Magnetically Levitated Slice Motors – An Overview

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***Abstract*– This publication gives a comprehensive overview over different concepts of magnetically levitated motors with slice-shaped rotors that differ in their construction and the way the bearing and drive forces are created. After a description of the technical principle of the topologies the motor concepts are then compared by different criteria such as the acceleration behavior, the compactness and the complexity of the control. The qualitative comparison is supported by performance measurements on the laboratory prototypes.**

***Index Terms*— motor acceleration, magnetic levitation, permanent magnet machines, synchronous motor drives.**

I. INTRODUCTION

The everlasting trend for miniaturization and the increasing cleanness specifications in chemical, pharmaceutical, biotechnology and semiconductor industry applications [1] demand for high-purity process environments, since already smallest particles can damage the processed structures. Several process steps demand the equal distribution or the centrifugation of a process liquid through rotation (such as washing, coating, edging processes). A high acceleration capability of the drive is crucial for these processes in order to keep the process times and therefore the clean room costs as low as possible. The standard motors for these kinds of applications are servo motors, whose mechanical bearings and fittings cause small particles that decrease the process purity.

The implementation of magnetically levitated slice motors in these application fields gives the advantage of an almost unlimited life time, frictionless and wearless operation and the possibility of inserting a process chamber into the air gap that creates a completely encapsulated miniature clean room as depicted in Fig. 1. Process dependent conditions (pressure, temperature, humidity) can be provided locally and therefore also very cost efficiently in this process chamber. In order to construct a chemically resistant and mechanically stable process chamber a minimum wall thickness has to be provided directly affecting the minimum air gap size.

The application spectrum of magnetically levitated slice motors is not limited to process equipment. With the aid of these motors also mixing of fluids in stirred tanks and bioreactors [2] can be realized as well as pumping of highly pure fluids, such as acids in the semiconductor industry or blood [3] in medical applications.

Generally, magnetic bearings can be classified into active and passive bearings (cf. Fig. 2). The topic of superconducting magnetic bearings is not covered in this publication, since the cooling effort to sustain the superconduction is too big for the application areas at hand.

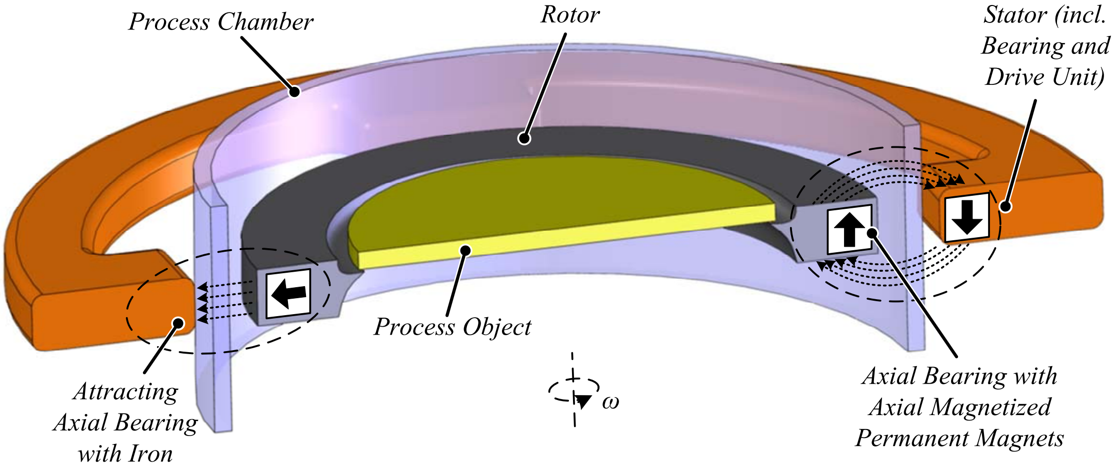


Fig. 1: Schematic cut view through a magnetically levitated slice motor with the process chamber in the air gap and with the two examples of bearing structures of the passive axial bearing with radially magnetized permanent magnets (left) and with axial magnetized permanent magnets (right).

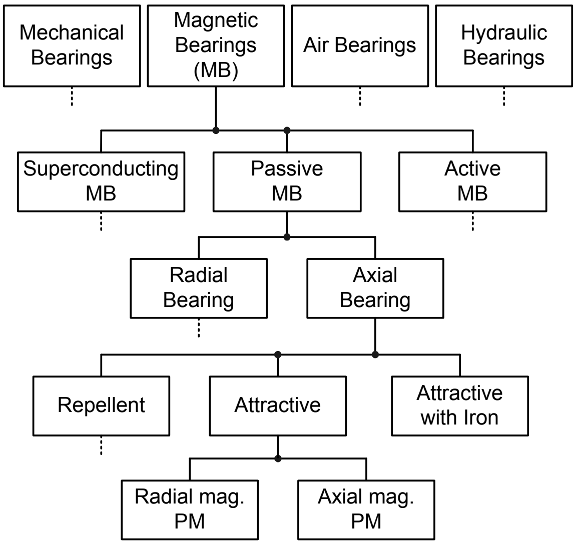


Fig. 2: Classification of the passive magnetic bearings at hand.

