

520-37
5.2.10.7

DESIGN OF A BEARINGLESS BLOOD PUMP

Natale Barletta
Laboratory for Electrical Engineering Design (EEK)
Swiss Federal Institute of Technology
Zurich Switzerland

Reto Schöb
Sulzer Electronics AG
Winterthur, Switzerland

SUMMARY

In the field of open heart surgery, centrifugal blood pumps have major advantages over roller pumps. The main drawbacks to centrifugal pumps are however problems with the bearings and with the sealing of the rotor shaft. In this paper we present a concept for a simple, compact and cost effective solution for a blood pump with a totally magnetically suspended impeller. It is based on the new technology of the "Bearingless Motor" and is therefore called the "Bearingless Blood Pump". A single bearingless slice motor is at the same time a motor and a bearing system and is able to stabilise the six degrees of freedom of the pump impeller in a very simple way. Three degrees of freedom are stabilised actively (the rotation and the radial displacement of the motor slice). The axial and the angular displacement are stabilised passively. The pump itself (without the motor-stator and the control electronics) is built very simply. It consists of two parts only: the impeller with the integrated machine rotor and the housing. So the part which gets in contact with blood and has therefore to be disposable, is cheap. Fabricated in quantities, it will cost less than \$10 and will therefore be affordable for the use in a heart-lung-machine.

MOTIVATION AND INTRODUCTION

In the field of open heart surgery, roller pumps are most often used to maintain the blood flow during an operation. However, they cause a lot of problems such as blood damage, material fatigue, particulate contamination and unlimited pressure at a given speed. Centrifugal pumps would therefore have major advantages. There are several centrifugal pumps commercially available i.e. from Biomedicus, Sarns Centrimed and St. Jude. All these pumps have a disposable pump head with a magnetically coupled driving system (see Fig. 2). This avoids the entry of blood into the electric motor. Unfortunately not all problems are solved by this construction. There are still severe problems related to the rotor-bearings and the sealing of the rotor shaft. Thromboemboli 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 bearing-failures, when blood seeps into the bearing.

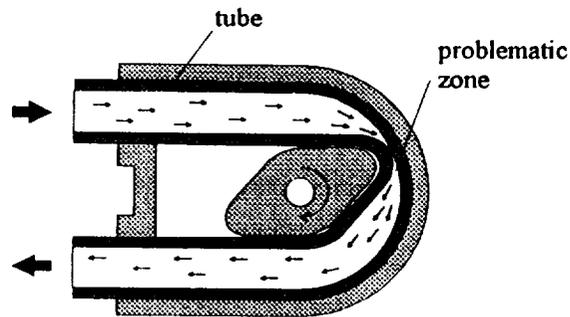


Fig. 1: Functional principle of a roller pump.

