Principle and Application of a Bearingless Slice Motor

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Abstract: Recent developments in the field of electrical drives and magnetic bearings have led to so called "bearingless motors". The innovation is that the magnetic forces for the suspension of the electrically powered rotor are generated in the motor itself and not in separate magnetic bearings. Normally, two motor/bearing units are needed for the full stabilisation of five spatial degrees of freedom. In this paper a bearingless motor with a slice-shaped rotor is presented, where three spatial degrees of freedom are passively stable. Only one active radial bearing is needed. Possible applications for the "bearingless slice motor" lie typically in the field of small centrifugal pumps, high speed centrifuges, blowers for dangerous gases or flywheels. The possibilities and advantages of the bearingless slice motor are demonstrated by the example of a disposable blood pump for heart surgery.

1. The Principle of the Bearingless Slice Motor

Recent developments at the Laboratory for Electrical Equipment Design (EEK) of the Swiss Federal Institute of Technology (ETH) in Zurich and at several universities in Japan in the field of electrical drives and magnetic bearings, have led to so called "bearingless motors" (see [1], [2], [3]and [4]). "Bearingless" does not mean the lack of bearing forces, which are necessary in any case to stabilise the rotor, but the absence of significant bearings. In principle the bearingless motor is based on the contactless magnetic support of the rotor. In contrast to conventional magnetic levitated drives, the bearing forces are not generated in separate magnetic bearings, placed on the left and right side of the motor, but in the motor itself. The active motor part generates not only the torque, but also the radial magnetic bearing force, which is needed for the suspension of the rotor.

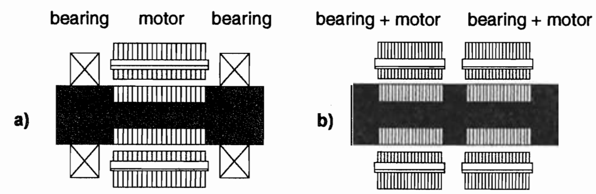

figure 1: *a) conventionally mounted motor*
b) bearingless motor

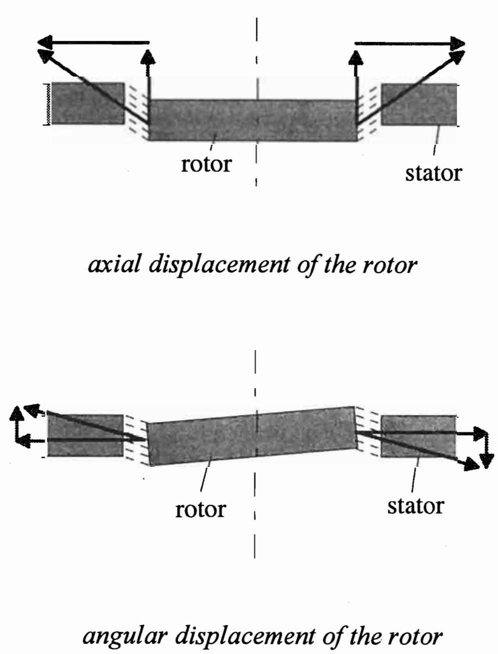

figure 2: Passive stabilisation of the axial and angular displacement of the slice rotor

Normally, in a electric motor two radial bearings and therefore in a bearingless motor design two motor/bearing parts are needed for the full stabilisation of five spatial degrees of freedom. Such a motor construction becomes rather long. There is a minimal distance between two motor/bearing parts because of the necessary space for the turn windings. For the levitation and driving of slice shaped rotors like flywheels, rotors of small centrifugal pumps, high speed centrifuges or blowers, the previous arrangement is not ideal.

The idea is now to choose the length of the rotor small compared to its diameter. In this case it is possible to stabilise three spatial degrees of freedom passively. Only one active radial bearing is needed. Figure 2 shows the functional principle of such a bearingless slice motor. Active control of the rotation and the radial position of the motor slice is assured by the principle of the bearingless motor. The upper part of figure 2 shows an axial displacement of the rotor. The displacement results in attractive magnetic forces, which act in the opposite direction to the displacement and therefore stabilise the axial position of the rotor. The lower part of the picture shows an angular displacement. It leads to stabilising magnetic forces too.