However, for the sake of completeness it is mentioned here.

The stabilizing effect of the passive magnetic bearings is generated through reluctance forces of attracting and repellent permanent magnets. The force of active magnetic bearings is generated through controlled electro magnets. Passive magnetic bearings are preferred, since they are highly compact and have a low complexity. Though, not all degrees of freedom can be stabilized passively as was shown in [4]. For the slice-shaped rotors at hand (large ratio of rotor diameter to rotor height) three of the six degrees of freedom can be stabilized passively. Therefore, passive and active magnetic bearings have to be used in combination.

In [5] a multitude of possible permanent magnet arrangements for passive magnetic bearings is introduced. The introduced group of passive radial bearings is less suited for an application with a process chamber wall, since the passive displacement is only controlled passively. Consequently, the rotor could touch or damage the process chamber wall for higher rotational speeds and possibly occurring resonances. Therefore, the group of axial bearings is preferred. Here, the concepts based on repellent forces seem disadvantageous, since rotor and stator level have to be arranged on top of each other. This would lead to an axially high and therefore less compact setup.

Therefore, the following overview over magnetically levitated slice motors covers only the preferred passive axial magnetic bearings with attractive forces (between PM or between PM and iron), since they are most favorable for the application areas of interest. For this purpose four motor topologies are explained in more detail in section II. In section III a qualitative comparison is presented that is supported by experimental results showing selected performance parameters. Section IV summarizes the conclusions of the paper.

II. TOPOLOGIES

This section presents four different magnetically levitated slice motor topologies in the scope of the introduced application areas of interest. All the presented motors have a ring-shaped interior rotor, but can be differentiated by the coupling between the magnetic circuits responsible for bearing force and drive torque generation, respectively.

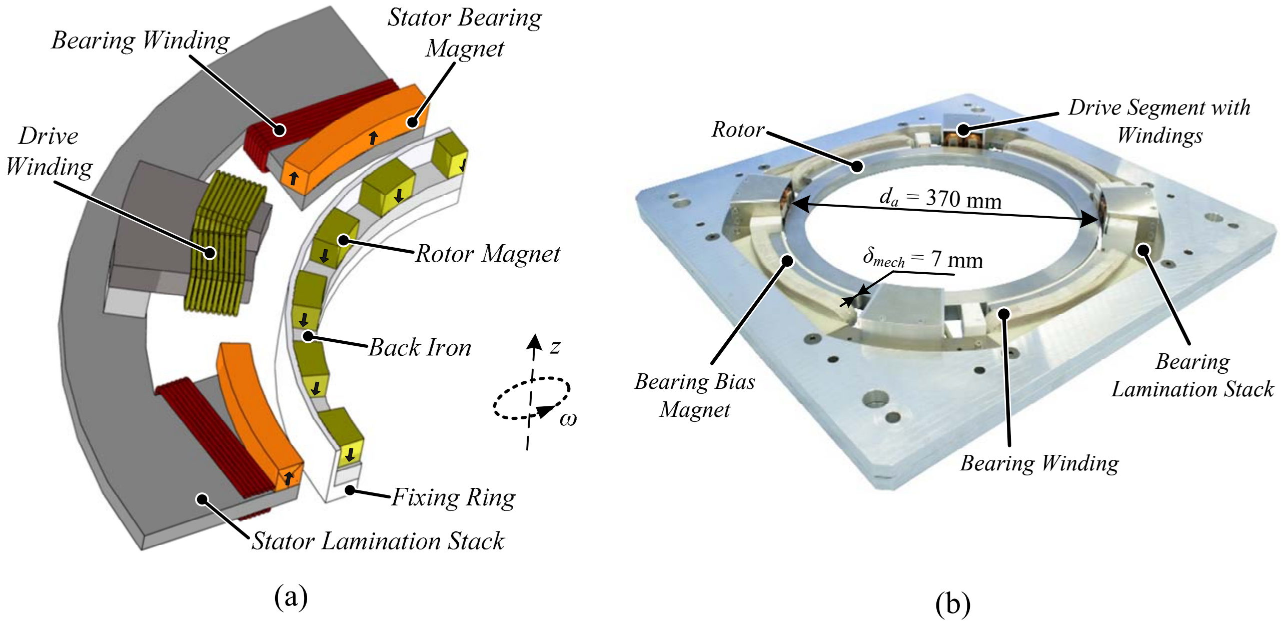
A. The Magnetically Levitated Homopolar Motor (MHM)

