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Large-gap passive levitation mechanism combined with thrust and magnetic force for pump applications

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Abstract
Blood pumps are used to treat patients with heart failure. In recent years, non-contact support of the impeller by active magnetic bearings or hydrodynamic bearings has improved the durability. In this study, we propose a pump mechanism with a large gap and passive levitation to achieve higher reliability and blood compatibility. According to Earnshaw's theorem, one degree of freedom becomes always unstable when using only static magnetic field. Therefore, in this study, positive stiffness is achieved for unstable degrees of freedom (axial direction) by using thrust. Thrust is the force that acts on the impeller from the fluid as a reaction when the impeller discharges the fluid. In the proposed mechanism, the flow rate inside the impeller changes with the axial displacement of the impeller, and as a result, the thrust force increases as a restoring force against the displacement. Since positive stiffness can be achieved in the axial direction with thrust, an axial motor with an iron core is employed to achieve a smaller size compared to conventional mechanisms. In the experiments, the impeller can move freely only in the axial direction, and is supported by a slider in the radial and tilt directions. Axial levitation experiments were conducted using water as the working fluid, and levitation was confirmed at an impeller speed of 7,000 rpm. From the result, we conclude that the use of an axial motor in a levitation mechanism using thrust has advantageous in terms of miniaturization.

Keywords : Passive magnetic bearing, Thrust, Earnshaw’s theorem, Passive levitation, Pump, Large gap

1. Introduction

Non-contact support of the impeller using magnetic bearings improves the durability of the blood pump and enables long-term use. However, according to Earnshaw’s theorem, levitation in all six degrees of freedom cannot be realized using a static magnetic field. Therefore, all the magnetically levitated (MagLev) blood pumps utilize active magnetic bearings or hybrid bearings with passive magnetic bearings and hydrodynamic bearings. Active magnetic bearings in the field of blood pump have been proposed as a new value in systems that provide additional functions such as flow sensors (Shida et al., 2022)(Hijikata et al., 2015), thrombus detection (Hijikata et al., 2020) and thrombus prevention (Murashige et al., 2019)(Hatakenaka et al., 2023).

However, the active magnetic bearings exhibit a risk of malfunctioning of their control system, and the hydrodynamic bearings exhibit a risk of blood trauma owing to their narrow gaps. To overcome these challenges, we previously developed a novel hybrid levitation mechanism with a large gap without any active control system by combining thrust force and passive magnetic bearings using coreless radial motor (Magari et al., 2022)(Magari et al., 2024). In this study, a new levitation mechanism using an axial motor with an iron core was developed to improve the motor torque as well as improve levitation stiffness.

2. Proposed passive levitation principle

Fig. 1 shows an overview of the blood pump with the proposed hybrid levitation mechanism. The mechanism consists of a housing, impeller, flow straightener, diffuser, axial gap motor, and passive magnetic bearing. Key feature for levitation of this mechanism is thrust force acting on the impeller as a reaction force against blood flow generation. The proposed levitation mechanism, which passively supports five degrees of freedom, except for rotation around the axial direction, is realized by satisfying conditions (i)–(iii) shown below.

(i) Axial direction: As shown in Fig. 2, an equilibrium point exists, and the resultant force of thrust and magnetic force (generated by the motor core and passive magnetic bearing) exhibits a positive stiffness around it.

(ii) Radial directions: An equilibrium point exists, and the magnetic force exhibits a positive stiffness around it.

(iii) Angular directions: An equilibrium point exists, and the torque generated by the magnetic force exhibits a positive stiffness around it.

Conditions (ii) and (iii) can be realized with normal passive magnetic bearings using permanent magnets, but in this case, the axial direction has negative stiffness(Earnshaw et al., 1842). In the mechanism, positive stiffness is achieved in the axial direction using thrust. The strainer has a spherical cap, and the gap between the cap and the vane inside the impeller changes as the impeller is displaced. The amount of blood flowing inside the impeller changes according to the change in the gap, resulting in a change in thrust. When the impeller is displaced in the positive direction, this thrust force increases in the negative direction and thus has positive stiffness. Therefore, if the positive stiffness due to the thrust force exceeds the negative stiffness due to the magnetic force, and if the impeller is designed so that the resultant force has an equilibrium point, condition (i) is also satisfied and fully passive levitation can be achieved.

