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20 Years Bearingless Slice Motor – its Developments and Applications

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Abstract
Bearingless slice motors are very compact and cost effective systems that allow full magnetic levitation in all degrees of freedom. Due to the disc shaped rotor, tilting and axial position are passively stabilized by the permanent magnetic biased air gap field, whereas the radial position and the rotor speed are actively controlled. This paper summarizes the continuous development in the field of bearingless slice motors ongoing for over 20 years. Different implemented topologies are outlined and basic characteristic values are compared. Such an extensive overview will help to show general trends, limits and capabilities of bearingless slice motors and their applicability in industry and academia.

Keywords : Bearingless Slice Motor, Disc Drive, Permanent Magnet Synchronous Machine, Motor Topology

1. Introduction

Bearingless slice motors are known for quite a long time now. Characteristic of this system is the passive stabilization of tilting and the axial direction by passive reluctance forces created from a permanent magnetic air gap field. The first report of such a system dates back to 1995 by Barletta and Schöb [1]. However, the idea of passive stabilization featuring slice shaped rotors was even reported a year earlier in 1994 by Bleuler et al. in [2]. This concept leaves only three degrees of freedom, the radial and the rotational motion of the rotor, to be stabilized and controlled actively by the stator coil currents. Hence, such systems feature a very compact and mechanically simple setup, compared to other fully magnetically levitated systems.

As a consequence of the passive stabilization, the process forces and torques in axial and tilting directions have to remain within certain boundaries, because no active control is possible in these directions. Due to the disc shape of the rotor, there is normally no shaft to transmit the drive torque. Thus, the rotor typically acts as an impeller wheel, limiting the applications of such devices.

However, the bearingless slice motor development advanced constantly over the last 20 years and several applications became very successful in certain industrial environments, where the advantages of bearingless motor technology are essential. Since 1995, many different types of bearingless slice motor have emerged. In the beginning, the research on this specialized machine was mainly conducted in three countries. In Europe two research groups located in Zurich (Switzerland) and Linz (Austria) pushed the development, often in joint cooperation. Apart from that, research groups from Tokyo and Ibaraki (both from Japan) have been spearheading the innovations of this technology. Recently, also research work conducted in Nanjing and Zhenjiang (both in China) has been published.

The next sections will show the different topologies and capabilities of bearingless slice motor designs and in which directions the development has evolved.

2. Developed Bearingless Slice Motor Topologies

The slice motor systems can be categorized by their force and torque generation. There are systems with separated winding sets featuring separated suspension phases and torque phases, whereas with combined winding sets, each motor phase is capable to create suspension forces as well as drive torque. In the combined winding systems the copper losses are usually lower [3], coming at the cost of a more complex control scheme, which is responsible to decouples force and torque generation properly [4].

However, in this paper, the bearingless slice motors are divided into certain classes according to their topology. We used the following categories: standard radial motor setups with interior rotor, standard radial motor setups with external rotor, temple motors, segment motors, consequent pole motors, high speed motors with toroidal windings, systems with separated bearing and motor units and devices without permanent magnetic rotors. Fig. 2 illustrates exemplary pictures for each category, which are one by one described more closely in the following.

The *standard motor setup* with interior or exterior rotor features a stator and rotor setup which is very similar to start-of-the-art mechanically suspended brushless synchronous machines. In the *temple motor design* the stator coils are wound on L-shaped iron cores. The cores are arranged like columns around the rotor in a way that the L-shaped end of a core points to the rotor. This arrangement leads to a more compact form factor (regarding diameter to axial length ratio) and opens up space above the rotor, what is important for disposables and the fluid mechanics in pumps. The stator of the *segment motor* is separated, leading to potentially lighter and compacter systems because the sensors and electronic can be easily placed in-between the stator elements. The *consequent motor* feature*s* a rotor with inset permanent magnets. This allows a force generation that becomes independent from the rotor angle, what is favorable especially at higher rotational speeds. The bearingless *high-speed drives* operate with quite small rotors to keep the centrifugal forces low and toroidal windings to save copper losses. To reduce iron and proximity losses a slot-less stator with air coils made of stranded wires are used. Systems with *separated bearing and motor part* often use the inner and the outer side of the rotor to independently create suspension force and drive torque. Only recently systems *without any permanent magnetic rotor material* have been introduced. The air gap biasing permanent magnets are transferred into the stator. In dependence of this bias flux, this category can be divided in homopolar and heteropolar biased systems. The heteropolar system is normally favorable considering the torque generation.

