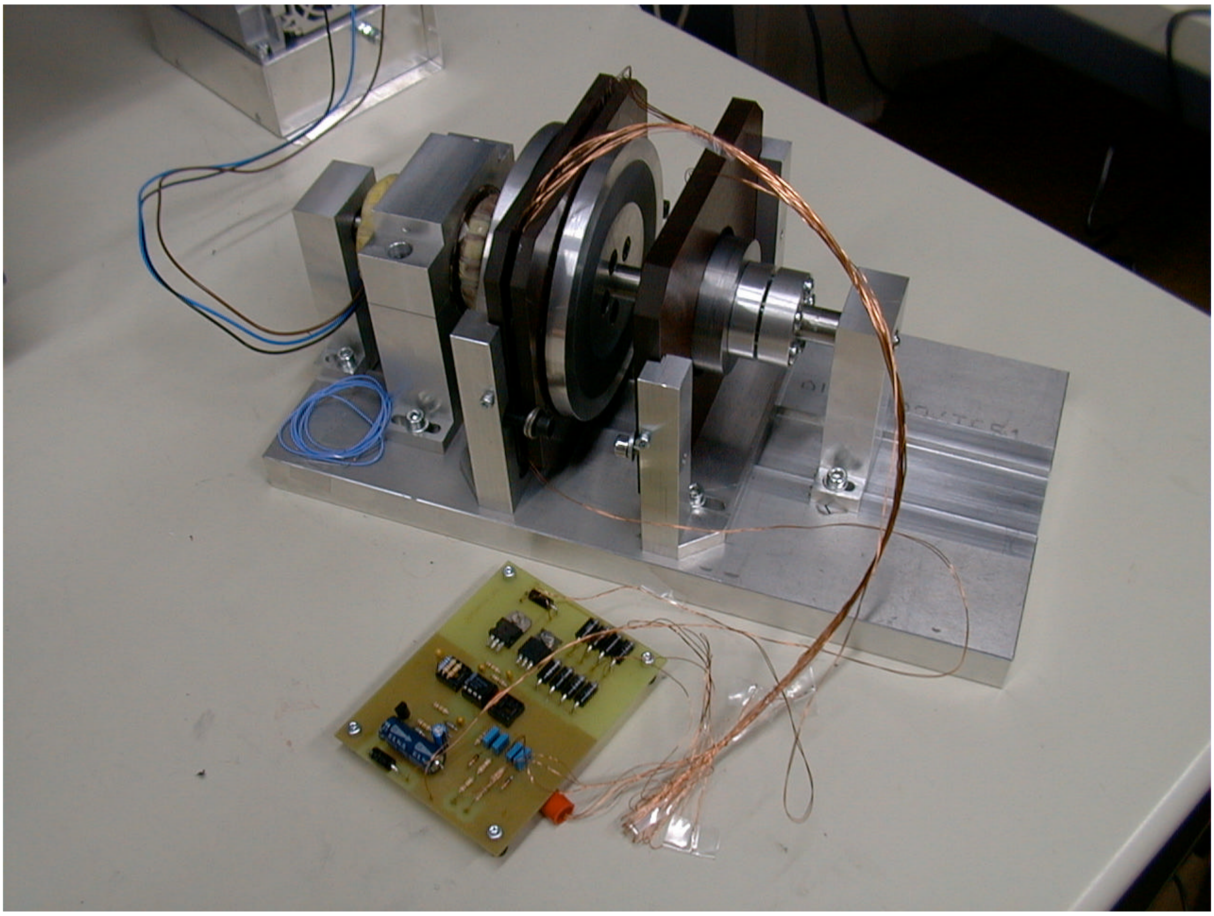
EIDGENÖSSISCHE TECHNISCHE HOCHSCHULE LAUSANNE
POLITECNICO FEDERALE LOSANNA
SWISS FEDERAL INSTITUTE OF TECHNOLOGY LAUSANNE

Faculty STI – Section of Microtechnology – Institute of Microsystems
October 2001 to February 2002

Realisation and test of a passive magnetic bearing with an inherent power generator / sensor

Semester project



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Abstract

The axial passive magnetic bearing comprises an inherent ironless permanent magnet power generator, a simple signal control unit and an electromagnetic actuator. The power generator comprises three coil systems – the first furnishes raw actuator power, the second senses axial position and the third supplies the signal control unit. The actuator was designed similar to a loudspeaker coil. It is located in the close vicinity of the power generator. Hence, the electrical energy does not need to be transported over long distances.

The bearing possesses load capacity and stiffness characteristics that can be similar to those of conventional active magnetic bearings but without the need of expensive and complicated sensors, power amplifiers and control systems. It can be conceived for almost arbitrary available power and stiffness requirements. As long as the rotor is in the axially centred position, very low losses are present. To achieve this goal, the present design does take advantage of some few active electronic elements.

Therefore, the project result is a newly designed and build demonstrator. Its actuator was designed to supply a steady force of about 10N and peak forces of about 30N. By means of a simple analogous proportional–differential regulator, an axial stiffness of about 1N/m·rpm was measured – giving 2kN/m to 25kN/m depending upon the rotation speed. The use of a more sophisticated regulator will allow better actuator control and hereby push stiffness above 100kN/m. In this case, of course, the actuator should be enforced to sink more power without overheating.

Lausanne, February 8, 2002

The author:

Marcel Leutenegger

Acknowledgements for assistance to:

Jan Sandtner
Prof. Bleuler
Roland Moser

Table of contents

Lausanne, February 8, 2002

Project brief

The axial passive magnetic bearing comprises an inherent ironless permanent magnet generator, which acts simultaneously as a position sensor. The energy coming from the generator is transferred via a small number of semiconductor diodes to an actuator, which is similar to those used in ordinary active magnetic bearings. The stator contains three sets of air coils: main generator coils, sensor coils and compensating generator coils. The generator coils are connected additionally thus producing a steady voltage independent of the rotor's axial position. The sensor coils are connected differentially; the induced voltage depends strongly on the axial position, being zero when the rotor is exactly at the centred position. The third coil system serves as a compensation of a steady current, which would circulate even at the rotor's centred position. As long as the rotor is at the centred position, practically no losses are present. Stability is only achieved in the rotating state.

Theory: 30%

Praxis: 70%

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Delays:

Report
a hand out until 17^{00} on 8^{th} February 2002 to Prof. Bleuler and Mr Sandtner

Presentation
20´ presentation followed by 30´ discussion
begin at 13^{15} on 13^{th} February 2002
room ME A31 at campus

1. Introduction

Global implications

Rotating machines are indispensable elements of modern civilisation. In most of these machines, mechanical bearings are used, involving lubrication, friction, wear and therefore a finite life. It would be very interesting if it was possible to replace mechanical bearings by contactless ones. No contact means no mechanical friction, thus no lubrication and no mechanical wear. This makes maintenance-free long life bearings available.

At the moment, mainly two contactless bearing types are used:

1. Gas bearings – often air bearings – providing astonishing high load capacities and stiffnesses. They are of relatively simple mechanical construction. The gas film between the moving parts is either created by gas injection using an external compressor or by an intermediate sheet providing a self-filling while parts are moving.
   Their characteristics are influenced by gas pressure – especially if atmospheric air is used. Particularly, gas bearings are completely inapplicable in vacuum.
   Note that particles in the gap like dust can be abrasive, thus causing wear problems.
2. Active magnetic bearings achieving load capacities and stiffnesses of mechanical bearings at the price of expensive and complicated sensors, power amplifiers and control systems.
   They do not wear and they are nearly friction-free. If the energy needed for the electromagnetic actuators comes from an external source, energy losses of moving parts are almost zero. Nevertheless, total energy consumption of magnetic bearings is rather greater than for competitive gas bearings. On the other hand, magnetic bearings work well in almost any environment.