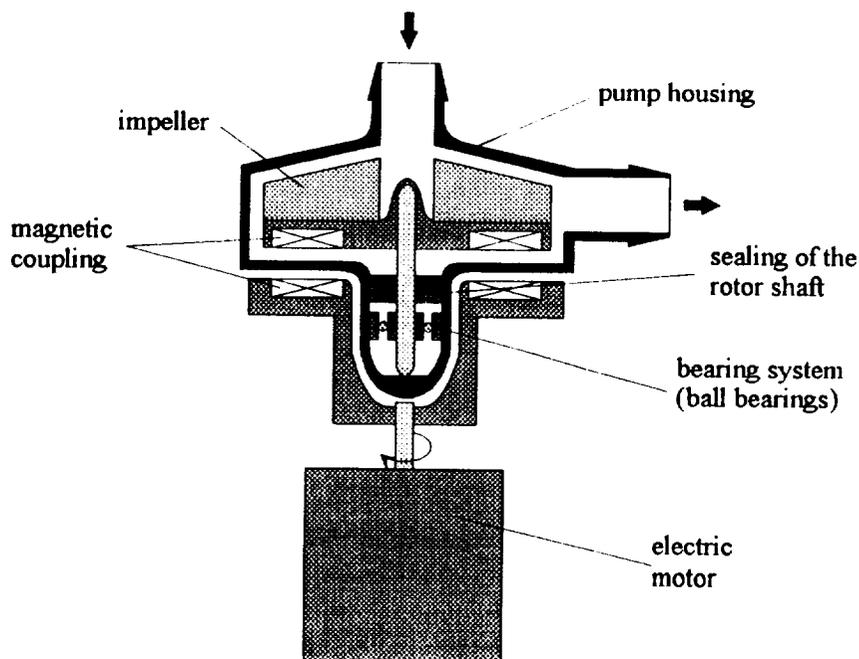


Fig. 2: Functional principle of a centrifugal blood pump with magnetic coupling and ball bearings.

These problems are mentioned by many authors i.e. in [1], [2], [3], [4] and [10]. One possibility to overcome these problems is to drive the pump impeller through the pump housing by an AC motor and to mount the impeller by magnetic bearings. Such constructions have been proposed i.e. in [5], [6], [7] and [8]. 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 bearing-system is not separable from the pump. The pump is therefore not disposable because the whole system would be 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-lung-machine and small priming volume (to save blood). A construction with active magnetic bearings can barely meet those specifications, mainly because of its high costs.

A very interesting solution for a disposable pump is presented by Mendler in [10]. The paper describes a seal-less centrifugal pump with a radial magnetic coupling. 4 of the 6 spatial degrees of freedom of the impeller are stabilised passively by magnetic forces. The other 2 degrees of freedom are stabilised by a blood-flushed pivot bearing with minimal load and friction. Even if this pump could be a big step forward for centrifugal blood pumps, the pivot bearing remains a problematic point. The need for a cheap disposable blood pump with a fully magnetically suspended rotor is still in demand.

THE NEW APPROACH

Developments at the Laboratory for Electrical Engineering 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 the so called "Bearingless Motor" (see [12], [13], [14], [15] and [16]). Recently the ETH Zurich founded a co-operation with two industrial companies: Sulzer Electronics AG, Switzerland and Lust Antriebstechnik GmbH, Germany, for the further development of this new technology. The expression "Bearingless Motor" was first used by Bichsel in [12]. In this content "bearingless" does not mean the lack of bearing forces, which are necessary in any case to stabilise the rotor, but the omission of significant bearings. The principle of bearingless motor is based on the contactless magnetic bearing of the rotor. In contrast to conventional magnetic levitated drives, the bearing forces are not built up in separate magnetic bearings, which are 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.

Normally two motor parts are needed for the full stabilisation of five spatial degrees of freedom. If the length of the rotor is small compared to its diameter, it is possible to stabilise three spatial degrees of freedom passively. Only one active radial bearing is needed. Figure 3 shows the functional principle of such a bearingless slice motor. It is arranged that the rotation and the radial position of the motor slice is controlled actively by the principle of the bearingless motor. The right part of Figure 3 shows an axial displacement of the rotor. The displacement results in attractive magnetic forces, which acts in the opposite direction of the displacement and therefore stabilizes the axial position of the rotor. The left part of the picture shows an angular displacement. It leads to stabilising magnetic forces too.

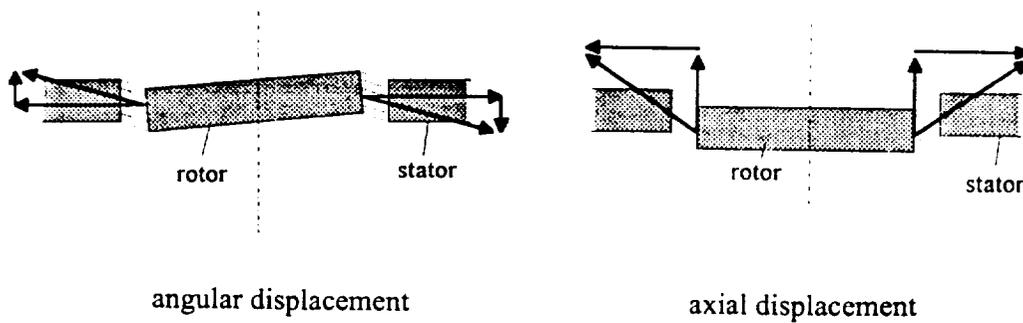


Fig. 3: Passive stabilisation of the angular and axial displacement of the slice rotor