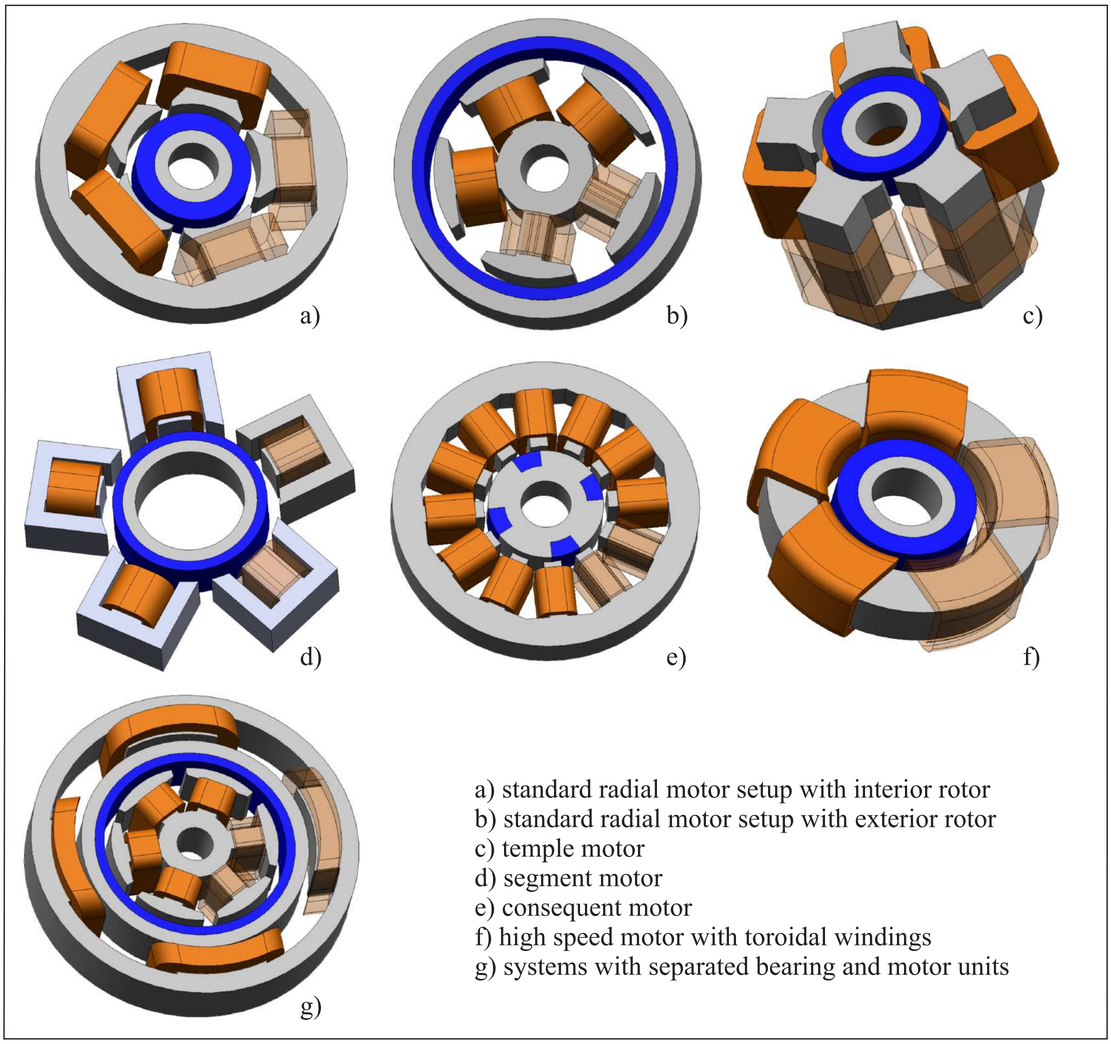

Figure 1: Different implemented bearginless slice motor topologies.

