BEARINGLESS SINGLE-PHASE MOTOR WITH FRACTIONAL PITCH WINDINGS

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ABSTRACT
The bearingless single-phase motor with four concentrated full pitch windings performs levitation force and torque generation with only one winding system. The axial position and the tilt angle are stabilized passively by magnetic reluctance forces achieved by the permanent magnet disk rotor.
Flux distribution in the air gap due to the permanent magnet shape is sinusoidal. Owing to the non-sinusoidal stator current distribution, the levitation force vector describes an elliptical force locus curve when the rotor is turned and current density distribution is kept constant. The slim shape of the elliptical locus curve causes problems concerning the stability of the position controller at certain rotor angles, especially, where the force vector crosses the flat parts of the locus curve.
To improve the behavior a method is shown which influences the shape of the force locus curve by means of a modified magnetic circuit design of the stator. A fractional pitch winding system with four concentrated coils is used. The space between the poles is filled with an intermediate pole without coil.
The result of the modification is a wider shape of the elliptical force locus curve which leads to a better behavior of the position controller in the sections where the force vector crosses the critical flat parts of the locus curve. The disadvantage of a fractional pole pitch is reduction in torque which must be considered for the motor design.

INTRODUCTION
A new concept of a bearingless single-phase motor has been worked out in the last few years [1]-[3]. In contrast to other principles [4]-[9] this motor is a four pole single-phase motor with only four concentrated full pitch windings as shown in figure 1. Only one winding system with concentrated coils is used to control both radial force and torque.
As a result of the disk rotor design only three degrees of freedom have to be controlled actively (x-position, y-position and rotor angle). The axial position and the tilt angle are stabilized passively by the magnetic reluctance forces and an appropriate selected diameter / axial-length ratio of the permanent magnet rotor [6],[7]. Thus, mechanical and electrical costs can be reduced.
The major disadvantage of a single-phase motor is the low starting torque. Therefore it can only be used for applications which do not require high starting torque, e.g. blowers, fans or pumps.

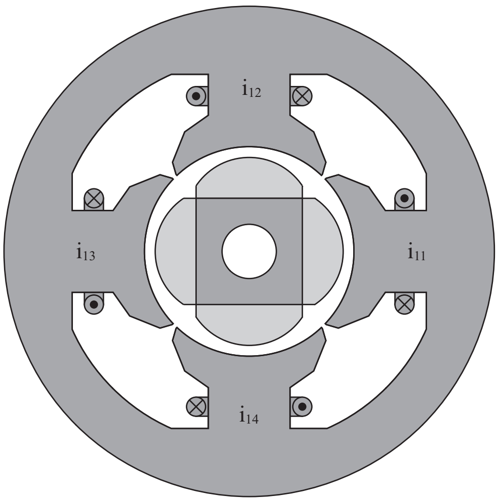

FIGURE 1: bearingless single-phase motor with four concentrated full pitch windings (i_{11}, i_{12}, i_{13}, i_{14}) for radial force and torque generation

CURRENT DISTRIBUTION FOR LEVITATION FORCE AND TORQUE

In general at least two independent bearing windings are required to generate controllable levitation forces in x- and y-directions of the rotor plane. In figure 2 these windings are denoted by i_a and i_b, whereas the winding denoted by i_m is responsible for torque generation.

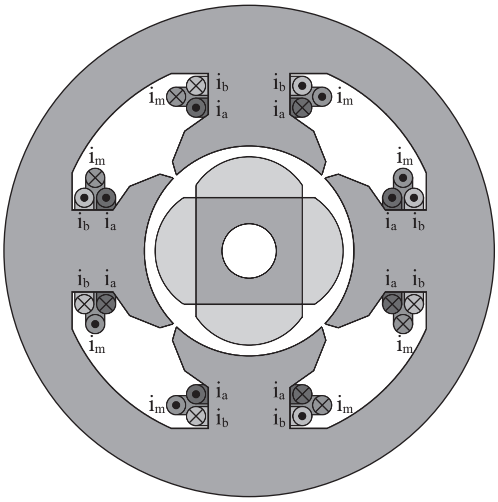

FIGURE 2: bearingless single-phase motor with two levitation windings (i_a, i_b) and one separate torque winding (i_m)

