Vibration Optimized Magnetic Rotor Suspension with Individual Permanent Magnets

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Abstract
An investigation of a vibration-optimized arrangement of individual permanent magnets for radial magnetic suspension of a machine rotor is presented. The individual permanent magnets are arranged to form a ring on the rotor which is aligned with an adjacent ring formed by individual permanent magnets on the stator. In contrast to previous work, a spacing between the individual permanent magnets is explicitly considered to facilitate the incorporation of the magnet arrangement into a 3D printed machine design. The investigation is performed with finite element analysis using open source software GetDP and Gmsh.

Keywords: permanent magnetic bearing, cuboid permanent magnet, finite element analysis, GetDP, Gmsh

1. Introduction

In this paper, an investigation of a vibration-optimized arrangement of individual permanent magnets for radial magnetic suspension of a machine rotor is presented. In contrast to previous work, e.g. (Nielsen et al., 2021), the investigation considers spacing constraints between individual magnets that may appear in 3D printed machine designs. It is shown that the magnitude of the suspension force fluctuates depending on the rotor's angular position and may hence cause machine vibrations during machine operation, i.e. when the rotor rotates. It is investigated how these magnitude fluctuations depend on the configuration of the individual magnets and which configurations lead to a minimum of fluctuations and hence machine vibrations.

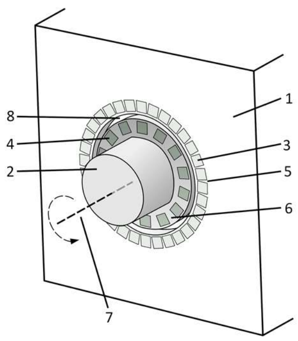

Fig. 1 Magnetic ring implementation of a radial magnetic bearing with individual magnets: stator (1), rotor (2), stator (outer ring) magnet (3), rotor (inner ring) magnet (4), space between stator magnets (5), space between rotor magnets (6), rotational axis (7), air gap (8).

Rotor suspension with permanent magnets has been applied to rotating machinery and has been optimized for many decades, see e.g. (Yonnet, 1978, Filatov and Maslen, 2001, Lang, 2003, Moser et al., 2006, Gruber et al., 2014, Lijesh and Hirani, 2015, Nielsen et al., 2021). For radial suspension it is common practice to use one or more pairs of mutually aligned magnetic rotor and stator rings. Multiple such pairs can be used to form, for example, a Halbach like array in axial direction of the rotor to increase magnetic forces and stiffness, see e.g. (Lijesh, 2015).

The magnetic rings can be built up with individual cuboid permanent magnets, see e.g. (Nielsen, 2021), wherein, to achieve ring-like properties, the permanent magnets are positioned close to each other. However, due to mechanical constraints, a spacing between the magnets may become necessary, e.g. for mounting purposes. In particular in 3D printing it may be a mounting option to place the individual magnets into separate pockets for mechanical fixation as shown in Fig. 1. This effectively introduces a space between the individual magnets. Due to this space the approximately homogeneous magnetic properties of a magnetic ring go lost and, during rotor rotation, fluctuations of suspension force and stiffness may occur which, in turn, may result in additional vibrations during machine operation.

In the sequel it is shown by means of simulation based on finite element analysis that these force fluctuations may be reduced with appropriate arrangements of the individual magnets and that a trade-off can be found to balance the mean suspension force and the magnitude of the suspension force fluctuation.

2. Methods

2.1 One-Pair and Two-Pair Configuration

In order to analyze possible arrangements of the individual magnets of a permanent magnetic bearing with respect to their vibration excitation properties, two configurations are investigated:

- an one-pair configuration which includes one annular arrangement of individual cuboid magnets on the rotor and one adjacent annular arrangement of individual cuboid magnets on the stator, and
- a two-pair configuration which is a combination of two one-pair configurations.

The one-pair configuration and the two-pair configuration are depicted in Fig. 2 and Fig. 3, respectively, wherein each of the inner annular arrangements (inner rings) represents magnets on the rotor and each of the outer annular arrangements (outer rings) represents magnets on the stator. In case of the two-pair configuration, the second ring of rotor magnets is angularly shifted with respect to the first ring of rotor magnets.