3. Bearingless Slice Motor Prototype Drives

First publications introducing the bearingless slice motor emerged around 1995. Since then, the authors are aware of more than 50 publications describing manufactured prototype systems with measurement test results. Fig. 1 shows the timeframe of the developments, featuring a quite steady appearance of new prototypes.

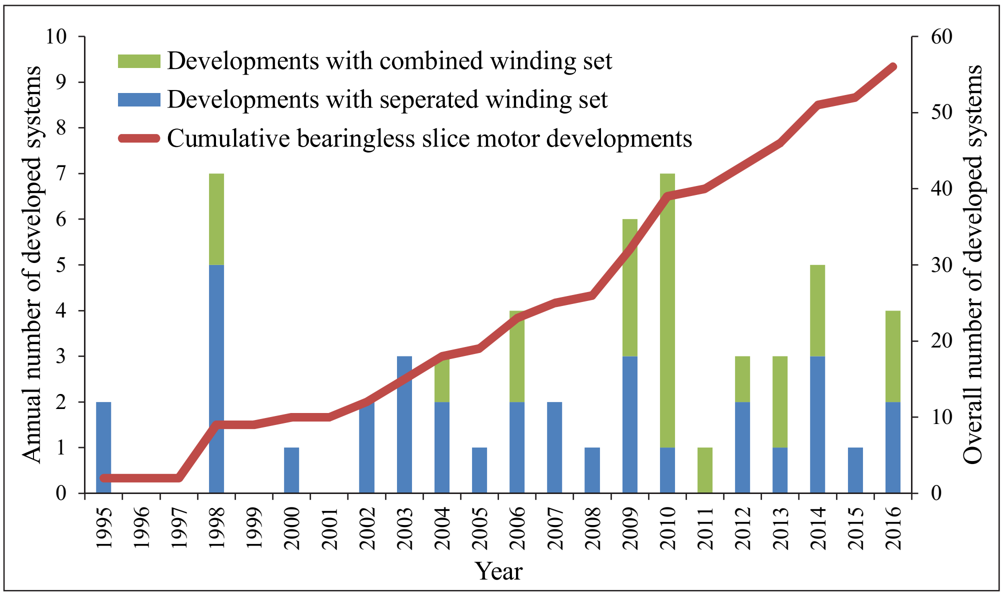

Figure 2: Timeline of reported bearingless slice motor developments.

	topology, reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/rad)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
standard radial motor setup with interior rotor setup	[6] 1998	30.000	2	15	4	n/a	1	sep. double 2-phase	0,52 -3,7	n/a	1	0,0064	24	n/a
	[7] 1998	9.000	1	60	8	0,09	2	sep. 2- and 3-phase	n/a n/a	0,029	n/a	n/a	36	2,1
	[8] 2003	n/a	3	80	20	n/a	1	sep. 2- and 3-phase	15,8 -63	n/a	22,8	0,24	325	5
	[9] 2004	n/a	4	80	25	n/a	2	sep. 2- and 3-phase	26 -70	n/a	28	0,48	325	8,5
	[10] 2004	3.000	3,5	70	14,5	0,136	2	com. 4-phase star	n/a -45,8	8	8	0,15	72	6
	[11] 2006	8.000	3,75	46	15	0,175	1	com. 5-phase star	6,85 -22,4	2,93	6	0,10	72	3,5
	[12] 2009	2.500	7,5	370	20	4	13	sep. double 3-phase	16,5 -70	260	16,3	0,93	325	15
	[13] 2009	1.000	4	113	25	0,725	13	com. double 3-phase	n/a -110	n/a	18,8	1,16	80	4,3
	[14] 2012	1.100	8	520	20	N/A	16	sep. double 3-phase	31 -129	975	19,6	2,16	325	15