The currents i_{11} to i_{14} of the four concentrated coils from figure 1 can be expressed in terms of i_a, i_b and i_m

$$\begin{aligned} i_{11} &= i_a + i_b + i_m \\ i_{12} &= i_a - i_b - i_m \\ i_{13} &= -i_a - i_b + i_m \\ i_{14} &= -i_a + i_b - i_m \, . \end{aligned} \quad (1)$$

In the following paragraphs the currents i_a and i_b for levitation force generation are discussed. The current i_m for torque generation is not taken into account anymore.

LEVITATION FORCE LOCUS CURVE

In general, levitation force can be written as a nonlinear (non sinusoidal) function[1] of the rotor position $\mathbf{x}_r$, the stator current $\mathbf{i}_1$ and the rotor angle φ.

$$\begin{bmatrix} F_{rx} \\ F_{ry} \end{bmatrix} = \mathbf{F}_r(\mathbf{x}_r, \mathbf{i}_r, \varphi) \quad (2)$$

with

$$\mathbf{x}_r = \begin{bmatrix} x_r \\ y_r \end{bmatrix}$$

and

$$\mathbf{i}_1 = \begin{bmatrix} i_a \\ i_b \\ i_m \end{bmatrix}.$$

Equation (2) can be simplified and rewritten[2] as

$$\begin{bmatrix} F_{rx} \\ F_{ry} \end{bmatrix} = \mathbf{T}_m(\varphi) \begin{bmatrix} i_a \\ i_b \end{bmatrix}. \quad (3)$$

With a constant current i_a at a certain value ($i_b = 0$, $i_m = 0$) and a turned rotor the locus curve of the levitation force vector can be determined whereas no torque is generated.

For a motor design with concentrated windings and rectangular flux density of the permanent magnet field the amplitude of the force vector depends on the rotor angle φ as shown in figure 3. The force amplitudes in the two main axes of the locus curve differ significantly [10].

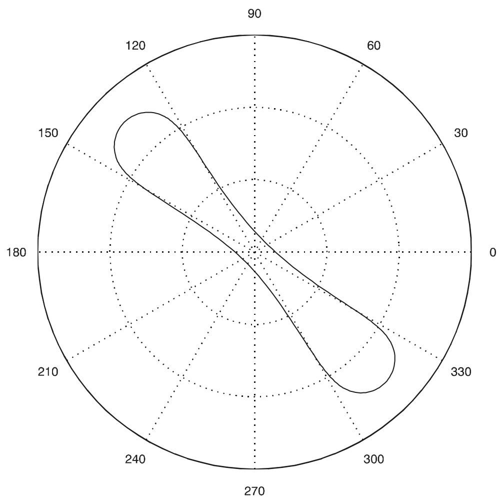

FIGURE 3: Force locus curve (φ = 0...180°) for a motor design with concentrated full pitch windings and rectangular flux density

[1] Calculated by the Maxwell Stress Tensor on the following conditions: The tangential component of the flux density in the air gap can be neglected ($\mu_{Fe} >> \mu_0$), the winding currents form an infinitesimal thin current density distribution on the stator surface[1]-[3].

[2] On the following conditions: Linearization about the center point $\mathbf{x}_{r0} = \mathbf{0}$, with no rotor displacement (closed control loop) and negligible influence of i_m on the levitation force (permanent magnet motor with large air gap) [1],[2].

The conditions are far from ideal conditions with sinusoidal current and field distributions where the levitation force vector describes a circular locus curve.
Owing to the circumstance that the levitation forces generated in the direction of the minor axis are insufficient, it is not possible to realize a force or position control loop under real conditions.
A better performance can be achieved by a sinusoidal distribution of the permanent magnet field. The force locus curve has an elliptical shape, as shown in figure 4, where the length of the two main axes do not differ that much.