The magnetically levitated homopolar motor was introduced in [6] and a schematic cut view is presented in Fig. 3(a). The schematic cut view of the concept is shown along with the laboratory prototype in Fig. 3(b). The passive axial bearing is composed of the contrarily magnetized permanent magnets on rotor and stator, which stabilize the axial deflection and the tilting. Thus, only the radial deflection of the rotor has to be controlled actively.

In order to reach a highly compact construction this motor uses the stray fields of the permanent magnets of the magnetic bearing also for the drive unit. The rotor magnets are fixed on a back iron that constitutes the feedback path for the bearing and the drive flux. Since the drive principle is based on the permanent magnet synchronous machine (PMSM) [7] the flux density distribution in the air gap should ideally be sinusoidal, but has to be at least alternating. Therefore, the negative poles of the drive are achieved by leaving gaps between the rotor magnets. This results in a decrease of the bearing stiffness, which is compensated by increasing the bearing opening angle. A disturbing interaction between bearing and drive unit can only be avoided by offsetting the bearing and the drive along the perimeter, which also provides the targeted low profile height. However, the large bearing opening angle limits the space that is available for the drive unit. In order to still reach an acceptable torque and low acceleration times the drive coils should be implemented as concentrated windings with high imposed drive currents. Here, the torque generation is limited through occurring saturation effects.

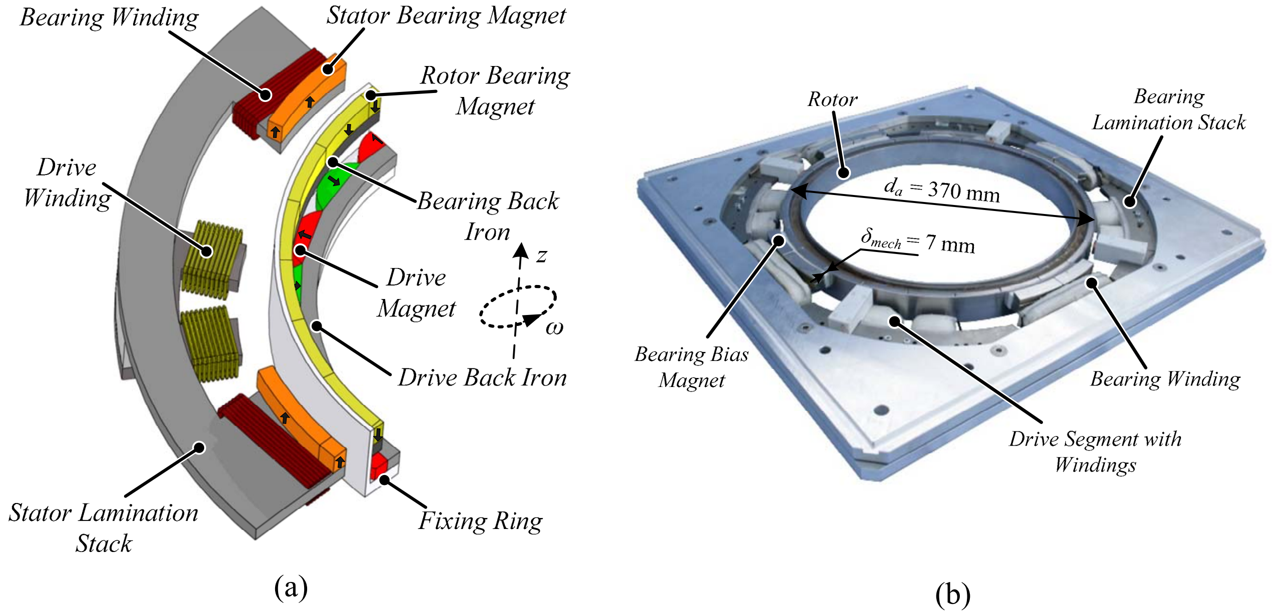
The two phase bearing windings and the two phase drive winding are depicted in Fig. 3. The offset from the middle position is measured by position sensors [8] and controlled to zero through the position control. The rotation speed signal demanded for the speed control is generated through angle sensors located in the stray field of the rotor magnets. The bearing and drive currents demanded by the subordinate current controllers can be provided by an inverter in half-bridge, full-bridge or middle point configuration [9], respectively.

