Passive Tilt Bearings with Zero Translational Stiffness Composed of Two Permanent Magnet Rings

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Abstract.: This paper deals with the computation of the axial, radial and tilt stiffness of two concentric permanent magnetic rings with axial polarization. Such compositions normally correspond to either radial or axial passive magnetic bearings. In contrast to the translational degrees of freedom this paper focuses on therotational and therefore passive tilting stiffness of such systems. An important result is the exact relative position of the concentric rings for which the radial and axial stiffness is zero and the tilt stiffness is positive. Thus, such a configuration represents a pure passive magnetic tilt bearing.

Keywords: Passive Magnetic Bearing, Tilt Bearing, Permanent Magnetrings

1 Introduction

Passive magnetic bearings for stabilization of radial or axial degrees of freedom are well known and investigated. This originates in the fact that passive magnetic suspension offers various advantages. Theses systems need no power, are extremely reliable and have a long lifetime. Unfortunately theses systems lack damping and are therefore prone to disturbances and resonance effects. However, due to Earnshaw’s theorem [1]

$$2\,k_r + k_z = 0\,, \tag{1}$$

where k_r is the radial stiffness and k_z represents the axial stiffness, it is not possible to stabilize a stationary body in all degrees of freedom merely by the utilization of permanent magnets. It is a matter of common knowledge, that either an axial or a radial bearing can be realized by the help of permanent magnet rings [2]. In both cases, attractive and repulsive compositions are possible. Nowadays these passive ring bearing are utilized in various applications like flywheels, artificial hearts or spinning machines [3-5]. Due to easier manufacturing of the permanent magnets nearly at all times the simple axial magnetization is used instead of the radial magnetization. However, in most cases the tilt of the rotor is stabilized by the fact that two axially displaced bearing positions are present. This leads to the need of increased axial constructional depth. However, this paper investigates magnetic two-ring-compositions that do not create any radial and axial stiffness but only positive tilt stiffness. Thus, it is possible to boost the tilt stiffness of a system without changing any other stiffness parameters of the configuration. This approach can be favorable in bearingless drives (especially the bearingless slice motor) and in flat and compact magnetic levitated devices.

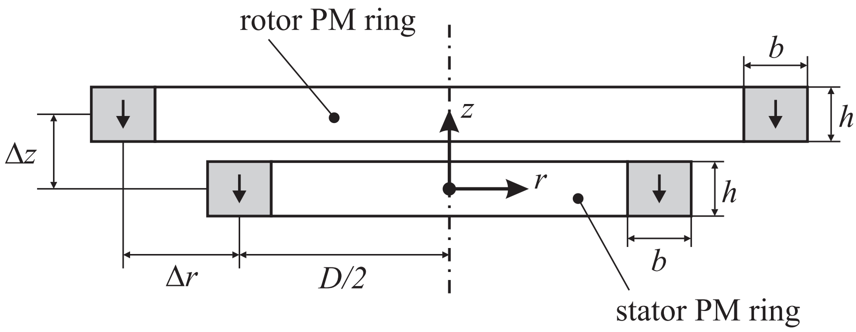

Figure 1: Cross-section of the considered two concentric permanent magnet rings.

2 Considered Magnetic Ring Configurations

In this work systems consisting of two concentric magnetic rings are investigated. It is presumed that both magnetic rings have congruent cross sections. The remaining parameters (the mean stator ring diameter D, the axial magnet height h, the radial magnet breadth b, the difference of the mean ring diameters Δr, and the axial rotor ring displacement Δz) are illustrated in Fig. 1 and can be chosen freely.

Scaling Rules. The resulting axial force and stiffnesses of such a composition are functions of the permanent magnets remanence flux density B_r and of the geometry. The remanence flux density features a quadratic dependency, therefore

$$F_z^{PM}, s_r^{PM}, s_z^{PM}, s_{\varphi r}^{PM}, s_{\varphi\varphi}^{PM} = B_r^{\,2} \cdot f\left(D, b, h, \Delta z, \Delta r\right) \tag{2}$$

holds true. It is obvious that due to the rotational symmetry the radial force disappears.
Additionally, there exist scaling rules between two geometrically similar permanent magnetic ring bearings [6]. Using the scaling factor S ($S = 0.5$ represents a downsizing to one half and $S = 2$ a duplication of the geometric sizes) Table I gives the changes of the force and stiffnesses for this case. The left column also takes into account the specific value (related to the volume V_{PM} of the tow magnets).