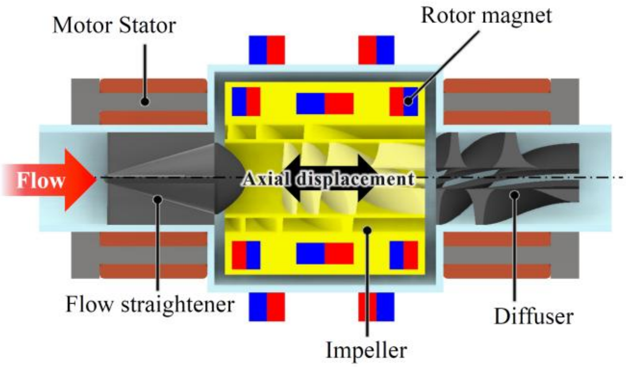

Fig. 1 Configuration of hybrid levitation mechanism.

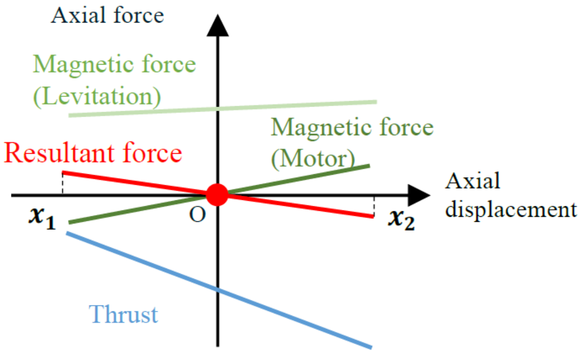

Fig. 2 Concept of axial force acting on the impeller.

3. Design and fabrication

Figure 3 shows a schematic view of the axial motor. The rotor consists of permanent magnets and two stators are placed on the both sides of the rotor. *ISD* and *OSD* are the inner and outer diameters of the iron core, respectively, and the iron core center diameter *D* calculated by the following equation is used as a design variables.

$$D = \frac{ISD + OSD}{2} \tag{1}$$

In addition, the rotor magnet height *Mh*, rotor magnet width *Mt*, and coil height *Ch* were also used as design variables, and the dimensions that would provide higher torque were determined by magnetic field analysis. From the results of the magnetic field analysis, the dimensions of the motor and rotor magnet were determined to be *Ch* = 18 mm, *D* = 25 mm, OS*D* = 35 mm, *Mh* = 2 mm, and *Mt* = 4 mm.

Next, the torque was calculated when a rectangular permanent magnet, which is easily available, was used instead of a fan-shaped magnet. Figure 4 shows the calculated motor torque for a rectangular magnet with 12 to 28 divisions of 360 degrees. Although the torque is about 20% lower than that of a fan-shaped magnet, a rectangular magnet is used because of its easy availability. The number of divisions does not make a large difference in torque, and 16 divisions were used. The designed motor could generate 25 mNm at the current density of 10 A/mm^2.

Figure 5 shows an overview of the designed pump for the axial levitation test, and Fig. 6 shows a photograph of the prototype blood pump. In this study, a shaft that can move freely in the axial direction was inserted in the center of the impeller to measure the axial thrust force. Load cells are installed at both ends of the shaft to measure the axial resultant force of the motor and thrust acting on the impeller. The axial displacement of the impeller can be changed by turning a screw on the outside of the load cell. Figure 7 shows the measurement results of the axial force, that is the combination of the thrust force and attractive force of the axal motor. It was confirmed the axial force had the positive stiffness.

Based on the measurement results, the passive magnetic bearing was designed so that the resultant force due to motor, thrust, and passive magnetic bearing have positive stiffness not only in the axial direction, but also in the radial and tilting directions. Outer and inner diameters of the permanent magnets of the stator for the passive magnetic bearing was determined as 50 mm and 42 mm respectively. The thickness of them were 5 mm. Figure 8 shows the resultant force in the axial direction. Axial forces generated by the thrust and motor were referred from Fig. 7 and force generated by the passive magnetic bearing was calculated by the magnetic field analysis. As a result of above-mentioned design, the pump achieved positive stiffness in all directions; 0.47 N/mm in the axial direction as shown in Fig. 8, 0.84 N/mm in the radial direction, and 4.28 mNm/deg. in the tilt directions.