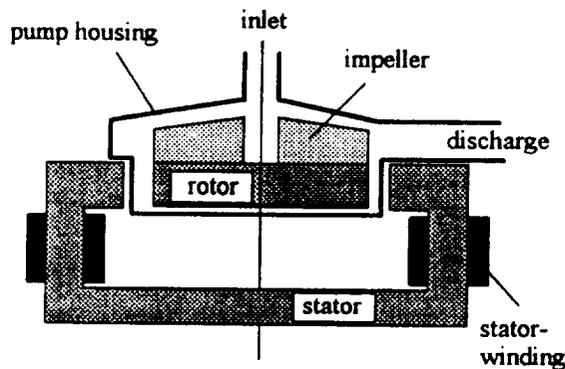


Fig. 4: Principle of the bearingless blood pump

With this "Bearingless Slice Motor", a simple, compact and cost effective solution for a blood pump with a disposable pump part becomes feasible. The rotor-slice can be directly integrated in a plastic impeller by injection moulding. The pump consists of two parts only: the impeller with the integrated motor-rotor and the housing. The principle of this "Bearingless Blood Pump" is shown in Figure 4.

MOTOR DESIGN

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 5. The stator with 24 slots has two separate two-phase windings. One with one pole pair to generate torque and in the case of the induction motor the machine flux, and one with two pole pairs to generate 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 these first prototypes were to demonstrate the functional principle of the bearingless slice motor and to prove that the demands of future application could be fulfilled. A

maximum speed of 6000 rpm and a torque of over 10 Ncm were reached with both motors. This exceeds the requirements for the blood pump.

After the feasibility of the bearingless slice motor was proved, two main problems had to be solved: the integration of the disposable pump part into the motor-stator and the measurement of the rotor position through the blood (the solution of the second problem will be described later). Figure 6 shows the disadvantages of the conventional motor design. It is not possible to exit the pump through the stator windings. It was necessary to build the stator in a way that the disposable pump part can be easily changed. Extensive investigations have been done at our lab to achieve this. The solution is a special motor design called temple motor. Its principle is shown in Figure 7.