Table 1: Bearingless slice motor developments with standard radial setup and interior rotor.

	topology, reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/rad)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
standard radial motor setup with exterior rotor setup	[15] 1998	3.000	2,25	70	14,4	0,475	2	com. 4-phase in star	n/a -33,1	n/a	n/a	0,14	30	3,5
	[16] 2002	2.400	1	53,4	8	0,07	2	sep. 2- and 3-phase	2,5 -31,5	0,57	5,8	0,0386	36	2,1
	[17] 2009	500	4	114	40	1	6	com. 4-phase in star	n/a -25	n/a	14,2	0,71	48	5,65
	[18] 2010	500	5	126	45	1,8	8	com. double 3-phase	3,3 -35	5,7	22,6	1,44	325	7
	[19] 2012	500	5	126	45	1,8	5	com. double 3-phase	5,8 -37	10,1	50,9	1,87	325	n/a
	[20] 2012	5.000	0,8	31,8	5	0,012	4	sep. 2- and 3-phase	2,8 -20	0,1	2,4	0,23	36	2,1
	[21] 2014	1.600	1,5	58	8	0,08	4	sep. 2- and 3-phase	3,5 -27,5	0,57	9,4	0,129	36	2,1

Table 2: Bearingless slice motor developments with standard radial setup and exterior rotor.

topology	reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/rad)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
bearingless temple motor	[22] 1995	4.500	5	45	10	n/a	1	sep. double 2-phase	2,7 -6	n/a	2,69	0,11	60	7
bearingless temple motor	[22] 1995	4.500	5	45	5	n/a	1	sep. double 2-phase	1,4 -3	n/a	4,10	0,054	48	3,7
bearingless temple motor	[23] 1998	5.000	3	45	5	n/a	1	sep. double 2-phase	3,8 -4,6	0,69	3,68	0,033	48	2,5
bearingless temple motor	[23] 1998	n/a	5	100	18	n/a	1	sep. double 2-phase	7,4 -26	n/a	11,31	0,453	60	15
bearingless temple motor	[24] 2000	5.500	n/a	28	n/a	0,035	1	sep. double 2-phase	7 -18,69	n/a	2,6	0,0224	14	3,5
bearingless temple motor	[25] 2002	8.000	3,75	48,5	12	0,135	1	sep. double 2-phase	5,7 -17,5	n/a	6,2	0,08	72	6
bearingless temple motor	[26] 2003	8.000	4,35	65	16	n/a	1	sep. double 2-phase	10,1 -41,4	n/a	15,7	0,17	160	10
bearingless temple motor	[27] 2004	8.000	5	78	25	n/a	1	sep. double 3-phase	22,8 -148	n/a	41,4	0,25	325	35

Table 3: Bearingless slice motor featuring the stator temple design.

topology	reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/rad)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
bearingless segment motor	[28] 2006	4.000	0,75	101,5	10	0,37	6	com. 4-phase in star	5 -28	7,5	1,5	0,083	72	6
bearingless segment motor	[29] 2009	4.000	0,75	101,5	10	0,37	6	com. 5-phase in star	7 -40	10	3,17	0,125	72	6
bearingless segment motor	[30] 2010	6.000	1	94	10	0,087	10	com. 4-phase in star	1,3 -9,7	1,8	1,67	0,050	48	3
bearingless segment motor	[31] 2010	2.500	7,5	370	20	4	13	com. double 3-phase	15 -60	280	9,33	1	325	15
bearingless segment motor	[32] 2011	1.400	1	100	16	0,15	6	com. 5-phase in star	4,8 -18,4	7,2	1,5	0,092	72	6

Table 4: Bearingless slice motor featuring a segmented stator.

