Magnetisches Getriebekonzept für eine dichtungsfreie Kraftübertragung bei einer Drehkolbenpumpe
Magnetic gear concept for a sealless power transmission of a rotary piston pump

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Kurzfassung

Pumpen werden zum Fördern von Flüssigkeiten mit unterschiedlicher Viskosität, sowie zum Transport und Komprimieren von Gasen eingesetzt [1]. Kälteanlagen und chemische Verfahrenstechnik sind weitere mögliche Anwendungsgebiete. Eine Hauptproblematik von Pumpen besteht in der Abdichtung des Pumpkreislaufes mit den eingesetzten Komponenten. Die dafür benötigten Dichtungen werden sowohl bei linearen, rotatorischen und Zentrifugalpumpen eingesetzt. Um diese Problematik zu überwinden wird ein elektromagnetisch angetriebenes Konzept auf Basis des Drehkolbenprinzips präsentiert. Der konstruktive Aufbau ermöglicht eine Aufteilung in zwei Pumpkammern. Die meisten Entwürfe enthalten ein Zahnrad im Rotor, welches mechanisch an die Welle eines externen, elektrischen Motors gekoppelt ist. In diesem Beitrag wird ein Konzept auf Basis von magnetischer Kraftübertragung vorgestellt, welches einem magnetischen Zahnrad [2] ähnelt und somit den Vorteil von minimaler Kontaktfläche und Reibung besitzt [3]. Dadurch könnten Abnutzungen minimiert und Verunreinigungen vermindert werden. Die Übertragung der mechanischen Leistung erfolgt hierbei über eine dichtungsfreie, magnetische Kopplung.

Abstract

Pumps are used to transport fluids or to compress gases [1]. One of the main problems is to separate the fluid of the pump from the environment. Such sealings are in the focus of studies for linear, rotational and centrifugal pumps. To overcome this problem a new electromagnetic concept based on a rotary piston engine is introduced. This particular construction consists of two fluid chambers. Most conventional designs consist of a rotor with a toothed wheel which is mechanically connected to the shaft of an external, electrical motor. Here, a magnetically force transmission, similar to a magnetic gear [2] is introduced, which offers the advantage of minimal contact surfaces [3]. This avoids the problem of impurities and the tribological behavior could be minimized as well. The mechanical power is transmitted via a magnetic coupling to achieve a closed housing.

1 Introduction

The presented pump configuration with a three-arched shaped rotor (Figure 2) allows to provide two streams simultaneously. The pumping process consists of compressing and emitting the fluid. Mechanical valves, which are required in displacement pumps to control the flow direction of the streams, are here redundant. These valves can lower the durability of the system and they can cause flow turbulence.

One of the major challenges is the usage of shaft seals. The shaft connects an external, electrical motor with the rotor. The seals are used to separate the fluid circuit of the pump from the environment. The shaft sealings which could become leaky during operation reduce the system's reliability. In addition, fluid particles can accumulate around the toothed wheel, that is located inside the rotor. The power transmission depends on a fully functional system and a blockage of the mechanical parts must be avoided.

To overcome these problems, a valveless and sealless electromagnetic concept is introduced which uses a magnetic transmission gear [2] instead of the toothed wheel and a magnetic coupling [4] as a substitution for the mechanical shaft. The electromagnetic concept avoids these problems: Leakage around the radial shaft sealings and accumulation of particles inside the rotor. The magnetic coupling transmits the external motor power without any mechanical contact. A usage without the critical mechanical components, which can block the pump, can be achieved by this approach. The magnetic transmission gear and the magnetic coupling are presented in detail in the following sections.

2 Rotary piston engine

2.1 Working principles

The geometrical form and motion are presented to explain the functional principles of the pump. The outline of the rotor is a three-arched hypotrochoid which is a special form of a cycloid. A hypotrochoidal curve is generated by tracing a point P attached to an inner circle of radius r rolling around the inside of a fixed outer circle of radius R. The

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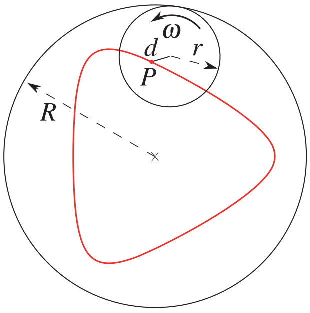
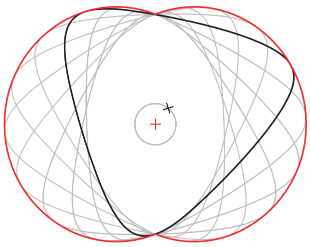
point P is at a distance d from the center of the inner circle [5].