2. The Bearingless Motor

The idea of combining radial magnetic bearing function and torque generating means in magnetic microbearings is already documented in [5]. In this paper a magnetic bearing-motorcombination with a disk-shaped rotor of only 3 mm diameter is described. The proposed arrangement combines a four pole radial active magnetic bearing with an 8 pole stepper motor. In this solution, the flux density between two bearing poles is modulated by the torque building machine flux. Because of the high number of poles, for high rotor speeds a very high stator current frequency results, which can become a limiting factor for the maximum speed. There is also a slight disturbance of the magnetic bearing flux by the torque generating motor flux. The achievable torque of the drive is smaller than with other motors of the same size because the active motor area is reduced and the motor flux modulation is limited to one quadrant. This is a major disadvantage because the length of the motor and therefore the active area is already rather small.

In [1], [2], [3] [4] and [6] another way to the bearingless motor is proposed, which avoids the above mentioned problems. With the superposition of a steering-flux (with the pole pairs $p_2 = p_1 \pm 1$) upon the motorflux (with the pole pairs p_1), radial magnetic forces can be built up in every a.c. motor. The radial forces can be controlled by the current in a steering winding (with the pole pairs $p_2 = p_1 \pm 1$) and are therefore suited for the contactless mounting of the rotor.

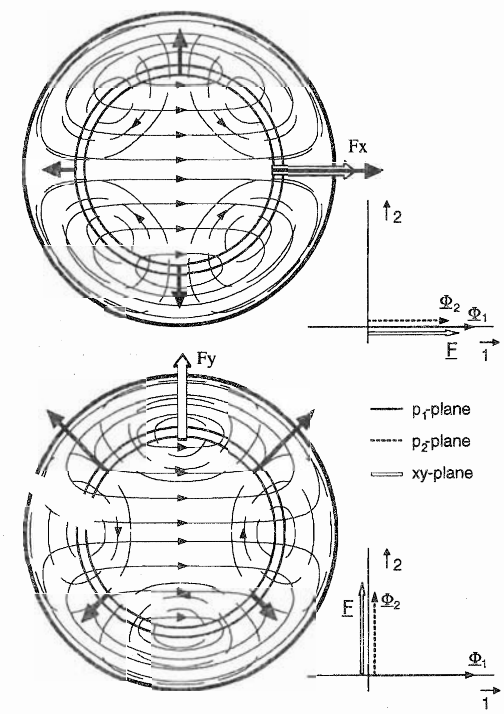

figure 3: Generation of controllable radial forces in a a.c. motor by superposition of a four pole steering-flux over a two pole machine-flux

3. Motor Development

In a first step, two prototypes of bearingless slice motors, a synchronous machine and an induction machine were built. Both motors worked with the same type of stator, which is shown in figure 4. The stator with 24 slots has two separate two-phase windings. One with two pole pairs to generate the torque and in the case of the induction motor the machine flux and one with four pole pairs to generate the steering flux. Flux sensors were arranged in the air gap to control the flux and the speed of the motor. An optical sensor system was used to measure the radial position of the rotor. The goals of this first prototypes were to demonstrate the functional principle of the bearingless slice motor.

After the feasibility of the bearingless slice motor was proved two main problems had to be solved: the non optical measurement of the radial rotor position (it is crucial that the position is exactly measured in the middle of the rotor in order to prevent coupling between the angular displacement of the rotor and the measurement)