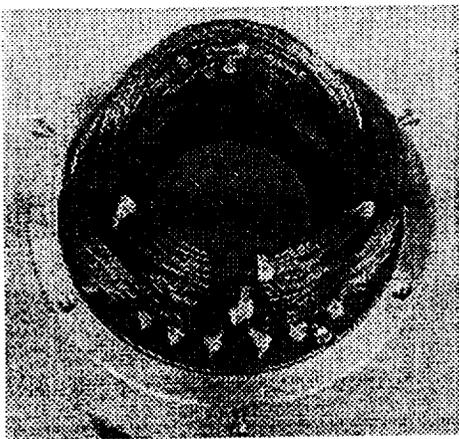


Fig. 5: First prototype of a bearingless slice motor

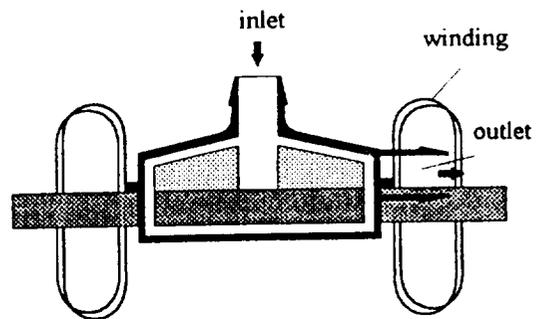


Fig. 6: Problems with the turn windings and the outlet of the disposable pump

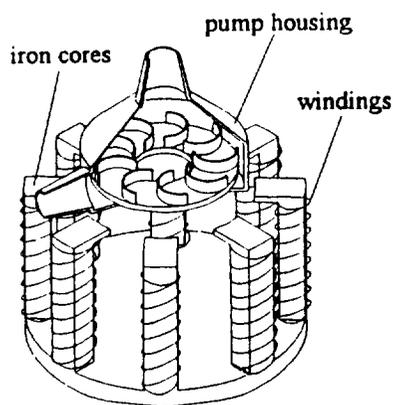


Fig. 7: Principle of the temple motor



Fig. 8: First prototype of a temple motor for use in a bearingless blood pump

The motor coils are wound on L shaped iron cores and the cores are arranged like columns around the rotor in a way that the L shaped end of a core points to the rotor. With this

arrangement, the disposable pump can easily be pressed in at the top of the stator. The pump can be changed in only a few seconds. For applications in a heart-lung-machine, this is very important because it affects massively the overall setup time of the system.

In the second step an experimental prototype with the above described temple motor design was constructed. Figure 8 shows this prototype. It works after the principle of the bearingless synchronous motor. With this motor a speed of 4500 rpm and a maximum torque of 70 Ncm was reached. It gives the output power of 320 W and exceeds the requirements for the blood pump by a factor of 20. The prototype was already designed for pumping tests. The pump was built with parts of a commercially available blood pump (Saint Jude). After it was proved that bearingless pumping is possible with this arrangement, we immediately started the development of a smaller motor, which is more adapted to the duty of pumping blood. Figure 9 shows this smaller motor with the disposable pump. It reaches again speeds of 4500 rpm but at a lower torque of only 32Ncm. With the St. Jude impeller a maximum flow rate of 12 l/min and a maximum pump height of 5m was reached with water.

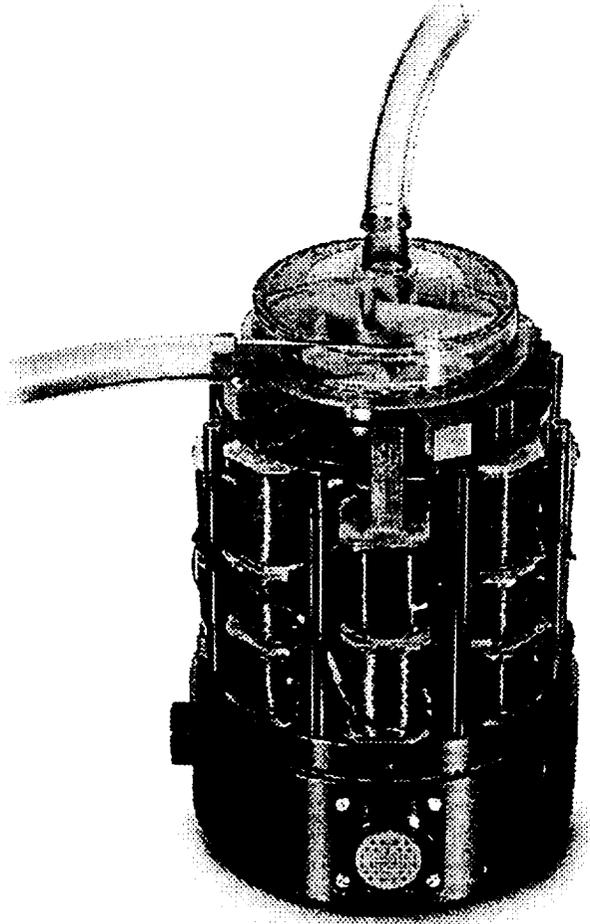


Fig. 9: Actual model of the motor with a disposable pump. The disposable part is built from parts of a commercial blood pump (St. Jude).