topology	reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/ra d)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
bearingless consequent pole motor	[33] 2005	1.000	1	92	35	n/a	8	sep. double 3-phase	45 n/a	21	n/a	n/a	100	3
bearingless consequent pole motor	[34] 2007	500	1	150	10	1,7	20	sep. double 3-phase	n/a -200	41,4	50	n/a	100	2
bearingless consequent pole motor	[35] 2008	1.000	1	92	35	2	8	sep. double 3-phase	75 -475	55	n/a	n/a	100	1
bearingless consequent pole motor	[36] 2009	4.000	0,85	45	10	0,11	4	sep. double 3-phase	7,3 -29	1,7	2,5	0,031	48	0,7
bearingless consequent pole motor	[37] 2009	4.000	1,125	80	10	0,335	8	sep. 2- and 1-phase	3,5 -38	3,4	3,5	0,08	48	6
bearingless consequent pole motor	[38] 2013	6.000	8	80	40	1,64	4	sep. double 3-phase	16,3 -45,6	8,2	12,5	0,17	141	3

Table 5: Bearingless motors with inset rotor permanent magnets.

topology	reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/rad)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
bearingless high-speed motors	[39] 2010	115.000	4,5	32	10	0,05	1	com. 5-phase in star	2,2 -7	0,5	0,165	0,0027	48	10
bearingless high-speed motors	[40] 2013	20.000	9,5	102	15	0,88	1	com. double 3-phase	8 -14	10	2,7	0,188	325	6
bearingless high-speed motors	[41] 2015	12.000	11	164,8	20	1,35	2	sep. double 3-phase	17 -26	19	4,34	0,188	325	6
bearingless high-speed motors	[42] 2016	105.000	5,5	31,2	12	n/a	1	com. 6-phase in star	2 -8	0,8	0,165	0,0039	48	10

Table 6: Bearingless high speed motors with toroidal winding sets.

The Tables 1 - 8 summarize the basic characteristic data for each reported bearingless slice motor prototype drive in the announced categories. According literature references are given to allow closer examination of the systems. Not available values are marked with n/a. The implemented winding schemes are abbreviated by sep. for separated winding set and com. for combined winding sets. The given currents represent root mean square values.

	topology, reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/rad)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
motors with separate bearing	[43] 1998	1.200	4	188	20	2,2	8	sep. double 2-phase	22 n/a	63	n/a	n/a	n/a	n/a
	[44] 2003	2.400	n/a	44/20	22,2/10	0,07	0/4	sep. 2- and 3-phase	33 n/a	3,9	n/a	n/a	n/a	n/a
	[45] 2006	2.000	1/2	50	10	0,077	0/4	sep. 2- and 3-phase	16 -43	3,7	4,3	n/a	n/a	3,5
	[46] 2006	2.500	0,8/1,05	40,4/2 7	7,4/6	n/a	0/4	sep. 2- and 3-phase	8,5 -65	1,7	2,4	0,049	n/a	n/a
	[47] 2007	4.000	7	370	40	4,5	12	sep. double 2-phase	25 -20	57	13,2	1	325	15
	[48] 2010	2.200	6	370	24	2,8	22	sep. double 2-phase	45,5 -44	400	15	0,35	325	15

Table 7: Bearingless slice motor developments with a separated bearing and torque unit.

	topology, reference and year of publication	maximal speed (rpm)	magnetic air gap (mm)	rotor dia-meter (mm)	rotor height (mm)	rotor mass (kg)	pole pairs	winding scheme and phases	axial/ radial stiffness (N/mm)	tilt stiffness (Nm/rad)	force coeff. (N/A)	torque coeff. (Nm/A)	DC voltage link (V)	rated current (A)
bearingless motors without rotor permanent magnets	[49] 2010	5.000	2	94	10	0,227	5	com. 4-phase in star	4,3 -28,5	5,73	5	0,05	72	6
	[50] 2013	1.000	4,8	65	17	0,18	4	com. double 3-phase	3,4 -60	1	12,6	0,12	325	10
	[51] 2014	2.000	3	150	10	0,8	10	sep. double 3-phase	7,3 -41,6	21,4	3	0,15	325	10
	[52] 2014	3.200	1,5	50	15	0,074	8	sep. double 3-phase	4 n/a	1	n/a	n/a	n/a	n/a
	[53] 2016	5.000	3	78	20	0,4	10	sep. double 3-phase	4 -43	n/a	12	0,15	48	2
	[54] 2016	2.000	4	150	25	1,6	10	sep. double 3-phase	13 -115	30	0,9	0,6	325	10
	[55] 2016	n/a	2	45	5	0,026	0	com.12-phase in star	3 -13	1	10	n/a	n/a	1

Table 8: Bearingless motors without permanent magnetic material in the rotor.