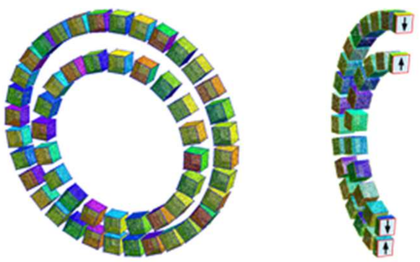

Fig. 2 One-pair configuration: one pair of magnet rings.

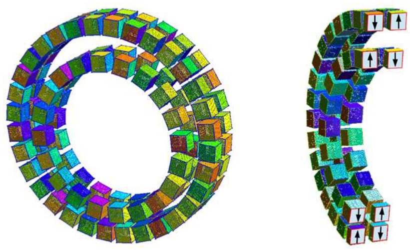

Fig. 3 Two-pair configuration: two pairs of magnet rings with repelling magnetization (inner rings: on rotor; outer rings: on stator).

2.2 Finite Element Analysis

In order to calculate the resulting force between the entirety of magnets of the inner ring(s) and the entirety of magnets of the outer ring(s), the B-field (B: magnetic flux density) is calculated based on Maxwell's equations, a vector potential formulation for the B-field, i.e. $\boldsymbol{B} = \nabla \times \boldsymbol{A}$, and Coulomb gauging which gives (Silvester, 1996)

$$1/\mu \nabla^2 \boldsymbol{A}=0. \tag{1}$$

Equation (1) is solved in three dimensions (3D) with a weak formulation using a finite element solver (Dular et al., 1998).

The force between inner and outer magnet rings is calculated from the B-field (an electric field is considered as not present) using Maxwell's stress tensor at the surface of each of the rotor magnets

$$T_{ij} = B_i B_j / \mu_0 - 0.5 B^2 \delta_{ij} \tag{2}$$

and its subsequent integration over all rotor magnet surfaces. The suspension force of the magnetic bearing is then the vertical component of the calculated force.

3. Simulation Setup

3.1 Simulation Objective

The objective of the simulation is to estimate the mean of the suspension force of the magnetic bearing and its fluctuation magnitude during rotor rotation. The mean and the fluctuation magnitude of the suspension force depend on the arrangement of the individual magnets. Therefore, different configurations and setups are investigated to find a vibration-optimized solution, i.e. a minimum suspension force fluctuation for a given (required) mean suspension force.

For the simulation, cuboid magnets of size 2x2x2 mm are assumed, since they are commercially well available. The magnets are assumed to be neodymium (NdFeB) magnets with a remanence field strength of 1.25T, a μr=1.07 and a magnetization in radial direction wherein rotor and stator magnets are mutually repelling. All of the magnets are assumed to be identical. The surrounding material is modeled as non-magnetic, e.g. 3D printing material polylactide (PLA). This implies that there is no explicit magnetic return path.

3.2 One-Pair Configuration

The stator magnets (outer ring) are positioned such that their center points are evenly located on a circle with radius 13mm. Similarly, the rotor magnets (inner ring) are positioned such that their center points are evenly located on a circle with radius 9.5mm. Assuming a common center point of all rings, the air gap between inner and outer ring is 1.5mm. However, to avoid a mutual force cancellation due to symmetry, which may occur if the inner ring is positioned in the common center, the inner ring is shifted downward (assumed direction of gravity) by 1mm such that a resulting radial force is achieved.

In order to simulate a rotor rotation, the angular position of the inner ring is varied in 41 steps in such a way that, by rotation, all inner magnets move to the position of the neighbor magnet in positive circumferential direction (i.e. the rotor is rotated in 41 steps by an angle of 360° divided by the number of magnets on the inner ring). For different numbers of magnets on the inner ring the angular step size will hence be different.

The one-pair configuration is analyzed for the following setup: The number of magnets on the outer ring is 32, the number of magnets on the inner ring is varied during the simulation between 1 and 26 magnets wherein the 26 rotor magnets are the densest arrangement possibility for the given radius of 9.5mm.

3.3 Two-Pair Configuration

The two-pair configuration is basically the arrangement of two one-pair configurations with an axial gap of 0.5mm between the two pairs of rings. Although magnetically disadvantageous, this axial gap may simplify the mechanical design of the bearing. In order to obtain an amplifying superposition of the magnetic fluxes of both pairs of magnet rings, the magnetization direction of the second pair of magnet rings is opposite to magnetization direction of the first pair of magnet rings.