CONTROL

With the superposition of a steering-flux (with the pole pairs $p_2 = p_1 \pm 1$) to the motor-flux (with the pole pairs p_1), radial magnetic forces are built up in the bearingless motor. These forces are controlled by the current of the steering winding (with the pole pairs $p_2 = p_1 \pm 1$) and are used for the contactless mounting of the rotor in radial direction. The idea of a radial magnetic bearing in an a.c. motor which uses such a steering winding for the control of the magnetic tensile forces is published by several authors (i.e. [11], [13]). However, the proposed control schemes would work only under limited (steady state) conditions because they are based on the steering of the motor flux. A better control approach, which works also under transient conditions, is described in [15] and [17]. It is based on vector control and considers not only the Maxwell-forces but also the Lorentz-forces in the machine. The second point is especially important for the control of a bearingless synchronous motor with a large air gap like in our application. That is, why we use a vector control based control scheme for our bearingless slice motor. The digital controller is implemented on a self designed TMS 320C50-80 MHz based signal processor board. Commercial switched power amplifiers are used for the actuation of the motor windings. Figure 10 shows the complete blood pump with the necessary control electronics.

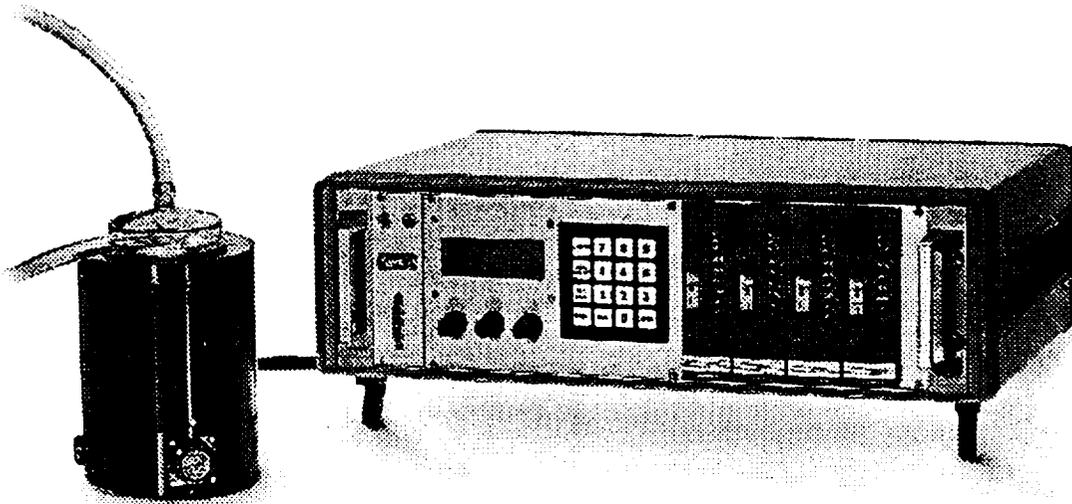


Fig. 10: Complete blood pump with the necessary control electronics.

SENSORS

An exact and fast determination of the flux has a major meaning for the overall quality of the position control. In the prototype system the flux is directly measured in the air gap with hall probes. To achieve immunity to radial rotor displacements it is measured differentially. The arrangement of the flux probes is shown in Figure 11. A total of four flux probes are needed with this method. A much bigger problem is the measurement of the radial rotor position. It is crucial that the position is exactly measured in the middle of the rotor. Otherwise there is a coupling

between the angular displacement of the rotor and the measurement. This coupling leads to instability of the radial position control. The red colour of the blood makes an optical measurement nearly impossible. Ultrasonic measurement is difficult because of the changing flow of the blood and the poor resolution of ultrasonic sensors. With inductive sensors a measurement, free of coupling, is not achievable. An interesting solution for the problem can be found by integrating the air gap flux over two halves of the circumference and by differentially weighting the corresponding magnitudes. If this is done in two quadrants, the radial position of the rotor can be determined. For this principle at least 8 flux probes have to be arranged in the air gap (see Figure 12).

