Magnetically suspended motor system for artificial hearts and blood pumps

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***Abstract*—Magnetic levitation technology, for magnetic bearings and magnetically suspended motors, is a cutting edge technology to produce artificial hearts and higher performance blood pumps. A wider blood gap and eliminating the contacting parts in the device based on the maglev technology provide better blood compatibility and higher durability of the device. Novel inventions about the maglev mechanism are required to overcome the size and power limitation of artificial hearts. Specialization of the maglev system is also necessary due to different requirements with the spreading application of artificial hearts. The current research topics of the maglev system for artificial hearts and blood pumps will be presented in the mini-symposium.**

I. INTRODUCTION

Artificial hearts and mechanical circulation support devices have been studied since 1958. Ventricular assist devices with rotary blood pump are commercially available at the outset of the 21st century [1]. The rotary blood pumps are very common as blood pumps for the mechanical circulatory support right now, but the mechanical bearing mechanism has potential problems at the contacting part suspected to be a cause of hemolysis and thrombogenecity. The magnetic bearing or self-bearing motor are promising technologies to give us long device durability and higher blood compatibility of the blood pumps. The magnetic suspension technologies produce wider blood gaps between the levitated and rotated impeller and pump casing which eliminates mechanical contact and wear. These features provide better blood compatibility to avoid such as blood trauma and thrombogenecity. Active position control of the levitated impeller provides safer operation of the blood pumps and new feature of the devices. I will introduce several types of the magnetic suspension system for artificial heart and blood pumps developed in Ibaraki University.

II. MAGNETIC SUSPENSION SYSTEM AND BLOOD PUMPS

A. *Axial magnetic suspension system for mechanical circulatory support*

A levitated impeller is set between a magnetic bearing stator and a motor stator and is axially suspended by the magnetic suspension system to which balances axial forces on the impeller [2] [3]. Fig. 1 shows the extracorporeal blood pump with an axial magnetic suspension system. This pump has been developed under collaborative research with the Department of Therapeutic Strategy for Heart Failure, the University of Tokyo, National Cerebral and Cardiovascular Center Research Institute and Ibaraki University. The pump is developed for acute heart failure patients to enhance recovery of natural heart. The magnetic bearing produces an upward attractive force to balance the downward attractive force produced by the motor stator. There are bias permanent magnets on the impeller and a hybrid magnetic bearing is constructed to produce sufficient attractive force with the miniaturized device. The position and tilting are controlled actively with the magnetic bearing, and radial position is restricted with passive magnetic stability .

The structure of the magnetic bearing is shown in Fig. 2.

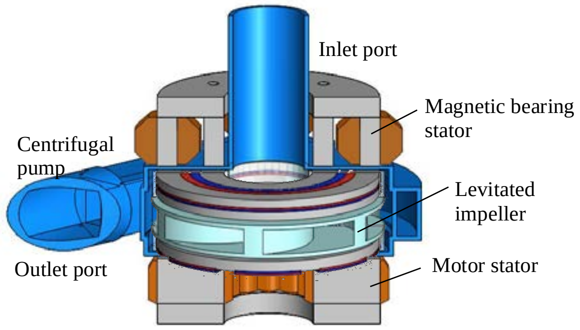

Figure 1. Cross sectional view of maglev blood pump with axial suspension system. A centrifugal pump is set between magnetic bearing and axial motor stator.

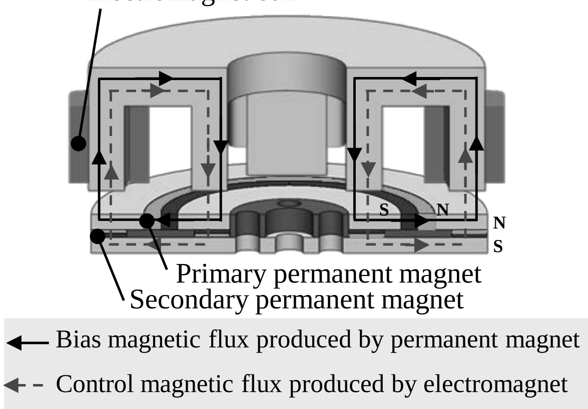

Figure 2. Structure of double bias hybrid magnetic bearing. Magnetic flux produced by the secondary permanent magnet is overlapped with it of the primary permanent magnet.