The second pair of magnet rings is intended to increase the mean of the suspension force but also to reduce its fluctuation magnitude. For the latter purpose, the rotor magnets of the second inner ring are angularly shifted with respect to the first inner ring by half an angular distance between two adjacent rotor magnets (see Fig. 3). The stator magnets of the second outer ring have the same angular position as the stator magnets of the first outer ring. This way, assuming that exactly one complete oscillation of the suspension force fluctuation occurs when rotating the rotor to the position of the neighbor magnet in 41 steps, the force fluctuations of first and second pair of magnet rings are in opposite phase and cancel each other.

For the two-pair configuration, the number of stator magnets is 32 and the number of rotor magnets is varied between 1 and 26. Similar to the one-pair configuration, rotor rotation is simulated by changing the angular position of the inner rings in 41 steps from one rotor magnet's position to the position of the rotor magnet's neighbor.

3.4 Simulation Software

The geometries of the one-pair configuration and the two-pair configuration are defined using the open source software Gmsh (Geuzaine, 2009). The actual finite element analysis was performed with GetDP (Dular, 1996) and the execution and result analysis were done with Matlab and/or Python. From the results of the finite element analysis, the suspension force, i.e. the force in vertical direction, is estimated.

4. Simulation Results

For the one-pair configuration, Figure 4 (left) depicts the course of the suspension force vs. rotation step (41 steps from one magnet's angular position to the adjacent magnet's angular position) for 32 stator magnets and a variation of rotor magnets between 15 and 26 magnets. The calculation scheme for the mean suspension force and the fluctuation of the suspension force is shown in Fig. 4 (right). As visible in Fig. 4 (left), the mean suspension force decreases with the decreasing number of rotor magnets, the fluctuation of the suspension force differs for different configurations.

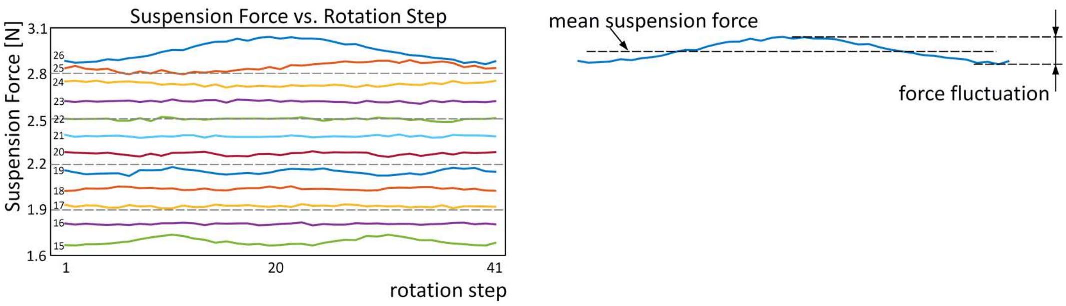

Fig. 4 Left: One-pair configuration: Suspension force (32 stator magnets) for different number of rotor magnets (15 to 26) vs. rotation step; Right: calculation scheme for mean suspension force and force fluctuation

For a clearer impression of how the mean suspension force depends on the number of rotor magnets, Fig. 5 (left) provides an overview of the mean suspension forces for 1 to 26 rotor magnets (number stator magnets: 32). Fig. 5 (right) depicts the suspension force fluctuation during rotor rotation in per cent of the mean value of the suspension force as shown in Fig. 5 (left).

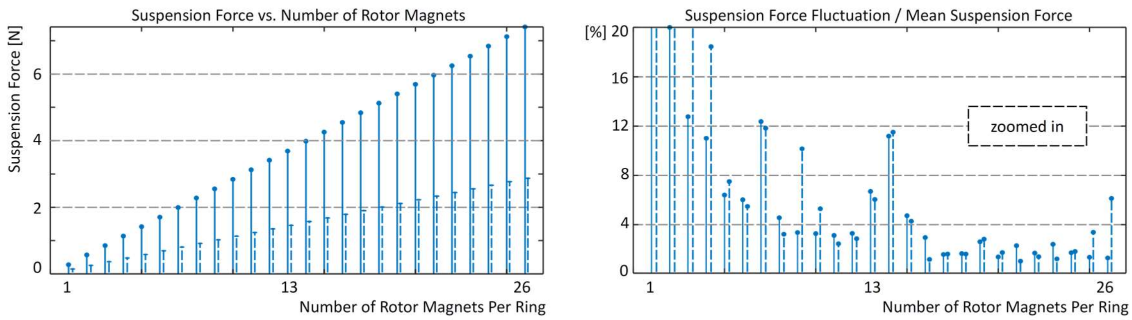

Fig. 5 Left: Suspension force vs. number of rotor magnets; Right: Ratio of suspension force fluctuation to suspension force vs. number of rotor magnets per ring. (dotted line: one-pair configuration, solid line: two-pair configuration)

In Fig. 6 (left), the harmonic composition of the suspension force fluctuations is, as an example, depicted for the case 32 stator magnets and 26 rotor magnets in a one-pair configuration. There is a strong component at 26 times the rotational frequency.