Project circumstances

This semester project is part of the development of a "flywheel" – a temporary energy storage system to replace electrochemical cells by a mass storing rotational kinetic energy. By using a flywheel instead of a lead accumulator, it should be possible to i) double energy/mass ratio, ii) increase charge/discharge efficiency and iii) overcome the limited number of charge/discharge cycles. Plausible applications would be power supplies for satellites or electromobiles where these characteristics are looked for.

If the flywheel's rotational speed varies from 30% to 100% of its maximum speed, it enables discharge of up to 90% of stored kinetic energy. Maximum speed would be about 250krpm – depending on materials and geometry used for the rotor. The rotor would be held in vacuum to eliminate gas friction. Its radial stability is achieved by a permanent magnet suspension causing no energy losses at all. Unfortunately, this permanent magnet suspension introduces axial instability which cannot be compensated by another permanent magnet system. For maintenance-free systems, mechanical contact during rotation is prohibited. So a passive axial magnetic bearing offering enough axial stiffness/force should do the job.

Project goals

Realisation of a demonstrator to test the concept mentioned by Jan Sandtner et al [1]. The demonstrator comprises i) a standard asynchronous motor supplying rotational kinetic energy, ii) an inherent ironless generator/sensor creating the electrical power needed for iii) the axial electromagnetic actuator.

To prove feasibility of a flywheel mentioned above, it should be possible to *measure restoring forces of the axial actuator* depending upon rotation speed and axis position. It was decided to use a mechanical bearing for radial stability – at the condition that this bearing does not provide any axial forces.

The demonstrator should work within *3krpm to 30krpm* of rotor speed. This upper limit has been given by the used power supply / motor pair. It allows to use cheaper aluminium parts for the rotor assembly instead of high strain materials and assures operator's security while manipulating the system.

In the sense of a flywheel application, the axial magnetic bearing should work at *minimum energy consumption*. Especially, it should present no consumption as long as the rotor is in the axially centred position. Furthermore, the generator and the actuator should not introduce radial instability. Note that the motor used for this demonstrator is not of the same type as it will be used for the flywheel, so there is no special constraint on it.

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[1] J. Sandtner, J. Bermudez, H. Bleuler, "High speed passive magnetic bearing with increased load supporting capabilities" presented at the 7th International Symposium on Magnetic Bearings, August 23-25, 2000 at the Swiss Federal Institute of Technology Zurich (ETHZ) [consult annexe for a copy]

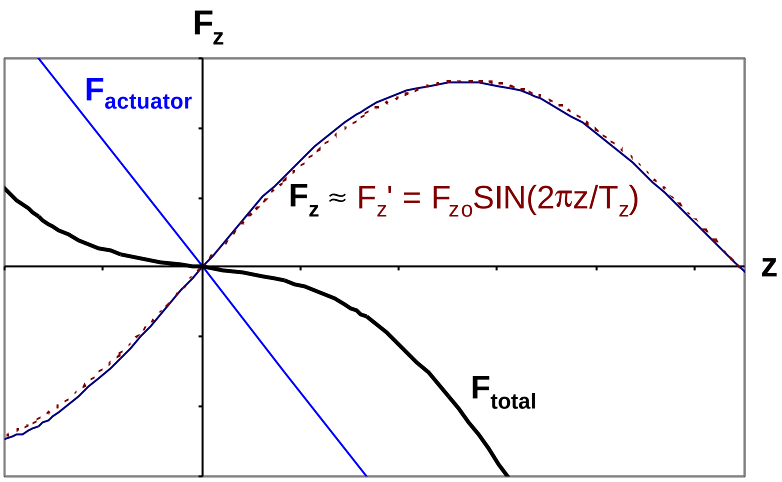
2. Basic concept

Please consult the article by Jan Sandtner et al [2] attached to the annexe. It describes a raw design to increase radial stabilisation forces for a magnetically suspended rotor – a basic design for axial stabilisation will be deduced from.

It is known that it is not possible to maintain tridimensional stability with a steady permanent magnet configuration. Thus, bidimensional suspension is easily obtained to the price of inevitable instability in the third dimension.

Therefore, different to the radial design, this demonstrator aims to set into practice an axial position regulator as a source of axial rotor stability and not only as a load capacity increment.

As the graph at the right shows, the actuator must provide higher restoring forces than the radial magnetic bearing compensates. If the total force stays retroactive, there is a good chance to obtain a stable rotor position.



Graph 1: Axial force caused by a radial bearing comprising five consecutive ring magnets on rotor as well as on stator. The period T_z is about two times the ring magnet thickness. For positions $z \in [-20\%, +20\%]T_z$, radial stability is maintained.

2.1 Demonstrator layout

Thanks to a similar system made by Jan Sandtner, the raw layout has been given as shown at the right.

All the rotor as well as their respective stator parts are movable parallel to the axis. This allows great flexibility to test several similar parts by simple exchange.

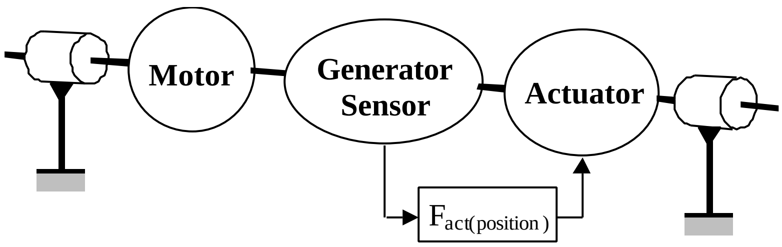


Figure 1: Coaxial arrangement of asynchronous motor, power generator/ position sensor and electromagnetic actuator. The rotor is kept on axis by two radial magnetic bearings [3]. A simple signal processing unit links generator and actuator.

Generator/sensor

The rotor assembly establishes a position and time dependent magnetic flux density. Time dependence is given by the rotation, while position dependence has to be set up carefully. One idea is to fix several permanent magnet pairs onto two identical discs. Then, the discs are mounted in front of each other. This gives a position dependent axial flux density between them [4].

The stator assembly contains several separated air coils. A number of coils are set up to give a nearly position independent AC voltage which can serve as a permanent current supply. Two other coil systems – one on the left and one on the right – supply each a position dependent AC voltage. If the rotor moves to the left, the left coils has to increase their voltage while the right coils decrease their own one. So, an excursion of the

2 J. Sandtner, J. Bermudez, H. Bleuler, "High speed passive magnetic bearing with increased load supporting capabilities" presented at the 7th International Symposium on Magnetic Bearings, August 23-25, 2000 at the Swiss Federal Institute of Technology Zurich (ETHZ) [consult annexe for a copy]

3 Replaced by mechanical bearings for this demonstrator. This allows measure of net actuator forces.

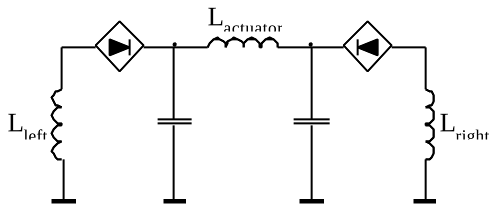
4 Take care about eddy currents appearing in stator parts because they would brake down rotation speed. It is recommended to restrain magnetic flux to the generator's interior.

rotor causes a voltage difference to appear. This voltage difference indicates the actual rotor position and also supplies power to the actuator.