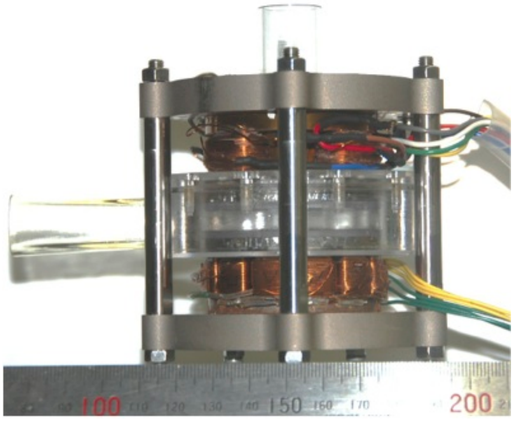

Figure 3. Exterior view of the extracorporeal maglev blood pump with axial magnetic suspension system.

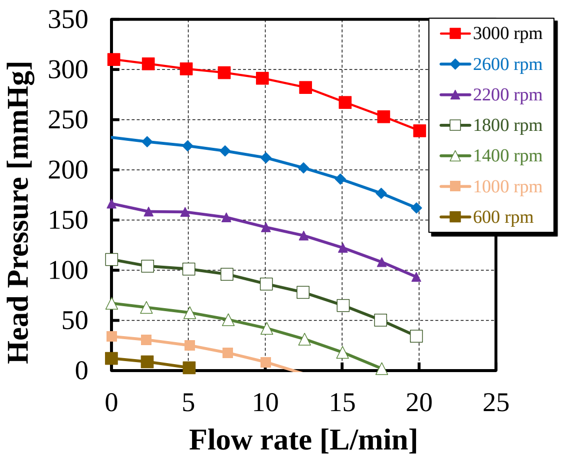

Figure 4. Pump performance of the extracorporeal maglev blood pump with the axial magnetic suspension system.

The double bias hybrid magnetic bearing had been invented to develop a small and powerful magnetic bearing. In the hybrid magnetic bearing, the bias permanent magnet is used to produce bias magnetic flux, but the permanent magnet (PM) inserted in the magnetic circuit is a resistance for the electric magnet. We can enlarge the net of the attractive force but the force factor to the exciting current into the electro magnet is reduced by the PM. We have tried to overcome the problem with deterioration of the force factor by using double bias PMs. The primary PM produces main bias magnetic flux and the secondary PM regulates the magnetic flux path. The primary PM is magnetized in the radial direction and the secondary PM is magnetized in the axial direction. The yokes are set at the both circumferential side of the primary PM and the back of the secondary PM. The PM are set like the same pole of the PMs faces to face. The magnetic flux produced by the primary PM, indicated as solid line in Fig. 2, goes through the yoke, the air gap, and the stator core of the magnetic bearing and restricted its direction with the secondary PM. The magnetic flux produced by the secondary PM is overlapped with that of the primary PM at the air gap and enhances the magnetic attractive force at the air gap. The magnetic path of the magnetic flux produced by the electromagnet of the magnetic bearing, indicated with dashed line in Fig. 2, is constructed with the stator core of the magnetic bearing, the air gap, the secondary PM and the back yoke of the secondary PM. This is the shortest path for the magnetic flux because the primary PM exhibits a higher magnetic circuit resistance. The double bias hybrid magnetic bearing produces higher magnetic flux in the air gap coupled with lower magnetic resistance for the electromagnet which enables a higher attractive force and higher force factor with excitation current. In our maglev pump, the PMs and the yoke behind the secondary PM is set on the impeller.

Fig. 3 and Fig. 4 show the extracorporeal maglev blood pump with the axial magnetic suspension system and the pump performance. The blood pump is designed to produce higher flow rate with extracorporeal connection and to produce pulsatile flow by changing the rotating speed synchronized with the heart beat to possibly enhance the chance for myocardial recovery due to increased coronary artery flow. The developed maglev pump can produce more than 20 L/min against a head pressure of 250 mmHg.