$$\vec{x} = \begin{pmatrix} R_0\{\cos\alpha + \frac{B}{2}\cos 2\alpha\} \\ R_0\{-\sin\alpha + \frac{B}{2}\sin 2\alpha\} \end{pmatrix} \tag{1}$$

Equation 1 describes the trajectory of the hypotrochoidal curve with $\alpha \in [0, 2\pi]$ and $R_0 = R - r$.
Figure 1a shows the resulting form. By rotating the hypotrochoidal rotor around an eccentric wheel, which can be connected to the shaft, the envelope curve in Figure 1b is generated by the covered area. This area will contain the rotor components, a coating for reduced friction losses and the fluid, resulting in no dead space within the motor.



(a) Hypotrochoidal curve.



(b) Envelope curve.

Figure 1 Drafting of the relevant curves.

The reduced eccentricity B in equation 1 and 2 is used to describe the ratio between the eccentricity e and the difference between the two radii.

$$B = \frac{2e}{R_0} \tag{2}$$

Similar to the hypotrochoidal curve, the envelope curve of the rotor can be described as [5]:

$$\vec{x} = \begin{pmatrix} R_0\cos\alpha\{1 + B\{|\cos\alpha|\sqrt{(1-b^2\sin^2\alpha)} - b\sin^2\alpha\}\} \\ R_0\sin\alpha\{1 + B\{|\cos\alpha|\sqrt{(1-b^2\sin^2\alpha)} + b\cos^2\alpha\}\} \end{pmatrix}$$

The motion of the rotary piston is a superposition of two different motions. When the piston rotates round its own center with an angle of ϕ, the center point itself is moving along a circular path, which has a distance of e to the origin, with an angle of 3ϕ.
As a result, the rotary motion by the drive shaft is transferred via an eccentric wheel to an eccentric rotary designed motion, which may be used for compressing and emitting a fluid.

2.2 Toothed wheel

In a rotary piston engine a toothed wheel is used to transfer the mechanical power from the rotor to the eccentric gear respectively the mechanical shaft. Pump concepts using the un-toothed magnetic version instead of the toothed wheel can avoid problems with deposits blocking the mechanical system. Therefore, a toothed wheel requires higher maintenance and reduces reliability when compared to a non-toothed concept with less contact area.

2.3 Mechanical shaft

In an engine, the rotating shaft transmits the power out of the combustion chamber. The mechanical shaft needs sealings and an opening through the housing. It is assumed that this concept can cause damage to the fluid and problems with leakage can occur which needs to be considered strictly in fuel pumps [6]. Therefore this component will be substituted in the next chapters by a magnetic torque transmission via a magnetic coupling.

3 Rotary piston pump

In this study, we focus on the development of an electromagnetic gear wheel for a pump based on a rotary piston principles. If the rotor is rotated by an external motor, the left and a right chamber can be used to pump two closed circuits of fluid systems which are separated by the rotor.
The elliptically shaped rotor controls the inlet, and outlet of each chamber, respectively. While one chamber is being filled, the other chamber is compressing and emitting its fluid [7].

3.1 Magnetic transmission gear

The toothed wheel is substituted by two magnetized permanent magnet cylinders [8] (Figure 2). This magnetic transmission gear is designed by high energy rare-earth magnets (NdFeB) to transmit the required forces. A polished, minimal contact area between the two cylinders is actually the cause of the reduction of the mechanically induced damage to the fluid. It can be noticed that this magnetic transmission gear design reduces maintenance and improves reliability when compared to a toothed wheel gear [9]. An electrical motor can be used to rotate the inner magnetic wheel of the magnetic gear. In Figure 2 the cross section of the pump with a magnetic gear is presented.

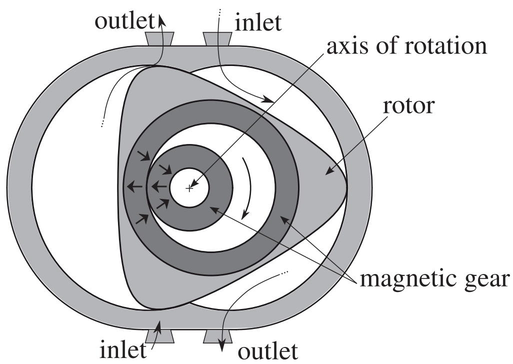


Figure 2 Cross section of the pump with magnetic gear [2].