Signal processing

This unit conditions generator's output power and transfers it to the actuator. Usually, the actuator needs a DC current while the generator delivers an AC one. Therefore, it will be necessary to control the sense of actuator's current depending upon the rotor position.

The unit has to comprise as few electronic parts as possible. At least, it should not rely on any active electronic device. Thus, the electric schema at the right was proposed. It uses only passive elements but lacks of steady actuator current because either the first or the second full wave rectifier is blocked.



Schema 1: Completely passive signal processing

In fact, it requires supplies with current sinking capabilities.

Actuator

The actuator is build of one or several coils. Either the coils attract to a ferromagnetic surface when a current (AC or DC) flows through them or, if permanent magnets are used, the coil's current (DC only) in the transversally magnetic field will create a Lorenz force.

Having a dedicated actuator aims to improve the energy loss/force ratio. In this sense, permanent magnets are a must. They enable a bi-directional configuration by means of one single coil. They also help save space and energy – the higher flux they offer, the better.

2.2 System stability

With an electromagnetic actuator, a position $x_{(t)}$ has to be regulated to zero:

The current $I_{act(t)}$ is controlled. Flowing in a copper coil of the actuator, $I_{act(t)}$ creates a linearly proportional magnetic field which causes a linearly proportional force $F_{act(t)}=C\cdot I_{act(t)}$ to appear. Given Newton's law, it solves for $F_{act(t)}=m\cdot d^2x_{(t)}/dt^2$.

If a pure proportional regulator $I_{act(t)}=K_p\cdot x_{(t)}$ is used, the system behaviour suites $m\cdot d^2x_{(t)}/dt^2=C\cdot K_p\cdot x_{(t)}$. The result of this homogenous differential equation is $x_{(t)}=A\cdot\cos(2\pi\cdot t/T)$ with period $T=2\pi\cdot[m/(C\cdot K_p)]^{0.5}$ and amplitude A. There is a resonance at frequency $f_T=1/T$, thus the system will be unstable if it is not introduced additional damping.

Another approach uses a proportional-differential regulator giving $I_{act(t)}=K_p\cdot x_{(t)}+K_d\cdot dx_{(t)}/dt$. The proportional term serves to kill any steady state error and to counterbalance constant force perturbations. The differential term leads to an exponential behaviour $x_{(t)}\approx A\cdot e^{-k\cdot t}$ of the system and damps it. Fortunately – because damping is done by the regulator – it will not necessarily cause additional energy losses.

A more careful study of system behaviour leads to an optimised regulator frequency response of the form $K_{(f)}=K_p\cdot(1+j\cdot f/f_z)/(1+j\cdot f/f_p)$ with $0.3f_p\approx f_b\approx 3f_z$ where f_b is the bandpass frequency for unitary gain of the system's open loop transfer function $X_{(f)}\cdot K_{(f)}$. This regulator type better suppresses steady state errors and high frequency modes.

Note that the above considerations only applies if F_{act} depends exclusively on I_{act}.

2.3 Application limits

For proper contactless function, the generator/actuator pair has to overcome the axial destabilising effect of the radial permanent magnetic suspensions. This condition imposes that the generator/actuator pair provides higher stiffness than the suspensions compensate.

Thus, in a limited axial range, the rotor's position can be regulated. Out of this interval, the rotor's position cannot be kept stable – the bearing's permanent magnets would attract each other establishing mechanical contact. Therefore, it is a good idea to impose mechanical emergency bearings keeping the rotor in a save position range.

3. Design

3.1 Power generator / sensor

The basic idea was to use two planar slices equipped with permanent magnets face to face. In the space between the slices, an axially variable magnetic field is established. A coil placed somewhere in this field produces a periodic voltage with variable amplitude depending upon axial position and rotation speed.

A planar multipolar Halbach arrangement of the permanent magnets has been tested earlier. To simplify the construction – and also to test another configuration – it was replaced by a planar multipolar field shielded externally by ferromagnetic rings.

Figure 2 shows the retained design for the generator discs. Their interior will be equipped with several coil pairs – one coil at left side, one at the right. A coil pair connected in differential mode creates a voltage proportional to the excursion of the rotor, while additionally connected coil pairs return a nearly position independent voltage.

It is possible to put the permanent magnets in two configurations – either the magnets pull or push their opposite neighbours. If they push their neighbours, they are in the *repulsive mode*, otherwise in the *attractive mode*.

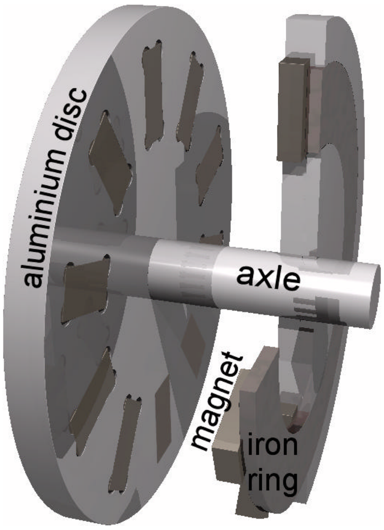


Figure 2: Basic generator design.

Geometry

The external diameter of the generator has been fixed to 115mm [5]. While the axle diameter was given by other existing systems, the generator's axial position has to be adjustable. So a fixation by means of a conic ring was designed to enable easy displacement of the discs. It results an inner keep out area of ∅36mm. So, the permanent magnets are best centred at about ∅80mm. The highest magnetic flux is achieved by cubic NdFeB magnets. Their dimensions were chosen to standard 10mm·20mm, 5mm thick [6].

Simulation showed that a 3mm thick iron ring shields over 99% of the magnetic field. Also, it pointed out that an arrangement of ten to twelve magnets impose a nearly sinusoidal change of the axial field density between two successive magnets. It was decided to use ten magnets per disc because this design fits well for either a four or six phase generator [7].

Characteristics

The following figures result from simulation to compare both modes. They show a section through the discs at constant radius from the axle of the rotor. The left and right sides are limited by the iron rings, keeping the field entirely in the inner space between the discs. At the centre is the air gap.

[5] Prevents destruction of the rotor when rotating at 30krpm. See "3.3 Mechanical design tips".
[6] Thicker magnets will not increase significantly flux density through the air gap, but consume more space.
[7] Each phase needs at least one coil. More phases would have been too difficult to realise – without mentioning increased cost for rectifiers and so on.