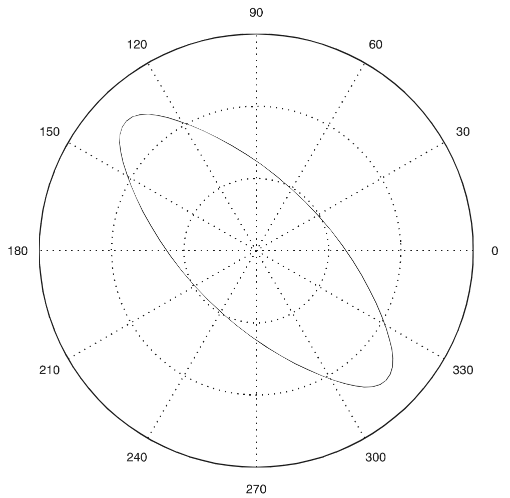

FIGURE 4: Force locus curve (φ = 0...180°) for a motor design with concentrated full pitch windings and sinusoidal flux density

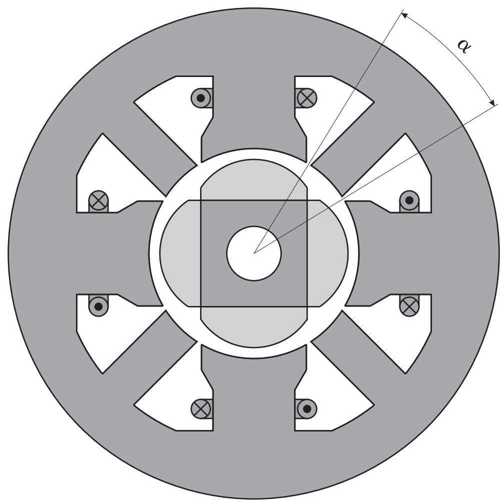

FIGURE 5: Bearingless single-phase motor with concentrated fractional pitch windings

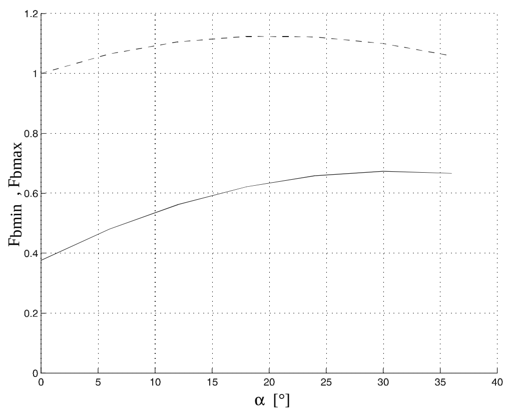

FIGURE 6: Influence of the intermediate pole width α on the axis of the force locus curve (solid line: minor axis F_{bmin}, dashed line: major axis F_{bmax})

With an appropriate current distribution a levitation force can be generated in any direction. However, the slim shape of the elliptical locus curve still causes problems concerning the stability of the position controller at very low rotary speed or at zero speed with levitation only. These problems occur at certain rotor angles, especially where the force vector crosses the flat parts of the locus curve.

FRACTIONAL PITCH WINDING

To improve the behavior and to get closer to the ideal conditions the shape of the force locus curve can be modified by the magnetic circuit design of the stator. The arrangement of the winding system is not changed so the simple mechanical design can be kept. A fractional pitch winding system with four concentrated coils is used. In this context fractional pitch winding means that the magnetic pole does not cover the whole pole pitch. The space between the poles is filled with an intermediate pole without coil (see figure 5).