3.1.1 Geometrical parameters

The electromagnetic pump is designed to be small. Volume, height, diameter as well as weight are limited. The

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combination of displacement volume and a moderate rotational speed of approximately 100-120 rpm determine the pressure build-up. Table 1 lists the geometrical and functional parameters of the pump.

Description	Variable	Value	Unit
base circle radius	R	30	mm
red. eccentricity	B	0,4	-
height	h_{total}	94	mm
diameter	d_{total}	84	mm
piston displacement	ΔV	60	ml
pressure build-up	Δp	10^{-4}	N/mm^2

Table 1 Geometrical requirements for the studied pump.

3.1.2 Torque and stiffness requirements

The torsional stiffness of the system and the radial attraction force are analyzed to ensure proper, smooth motion of the rotor without slip or blocking. The stiffness can be computed by analyzing the change of torque by a displacement in location (Equation 3). Only the z-component is considered and the angle γ describes a motion around the contact point between the two rings.

$$K_{M,z} = \frac{\delta M_z}{\delta y} \tag{3}$$

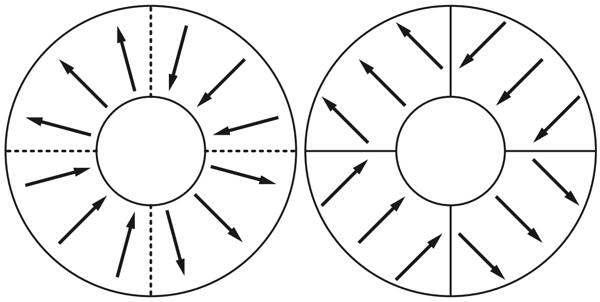
Table 2 shows the stiffness and force requirements for the rotor. A 3D computer-aided design simulation showed that a slippage of only $\gamma \in [-0,5°, +0,5°]$ is valid. To avoid a blocked pump, the minimal stiffness needs to be considered.

Description	Variable	Value	Unit
radial attraction force	F_r	45	N
torsional stiffness	$\overline{K}_{M,z}$	0,4	Nm/°
height of gear	h	10	mm

Table 2 Force and stiffness requirements for the application.

3.1.3 Type of magnetization

For the considered magnetic wheel different types of magnetization can be applied. Figure 3 shows the direction of the magnetic field lines for radial and parallel magnetization. It has to be considered that a parallel magnetized magnet has to be constructed by multiple ring segments. In [10] a comparison between different types of magnetization showed, that the transmittable torque can be increased by 28 % by using a parallel magnetization.
The ratio of the inner ring's pole-pair number p_{in} to the outer ring's pole-pair number p_{out} is implied by the ratio of the inner's ring outer radius to the outer's ring inner radius $R_{in} : r_{out}$.



(a) radial magnetization. **(b)** parallel magnetization.

Figure 3 Two possible types of magnetization.

3.1.4 Parameter definitions

This concept is defined by nine parameters such as the type of magnetization, the number of pole pairs and their interactions etc. . Figure 4 shows the geometric variables such as the eccentricity e, thickness of coatings and height of the magnets and the iron yoke. The variation of these parameters leads to the proper construction fulfilling the requested specifications. The radius of the outer ring is limited due to the rotor's hypotrochoidal shape (Figure 2).

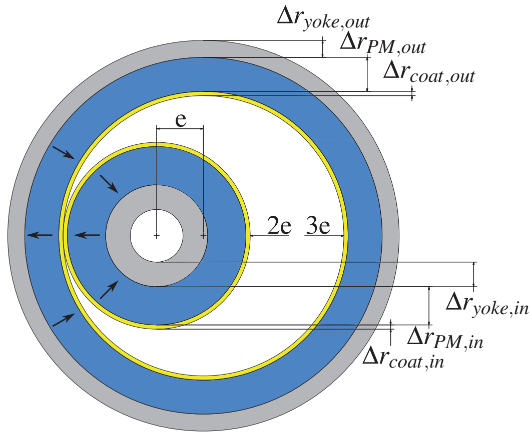


Figure 4 Definition of geometric variables of the magnetic transmission gear.