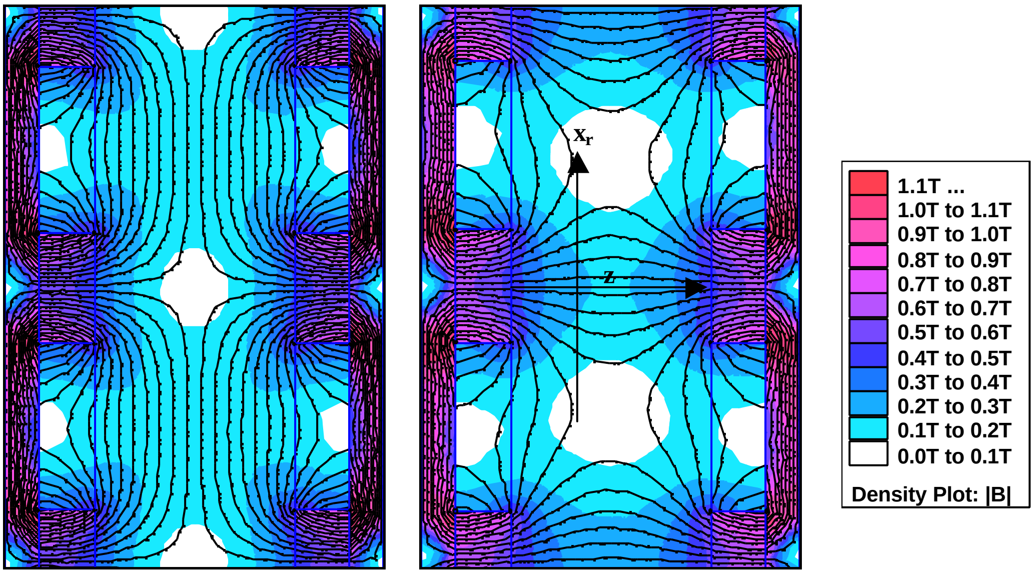
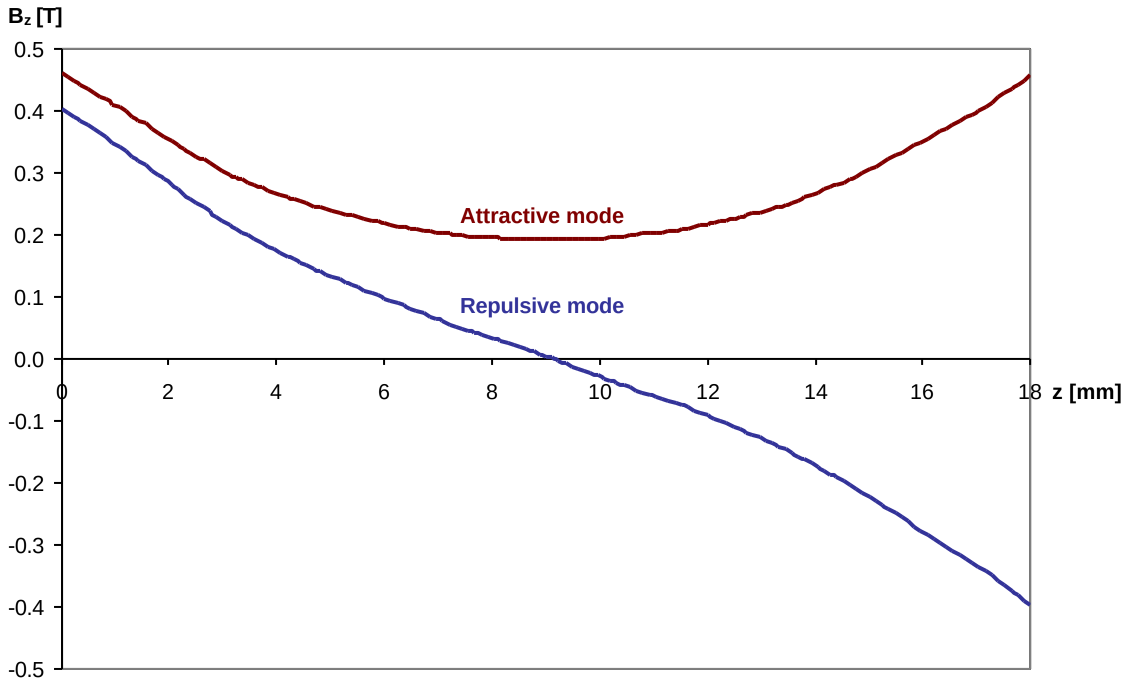


Figure 3: Section through magnets in repulsive mode.

Figure 4: Section through magnets in attractive mode.

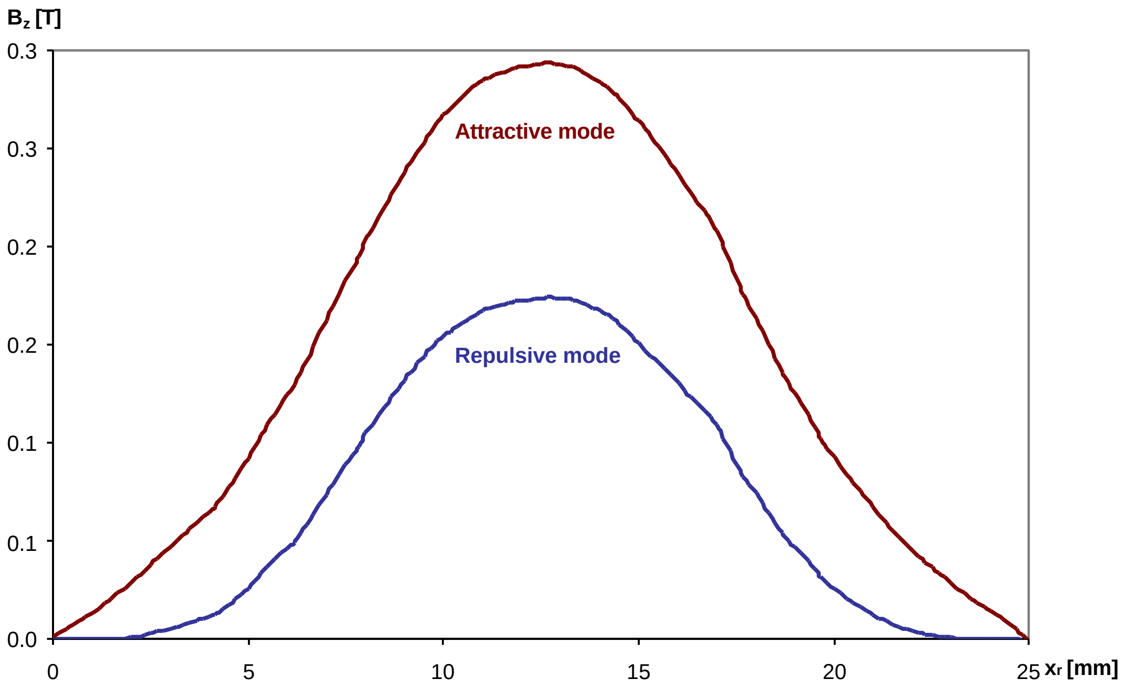
Figure 3 shows a highly flattened field towards centre position. Especially, the axial flux is zero there. In contrast, figure 4 presents a sort of bottle-neck flux between opposite magnets, giving a smooth decrease of axial flux towards the centre of the air gap.



Graph 2: Axial magnetic flux density between two opposite centres of permanent magnets [8].

Note the nearly equivalent decrease of magnetic flux for distances below 4mm from the disc surfaces. In attractive mode, it is possible to obtain a quasi position independent voltage by placing a thin coil in the centre of the air gap.

[8] Consult figure 4 for axis location.



Graph 3: Axial magnetic flux density over a permanent magnet at z=5mm from the disc surface [9].