4. Comparison of the Characteristic Data

The characteristic data of all these systems are compared by different categories in this section. Fig. 3 shows the speed map of the bearingless slice motor, starting from a few hundred up to over of a hundred thousand rpm. High speed systems tend to be smaller in diameter due to the smaller centrifugal forces in this case.

A common value to compare the torque densities of different drives is the shear stress. It is defined by

$$\tau = \frac{4 \cdot T_z}{d_r^{\,2} \cdot \pi \cdot l_z}, \tag{1}$$

where T_z is the rated torque, d_r represents the rotor diameter and l_z stands for the axial rotor height. The shear stress of all prototype systems is illustrated in Fig. 4. The values are typical for fractional horsepower drives and range up to 25kN/m².

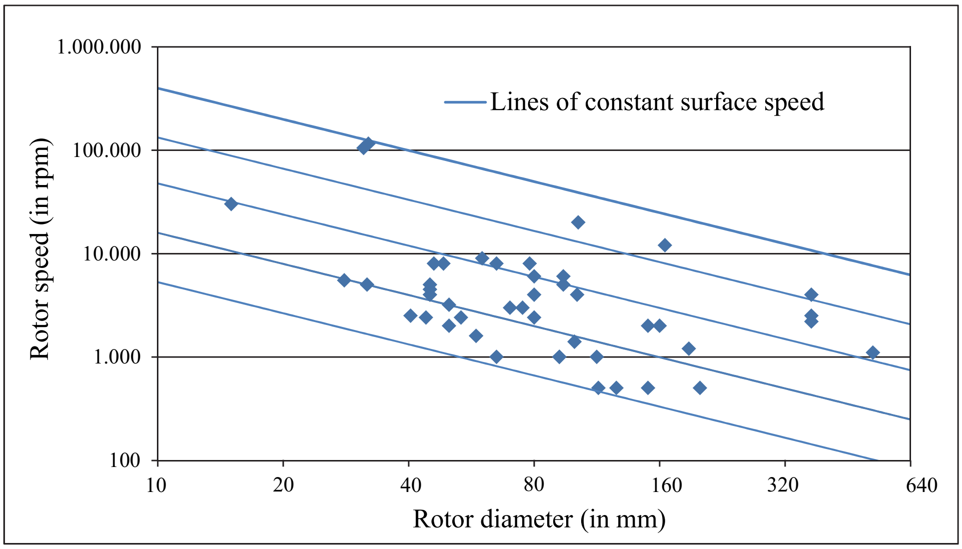

Figure 3: Logarithmic speed map.