In addition, the following restrictions can be formulated:

$$\Delta r_{coat,out} + \Delta r_{PM,out} + \Delta r_{yoke,out} < R_0 - 4e, \tag{4}$$
$$\Delta r_{coat,in} + \Delta r_{PM,in} + \Delta r_{yoke,in} < 2e. \tag{5}$$

The thicknesses of the different layers cannot exceed the geometrical restrictions due to the eccentric motion.

3.2 Magnetic coupling

The mechanical shaft is substituted by a magnetic axial-coupling for a sealless power transmission. The original function principles do not change, except the opening in the housing is not required. Two different working principles can be regarded: The eccentric wheel is completely encapsulated in the rotor or the eccentric motion is prescribed by the magnetic coupling outside the housing. Here we focus on the concept with an encapsulated eccentric wheel in the rotor. The magnetic coupling transmits the power contactless into the housing. The upper part of the

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coupling is rigidly coupled with the eccentric wheel which is only positioned in the bottom half of the rotor. By rotating the magnetic coupling, the rotor is driven on its eccentric motion. The top view in Figure 2 shows the magnetic gear, which is embedded in the top half of the rotor.

3.2.1 Torque requirements

The axial attraction force F_z and the torque T_z are shown as a function of the electrical angle $\theta_{el.}$ in Figure 5. The given hydraulic power and the rotational speed result in a required minimum torque transmission of $T_z = 0,50\ Nm$ to avoid slippage.

4 Process of modeling

To evaluate the resulted forces and torques, a 2D and 3D model are implemented using finite element method (FEM) software. In this paper the results are achieved by using the institute's in-house FE-package iMOOSE [www.iem.rwth-aachen.de].

4.1 Design of Experiments

The interactions between all nine different parameters for the magnetic gear are determined by using the *Design of Experiments* method. Statistical experimental design plans are used to reduce the amount of simulations and to clarify the parameter interactions by a fixed simulation plan. The implementations and executions are obtained from [11] and [12].

4.1.1 Full factorial experiment

Experimental designs are $m\ x\ k$-matrices. m is equal to the number of experiments and k is equal to the number of different factors which varies during the experiment. Nonlinearities are not considered by this approach. Used factor values are abbreviated as $+/-$. The number of possible combinations for a two-stage nested design is:

$$m = 2^k. \quad (6)$$

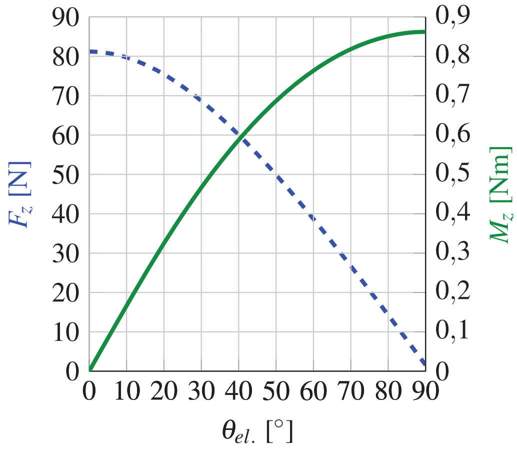


Figure 5 Axial force (dashed line) and torque (solid line) as a function of the electrical rotation angle.

Table 3 and Figure 6 show a scheme for a 2^k experiment with result vector y.

A	B	C	y
−	−	−	y_1
+	−	−	y_2
−	+	−	y_3
+	+	−	y_4
−	−	+	y_5
+	−	+	y_6
−	+	+	y_7
+	+	+	y_8

Table 3 Example structure of a 2^3 plan.

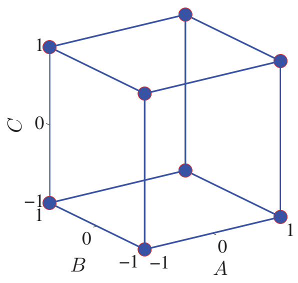


Figure 6 Spatial illustration of a full factorial experiment.

5 Results

The design parameters for the concept have to be designed to fulfill the requested specifications. A blocked pump or an inadequate performance of the pump has to be avoided for a long-term operation.