The compactness of the magnetically levitated homopolar motor can be traced back to the shared rotor iron path for bearing and drive flux. This also implies that only a small drive torque can be generated through the use of only the



(a) (b)

Fig. 3: (a) Schematic cut view through the Magnetically Levitated Homopolar Motor (MHM) and (b) picture of the laboratory prototype.



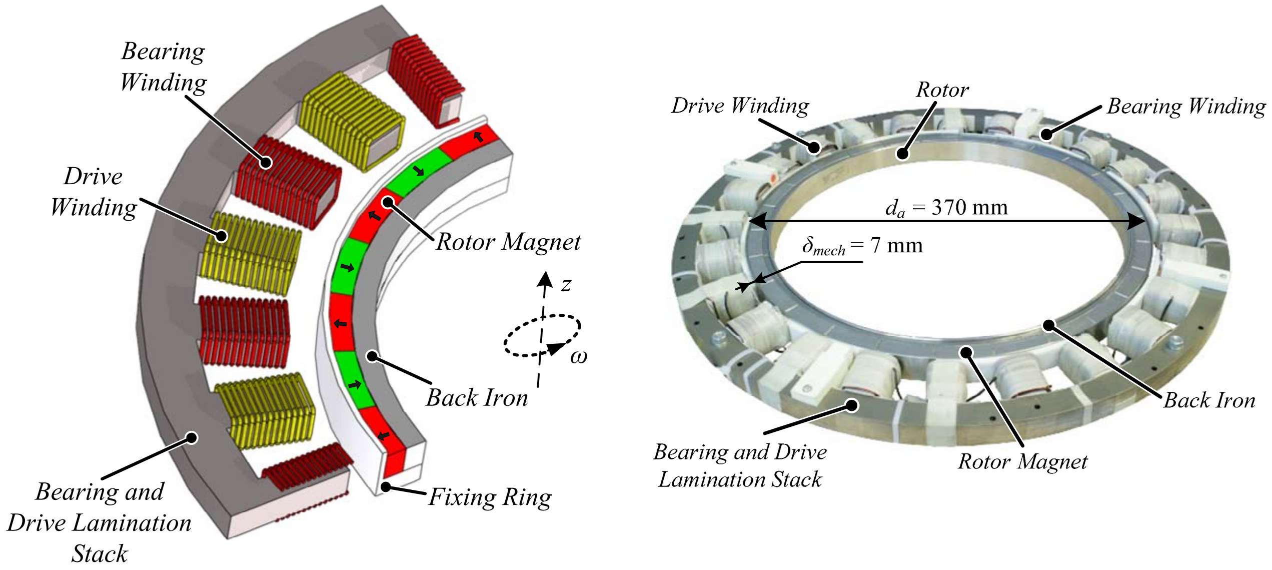
(a) (b)

Fig. 4: (a) Schematic cut view through the Magnetically Levitated Two-level Motor (M2M) and (b) picture of the laboratory prototype.

stray flux components of the rotor bearing magnets. The following subsection introduces a two-level motor concept that consists of two separated levels for the bearing force generation and the drive torque generation on both, the rotor and the stator side.

B. The Magnetically Levitated Two-Level Motor (M2M)

The basic functional principle of the magnetically levitated two-level motor that was introduced in [10] is that the bearing and drive forces are imposed on two different axial height levels on both the stator and the rotor side. A three dimensional cut view of such a motor is presented in Fig. 4(a). The corresponding laboratory prototype is depicted in Fig. 4(b). As for the MHM from the previous subsection also this motor uses an axial bearing with axially magnetized permanent magnets for the levitation of the hollow ring-shaped interior rotor. Due to the pure levitation functionality of the bearing the magnets can be implemented without any



(a) (b)

Fig. 5: (a) Schematic cut view through the Bearingless Fractional Pole/Slot Motor (BFM) and (b) picture of the laboratory prototype.

gaps between them.

On an axially lower level the radially magnetized drive permanent magnets are placed, which have an alternating magnetization direction and which are positioned on the drive back iron. The distance between bearing and drive level is chosen such that they do not influence each other and at the same time a minimal rotor height is provided. In Fig. 4(a) a possible construction with concentrated windings is shown that provides minimal profile height. Alternatively, also a stator construction with stator segments for bearing and drive being distributed along the whole perimeter would be possible. This variant would have the advantage of increased acceleration capability, but would also have a larger profile height.

Due to the radial magnetized drive magnets and the separated optimization of the bearing and the drive, the M2M can reach by far higher torque values than the MHM (cf. section II.A). However, the aforementioned increased rotor weight reduces the resulting acceleration capability and has a negative influence on the passive tilting stiffness.