Table I: Scaling rules for geometrically similar permanent magnetic bearings.

Force/Stiffness	Change in the absolute value	Change in the specific value
Axial force	$F_z^{PM} \sim S^2$	$\frac{F_z^{PM}}{V_{PM}} \sim \frac{1}{S}$
Axial stiffness	$s_z^{PM} \sim S$	$\frac{s_z^{PM}}{V_{PM}} \sim \frac{1}{S^2}$
Radial stiffness	$s_r^{PM} \sim S$	$\frac{s_r^{PM}}{V_{PM}} \sim \frac{1}{S^2}$
Tilting stiffness	$s_\varphi^{PM} \sim S^3$	$\frac{s_\varphi^{PM}}{V_{PM}} \sim 1$
Coupling stiffness	$s_{\varphi r}^{PM} \sim S^2$	$\frac{s_{\varphi r}^{PM}}{V_{PM}} \sim \frac{1}{S}$

Utilizing the scaling rules it is possible to simplify the effect of the geometric parameters on the considered values. For the axial force the scaling law is quadratic and yields

$$F_z^{PM} \cdot S^2 = B_r^{\,2} \cdot f_{F_z^{PM}} \left(S \cdot D, S \cdot b, S \cdot h, S \cdot \Delta z, S \cdot \Delta r \right). \tag{3}$$

In the same manner

$$s_\varphi^{PM} \cdot S^3 = B_r^{\,2} \cdot f_{s_\varphi^{PM}} \left(S \cdot D, S \cdot b, S \cdot h, S \cdot \Delta z, S \cdot \Delta r \right) \tag{4}$$

holds true for the tilt stiffness.

Standardization. The choice of the specific scaling factor

$$S = \frac{1}{D} \tag{5}$$

leads to the following possibility to describe the axial force

$$\frac{F_z^{PM}}{b\,D} \frac{1}{B_r^{\,2}} = f_{F_z^{PM}} \left(\frac{b}{D}, \frac{h}{D}, \frac{\Delta z}{D}, \frac{\Delta r}{D} \right) \Big/ \frac{b}{D} = f_{F_z^{PM}}{}^{*} \left(\cancel{\frac{b}{D}}, \frac{b}{h}, \frac{\Delta z}{h}, \frac{\Delta r}{b} \right) \tag{6}$$

and the tilt stiffness

$$\frac{s_\varphi^{PM}}{b\,D^2} \frac{1}{B_r^{\,2}} = f_{s_\varphi^{PM}} \left(\frac{b}{D}, \frac{h}{D}, \frac{\Delta z}{D}, \frac{\Delta r}{D} \right) \Big/ \frac{b}{D} = f_{s_\varphi^{PM}}{}^{*} \left(\cancel{\frac{b}{D}}, \frac{b}{h}, \frac{\Delta z}{h}, \frac{\Delta r}{b} \right) \tag{7}$$

Thus, by the help of standardization one parameter can be saved in the computation. This can be seen when the number of parameters in (3) and (6) are compared. Additionally, for technical relevant cases the normalized magnet breadth b/D is small and has only weak influence in the standardized functions $f_{s_\varphi^{PM}}{}^{*}$ and $f_{F_z^{PM}}{}^{*}$. Therefore this parameter is negligible as indicated in the equations.

3 Passive Stiffness and Axial Force Computation

Modeling the permanent magnet rings by proper current sheets allows computing the axial force as well as the axial and radial stiffness of the compositions illustrated in Fig. 1 [6-8].

Due to the fact that the determination of the tilt stiffness of such magnetic ring configurations is more complex, it is often simply derived from their axial or radial stiffnesses using certain additional approximations [7, 9]. As a matter of fact, this would lead to the assumption that there is no tilt stiffness without a coexisting radial or axial stiffness. However, this conclusion is not exactly true.

The accurate computation of the tilt stiffness from the magnetic field can be found in [10] and was implemented in a numerical computer algebra program in course of [11], allowing to study the behavior of permanent magnet rings quite conveniently in an automated analytical way. The only assumption that was made in this concept is the permeability of the magnets to be that of air. Apart from this approximation the computation is fully accurate, no further analytical presumptions are needed. Fig. 2 depicts a simulation run for fixed D, b, h and Δz under the variation of Δr. It is visible, that there is tilt stiffness at the zero-crossings of the radial stiffness.