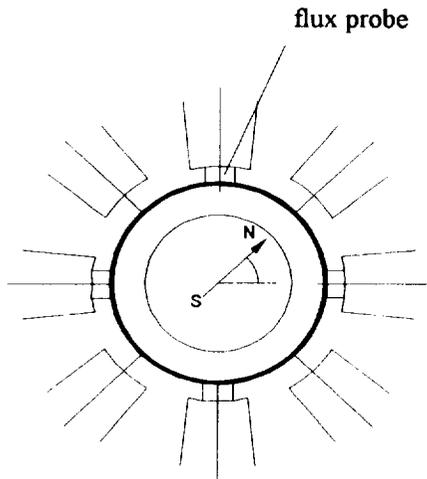


Fig. 11: Arrangement of the flux probes for measurement of the flux angle

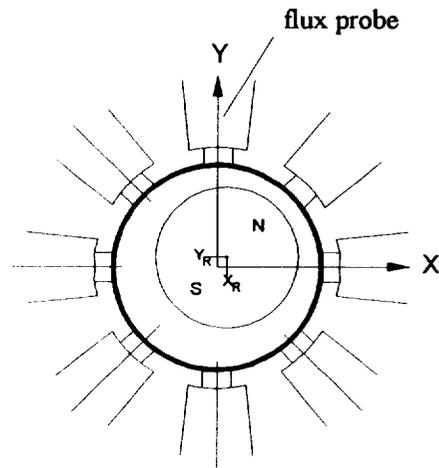


Fig. 12: Arrangement of the flux probes for measurement of the rotor position

TEST RESULTS

The test pump with St. Jude impeller reaches a maximum flow rate of 12 l/min and a maximum pump head of 5m with water at a rotor speed of 2200 rpm. The pumping power is not limited by the motor torque but by the axial forces which act on the rotor, due to the pressure differences on both sides of the impeller. The pressure-flow rate of the pump is more or less the same as of the original St. Jude pump. It is shown in Figure 13 for different rotor speeds. The requirements for the application in open heart surgery are easily achieved.

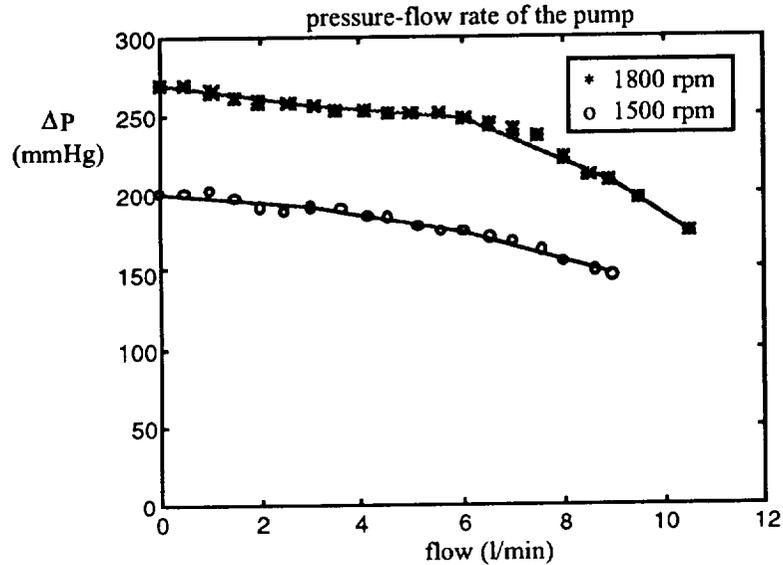


Fig. 13: Pressure-flow rate of the pump with St. Jude impeller for different rotor speeds.

CONCLUSION AND OUTLOOK

In this paper a new concept for a disposable blood pump with a totally magnetically suspended impeller was presented. The pump is based on the "Bearingless Motor" and is therefore called the "Bearingless Blood Pump". The disposable part of the system consists of two parts only: an impeller with the integrated machine rotor and a housing. Fabricated in quantities, it will cost less than \$10 and will therefore be affordable for the use in a heart-lung-machine. It was demonstrated that the principle works successfully and that it meets all the requirements for practical use. The "Bearingless Blood Pump" is a reasonable solution to overcome the bearing- and shaft-seal-problems of today's centrifugal blood pumps.

Until now, all experiments have been done by using water. The objective was to prove the functional principle. Further investigations are now planned together with the German Heart Centre of Munich in the field of the pump optimisation to achieve low blood damage.