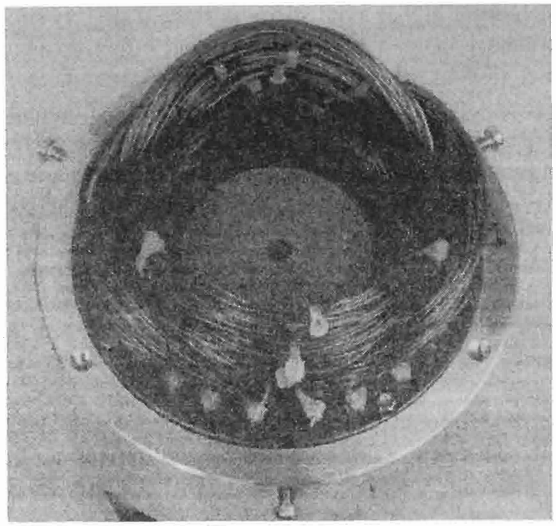

figure 4: *First prototype of a bearingless slice motor*

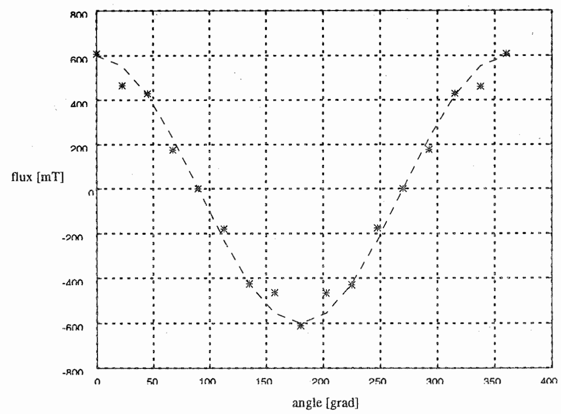

figure 7: *Flux distribution in the air gap of the temple motor*

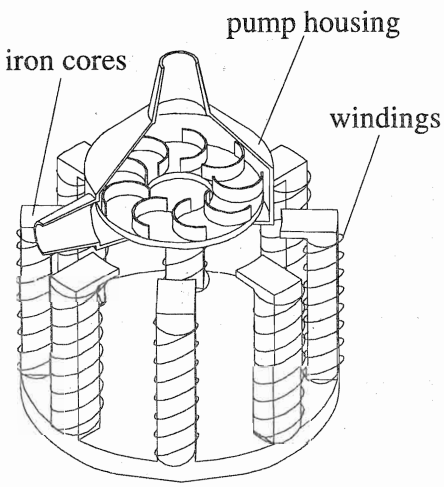

figure 5: *Principle of the temple motor*

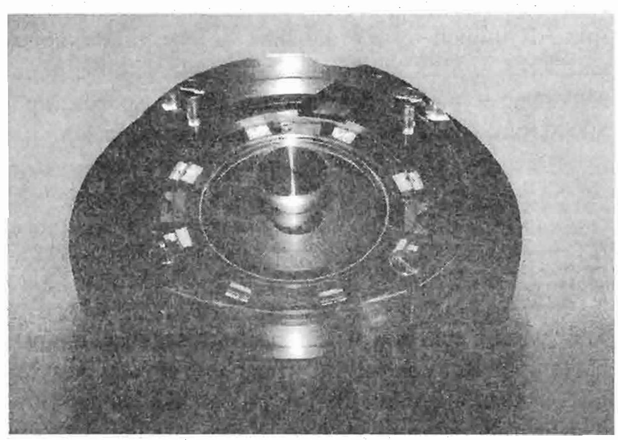

figure 8: *Bearingless slice motor for 42'000 rpm*

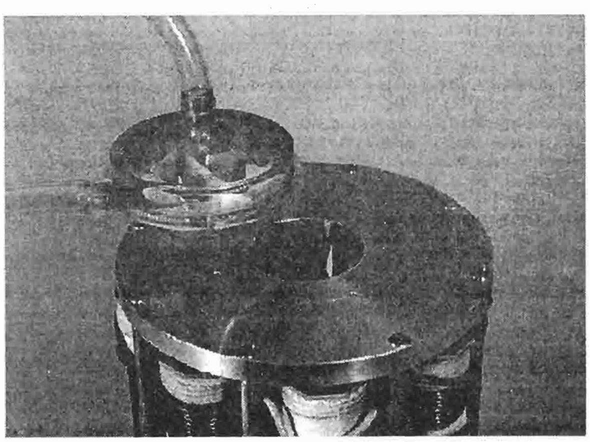

figure 6: *First prototype of a temple motor*

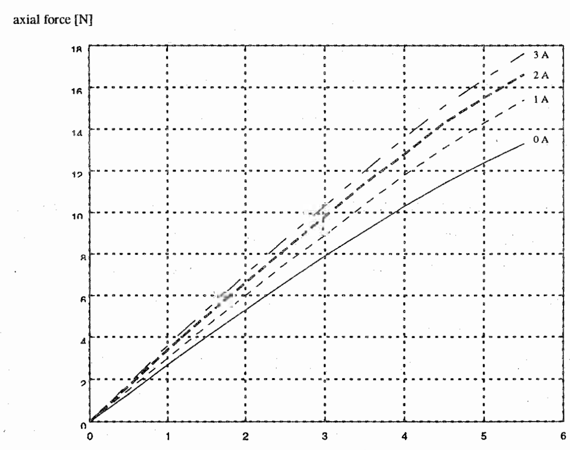

figure 9: *Measured axial forces of above bearingless slice motor*

and the elimination of the extremely large turn windings (large in comparison to the active motor length). The solution for the second problem was a special motor design, which we call temple motor. Its principle is shown in figure 5. Figure 6 shows a first demonstration prototype of this motor. With this motor speeds of 4500 rpm and a maximum torque of 70 Ncm were reached. This gives an output power of 320 W. Despite the fully opened slots and the small number of only 8, the flux distribution is well sinusoidal due to the large air gap (see figure 7).

A further prototype was designed to achieve high speeds. Since the rotor-dynamical behaviour of the slice shaped rotor is very favourable (self stabilising effect of the gyroscopic momentum, no relevant bending modes), it is ideally suited for high speed operation. To avoid the need for high magnetisation power (with large air gaps), a permanent magnet synchronous motor was chosen. A titanium ring gives the rotor with 45 mm diameter and 5 mm thickness the necessary mechanical stability. Figure 8 shows the high-speed bearingless slice motor. With this motor a maximum speed of 42000 rpm was reached. The speed is limited by the d.c. link voltage of the control unit, since no flux weakening is possible with the permanent magnet motor. A motor for higher speeds (up to 80000 rpm) is already under construction in our lab.

4. Control