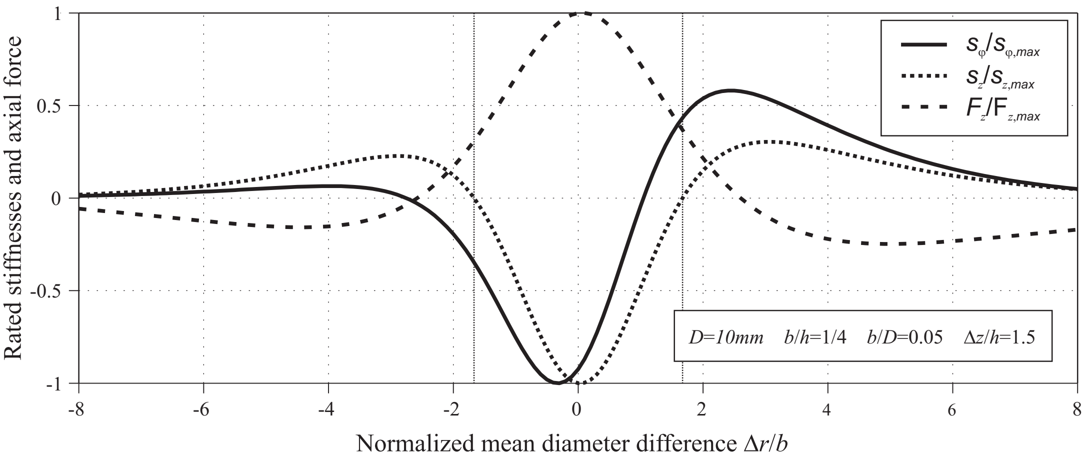

Figure 2: Exemplarily computed curve progression of the axial force, the axial and the tilt stiffness. Positions with zero axial stiffness are marked. The right mark (stable s_φ>0) denotes a tilt bearing.

4 Passive Tilt Bearings

This section presents possible passive tilt bearing configurations without any additional translational stiffness. The first section deals with the applicable geometric properties, the second section gives the associated producible tilt stiffness and axial force.

Principal Tilt Bearing Compositions. All permanent magnetic ring bearings that show no axial and thus also no radial stiffness are depicted in a 2D-plot, which is visible in Fig. 3. The plot features the mutual location of the two permanent magnet rings (described by Δr and Δz in Fig. 1) for all possible tilt bearings in dependence of b/h. Each line represents feasible configurations for the labeled fixed b/h relation. As a matter of fact the graph is symmetric around the *r*-axis. To ease the understanding the location of the fixed stator PM ring is depicted. Additionally there is a restricted area for $|\Delta r/b|<1$ and $|\Delta z/h|<1$ because in these cases a geometric overlapping of the magnet rings occurs. It is visible from the graph that there is the possibility to create a tilt bearing with a rotor ring that has a smaller diameter ($\Delta r<0$) and a rotor ring that has a