5.1 Magnetic transmission gear

The parameters for the magnetic gear are listed in Table 4. The geometrical parameters are explained in Figure 4. Nine different, independent parameters are analyzed to evaluate the influence on radial attraction force and the torsional stiffness. The model height is set to $h = 10\ mm$ for all simulations.

Figure 7 shows the results for the simulation without any interdependencies. The attraction force is doubled from 45 N to 90 N in the case of parallel magnetized rings. All simulations are based on a remanence flux density of $B_r = 1.35\ T$. The three factors: type of magnetization (a), number of pole pairs (b) and eccentricity (c) have the highest influence on the results. A change to radial magnetization also results in a loss of about 50 % in stiffness.

Symbol	Variable	Unit	Description
a	$magnetization$	-	$-1 \widehat{=}$ parallel $+1 \widehat{=}$ radial
b	p_{out}	-	number of pole pairs
c	e	[mm]	eccentricity
d	$\Delta r_{coat,in}$	[mm]	coating, inner ring
e	$\Delta r_{coat,out}$	[mm]	coating, outer ring
f	$\Delta r_{PM,in}$	[mm]	magnets inner ring
g	$\Delta r_{PM,out}$	[mm]	magnets outer ring
h	$\Delta r_{yoke,in}$	[mm]	yoke, inner ring
i	$\Delta r_{yoke,out}$	[mm]	yoke, outer ring

Table 4 Factors for the magnetic gear in a two-stage experiment.

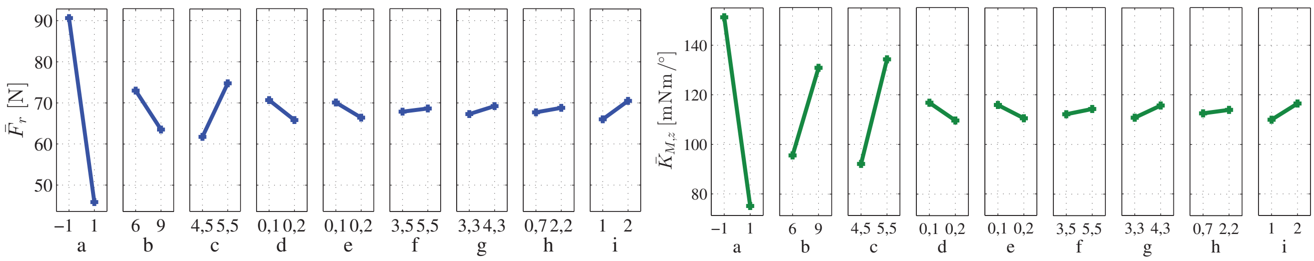


Figure 7 Effects on average attraction force (left) and torsional stiffness (right).

5.1.1 Interdependencies

Figure 8 shows the interdependencies of the parameters. The influence of the parameter a on a fixed parameter b can be seen in column a and row b. The most intensive interdependencies on the resulting average stiffness can be seen by an increased slope of the curves.

- ▷ A change from parallel to radial magnetization reduces the influence of pole pair number and eccentricity.
- ▷ An increased pole pair number of $p_{out} = 9$ results in a more fragile system in combination with radial magnetization.
- ▷ A larger eccentricity in combination with a radial magnetization decreases the stiffness more than a combination with parallel magnetization (on a percentage basis).

Thickness of yoke

An increased yoke height has no significant influence on force or stiffness. But in case of flux density values above saturation (Figure 11), a minimum yoke height has to be considered to prevent a loss in stiffness and attractive force.

Eccentricity

Figure 9 shows the progressive influence of eccentricity. An increasing eccentricity intensifies the stiffness, but the limiting dimensions restrict further increased values.

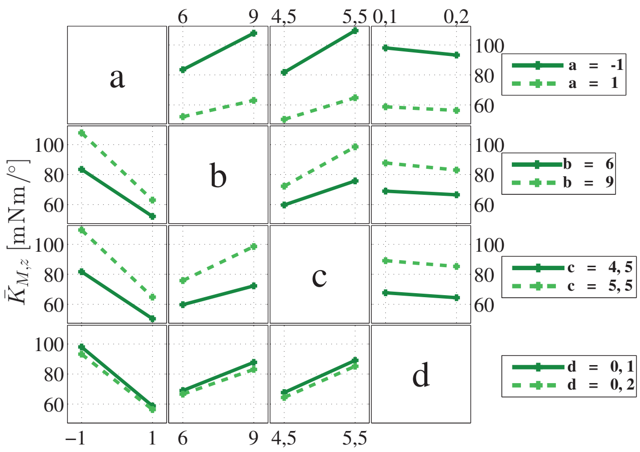


Figure 8 Interdependencies of the most important parameters on average torsional stiffness $\overline{K}_{M,z}$.

