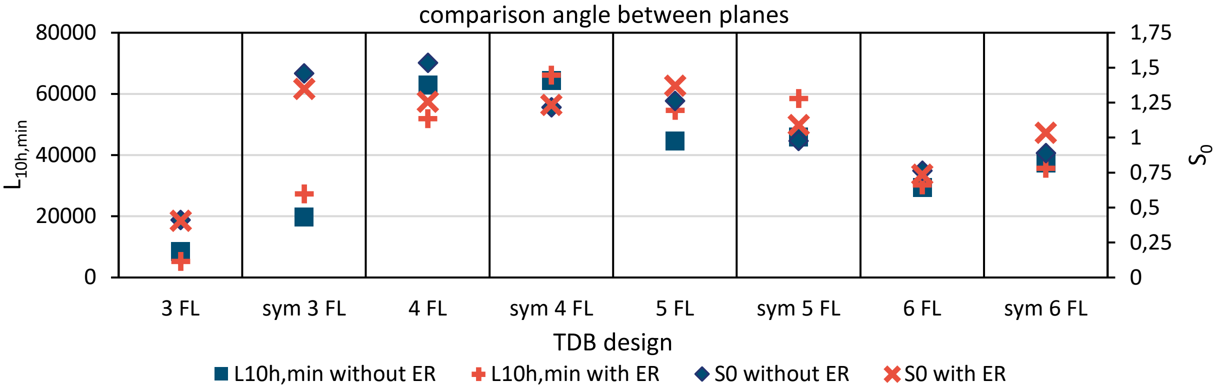

Figure 4 Results for the asymmetry "angle between planes"; one TDB plane is rotated by half of the angle between the individual TDB units

Based on these findings a parameter study with the most promising asymmetry has been performed. In the parameter study, three parameters have been varied between two values: the initial rotor speed (15,000 rpm; 20,000 rpm), the start direction towards the clearance boundary (+30 °; -30 °), and the coefficient of restitution influencing the contact damping (0.6; 0.8). A positive angle for the start direction leads to a first contact of the rotor with the TDB in the direction of a backward whirl, while a negative angle leads to a contact in the direction of a forward whirl. All combinations of these three parameters have been simulated in the parameter study. Hence, 8 simulations have been performed for all investigated TDB configurations. As a result of the first step of the simulative investigation, it was found that the highest values for the two severity indicators are reached, if all bearings are replaced by bigger ones. Therefore, in the parameter study bigger bearings of type HY S 6201 are used. This is the maximum bearing size, which can be mounted in the available assembly space in the TDB test rig.

The asymmetry selected for further investigation is the asymmetry, where in a 5-unit TDB the air gap at one TDB unit is reduced by 20 %. The results for this configuration are compared to the best symmetric case. In (Schüßler et al., 2021) it was shown that ER reduce the forces on the TDB and increase the bearing service life for a TDB with 6 TDB units. The first step of this investigation showed that the forces are even lower in a TDB with 4 TDB units with ER than in a system with 6 TDB units with ER. Therefore, the best symmetric case is the TDB with 4 TDB units and ER. Figure 5 shows the simulation results of the best symmetric configuration compared with the ones of the best asymmetric configuration. In every simulation S_o is higher for the asymmetric configuration, hence the maximum normal forces are lower in the asymmetric configuration. The calculated $L_{10h,min}$ is in the same range for the symmetric and the asymmetric configurations with the tendency to reach higher values for the asymmetric configuration.

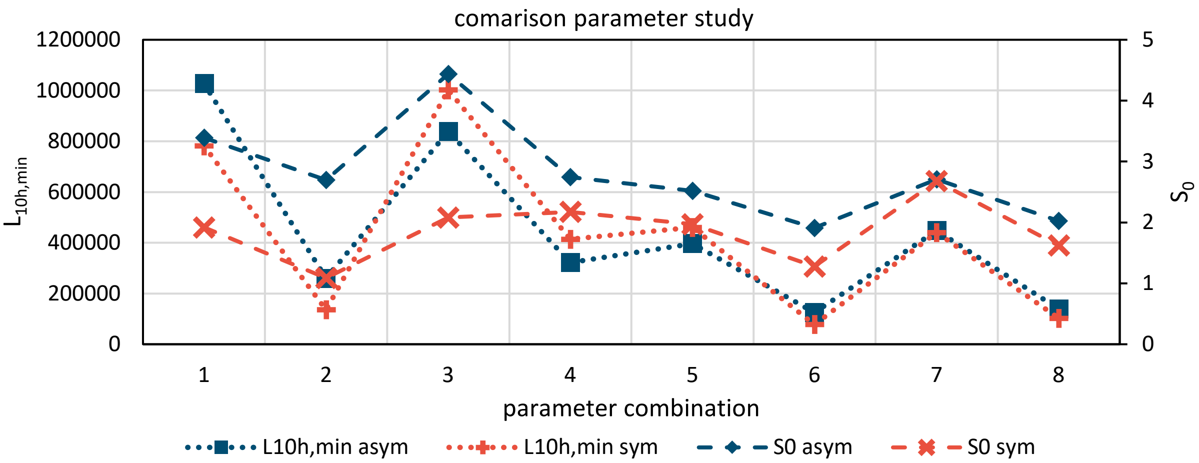

Figure 5 results of the parameter study for the severity indicators for the chosen symmetric configuration (red) in comparison to the investigated asymmetric configuration (blue)

In summary, it can be concluded that by using asymmetries the maximal forces on the TDB can be reduced significantly. For the investigated case in the parameter study, an average reduction in S_o of 52% was reached, whereas $L_{10,h,min}$ was only increased by 16%. Consequently, asymmetries can be considered in the design of planetary TDB to increase the performance of the TDB.

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