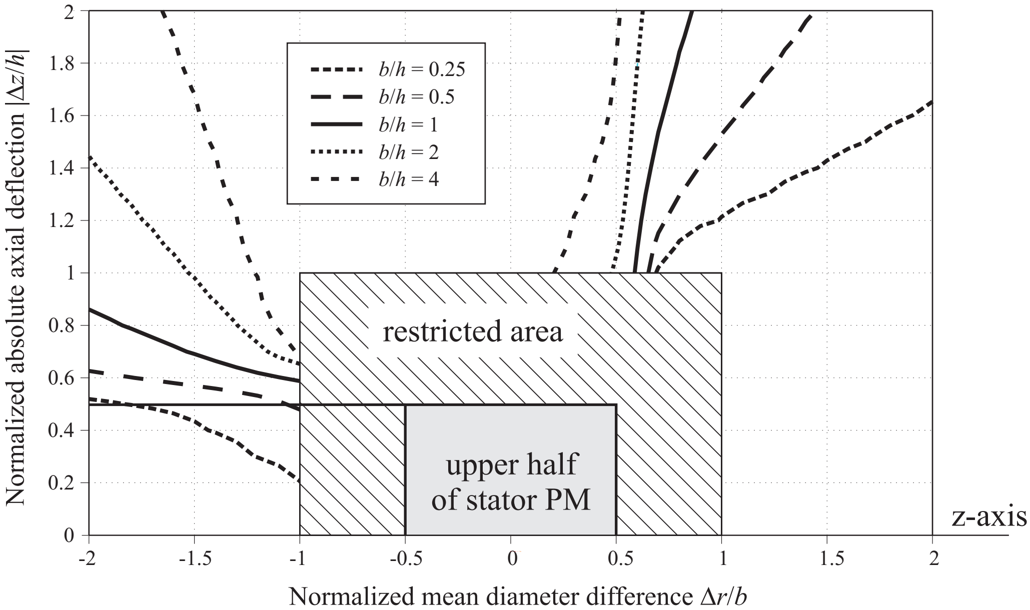

Figure 3: General geometric composition of passive two ring permanent magnetic tilt bearings without additional radial and axial stiffness (computed for $b/D \rightarrow 0$).

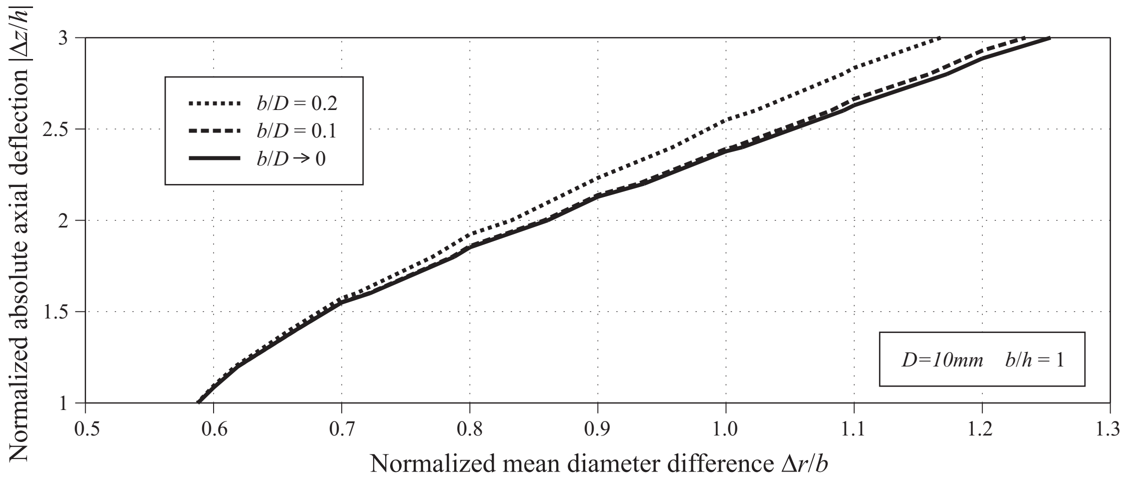

Figure 4: Comparison of the computation results for different b/D relations.

bigger diameter (Δr>0) in comparison to the stator permanent magnet ring.
However, as mentioned above in Fig. 3 the mean stator ring diameter D can be seen as mere scaling factor and has therefore no influence on the position where the translational stiffnesses vanish. Furthermore it was noticed that the relation b to D is normally small and has only weak impact on the computation. The latter fact is shown in Fig. 4. There is only a small noticeable effect in the characteristics when the chosen b to D relation becomes quite large.

Tilt Stiffness and Axial Force. As described, Fig. 3 shows the principal possible magnet ring compositions for passive tilt bearings without any additional axial and radial stiffness. The actual values of the standardized tilt stiffness and the standardized axial force can be obtained from Fig. 5 and Fig. 6.
To compute the actual tilt stiffness and the actual axial force, the standardized values $f_{s_\varphi^{PM}}{}^{*}$ and $f_{F_z^{PM}}{}^{*}$ from the graphs have to be applied to (6) and (7) respectively.