In attractive mode, the axial flux density is approximately of sinusoidal shape. Thus, the resulting voltage can be expected to be sinusoidal too. The repulsive mode introduces a flat zone between the magnets, where the axial flux disappears. Thus, the voltage will stay at zero while passing this region.

It was decided to keep possible both variants. The design of the generator discs has been adapted to allow easy switching between the modes. Turning one disc against the other is all. As a consequence, the generator coils are arranged as pairs – one in the left and the other in the right half of the air gap. This allows several connections – standalone, in parallel, additionally in series or differentially in series [10].

3.2 Axial actuator

The actuator designs shown below are both rotation symmetric. This symmetry reduces significantly the appearance of eddy currents in the actuator parts itself but also in the closer neighbourhood. Magnetic fields appear to be steady while magnets are in fact rotating.

[9] Consult figure 4 for axis location.
[10] Switch to “3.4 Signal processing” for explanation of the coil configuration.

Two unidirectional coils

This solution is based on a symmetric coil pair, each attracting to the opposite direction of the other. The coil's counterpart is of ferromagnetic material. The main advantages are rather high attraction forces which can additionally stabilise the radial position of the rotor. But on the other hand, it is difficult to obtain axial stability because the force $F_i \propto \Delta z_i^{-2}$ grows for a decreasing distance Δz_i between the coil and its counterpart.

Summing both forces leads to:

$$F_{tot} = F_{right} - F_{left} \propto \Delta z_{right}^{-2} - \Delta z_{left}^{-2}$$
$$= (z_0 - z_1 - z)^{-2} - (z - z_0 - z_1)^{-2} \propto \underline{\underline{z^{-3}}}$$

As long as the ferromagnetic parts are not saturated, the resulting force gives heavy positive feedback in direction of rotor's displacement, thus destabilising the axial position.

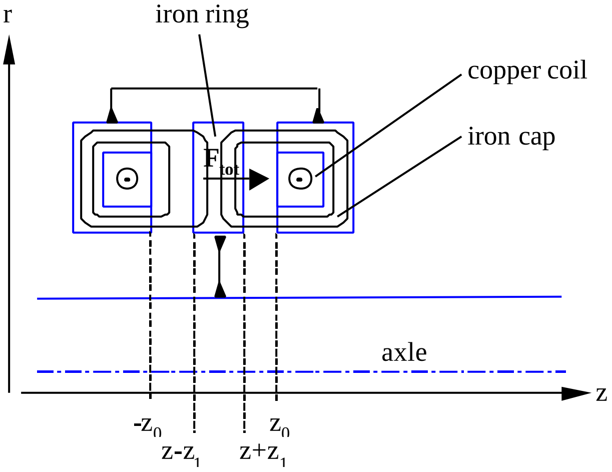


Figure 5: Axial section through rotation symmetric actuator.
The rotor is at position z out of centre.

One bi-directional coil

This solution is just like a loudspeaker. A single coil is placed into a radial magnetic field. So, an electric current through the coil causes an axial Lorenz force. Its direction and amplitude depends linearly on current's sense and amplitude.

This design has been retained, because it allows a more compact design and higher forces in spite of less current, thus an overall reduction of electrical losses. Even better, it could be designed to give a nearly constant force/current ratio over the entire moving range. In fact, the Lorenz force reduces slightly while excursion of the rotor increases. But fortunately, its direction is controlled by current's sense.

Geometry

The dimensions of the actuator has been limited by the size of industrially available NdFeB ring magnets. For a reasonable price, magnets of external ∅40mm, internal ∅23mm and length of 6mm were available. It was necessary to stack two magnets at each side to reach optimal height. In fact, simulation showed that a length above 9mm does no longer significantly improve the magnetic flux density through the coil. But at only 6mm, flux density would decrease by about 30%. Thus the 3mm overkill seemed reasonable.

The coil has to sit as close to the magnets as possible. It is stuck therefore at the interior of a cylindrical plastic frame. Because the best current/force efficiency is reached for a thin coil, inner ∅41mm and outer ∅47mm at a length of about 8mm were chosen.

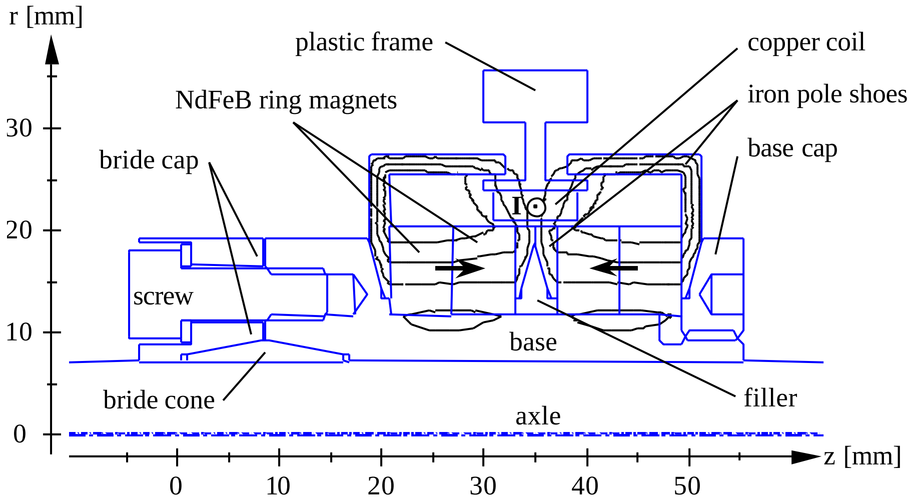


Figure 6: Axial section through rotation symmetric actuator.
The copper coil is stuck into the plastic frame. Both are part of the stator assembly.
Note that there are no radial forces between the stator and the rotor subassembly.
Please consult the annexes for exact dimensions.

Characteristics

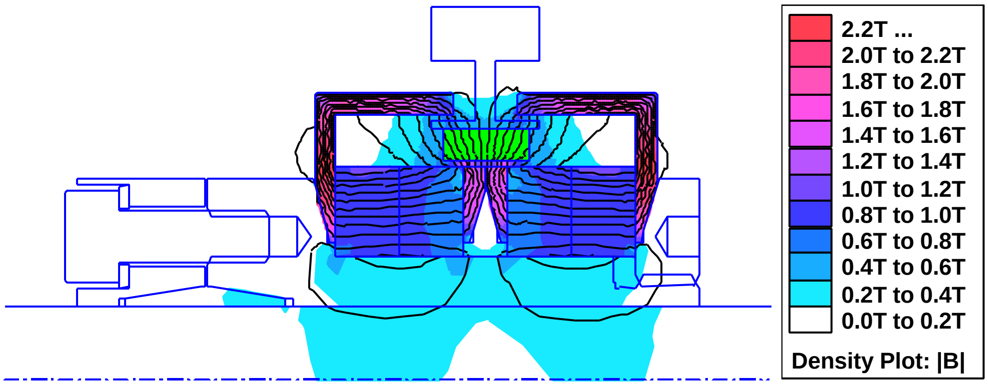


Figure 7: Magnetic field lines in actuator's axial section.
The conic pole shoes guide more than 50% of the magnetic flux through the region of interest.
Simulation calculates axial force F_{act}≈12N for a coil current density J_{act}=5A/mm^2.

The axial force is nearly position independent in a range of ±1mm like needed. Also, the radial forces are negligible.

3.3 Mechanical design tips

To keep rotor assembly simple and robust, it was decided to fix the entire electrical part onto the stator. The rotor comprises only some solely fixed parts like permanent magnets.