B. Axial magnetic suspension system for total artficial heart

An axial magnetic suspension system is also used for a total artificial heart [3, 4]. The maglev total artificial heart is developed under a collaborative research with BiVACOR Inc., Texas Heart Institute in Houston, TX USA, ICET lab in Brisbane, Australia and Ibaraki University in Hitachi, Japan. There are two types of the total artificial heart with the axial magnetic suspension system. The BiVACOR® device utilizes a similar structure with the axial magnetic suspension system for mechanical circulatory support explained already above [3] whilst another system, called the IBHEART and is explained as follows, has a reverse structure [4]. Fig. 5 shows the structure of the magnetically suspended motor. The stators of the magnetic bearing and the motor are combined at the center of the device back-to-back to form a single levitated motor. The left and right pumps are constructed at both ends of the stator core. Impellers of both pumps are connected with a rod through the center hole of the stator core. Permanent magnets generating the magnetic force toward the stator core are set on the backside surface of the impellers and attractive forces produced by the magnetic bearing and the motor are balanced by the digital PID controller to suspend the impellers. The unique feature of the artificial heart is its preload sensitivity and flow rate balancing function between the left

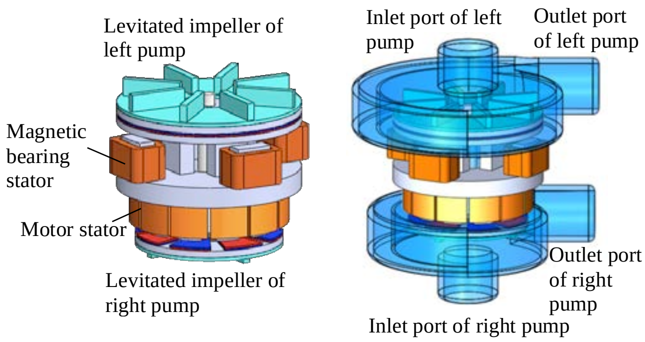

Figure 5. Axial magnetic suspension and motor system for total artificial heart (left) and configuration of the left and right pump with the actuator (right side). Centrifugal pumps are set at both sides of the actuator.

and right blood pump. Preload means an inlet pressure related with the atrial pressure. The pump flow rate must increase when the preload increases to prevent lung congestion because the increasing of the atrial pressure means large amount of the blood is accumulated in the lung. Management ability of the blood volume based on the preload is an essential function for the total artificial heart. But, implantation of the flow rate probes is difficult with current technology and an auto regulation mechanism of the pump flow rate is a key to develop the artificial heart. The auto regulation mechanism of the artificial heart is implemented based on the magnetic suspension mechanism and the zero power control with the hydrodynamic force in our device. The axial impeller position is regulated with a zero power controller. The zero power controller searches force minimal impeller axial position that makes a balance the PM attractive force and the hydraulic force acts on the levitated impeller. For example, the impeller is shifted upward when the left pump preload increases and is shifted downward when the preload decreases. The hydraulic pump efficiency and the flow rate increase when the impeller is shifted upward because the blood gap between the impeller vane tip and the pump casing changes narrower by shifting impeller position and the secondary flow that is a cause of the inefficiency of the pump decreases. The pump efficiency and the flow rate decrease when the impeller is shifted downward. The flow rate of the pump is changed with changing of the preload in our device.

Fig. 6 shows exterior view of the prototype pump of the total artificial heart. The diameter and the width of the IBHEART artificial heart are 76 mm and 62 mm, respectively. Fig. 7 shows pump performance of the prototype pump. Maximum flow rate is 20 L/min and the 10 % of the flow rate can be adjusted by shifting the impeller position by 0.8 mm with same rotating speed of the impeller.

C. Radial magnetic supesion sysstem

The radial magnetic suspension system that suspends the levitated rotor in the radial direction is used for the ventricular assist device to prevent severity of heart disease. Fig. 8 shows a thin cascade blood pump with the radial magnetic suspension system for the mild heart disease patients [5]. This pump has been developed under collaborative research with the Department of Therapeutic Strategy for Heart Failure and Ibaraki University. Ring shaped rotor is set around the maglev stator as an outer rotor structure. Two independent electric coils are wound on the stator poles to construct a self-bearing motor. One coil is used to control radial position of the impeller and the other is to control rotation of the impeller. The levitation coil produces attractive force toward the center of the stator and controls rotor radial position. The rotor position and rotation can be regulated independently with P+/-2 poles theory. Axial movement of the levitated rotor is

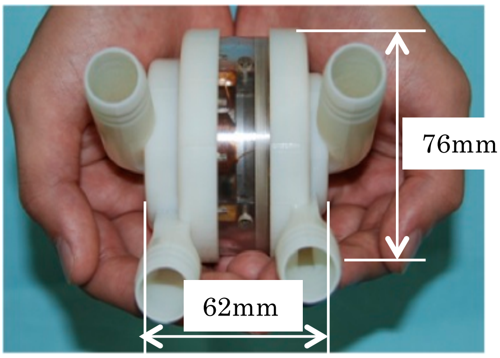

Figure 6. Exterior view of the maglev total artificial heart.