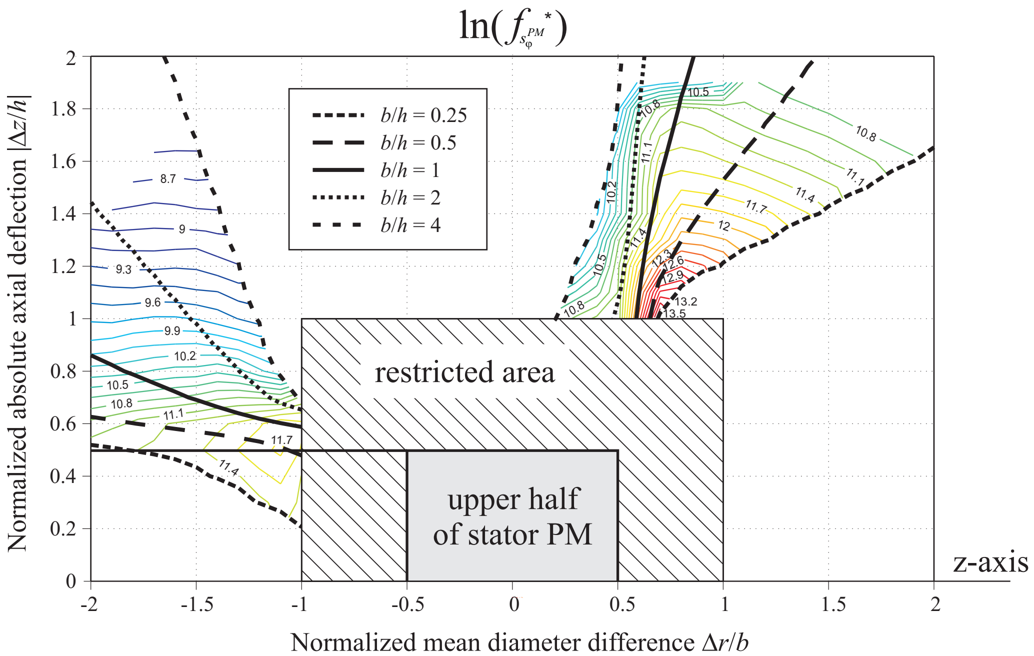

Figure 5: Standardized tilt stiffness of the permanent magnetic tilt bearing (computed for $b/D \rightarrow 0$).

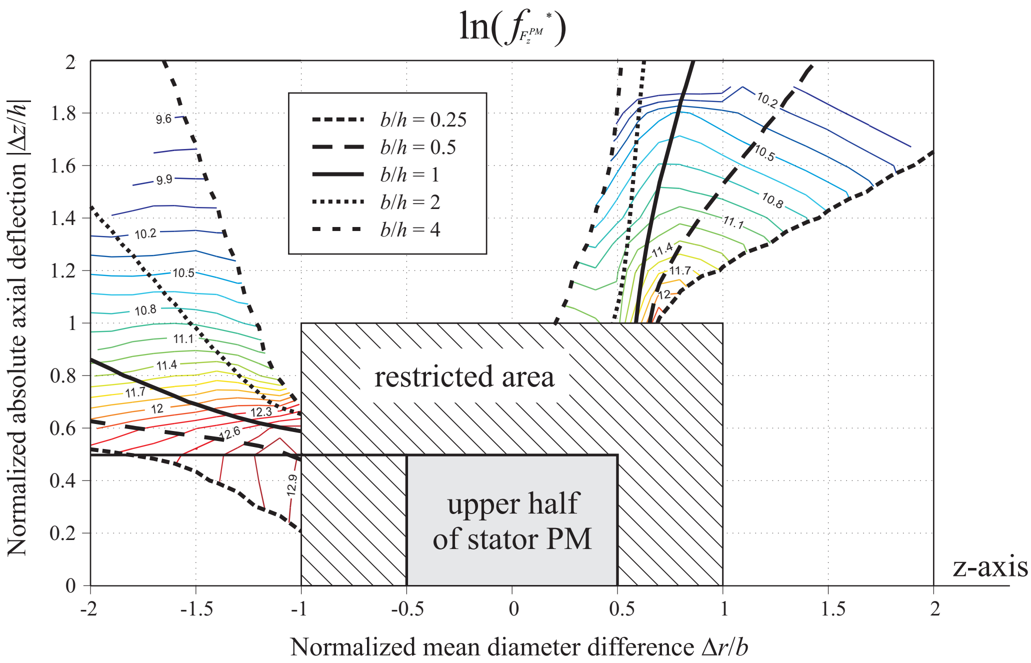

Figure 6: Standardized axial force of the permanent magnetic tilt bearing (computed for $b/D \rightarrow 0$).

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