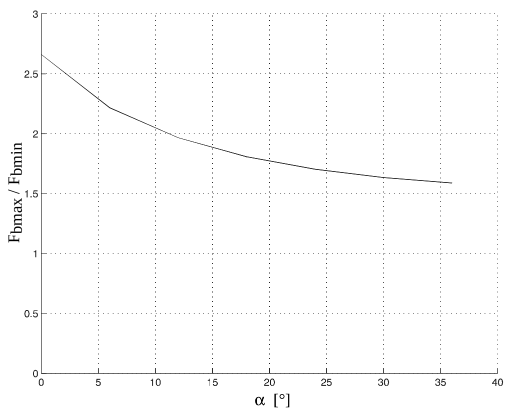

FIGURE 7: Influence of the intermediate pole width α on the ratio of major / minor axis (F_{bmax} / F_{bmin}) of the force locus curve

Figures 6 and 7 describe how the axes of the force locus curve are influenced by the change of the intermediate pole width which is determined by the angle α shown in figure 5.
To get a sufficient levitation behavior for a single-phase motor with fractional pitch windings, an intermediate pole with an angle of $\alpha = 24°$ is chosen. The result of the modification is a wider shape of the elliptical force locus curve as shown in figure 8.
The modified shape of the locus curve is caused by a longer minor axis of the elliptical curve and not by a smaller major axis (see figure 6). Thus the improved control behavior is accomplished by increasing the levitation force vector at minimum values and not by decreasing the force vector at maximum values. This leads to higher levitation forces of the overall motor.

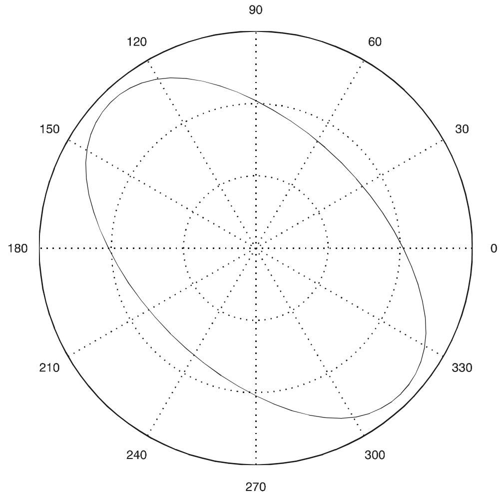

FIGURE 8: Force locus curve (φ = 0...180°) for a motor design with concentrated fractional pitch windings and sinusoidal flux density

The disadvantage of a fractional pole pitch is a reduction in torque (see figure 9). For the chosen design of the fractional pitch windings the reduction in average torque is about 10 % of the average torque with full pitch windings.

CONTROL OF THE LEVITATION FORCE

Matrix $\mathbf{T}_m(\varphi)$ from equation (3) can be rewritten

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \mathbf{T}_m^{-1}(\varphi) \begin{bmatrix} F_{rx} \\ F_{ry} \end{bmatrix} \quad (4)$$

and the inverse matrix can be substituted by the current-force transformation function $\mathbf{K}_m(\varphi)$

$$\begin{bmatrix} i_a \\ i_b \end{bmatrix} = \mathbf{K}_m(\varphi) \begin{bmatrix} F_{rx} \\ F_{ry} \end{bmatrix}. \quad (5)$$

With the help of equations (1) and (5) a control scheme with independent force controllers for x- and y-directions can be implemented as shown in figure 10 by using linear time-invariant methods. Since the controller design for magnetic bearing systems has been investigated intensively, it will not be discussed here [11],[1].

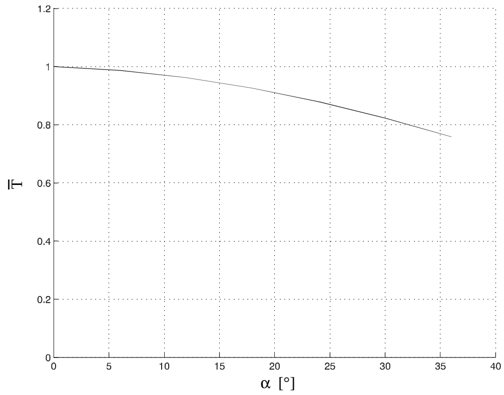

FIGURE 9: Influence of the intermediate pole width on the average torque of the motor