Another simplification could be done by using two conventional oil-lubricated sintered bronze glide bearings providing excellent radial stability and nearly no axial friction during rotation. For the flywheel, they will be replaced by two contactless permanent magnet bearings.

Materials

The axle has to be of highest stiffness possible with a good damping of mechanical vibrations to break down rotational resonance effects. It has to be paramagnetic to prevent influence on magnetic fields of generator and actuator. Therefore, a high strain steel has been chosen. The conic rings has been made of the same material for simple fabrication and for assembly reliability.

The ferromagnetic parts are made of pure iron or soft steel. This applies to the shield rings of the generator discs and to the pole caps of the actuator.

All other parts were cut out of high strain aluminium blocs. The chosen aluminium alloy is easy to work and offers an excellent mass/strain ratio [11]. The high strain is needed especially for the generator discs. At 30krpm, due to their external diameter and the implanted magnets, the discs have to withstand maximal stress of about 100MPa in both radial and azimuthal direction [12].

Of course, industrial parts (screws) are just of standard materials (stainless steel...).

3.4 Signal processing

The start point was the schema 1.

Actuator power supply

The actuator coil dimensions have been given by the size of available permanent magnets. Limiting the coils current density J_{act}<5A/mm^2 [13], the current I_{act} was deduced.

Current: $$I_{act} = \frac{T_{act} L_{act}}{N_{act}} J_{act} \approx d_{act}^2 J_{act}$$ [14]

The actuator current is designed to be a rather static DC current.

Voltage: $$U_{act} = R_{act} I_{act} \approx r \frac{4 L_{act} T_{act} (D_{act} + T_{act})}{f_{act}^2} J_{act}$$

If a simple diode is used instead of a full wave rectifier, the voltage loss across the diode is about 1V. Together with the loss in the generator coil, it leads to:

Total loss: $$U_{loss} = 1\text{V} + R_{gen} I_{act}$$

The generator coils should work as differential pairs to supply themselves a linearly position dependent voltage. But their resistive losses would double. For nominal actuator force at minimum speed and maximum excursion of the rotor, they had to give at least a differential voltage of:

$$\begin{aligned} \Delta U &= U_{act} + U_{loss} \\ &\approx 1\text{V} + 4r \left(\frac{L_{act} T_{act} (D_{act} + T_{act})}{f_{act}^2} + 2 \frac{L_{gen} T_{gen} (p T_{gen} + 2 H_{gen} + 2 W_{gen})}{p f_{gen}^2 d_{gen}^2} d_{act}^2 \right) J_{act} \\ &= 1\text{V} + 340 m\text{V} \left(\frac{1070\text{mm}^2}{f_{act}^2} + \frac{8.4 T_{gen} (19.1\text{mm} + T_{gen})}{f_{gen}^2 d_{gen}^2} d_{act}^2 \right) \end{aligned}$$

Used values:

$$D_{act} = 41\text{mm} \quad L_{act} = 8.1\text{mm} \quad T_{act} = 3.0\text{mm}$$

$$H_{gen} = 20\text{mm} \quad L_{gen} = 4.2\text{mm} \quad W_{gen} = 10\text{mm}$$

$$J_{act} = 5\text{A/mm}^2 \quad r = 17 m\Omega\text{m}$$

H_{gen} and W_{gen} were set to the dimensions of the magnets used. L_{gen} was set to keep the coils in the interval of variable magnetic flux as detailed in graph 2.

Furthermore, the voltage U_i is induced in the generator coils. At an excursion of 1mm, the flux density varies by $\Delta B_z \approx 45$mT and, at minimum speed, the phase frequency is $\omega = 10\pi \cdot 50$Hz [15].

11 AlMgSiMn T6 has a density of 2.9g/cm^3 and offers maximal resistance of at least 295MPa – the admissible steady stress is about 150MPa.

12 See “B.1 Centrifugal forces” for an example of calculation.

13 Heating due to resistive loss limits the static current density to about 4A/mm^2.

14 Description of symbols in “A.1 Resistance and inductance of circular coil” and “A.2 Resistance and inductance of rectangular coil”.

15 The permanent magnets of the generator supply five full periods.

Induction: $$U_i = N_{gen}\frac{d\Phi_m}{dt} - L_{gen}\frac{dI_{gen}}{dt}$$

$$\approx 2w\frac{L_{gen}T_{gen}H_{gen}W_{gen}}{d_{gen}^2}\left(\Delta B_z - \frac{m_0 d_{act}^2 J_{act}}{\sqrt{L_{gen}^2 + H_{gen}W_{gen}}}\right)$$

$$= 2.64m\text{Vm}\frac{T_{gen}}{d_{gen}^2}\left(45 - \frac{d_{act}^2}{2.35\text{mm}^2}\right)$$

$$\approx 118m\text{Vm}\frac{T_{gen}}{d_{gen}^2}$$

Now, set U_i=ΔU and solve for the undetermined variables while reducing the power loss $I_{act}\cdot U_i$. Limit T_{gen} to less than 7.5mm – say half the space between successive magnets.

The optimisation problem was solved on the computer. It showed that wire diameter has a minor influence on the total power loss. For geometric reason, the condition U_i=ΔU could not be fulfilled at minimum speed for an excursion of 1mm. Why not increase the excursion? Well, stiffness does not change at all and, if excursion exceeds about 1.5mm, U_i increases slower as a result of the magnetic flux density in the generator.

For this demonstrator, one single type of wire was used. So, $d_{act}=d_{gen}$=0.34mm and $\phi_{act}=\phi_{gen}$=0.30mm. The voltages reach ΔU=11.4V and U_i=7.7V for T_{gen}=7.5mm. This means that the nominal actuator force F_{act}=12N is obtained only for rotor speed above 4´500rpm. Nevertheless, the system works as long as the axial stiffness rests sufficiently high to beat the instability of the magnetic bearings. Otherwise, one could change to a nonlinear feedback and use single coils instead of differential pairs.

Having several solutions in mind, an adjustable configuration was chosen. It seemed reasonable to use a four phase generator because it would suffice to provide a rectified low ripple voltage U_{act}. The actuator power is drawn from four coil pairs. Each pair can be reconnected for experimentation.

Note that stability benefits from a nearly constant U_{act} giving a constant actuator force. Note also that if more phases had been used, the generator coils would have been very close together – thus more difficult to design and assemble. Not at least, the part of each generator coil to the total actuator power decreases with increasing number of phases.

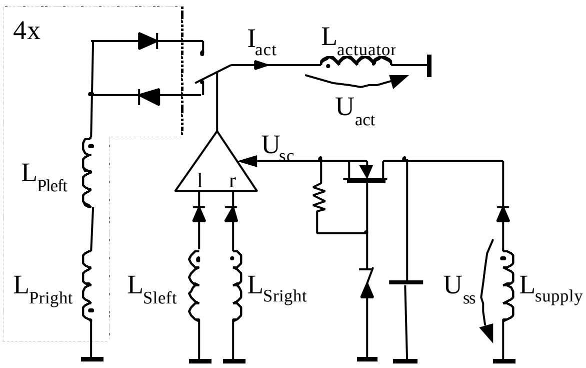
Modification of the regulator

As drafted in schema 1, the regulator has to do a little more work than rectifying and buffering the power arriving from the generator. The capability of withstanding steady forces is an obvious charge. Another is the need for reasonable damping and high precision of the rotor position. Either one places shunt resistors parallel to the capacities, or one uses some active electronic parts.