Height of magnets

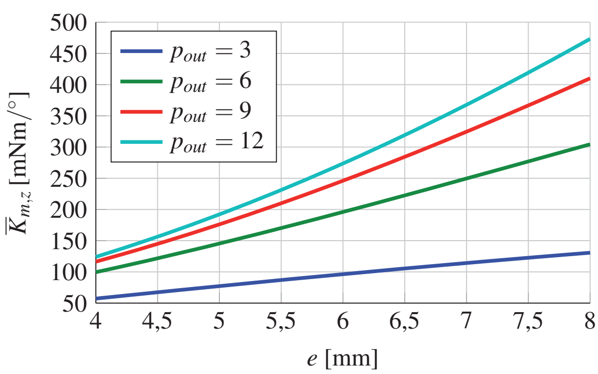
Due to the limited gear dimensions, the magnets cannot exceed a maximum height. Figure 10 shows that the attraction force of the gear increases with more magnet volume. The friction of the rotor should be considered and the rotor's mass should be as low as possible.

Type of magnetization

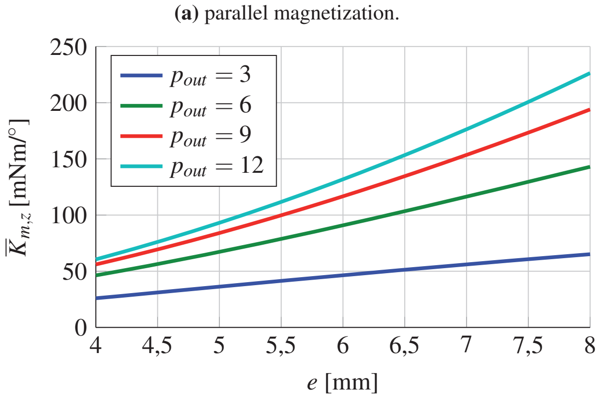
A tilt or slippage of the rotor can easily be avoided by selecting parallel magnetized rings and an adequate height of the gear.

Pole pair number

Figure 9 shows the progressive influence of pole pair number. An increasing pole pair number results also in an increased stiffness. For a radial magnetized system, the pole pair number depends on the magnetizing instruments. Nevertheless, higher pole pair numbers have a degressive effect on the stiffness.

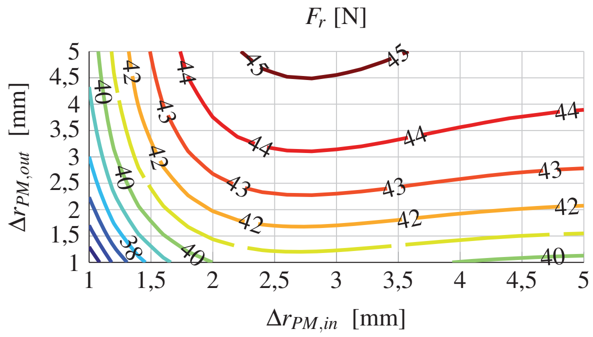


(a) parallel magnetization.

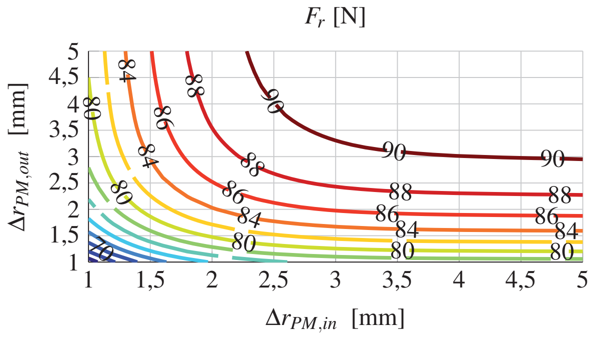


(b) radial magnetization.

Figure 9 Interdependencies of pole pair number and eccentricity in detail.



(**a**) radial magnetization.



(**b**) parallel magnetization.

Figure 10 Influence of magnet height variations.