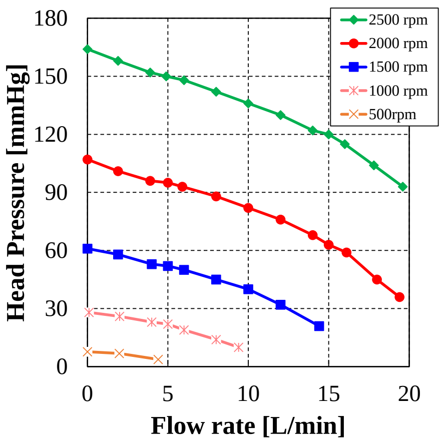

Figure 7. Pump performance of lefty pump of the maglev total artificial heart.

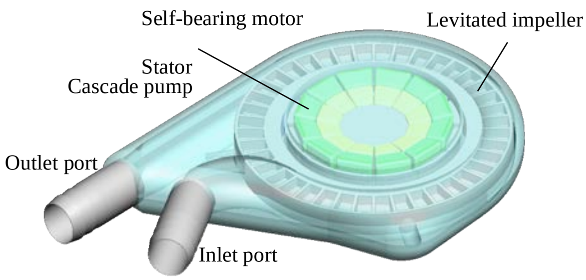

Figure 8. Blood pump with radial magnetic suspension system. A cascade pump is adopted to make the device thin.

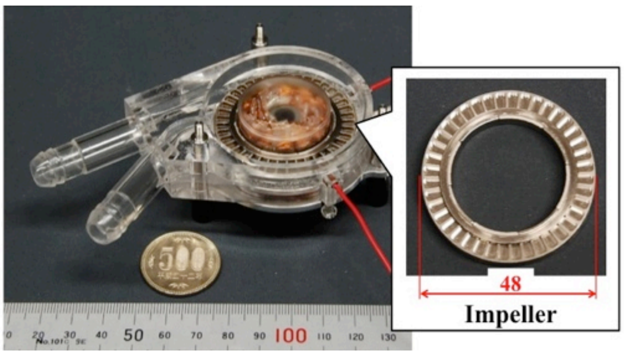

Figure 9. Exterior view of the maglev cascade blood pump.

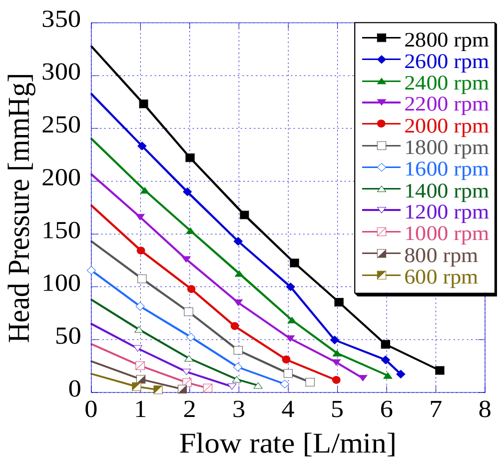

Figure 10. Pump performance of the maglev cascade blood pump.

restricted with passive stability of the magnetic system. The radial magnetic suspension system is good to make thinner device. A cascade pump with an inlet port and an outlet port on same plane is adopted as a blood pump to make the device thin. The pump is designed for implantation under thorax muscle layer to achieve easy pump replacement and for long term circulation assist more than ten years. Exterior view of the prototype pump is shown in Fig. 9. The ring shaped impeller has pockets at its circumference to convey the fluid from the inlet port to outlet port. There is a channel around the impeller to transport the blood with the rotation of the impeller and the channel is closed between the inlet and outlet port to pump out the blood from the outlet port. The outer diameter of the ring shaped impeller is 48 mm and the thickness of the prototype pump is 22 mm. Target flow rate of the pump is 2.0 L/min against a head pressure of 100 mmHg. Fig. 10 shows the pump performance of the maglev cascade pump. Maximum flow rate and maximum head pressure are 7 L/min and 300 mmHg, respectively. The pump indicates sufficient pump performance as a ventricular assist device.