ACKNOWLEDGEMENTS

The project was supported jointly by the Laboratory for Electrical Engineering Design (EEK) of the Swiss Federal Institute of Technology (ETH) in Zurich and the companies Sulzer Electronics AG, CH-Winterthur and Lust Antriebstechnik GmbH, D-Lahnau.

REFERENCES

- [1] Rhee, K. and Blackshear, P. L.: "Bearing and Bearing Seal Cavitation in Blood Pumps," International Workshop on Rotary Blood Pumps, Baden/Vienna, 1991.
- [2] Olsen, D. B. and Wamler R. K.: "Continuous Blood-Flow Pumps with Internal and External Motors," International Workshop on Rotary Blood Pumps, Obertauern (Austria), 1988.
- [3] Akamatsu, T.: "Development of Nutating Centrifugal Blood Pump," International Workshop on Rotary Blood Pumps, Obertauern (Austria), 1988.
- [4] Schistek, R.; Ghosh, P.; Unger, F.; and Matthias, H. B.: "Is it possible to Avoid Blood Contact of Sealing and Bearings in a Rotary Pump," International Workshop on Rotary Blood Pumps, Obertauern (Austria), 1988.
- [5] Bramm, G.; Novak, P. and Olsen, D. B.: "Blood Pump for the Long Term Application with Magnetically Suspended Rotor to Reduce Blood Trauma," 2nd International Workshop of Austrian Society of Artificial Organs, 1981.
- [6] Olsen, D. B. and Bramm, G., "Blood Pump with Magnetically Suspended Impeller," Trans. American Society of Artificial Internal Organs, Vol. 31, pp. 395-401, 1985.
- [7] Akamatsu, T. and Nakazeki, T., "Recent Development of a Centrifugal Blood Pump with Magnetically Suspended Impeller," 4th International Symposium on Artificial Heart and Assist Devices, Tokyo, 1992.
- [8] Allaire, P. E.; Maslen, E. H.; Bearnson, G. D.; Olsen, D. B.: "Design of a Magnetic Bearing Supported Prototype Centrifugal Artificial Heart Pump," to be presented at the STLE/ASME Tribology Conference, Orlando, 1995.
- [9] Mandler, N.; Podechtl, F.; Feil, G.; Hiltmann, P.; Sebening, F.: "Seal-less Centrifugal Blood Pump with Magnetically Suspended Rotor: Rot-a-Flot," Artificial Internal Organs, Vol. 19, Num.7, 1995.
- [10] Yamane, T.; Ikeda, T.; Orita, T.; Tsutsui, T.; and Jikuya, T.: "Design of a Centrifugal Blood Pump with Magnetic Suspension," Artificial Internal Organs, Vol. 19, Num.7, 1995.
- [11] Hermann, P. K.: Deutsche Offenlegungsschrift Nr.24 06 790
- [12] Bichsel, J.: Beiträge zum lagerlosen Elektromotor, Dissertation ETH Zürich, 1990
- [13] Chiba, A.; Power, D.T.; Rahman, M.A.: Characteristics of a Bearingless Induction Motor, IEEE Transactions on Magnetics, Vol. 27, No. 6, November 1991
- [14] Schöb, R.: Beiträge zur lagerlosen Asynchronmaschine, Dissertation ETH Zürich, 1993
- [15] Schöb, R.: Schweizerisches Patentgesuch Nr.00056/94-7
- [16] Ohishi, T.; Okada, Y.; Dejima, K.: Analysis and Design of a Concentrated Wound Stator for Synchronous-Type Levitated Rotor, Fourth International Symposium on Magnetic Bearings, Zürich 1994
- [17] Schöb, R.; Bichsel, J.: "Vector Control of the Bearingless Motor," 4th International Symposium on Magnetic Bearings, Zurich 1994.
- [18] Hugel, J.: "The Vector Method for Determination of Torque and Forces of the Lateral Force Motor," International Power Electronics Conference, Yokohama 1995.