6 Conclusions

In this paper, a magnetic pump based on a rotary piston is introduced. A detailed discussion of the design, its magnetic design and parameter variations are presented. A basic introduction in the motion and general structure of the rotary piston engine is given. All parameters are dimensioned to ensure a continuous operation and to avoid an inoperative tilt of the rotor which can result in a blocked pump. Design of Experiments structured plans have been designed to gain information about the different interactions of the parameters. FE simulations are conducted and by using parallel magnetized, high energy rare-earth magnets (NdFeB) for the components, the magnetic gear provides sufficient stiffness and radial attraction force for the application. The encapsulated eccentric wheel is driven by a magnetic coupling.

A major challenge for dimensioning the magnetic gear is not the radial attractive force but rather the torsional stiffness requirements. Almost all parameter combinations result in a system with a sufficient power transmission. Prototypes will be constructed to determine the rotor's friction forces by experiments. Needle-roller bearings could be used to minimize the friction losses. A more complex system could consist of two magnetic couplings, one per side of the housing in axial direction. In the double-sided concept the axial friction forces can compensate each other.

7 Literature

[1] W. Faragallah, *Rotierende Verdrängermaschinen: (Pumpen, Verdichter und Vakuumpumpen)*. Faragallah, 2004.

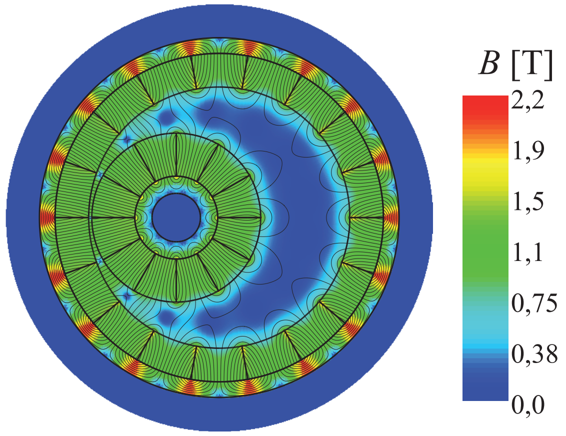


Figure 11 Flux density for a parallel magnetized gear.

[2] F. Jorgensen, T. Andersen, and P. Rasmussen, "The cycloid permanent magnetic gear," *Industry Applications, IEEE Transactions on*, vol. 44, no. 6, pp. 1659–1665, Nov 2008.

[3] K. Atallah and D. Howe, "A novel high-performance magnetic gear," *Magnetics, IEEE Transactions on*, vol. 37, no. 4, pp. 2844–2846, Jul 2001.

[4] E. Furlani, "Analysis and optimization of synchronous magnetic couplings," *Journal of Applied Physics*, vol. 79, no. 8, pp. 4692–4694, Apr 1996.

[5] D. Nosenchuck, "Wankel type pump for transporting fluid with entrained particulate matter," Patent, Jan. 2, 2001, US Patent 6,168,405.

[6] R. GmbH, *Kraftfahrtechnisches Taschenbuch*, ser. Kraftfahrtechnisches Taschenbuch. Vieweg+Teubner Verlag, 2004.

[7] S. Morita, Y. Watanabe, and T. Nakamura, "Rotary pump," Aug. 6 1997, EP Patent App. EP19,970,101,559.

[8] G. Schweitzer, *Magnetlager - Grundlagen, Eigenschaften und Anwendungen berührungsfreier, elektromagnetischer Lager*, softcover reprint of the original 1st ed. 1993 ed. Wiesbaden: Springer-Verlag, 2013.

[9] K. Atallah, S. Calverley, and D. Howe, "Design, analysis and realisation of a high-performance magnetic gear," *Electric Power Applications, IEE Proceedings*, vol. 151, no. 2, pp. 135–143, Mar 2004.

[10] F. Jorgensen, T. Andersen, and P. Rasmussen, "Two dimensional model of a permanent magnet spur gear," vol. 1, pp. 261–265 Vol. 1, Oct 2005.

[11] W. Kleppmann, *Taschenbuch Versuchsplanung - Produkte und Prozesse optimieren*. München: Hanser, 2011.

[12] K. Siebertz, D. v. Bebber, and T. Hochkirchen, *Statistische Versuchsplanung - Design of Experiments (DoE)*, 1st ed. Wiesbaden: Springer-Verlag, 2010.

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