Due to the two-level concept the bearing and the drive can be designed and optimized separately (number of poles, back iron depth, opening angle of drive and bearing), if a minimum axial distance between them is provided. An optimization of the M2M's drive unit yielding for minimal acceleration time is presented in [11].

Although the M2M has a far higher torque the acceleration capability is limited due to the mentioned reasons. Based on the concept of the bearingless motor technology [12] the bearing and drive forces can also be generated on just one level by the use of radially magnetized permanent magnets. Two motor concepts using this principle will be presented in the next two subsections.

C. *The Bearingless Fractional Pole/Slot Motor (BFM)*

The bearingless fractional pole/slot motor is characterized by a fractional ratio of the number of rotor poles and stator slots. This motor has been already implemented in several variants with interior rotor diameter smaller than 100 mm in industrial pump systems [2] and [3]. In these applications the rotor is a ring-shaped permanent magnet (number of poles is two) that is enclosed by an impeller housing.

Generally, the bearing force generation of bearingless motors can be described by the superposition of adjacent harmonics and the drive torque generation by the superposition of equal harmonics Therefore, a useful design can be found if the bearing winding generates an air gap field that is a harmonic order higher or lower related to the drive winding field. The drive winding itself has to produce the same harmonic order than the permanent magnet field.

For the BFM, this is achieved by a specific fractional pole/slot ratio along with an appropriate winding concept as described in [13]. Through the variation of these parameters (pole number, the number of stator slots and the number of phases), a multitude of topology variations can be found. These differ by utilization of the available electrical power for the torque and the levitation force.

In either case, large rotor diameters lead to an increased number of stator slots and to a high pole number in order to keep the magnet and back iron depth small and to utilize the windings efficiently. One possible motor structure is schematically depicted in Fig. 5(a). In Fig. 5(b) the

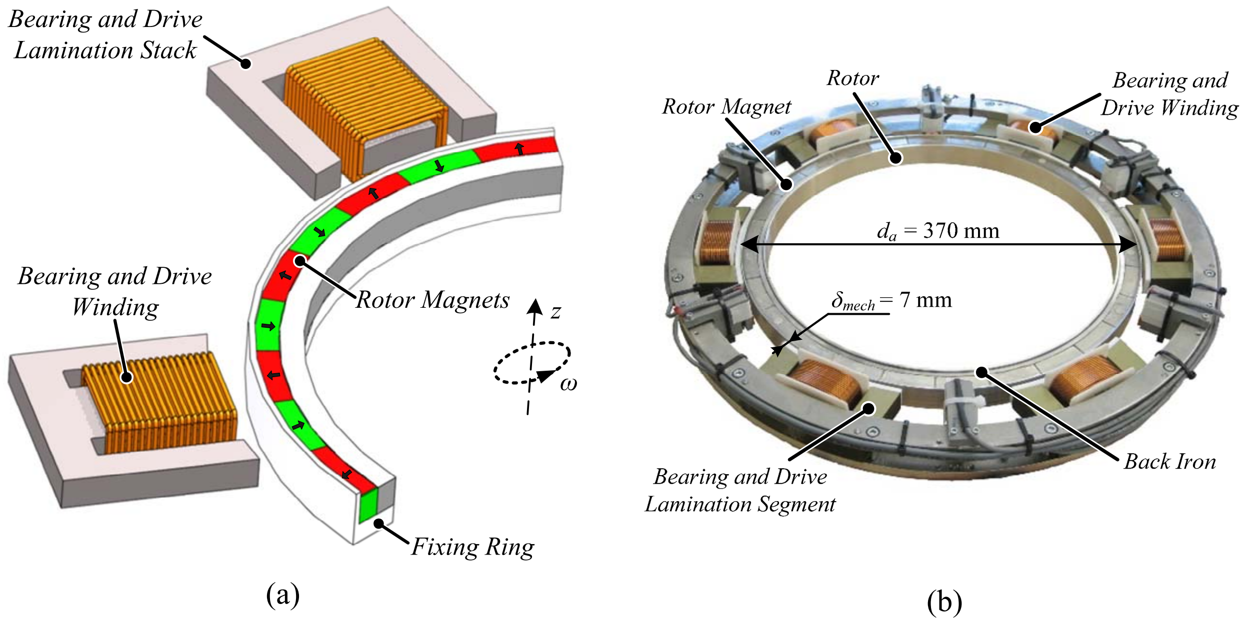


Fig. 6: (a) Schematic cut view through the Bearingless Segment Motor (BSM) and (b) picture of the laboratory prototype.

corresponding laboratory prototype is depicted. The figure shows that only alternately magnetized permanent magnets with the shape of circular segments are placed on the back iron and interact with the opposed stator teeth. Therefore, this magnetic bearing can be classified as an attracting passive magnetic bearing with iron. The bearing and drive winding can be alternately placed on the stator as shown in Fig. 5(a) or they can also be combined on a stator tooth. Here, the separate arrangement has the advantage of a separate winding design.