Shunt resistors would introduce permanent power loss, so power MOSFETs has been preferred although their gates has to be driven by a DC voltage. Passive parts would need high sensor voltages together with protecting Zener diodes to deduce the typical gate–source voltages from 4.5V at threshold to 20V at break through. This would waste energy at higher rotation speed.

Finally, the use of a standard operation amplifier came in favour. Unfortunately, it demands a constant supply voltage. On the other hand, it offers a far lower sensor threshold voltage for comparison. So, it consumes less power to adapt the sensor outputs to the amplifier inputs.

For the amplifier supply, a depletion mode MOSFET combined with a Zener diode gives a fairly robust solution. The output voltage U_{sc} stays clamped to the sum of the Zener voltage and the gate–source threshold voltage. Advantageously, the Zener diode can be supplied by the output. Therefore, its current stays constant for any input voltage U_{ss}.



Schema 2: Modified signal processing.

Regulator layout

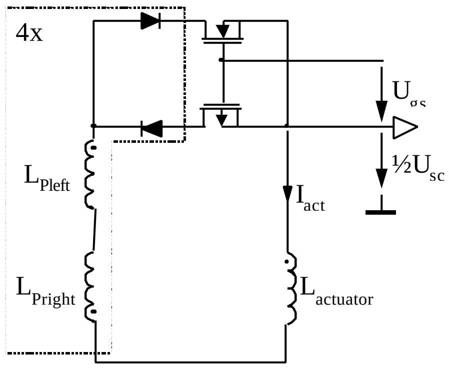
Fixing the concrete layout was not as easy as thought. The main problem was posed by the high dynamic range of each voltage coming from a generator coil. In fact, system components supporting more than a tripling of input/output voltages are rare.

Voltage and current requirements:

Operation amplifiers need a single supply from about 6V to 30V. If very low quiescent current is preferred, most available amplifier support 6V to 15V.

Power MOSFETs have typically a threshold voltage U_{th} from 2V to 6V. Maximum gate–source voltage U_{GS} is three to four times the threshold level but rarely above 20V. High maximum gate–drain voltage U_{GD} and drain–source voltage U_{DS} is only available for U_{th}>4V.

As calculated above, the actuator power supply coils create peak voltages of 7.7V at 3´000rpm, thus about 80V at 30krpm! Considering that a switched inductance induces voltage spikes, U_{DS}>120V was preferred. In this range, available transistors supporting drain currents I_D>1A have U_{th}≈4.5V and U_{GS}=20V [16]. Or, U_{GS} imposes that the transistor sources are both connected to a floating mass of half the operation amplifier supply potential. So, the drains are kept away from the more sensible electronic parts. They are separately connected by rectifier diodes to the generator coils.

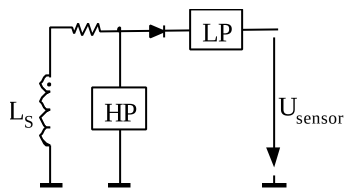


Schema 3: Switch configuration.

The operation amplifier output drives both gates. At high level, its output must be above U_{th} but below $-U_{th}$ [17] at low level. Therefore, an amplifier [18] having more than 12V output dynamic was chosen. A 13V supply seemed reasonable, enabling a ±6.5V output range.

The amplifier supply coil has to give a peak voltage of about 15V at 3´000rpm. After passing through a rectification diode, buffering and reduction by a voltage regulator, it will just rest the constant 13V supply voltage. It follows the same game as above: 15V at 3´000rpm ⇒ 150V at 30krpm. With a depletion mode pMOSFET and a 12V Zener diode, it was possible to supply the amplifier by drawing <50µA ⇒ 7.5mW peak consumption!

Finally, the sensor coils were chosen. The higher their peak voltage, the higher the voltage difference would be for a given excursion of the rotor position. But the higher the voltage, the higher the consumption and the more difficult the link from coil output to amplifier input. A good compromise was found with a peak voltage from 4V at 3´000rpm to 40V at 30krpm. A resistance in series with a high pass filter limits the voltage range at 3.5V to 9V. After rectification and low pass filtering, each sensor output links to an amplifier input.



Schema 4: Sensor adaptation.

Note that extraneous sensor coils were required due to the different voltage requirements of the actuator and the amplifier.

Regulator requirements:

Not knowing the exact behaviour of the system, it seemed reasonable to preview a variety of possible configurations for the amplifier inputs/output. The idea was to have a circuit allowing a quick modification of the regulator behaviour. The layout allows to reconfigure the amplifier as a proportional (P), differential (D) or combined (PD or even PD^2) regulator.

3.5 Electrical design tips

As a basic rule, keep circuit simple and put close together what is linked. The use of a mass plane can reduce electromagnetic noise too. Separate low and high voltage subcircuits and, only if necessary, link them by a single potential.

16 Refer to the datasheets “IRF9640 HEXFET® Power MOSFET” and “IRF620 HEXFET® Power MOSFET”.
17 In reference to the source potential = floating mass potential. See “D. Circuit of signal processing unit”.
18 Consult the datasheet “LMC6042 CMOS Dual Micropower Operational Amplifier”.

For convenience, use two operation amplifiers in series. The first calculates the difference of its input voltages and adjusts them to an arbitrary ground level. The second implements the PID regulator by comparing the output of the first amplifier to the chosen ground level. In general, ground level should be about half the supply voltage to work at best amplification and CMRR of the amplifiers.

Take care about voltage spikes appearing on a switched inductance. For example, use a double Zener diode as protection against disastrous spikes. Finally, do not forget to eliminate current loops where possible.

4. Realisation

4.1 Problems during construction

Mechanics [19]

The design asked for 10mm long glide bearings. Because of the very restraint quantity – two in this case – the trader did not order specially this length and furnished glide bearings 13mm long instead. Advantageously, the axle support was made moveable and able to handle bearing lengths up to 15mm.

The axle endings were at tolerance but not at the demanded surface quality. They needed manual polishing and decanting to prevent any damage of the bearings. In fact, if the axle does not fit into the bearings without notable resistance, it is a good idea to inspect their contact surfaces.

The coaxial alignment of the bearings was a critical point. Because of mismatched axle supports, the axle blocked whenever inserted into both bearings. To not rework the supports and the base plate, some thin metal pieces/papers were put under the axle supports – just for adjustment.

Finally, almost all dedicated parts were made of an aluminium alloy which made it simple to match the permanent magnets into their openings. The openings were fitted quite fast to exactly the needed dimensions.

Electronics [20]

The circuit did not pose problem at assembly time. But as formerly previewed, the regulator was somewhat difficult to adjust [21]. As predicted in “ 2.2 System stability”, the rotor oscillated nervously around the centre position if a simple proportional regulation was used. Its oscillation frequency was about 2Hz to 10Hz depending upon the connections of the generator coils.

Quickly, a proportional/differential (PD) regulator showed useful. It was able to damp the oscillation fairly well without introduce a significant regulation error.

Several coil connections were experimented. Finally, all non-proportional solutions had to be given up in lack of a reasonable regulation. These configurations created up to ten times higher actuator forces than the retained solution, but the oscillation could not be suppressed. A more powerful regulator would allow to

a) profit from the repulsive force in the generator if only one half the coils power the actuator at the same time
b) connect the generator coils in parallel, thus multiplying the actuator current [22].