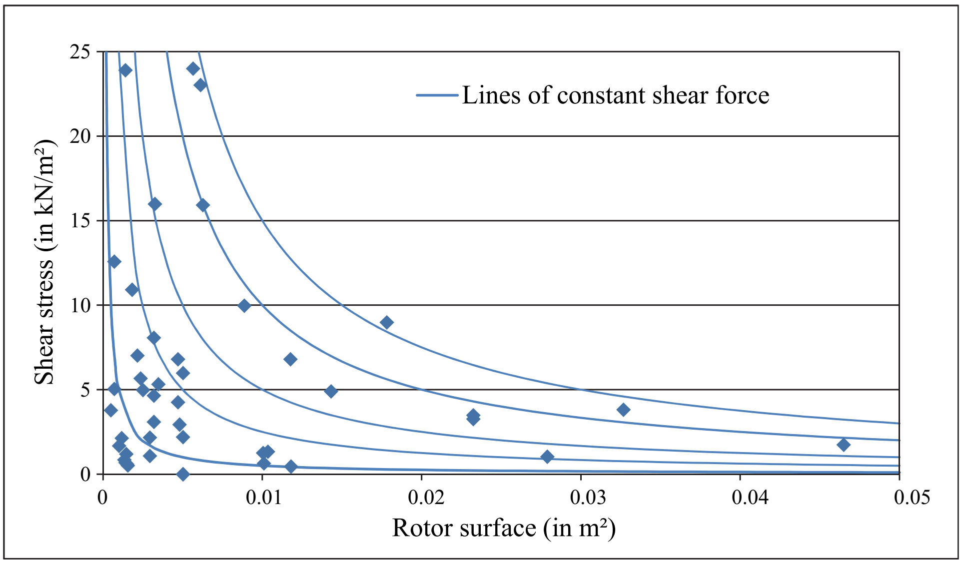

Figure 4: Shear stress plot of reported bearingless slice motors.

For bearingless motors also the force creation capability is important. Hence, as a value similar to the shear density the suspension force density is defined by

$$\sigma = \frac{F_r}{d_r \cdot \pi \cdot l_z} \tag{2}$$

with F_r as the rated radial suspension force. The computed values of all systems are visible in Fig. 5, ranging up to 150kN/m². The theoretical maximum is given by

$$\sigma_{\max} = \frac{B_{sat}^{\ 2}}{2 \cdot \mu_0} \approx 725\text{kN/m}^2\ , \tag{3}$$

where μ_0 represents the permeability of air and the saturation flux density B_{sat} was assumed to be 1,35T.

Additionally, in bearingless motors the stabilizing passive stiffness values are key parameter because they are fully set by the magnetic circuit and can hardly be influenced by the stator currents. Fig. 6 shows a survey of the normalized passive tilt stiffness values, which are computed by

$$\overline{k}_\varphi = \frac{k_\varphi}{d_r^{\ 2} \cdot l_z} \tag{4}$$

with k_φ standing for the absolute tilting stiffness [5]. In Fig. 7 the translational stiffness values are shown. The destabilizing radial stiffness is inverted to become a positive number. The used gap factor in the abscissa is defined as the ratio of magnetic air gap to rotor radius.

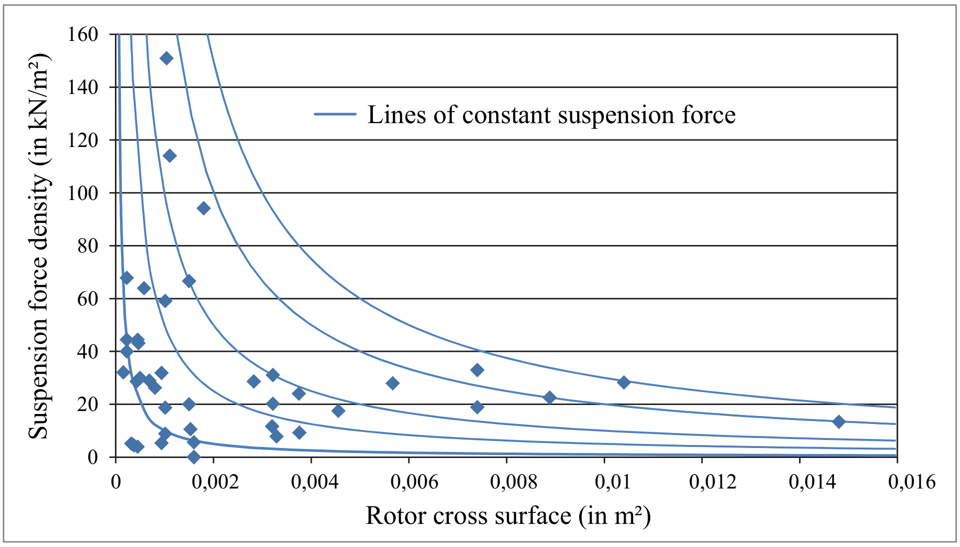

Figure 5: Suspension force density plot.