The concept of the bearingless fractional pole/slot motor obviously leads to a highly compact motor with a high acceleration capability. However, new challenges arise due to the high winding density along the perimeter when it comes to the positioning of the disturbance sensitive position and rotational speed sensors. Furthermore, the bearing fields of the BFM have to show the electrical rotation frequency, unlike the homopolar bearing concepts from subsections II.A and II.B. In combination with the high necessary number of poles, the ever existent limitation of the processing speed and resolution of the signal electronics and the limited current rise capability in the coils, very high rotational speeds are hardly achievable.

D. The Bearingless Segment Motor (BSM)

In Fig. 6(a) the bearingless segment motor, first presented in [14], is schematically depicted and the laboratory prototype is shown in Fig. 6(b). Here, the bearing forces and the drive torque are generated through the simultaneous superposition of the fluxes at several stator elements. This motor concept has an attracting passive magnetic bearing with iron as well. The motor structure is similar to that of the BFM from subsection II.C, but does not have a fully circumferential stator any more. Instead of that, the stator segments have explicitly formed feedback paths. The resulting lower iron area on the stator causes a lower passive axial stabilization in comparison to the beforehand presented motor concepts. Anyway, this also reduces the radial instability that has to be compensated actively.

The motor is characterized by a simple mechanical construction, a high compactness and flexibility regarding the radial positioning of the stator elements, whereas the complexity of the control of the bearing and the drive is much higher due to the individual contribution of every single stator element to the levitation force and torque.

Typically, with an increase of the rotor diameter also the number of stator elements, the necessary current sensors as well as the phases controlled by the power electronics have to be increased. Furthermore, with this motor a certain ratio between stator opening angle and number of poles has to be provided in order to ensure the function of the motor and the efficient utilization of the windings. The high electrical rotation speed leads to a limitation of the maximum achievable rotational speed similar to the BFM due to the limitation of the signal processing speed and the limited current rise speed in the bearing windings.

III. COMPARISON OF THE TOPOLOGIES

This section qualitatively compares the introduced motor topologies with the criteria depicted in Table 1.

On the one hand the MHM has a rather weak acceleration performance in comparison to all three other topologies (only the stray flux can be used for the drive torque generation).

TABLE 1

QUALITATIVE COMPARISON OF THE DIFFERENT MOTOR TOPOLOGIES, WHERE (+) IS AN ESPECIALLY GOOD PERFORMANCE, (✓) IS AN AVERAGE PERFORMANCE AND (-) IS A RATHER WEAK PERFORMANCE IN THE RESPECTIVE CATEGORY.

	MHM	M2M	BFM	BSM
Acceleration capability	–	✓	+	+
Operation at high rotational speeds	✓	+	–	–
Bearing stability	+	✓	✓	✓
Simplicity of design and control	+	+	✓	–
Compactness	✓	–	+	+
Flexibility of mech. construction	✓	✓	✓	+
Levels on rotor	1	2	1	1
Levels on stator	2	2	1	1

TABLE 2

MAIN PERFORMANCE AND CONSTRUCTIONAL PARAMETERS OF THE DIFFERENT MOTOR TOPOLOGIES

	MHM	M2M	BFM	BSM
Acceleration 0…1500 r/min	5.23 s	1.62 s	0.95 s	1.11 s
Deccelration 1500…0 r/min	3.96 s	1.06 s	0.78 s	0.87 s
Maximum rotational speed	3500 r/min	4000 r/min	2000 r/min	2300 r/min
Radial displacement @ 1500 r/min	± 59 µm	± 30 µm	± 89 µm	± 81 µm
Axial displacement @ 0…1500 r/min	± 0.59 mm	± 1.39 mm	± 0.33 mm	± 0.39 mm
Passive radial stiffness (destabilizing)	- 44 N/mm	- 20 N/mm	- 95 N/mm	- 80 N/mm
Passive axial stiffness (stabilizing)	45 N/mm	25 N/mm	20 N/mm	15 N/mm
Force-current factor	72 mN/Aturn	13 mN/Aturn	23 mN/Aturn	23 mN/Aturn
Outer rotor diameter	370 mm	370 mm	370 mm	370 mm
Mechanical air gap	7 mm	7 mm	7 mm	7 mm
Number of drive magnet poles	44	24	26	26
Rotor weight	2.8 kg	4.2 kg	4.2 kg	4.2 kg

The operation at high rotational speeds is limited, since the separation of bearing and drive leads to a high number of poles for this concept. In consequence this limits the maximum drive current to be impressed into the drive windings [11]. On the other hand, the concept of the MHM is characterized through its simple design and control and the bearing stability at moderate compactness.