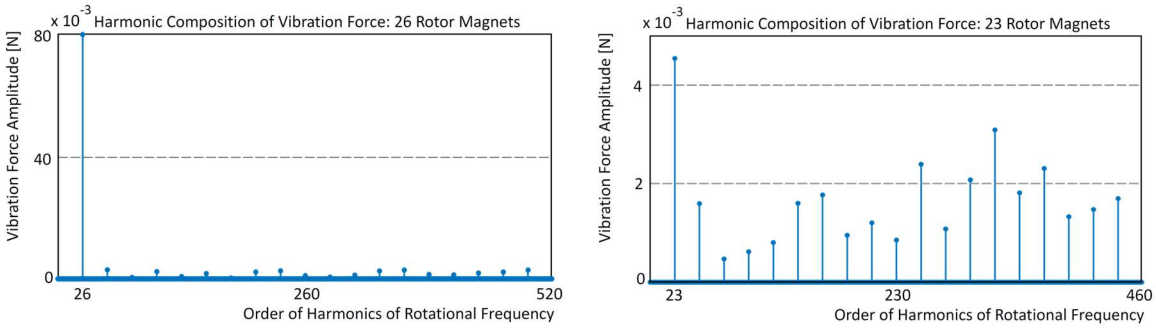

Fig. 6 One-pair configuration: Harmonic composition of force fluctuation (vibration force) vs. order of harmonics of rotational frequency. Left: 26 rotor magnets; Right. 23 rotor magnets. (both: 32 stator magnets)

For comparison with a low fluctuation case, Fig. 6 (right) shows the frequency composition of the suspension force fluctuation for the case 32 stator magnets and 23 rotor magnets. The magnitudes are significantly lower and the frequency composition is much 'whiter' than for the case depicted in Fig. 6 (left). That is, in contrast to the case in Fig. 6 (left) there is not just one dominant frequency component and the energy is much more spread among the existing frequency components.

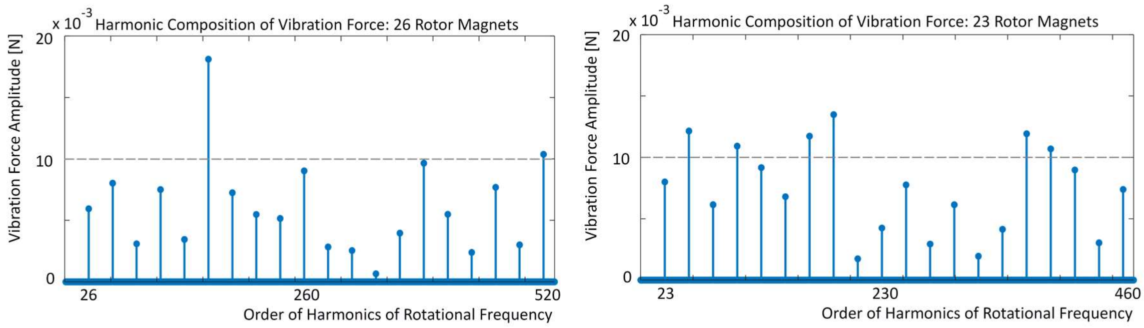

Fig. 7 Two-pair configuration: Harmonic composition of force fluctuation (vibration force) vs. order of harmonics of rotational frequency. Left: 26 rotor magnets; Right. 23 rotor magnets. (both: 32 stator magnets)

For the two-pair configuration, Fig. 7 depicts the frequency composition of the force fluctuation of the case with 32 stator magnets in combination with 26 rotor magnets (left) and 23 rotor magnets (right). In both cases, there is no dominant harmonic frequency component.