The control scheme of the bearingless slice motor is based on vector control. Its principle is already described in [7]. Vector control of the bearingless motor allows dynamic operation of all type of a.c. machines. The implemented control scheme considers not only the Maxwellforces but also the Lotentzforces in the machine. The second point is especially important for the control of a bearingless synchronous motor with a large air gap. A block diagram of the applied decoupling scheme is shown in figure 10 for an induction motor. The decoupling scheme for the synchronous motor is the same except for the flux controller. A detailed description of the control scheme can be found in [8].

For most applications the axial forces and stiffnesses of the passive bearing are of great interest. Since it is nearly impossible to calculate them analytically, they were determined first by numerical field calculation and subsequently measured in the test rig. Figure 8 shows the measurements of the above high speed motor. The measurements were made with zero magnetisation current (which is the normal operation case for a permanent magnet motor) but also with additional magnetisation currents. It is shown that a magnetisation current of 3 A increases the axial stiffness from 2.7 N/mm to about 3.6 N/mm. Of course it is not purposeful to use this effect to achieve a higher axial stiffness since a slightly stronger permanent magnet leads to the same effect at no additional loss in the stator winding. But since there is no other means to influence the stiffness and the damping of the passive bearing, this effect is extremely useful for handling the ridgid body modes. By this means it is not only possible to influence the stiffness of the passive bearing during operation in order to drive through resonances, but even to achieve some active damping. This requires of course an axial or angular position signal which can be gained for example from the flux probe signals.

The digital controller is implemented on a self designed TMS 320C50-80 MHz based signal processor board. Commercial switched power amplifiers are used for energizing the motorwindings.