The M2M is characterized by its axially rather long rotor, which reduces its compactness and consequently leads to reduced acceleration capability and bearing stability. However, due to the decoupling of bearing and drive the control is simple and the rotational speed is barely limited.

The BFM is characterized by its very good acceleration capability and high compactness. The control is dramatically simplified, if number of poles, stator pole number and number of phases are chosen advantageously. With this concept high rotational speeds can barely be reached. Also the positioning of the position and angular sensors is challenging.

Finally, the BSM has a high acceleration capability, a high compactness and a high flexibility of the mechanical construction but similar drawbacks as the BFM plus a more complicated control due to the combined coils for the bearing and drive system.

In order to substantiate the qualitative statements the performance and constructional parameters of all four motor topologies are summarized in Table 2.

The acceleration capability was determined with the aid of simultaneous start-stop tests up to 1500 r/min as depicted in Fig. 7. Here, the rather large acceleration time of the MHM is obvious, while BFM and BSM have almost the same performance.

The radial rotor displacement during constant operation at 1500 r/min is presented in Fig. 8. Here, the M2M shows a very good performance, although all motors are in an acceptable range.

The axial displacement of the rotor during an acceleration sequence is depicted in Fig. 9. The M2M stands out with its rather large axial movement. This is related to the fact, that a large drive current during acceleration causes an axial force, which cannot be compensated by the passive axial bearing. Once the target speed is achieved, the axial movement is low again. However, this behavior must be considered, when deciding for the right topology for a certain application field.

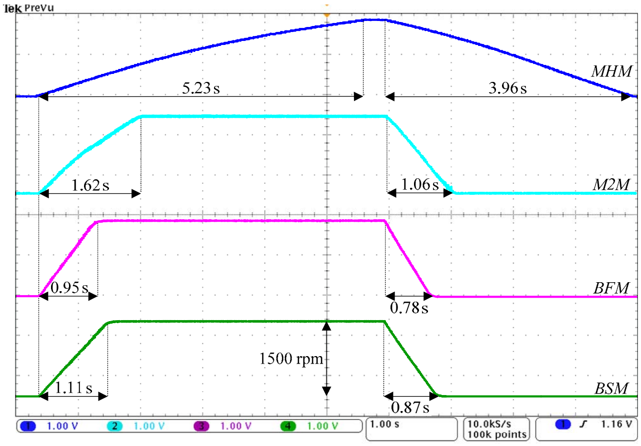


Fig. 7: Acceleration performance of introduced motor topologies from 0 to 1500 r/min with times indicated (scale: 800 r/(min·div), 1 s/div).

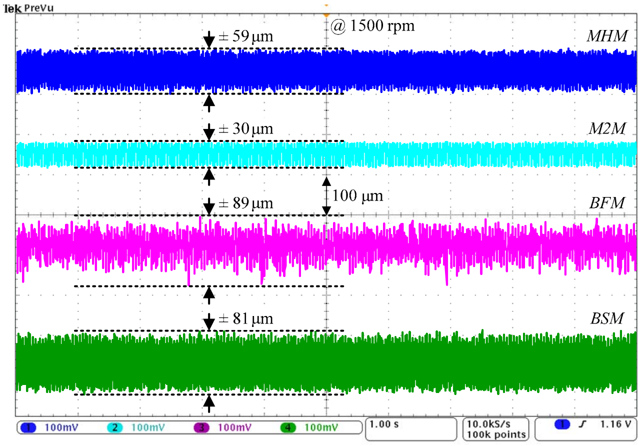


Fig. 8: Radial displacement during constant rotation at 1500 r/min of introduced motor topologies with maximum displacement indicated (scale: 100 µm/div, 1 s/div)

In total, it can be seen that with the BFM and BSM topologies both high acceleration performance and sufficient magnetic bearing stability can be achieved. Thus, they are preferable for many applications, unless very high rotation speeds are required. In the latter case, it has to be decided between the MHM and the M2M topologies.

IV. CONCLUSION

In this publication different slice motor topologies were compared that mainly differ in the coupling between the iron circuits responsible for bearing force and drive torque generation. This coupling has a direct influence on the acceleration capability, the bearing stability and the complexity of the control. The functionality, the advantages and challenges of each topology were described in detail and the main parameters were qualitatively compared. With the aid of this overview the best topology for a certain application can be selected.