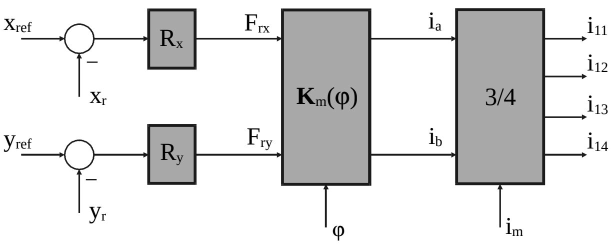

FIGURE 10: Block diagram of the levitation force controller with independent controllers for x- and y-directions

Through the calculation of the matrix $\mathbf{K}_m(\varphi)$ simplifications of the mathematical model are done which lose sight of the small coupling between x- and y-axes.
The measured system response to an impulse disturbance in x-direction for two different rotor angles is shown in figure 11. Rotor angle $\varphi = 0°$ is where the force vector is next to the major axis of the force locus curve (non critical part). Rotor angle $\varphi = 45°$ is where the force vector crosses the critical flat part of the force locus curve. The coupling between the axes, caused by the simplified mathematical model, is expected. However, this coupling is small enough to use the

control scheme with independent force controllers for the single-phase motor with four concentrated fractional pitch windings.

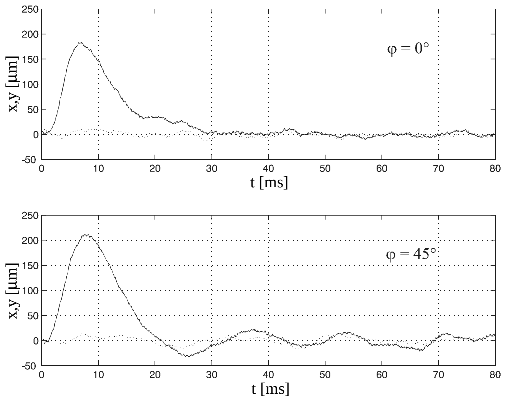

FIGURE 11: System response to an impulse disturbance in x- direction for different rotor angles (solid line: x-direction, dotted line: y-direction)

SUMMARY

Figure 12 shows the prototype of the bearingless single-phase motor with concentrated fractional pitch windings. The motor was tested under steady state and rotary speed up to 3000 rpm.

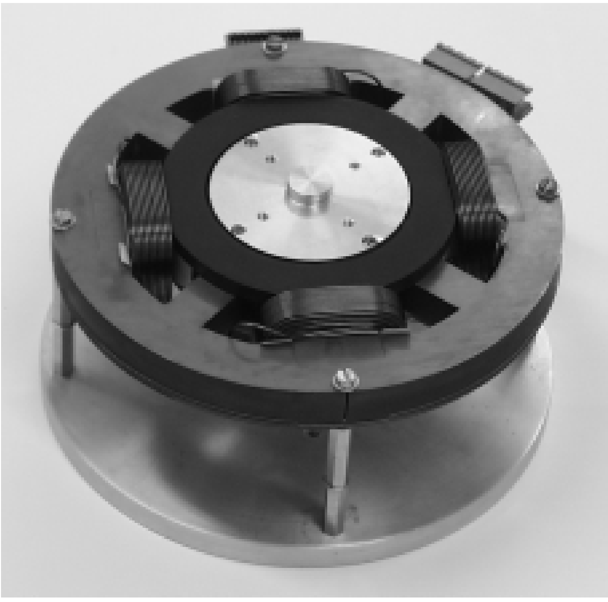

FIGURE 12: Bearingless single-phase motor with concentrated fractional pitch windings

The modified magnetic circuit design with intermediate poles and fractional pitch windings shows good results in magnetic levitation performance. The control behavior at the critical flat parts of the force locus curve is much better than with full pitch windings. The controller scheme shows sufficient accuracy for the operation of the motor and the coupling between x- and y-axes can be neglected. The reduction in average torque caused by the fractional pitch windings in comparison with the full pitch windings must be considered for the motor design.

ACKNOWLEDGMENTS

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