Miscellaneous

The used triphase asynchronous motor did not reach 30krpm. Although it spun up to 10krpm in reasonable time, its acceleration decreased for higher speeds. The effect was well notable and limited the rotor speed to about 12´500rpm. It is thought that its iron lamellas for the rotor and stator were too thick and therefore rejected the magnetic flux at higher frequency. In fact, the effect was always noted in common with the appearance of an axial force rejecting the rotor out of the stator cage, whereas it was pulled into before.

4.2 Chosen regulator behaviour

As a result of experimentation, these passive electronic parts were assigned to the following values [20]:

$C_3 = 1.5\mu F$ $R_2 = 4.7k\Omega$ $R_3 = 0$ (wire) $R_6 = 220\Omega$ $R_7 = 100k\Omega$

The other parts with unspecified values were not used. This concerns C_4, R_4, R_5 and R_8.

This regulator configuration sets the static regulator gain $K_p = -R_7/R_2$ to 21. The gain starts increasing at a frequency $f_z \approx 1/2\pi C_3(R_4+R_6)=22Hz$ and stops at $f_p \approx 1/2\pi C_3 R_6=480Hz$ at $K_p' = K_p(R_2+R_6)/R_6=475$. It came out that the regulator mainly eliminates the integration effect introduced by the sensor input stages to keep constant the mean voltages for any rotation speed. They have a cut off frequency at 63Hz for a better compare but destabilise the system meanwhile.

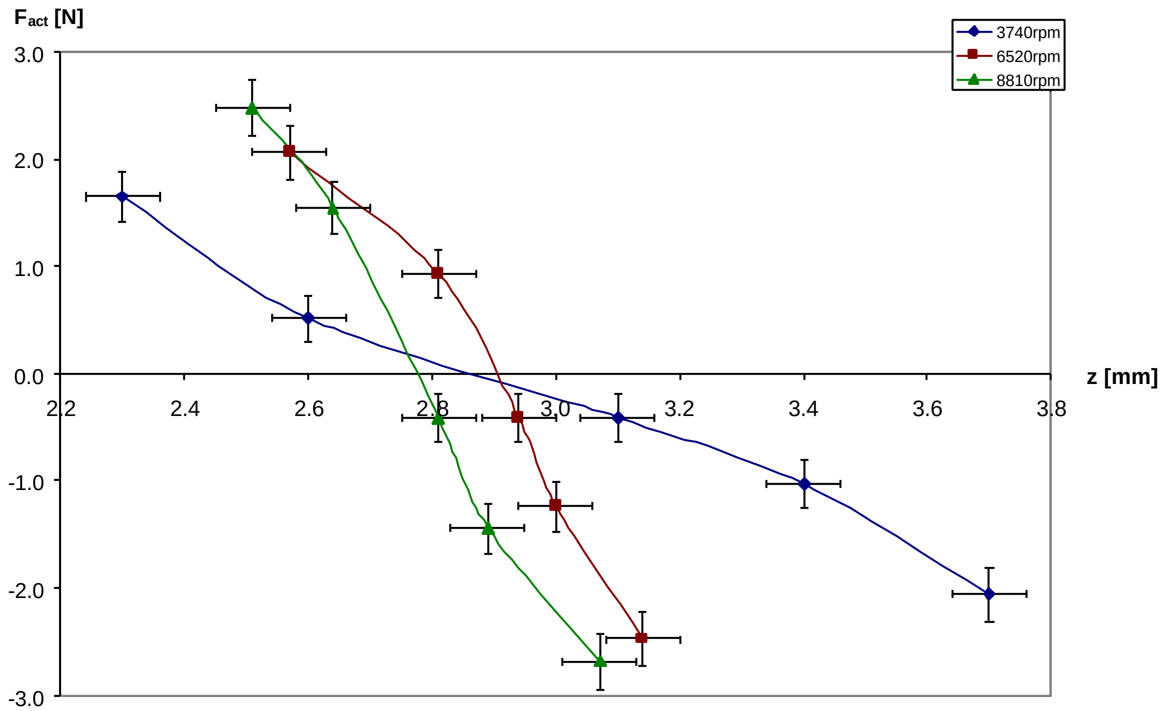
19 A description on how to build the demonstrator is given in “C. Assemblage”.
20 Consult “D. Circuit of signal processing unit” for more information.
21 It’s a good idea to use sockets for the parts configuring the regulator behaviour.
22 This solution corresponds to a non-linear ‘staircase’ regulation (quick advance, waiting, fast withdraw).

5. Verification

The generator was configured for the attractive mode offering more coil interconnection possibilities. The stiffness at centred position will not significantly increase for repulsive mode because, at the closer vicinity of the permanent magnets [23], the axial magnetic flux derives as well for both configurations.

First, some electrical characteristics were verified [24]. The data was taken with inactive motor to prevent getting noisy values. In fact, the PWM motor driver introduces heavy spiking – a good reason to take a slower operation amplifier for the signal processing unit.

Second, mechanical characteristics have been determined – as are maximal drawback force and stiffness while regulating the axial position of the rotor. The axial force was given mainly by the actuator, while the generator and the motor created lower forces by side effects. The system characteristics were determined by measuring the actuator current for a given rotor excursion. The axial force was then calculated from the actuator's force–current ratio [25], neglecting the contribution of the generator.



Graph 4: Axial restoring forces and stiffness.
Note that the z axis has an arbitrary reference. Concentrate on the stiffness k corresponding to the slope $|dF_{act}/dz|$.

The graph shows the influence of the diodes used to rectify the actuator current. Its trace is a smaller slope around the zero crossing of the actuator force F_{act} at lower rotation speeds. The maximal measure error for the axis position is estimated to ±0.06mm, for the rotation speed to ±1% and for the force F_{act} to ±0.2N.

Assuming a constant slope, the stiffness was determined to:

a) 2.5kN/m±0.3kN/m @ 3´740rpm±40rpm
b) 8.1kN/m±0.9kN/m @ 6´520rpm±65rpm
c) 9.7kN/m±0.9kN/m @ 8´810rpm±90rpm

This can be resumed by a constant $K = \left|\frac{dF_{act}}{dz}\right| \frac{1}{w_{rotor}} = \underline{\underline{1\text{N/m} \cdot \text{rpm} \pm 20\%}}$.

[23] Remember that the generator coils were put exactly in this region.
[24] See "E.1 Generator" for detailed characteristics.
[25] Refer to "E.2 Actuator" for measurements.

6. Conclusion

The demonstrator was realised and tested.

The chosen design allows various experiments. Quick changes in generator configuration and regulator behaviour are particularly simple – just reconnect some generator coils or replace some passive electronic parts of the regulator.

The system proved its function. The axial restoring force was measured at several rotor positions and speeds. So, the stiffness was evaluated to be 1N/m·rpm±20% giving about 2kN/m at minimal respectively 25kN/m at maximal rotation speed. This is many times better than for an unregulated passive magnetic bearing but still small compared to the demanded stiffnesses from 100kN/m to 10MN/m.

The currently used regulator was not able to suppress the self-resonance whenever a non-linear feedback was tested. Thus, by means of a more powerful regulator, it should be feasible to benefit from the full generator power increasing the axial stiffness above 100kN/m for any rotation speed.