D. Axial suspension sysstem with double stators

Fig. 11 shows five-axis control maglev motor for a pediatric ventricular assist device [6]. This device has been developed under collaborative research with National Cerebral and Cardiovascular Center Research Institute and Ibaraki University. We overcome the deterioration of the motor torque due to miniaturization of the motor by adopting double stator mechanism. The proposed mechanism also permits us to control five-axis of the levitated impeller. The stators set at both sides of the levitated impeller have two electric coils, one is to control axial position and rotation and the other is to control tilting and radial position of the impeller. The axial position and rotation of the levitated impeller are controlled with vector control algorithm. The tilt and radial position of the impeller are controlled with a double stator mechanism and P+/-2 poles theory. Fig. 12 explains generation of the restoring torque and radial force on the levitated impeller. The rotating magnetic field is generated with the P+/-2 poles theory and the torque and the radial force on the levitated impeller are generated simultaneously by both of the stator.

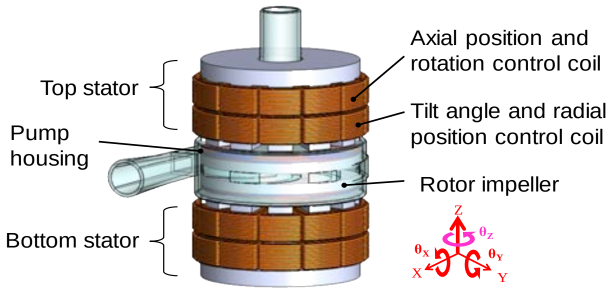

Figure 11. Five-axis controlled double stator levitated motor for pediatric ventricular assist device. A centrifugal pump is set between motor stators.

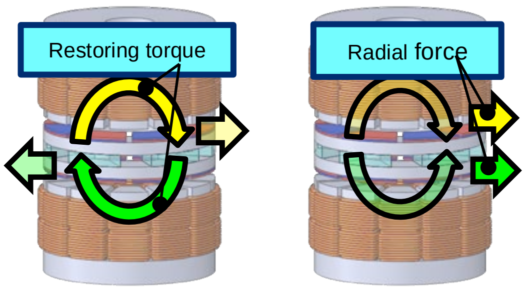

Figure 12. Generation of the restoring torque and radial force with double stators

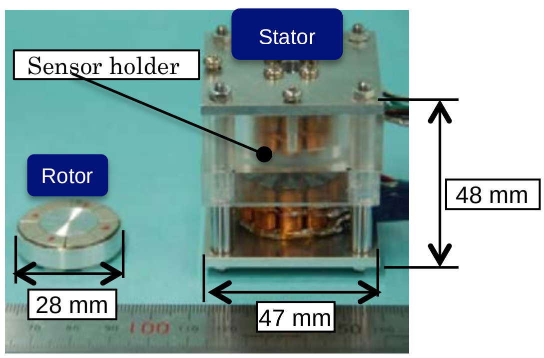

Figure 13. Exterior view of 5-axis controlled double stator levitated motor for pediatric ventricular assist device.

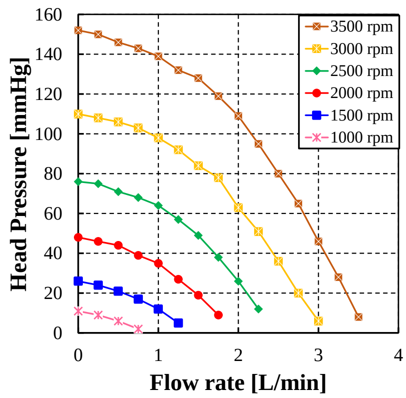

Figure 14. Pump performance of the maglev pediatric ventricular assist device.

The restoring torque only can be extracted by overlapping the forces produced by both stators. Also, only radial force can be extracted with same manner.

The exterior view of the prototype motor is shown in Fig. 13. The developed motor has an outer diameter of 28 mm, height of 41 mm and magnetic air-gap length of 1.5 mm. The impeller can be levitated and rotated up to a rotating speed of 6,500 RPM with an oscillation amplitude of less than 100 micrometers in air. Fig. 14 shows pump performance of a pediatric ventricular assist device with five-axis control maglev motor. Target flow rate of the pump is 1.5 L/min against a head pressure of 100 mmHg, the prototype pump can achieve the target performance with a rotating speed of 3000 RPM.

III. SUMMARY

Several types of magnetic suspension system for artificial heart and mechanical circulatory support devices developed at Ibaraki University are introduced. The roll of mechanical circulatory support and its usage spreads widely. Specialized magnetic suspension system should be developed corresponding to each device application.

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