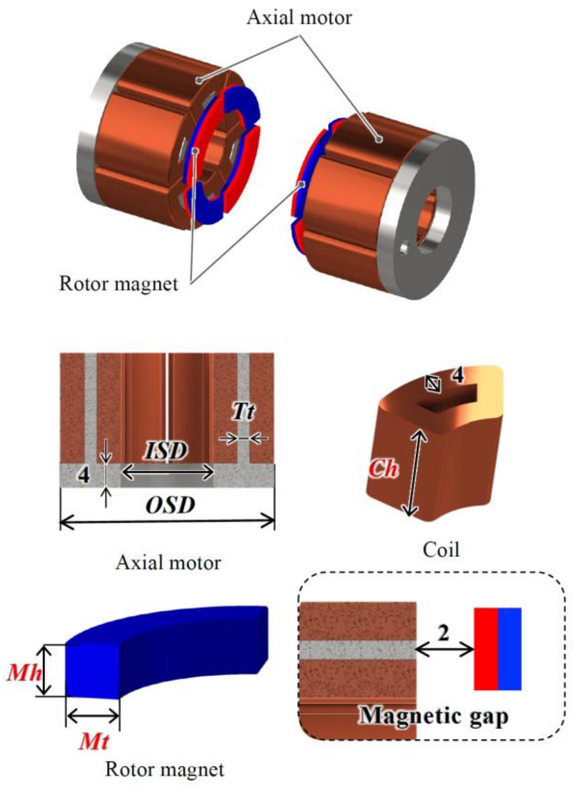

Fig. 3 Schematic view of the axial motor and design variables.

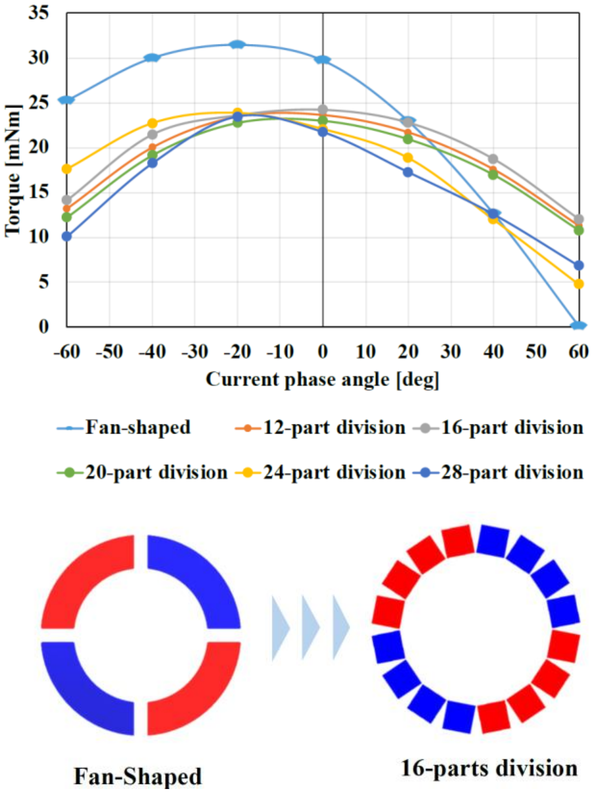

Fig. 4 Simulation result of the motor torque. The torque was calculated with both fan-shaped magnets and rectangular magnets. For the rectangular magnets, several number of divisions were evaluated.

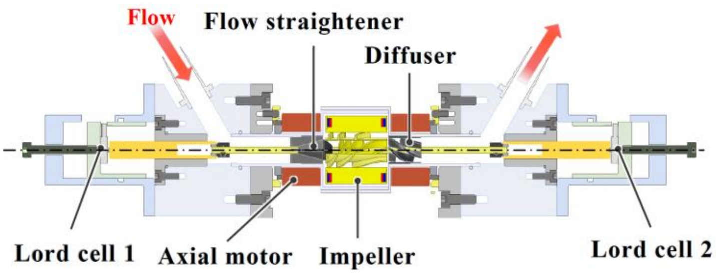

Fig. 5 Configuration of experimental setup.