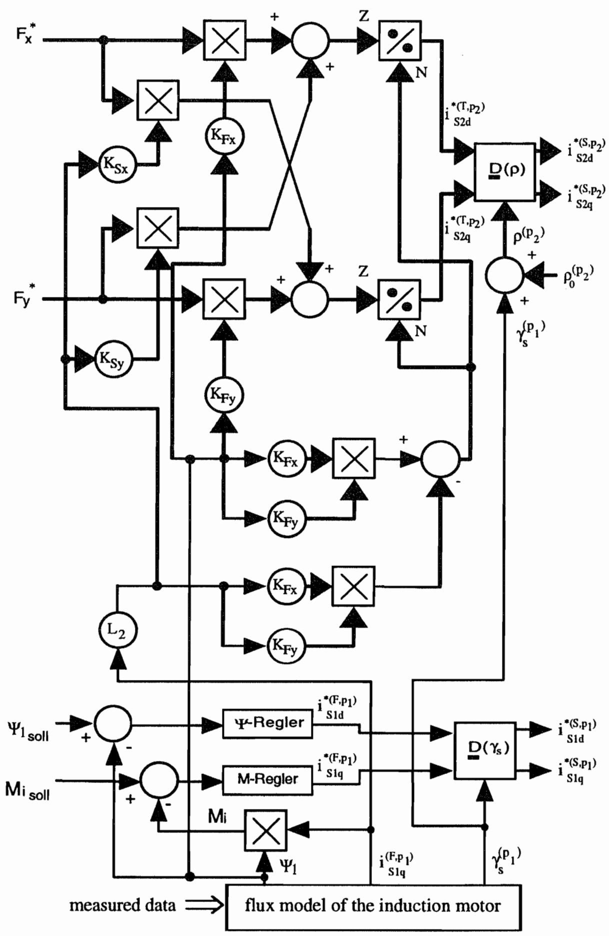

figure 10: Decoupling scheme for the lateral force induction motor

5. Applications

5.1. The Bearingless Blood Pump

In the field of open heart surgery, roller pumps are the most often used means to maintain the blood flow during an operation. However they cause a lot of problems like blood damage, material fatigue, particulate contamination and no limited pressure at a given speed. Centrifugal pumps would therefore have major advantages. There are several centrifugal pumps commercially available e.g. from Biomedicus, Sarns Centrimed and St. Jude. All these pumps have a disposable pump head with a magnetically coupled driving system (see fig. 11). This permits disposability of the pump head and avoids the entry of blood or blood fluids into the electric motor. Unfortunately not all problems are solved by this construction. There are still severe problems related to the rotorbearings and the sealing of the rotor shaft. Thromboembolisms can be caused by dead water spaces around the shaft and heat generation of bearings and seals. Leakage of seals can lead to infection and bearingfailures when blood seeps into the bearing.

A first solution to overcome these problems is to drive the pump impeller through the pump housing by an a.c. motor and support the impeller by magnetic bearings. Such constructions have been proposed in [9], [10], [11] and [12]. All these pumps are designed as artificial heart replacements or as ventricular assist devices (VAD). However the concepts are not appropriate for use in heart surgery. Their drive and bearingsystem is not separable from the pump. The pump is therefore not disposable because the whole system is far too expensive to throw away after usage.

The requirements for a blood pump in the heart-lung-machine are: simple and cost effective construction of the disposable pump, easy mounting of the pump head in the drive system and in the heart-lungmachine, and small priming volume (to save blood). A construction with active magnetic bearings can barely meet these specifications, mainly because of its high costs. A very interesting solution for a disposable pump is presented by Mendler in [11]. The paper describes a sealless centrifugal pump with a radial magnetic coupling. 4 of the 6 spatial degrees of freedom of the impeller are suspended passively by magnetic forces. The other 2 degrees of freedom are stabilised by a blood-flushed pivot bearing with minimal load and friction. Though this pump might be a big step forward for centrifugal blood pumps, the pivot bearing reminds a problematical point. The wish for a cheap disposable blood pump with a fully magnetically suspended rotor is still unfulfilled.