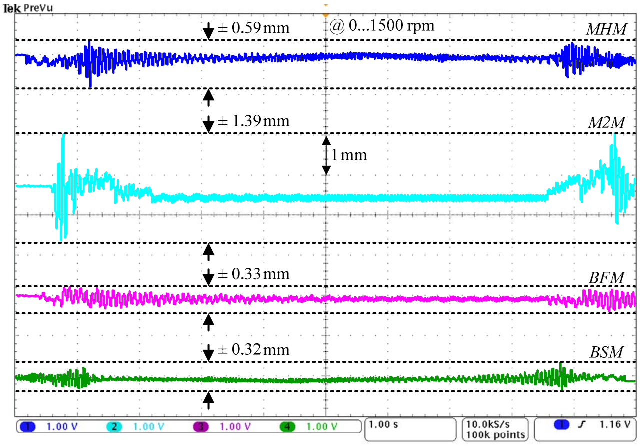


Fig. 9: Axial displacement during acceleration from 0 to 1500 r/min of introduced motor topologies with maximum displacement indicated (scale: 1 mm/div, 1 s/div)

REFERENCES

[1] Chartered Semiconductor Manufacturing, "IBM, Chartered, Infineon and Samsung announce process and design readiness for silicon circuits on 45nm low-power technology," *Press Release*, Seoul, 29th August 2006.

[2] R. Schöb, N. Barletta, M. Weber, and R. von Rohr, "Design of a bearingless bubble bed reactor," Proc. 6th Int. Symp. on Magnetic Bearings. Basel/Lancaster: Technomic-Publishing, 1998, S. 401-404.

[3] R. Schoeb, N. Barletta, A. Fleischli, G. Foiera, T. Gempp, H.G. Reiter, V.L. Poirier, D.B. Gernes, K. Bourque, and H.M. Loree, "A bearingless motor for a left ventricular assist device (LVAD)," Seventh International Symposium on Magnetic Bearings, Zurich, Switzerland, 2000, S. 383–88.

[4] S. Earnshaw, "On the nature of the molecular forces which regulate the constitution of the luminiferous ether," Trans. Camb. Phil. Soc, vol. 7, 1842, S. 97-112.

[5] J. Delamare, E. Rulliere, and J. Yonnet, "Classification and synthesis of permanent magnet bearing configurations," Magnetics, IEEE Transactions on, vol. 31, 1995, S. 4190-4192.

[6] T. Schneeberger and J. Kolar, "Novel Integrated Bearingless Hollow-Shaft Drive," Industry Applications Conference, 2006. 41st IAS Annual Meeting. Conference Record of the 2006 IEEE, 2006, S. 70-75.

[7] D.P.M. Cahill and B. Adkins, "The permanent magnet synchronous motor," Proc. Inst. Elec. Eng. A, vol. 109, 1962, S. 483–491.

[8] J. Boehm, R. Gerber, and N. Kiley, "Sensors For Magnetic Bearings," Magnetics Conference, 1993. INTERMAG '93., Digest of International, 1993, S. GF-11.

[9] M. Bartholet, T. Nussbaumer, D. Krahenbuhl, F. Zurcher, and J. Kolar, "Modulation Concepts for the Control of a Two-Phase Bearingless Slice Motor Utilizing Three-Phase Power Modules," Power Conversion Conference - Nagoya, 2007. PCC '07, 2007, S. 816-823.

[10] P. Karutz, T. Nussbaumer, W. Gruber, and J. Kolar, "Novel Magnetically Levitated Two-Level Motor," Mechatronics, IEEE/ASME Transactions on, vol. 13, 2008, S. 658-668.

[11] P. Karutz, T. Nussbaumer, W. Gruber, and J. Kolar, "Maximizing acceleration capability of magnetically levitated

slice motors," Electrical Machines, 2008. ICEM 2008. 18th International Conference on, 2008, S. 1-6.

[12] Shaoru Zhang and Fang Lin Luo, "Direct Control of Radial Displacement for Bearingless Permanent-Magnet-Type Synchronous Motors," Industrial Electronics, IEEE Transactions on, vol. 56, 2009, S. 542-552.

[13] F. Zürcher, T. Nussbaumer, W. Gruber, and J.W. Kolar, "Novel bearingless fractional slot motor," Intermag09, 2009, Sacramento, CA, USA.

[14] W. Gruber and W. Amrhein, "Design of a bearingless segment motor," Proc. of the 10th Int. Symp. on Magnetic Bearings.