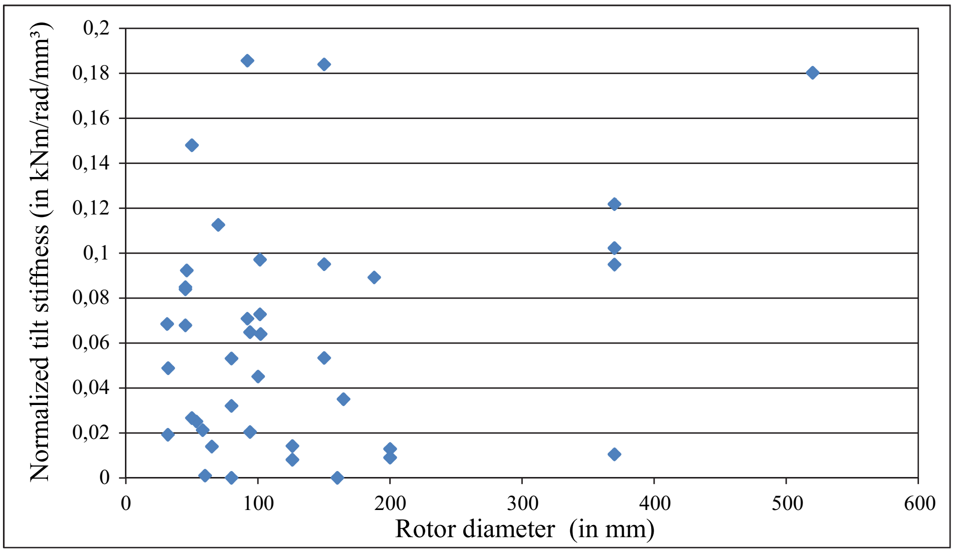

Figure 6: Comparison of the passive tilt stiffness values.

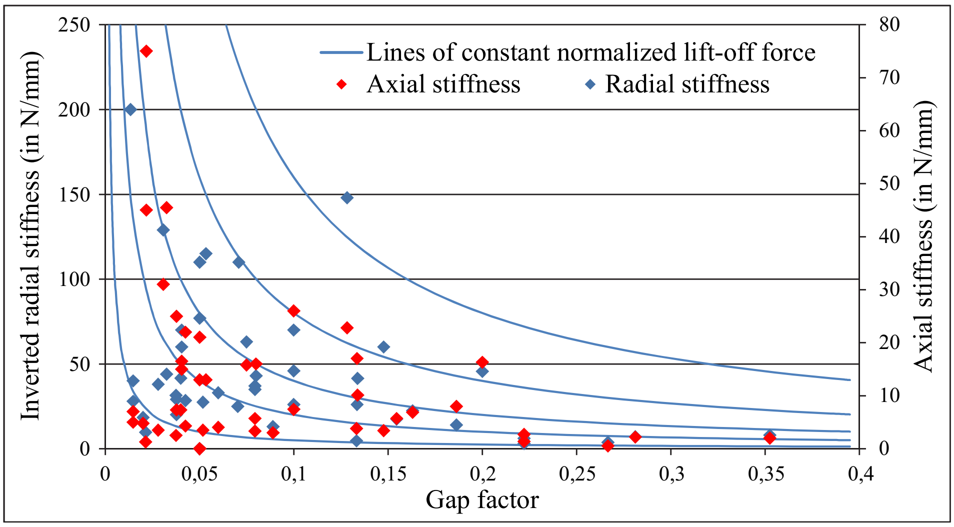

Figure 7: Comparison of the translational stiffness values.

3. Main Applications

Right from the start of bearingless slice motor development, *pumps* for ultra-pure fluids have been the main industrial application. Hence, a high number of different heart pump and chemical pump concepts have been designed and developed to market readiness. Especially the Swiss company Levitronix became quite successful in this market sector. Additionally, also *mixer* and *stirrer* with much higher torque capability and lower speeds have been designed. Moreover, the largest bearingless slice motor systems with rotors up to 0,5m are used in hermetically sealed *process chambers*, also featuring extremely high air gaps of up to 8mm. However, there are also some slice motor systems which have not been developed to market readiness yet and are currently remaining in an academic state, like bearingless *high speed* motors, bearingless *fans* and *blowers* or bearingless *flywheels*.

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Temple motor

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