With the "bearingless slicemotor" a simple, compact and costeffective solution for a blood pump for heart surgery with a disposable pump part becomes feasible. The rotorslice can be directly integrated in a plastic impeller by injection moulding. The pump consists of two parts only: the impeller with the integrated motorrotor and the housing. The principle of such a "bearingless blood pump" is shown in figure 12. Figures 13 and 14 show a functional prototype of this "bearingless blood pump" with its control electronics. A more detailed description of the system can be read in [14].

5.2. Further Applications

Of course the applications for the "bearingless slicemotor" go far beyond blood pumps. Other pumps such as small chemical process pumps or recirculation pumps for acids in etching processes could be built on the same principle. Small centrifuges or blowers for dangerous gases might be other fields of application. In the form of the outer rotor motor magnetically suspended mixers for hazardous chemicals or highly pure substances would be feasible, too.

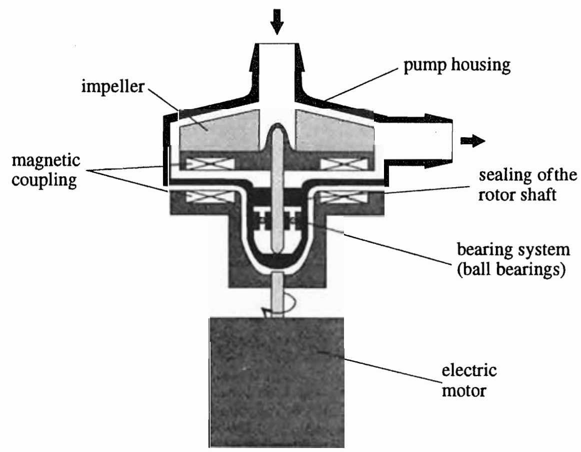

figure 11: *Functional principle of a centrifugal blood pump with magnetic coupling and ball bearings.*

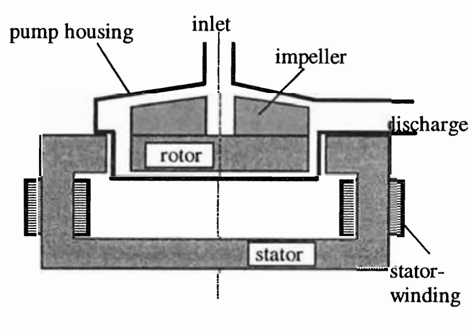

figure 12: *Principle of the bearingless blood pump*

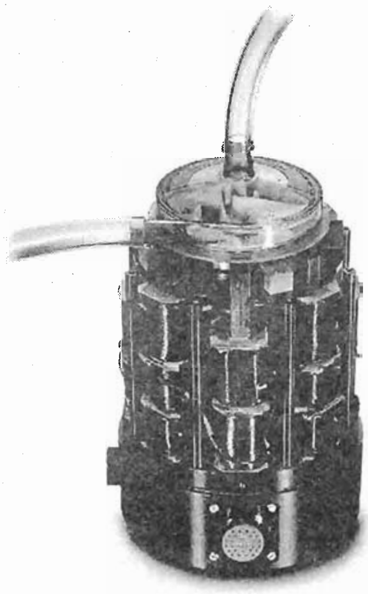

figure 13: Functional prototype of a bearingless blood pump

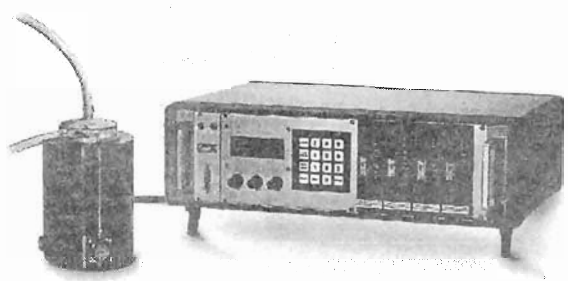

figure 14: Bearingless blood pump with control electronics

6. Acknowledgement

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