9. Discussion

It can be considered as a main result of the simulations for the one-pair configuration that, in addition to a suspension force, there is, during rotation of the rotor, a fluctuation component modulating the suspension force of the bearing. The mean of the suspension force and the magnitude of the force fluctuation depend on the details of the chosen magnet configuration. That is, for given radii of the inner magnet ring and the outer magnet ring, the mean suspension force and the fluctuation magnitude depend on the number of rotor magnets and the number of stator magnets. It is evident in particular from Fig. 5 that there is a trade-off possible between mean suspension force and force fluctuation magnitude. Certain parameter combinations, e.g. 32 stator magnets and 21 to 23 rotor magnets have very small fluctuation components - in this simulation in the range or even below numerical noise (see below).

Assuming a sufficiently high mean suspension force, these configurations (32 stator magnets and 21, 22 or 23 rotor magnets) may be considered as a solution for the desired vibration-optimized magnet arrangement. Furthermore, the force fluctuations of these configurations exhibit an almost flat spectrum, i.e. there is no (or at least no substantial) harmonic oscillation of the suspension force – see Fig. 6 (right). In contrast, configurations with a greater force fluctuation component exhibit one strong prominent frequency – see Fig. 6 (left).

Since in the two-pair configuration the magnetic flux densities of both pairs of magnet rings superpose to a stronger magnetic flux density field, the achievable suspension force of the bearing is greater than for the one-pair configuration. Due to the non-linear relationship between magnetic flux density and force, the suspension force is more than doubled. This fact is explicitly shown in Fig. 5 (left). In this sense, the introduction of a second pair of rings is advantageous.

Furthermore, as it is shown in Fig. 5 (right) for the two-pair configuration with 26 rotor magnets, the magnitude of the fluctuation force can be reduced in comparison to the one-pair case. This also proves that the angular offset of the second inner ring (with respect to the first inner ring) can be an effective strategy to cancel suspension force fluctuation.

The working principle of this cancellation strategy is a force fluctuation phase offset by 180° between first and second inner ring. Accordingly, this strategy works well if the corresponding one-pair-configuration has a strong first order (1 x number of rotor magnets) frequency component. In contrast, if the corresponding one-pair configuration has a strong second order (2 x number of rotor magnets) frequency component, this cancellation strategy will fail and it may make things even worse. Otherwise, if the second order frequency component is relatively small then the Fourier analysis exhibits a relatively evenly spread frequency content of the suspension force fluctuation – see Fig. 7 (left and right). The non-zero value of the first order frequency component (it should actually be zero) gives an indication about the numerical noise magnitude present in the FEM simulation.

Looking at the simulation results in general, it becomes apparent that it is possible to find optimum solutions for magnet configurations with large suspension force and small force fluctuations by a more or less excessive numerical search. As parameters of such a numerical search, the number of magnets of each of the magnet rings may be varied. In case of a two-pair configuration the angular offset may be used as an optimization parameter as well.

10. Conclusion

In this paper, an investigation of a vibration-optimized arrangement of individual permanent magnets for radial magnetic suspension of a machine rotor is presented. The interest in this investigation stems from the possibility to build radial magnetic bearings with individual magnets wherein each individual magnet is held within an individual pocket. This kind of mechanical design, which may be implemented when producing permanent magnetic bearings with a 3D printer, introduces spaces between magnets and hence a fluctuation of the suspension force during rotor rotation.

The presented simulation results reveal that, for given rotor and stator dimensions with one magnet ring on the rotor and one magnet ring on the stator (one pair of rings), the numbers of individual magnets on the rotor and the stator determine the mean suspension force. It is also shown that there are magnet configurations which have less suspension force fluctuations than others which are hence preferable. These vibration-optimized combinations can be found by means of numerical simulation.

When using a second pair of magnet rings (in total two pairs of rings), the achievable mean suspension force can be more than doubled in comparison to the one-pair configuration wherein the force fluctuation can be canceled if the second ring of rotor magnets is angularly shifted with respect to the first ring of rotor magnets. It is discussed above that a two-pair configuration should be made out of two one-pair configurations with a small second order harmonics of the suspension force fluctuation.

It can be assumed that further preferred magnet ring configurations (high mean suspension force, low force fluctuations) which are not presented in this paper can be found by excessive numerical search, e.g. based on finite element analysis. However, it might also be worth looking into numerically less expensive concepts, for example an approximation with an analytic formula and/or a superposition of already calculated B-fields and, based thereon, the calculation of Maxwell's stress tensor and the related force.

Further work will also include the 3D printing of rotor and stator hardware including the verification of the simulation results with vibration measurements.

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