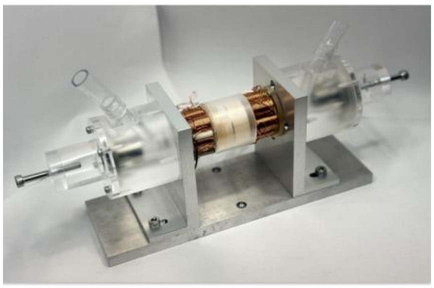

Fig. 6 Photograph pf prototype.

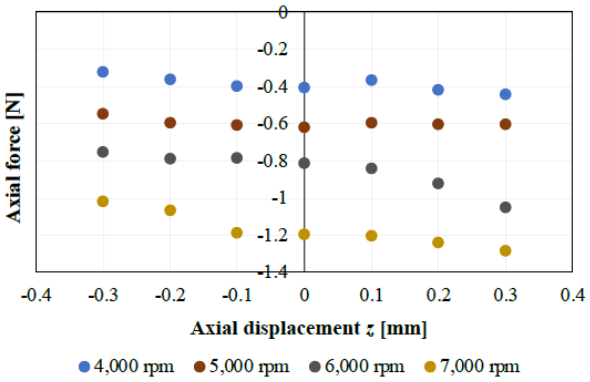

Fig. 7 Measurement results of the thrust force.

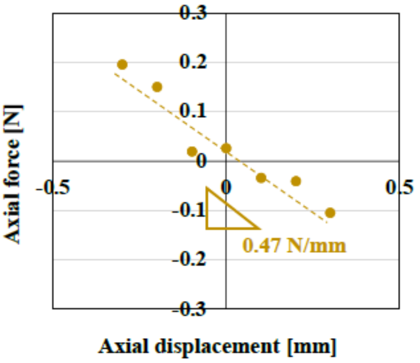

Fig. 8 Resultant force in the axial direction.

4. Experiment for axial levitation

To confirm axial levitation, the pump was filled with water, rotated at 7,000 rpm, and subjected to an external force in the axial direction by a screw, and the impeller displacement was measured with a laser displacement sensor. The results of pushing the impeller from the left and right sides are shown in Fig. 5 and Fig. 6, respectively. After displacement by the external force, it was confirmed the impeller returned to the equilibrium point and maintained its levitation. The results show that the feasibility of fully passive levitation using the newly proposed mechanism. In the next step, the shaft will be removed to demonstrate fully passive levitation in all directions.

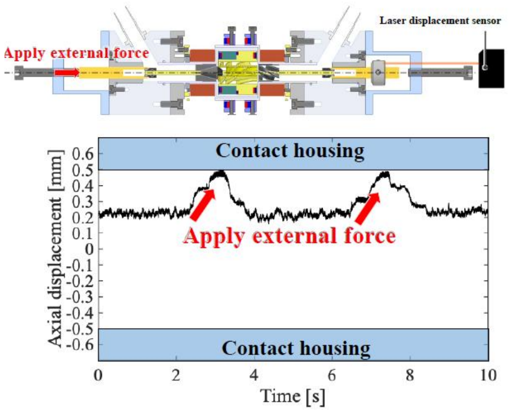

Fig. 9 Demonstration of axial levitation by applying external force from left hand side.

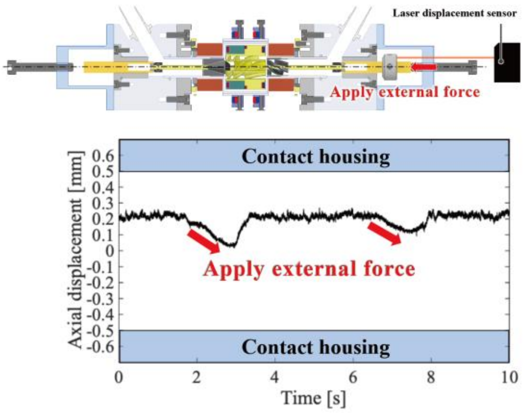

Fig. 10 Demonstration of axial levitation by applying external force from right hand side.

5. Conclusion

To realize a blood pump with a large gap and passive levitation, we proposed a levitation mechanism that combines thrust and magnetic forces. Since the thrust force provides positive stiffness in the axial direction, even if an axial motor with an iron core is employed, the resultant force still maintains positive stiffness and axial levitation is confirmed. The above results indicate that the use of an axial motor in a levitation mechanism using thrust may be advantageous in terms of miniaturization.

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