Hybrid passive levitation mechanism utilizing thrust force and magnetic force for a pump application

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Abstract

The durability of a blood pump has been enhanced owing to the development of contactless bearings. According to Earnshaw’s law, levitation in all six degrees of freedom cannot be realized using a static magnetic field. Therefore, the combination of passive magnetic bearings and active magnetic bearings or passive magnetic bearings and hydrodynamic bearings are commonly adopted in the blood pump. 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. Therefore, the objective of this study is to develop a passive levitation system for an impeller with a large gap without active control. The large gap prevents blood damage, and passive levitation contributes to reduce the risk of device malfunction. In this study, hybrid passive levitation mechanism utilizing thrust force and magnetic force is proposed. The thrust force generated by the rotation of the impeller changes depending on the interaction between the housing geometry and impeller position, even with a large gap. Considering this characteristic, the impeller was levitated by balancing the magnetic force generated by the permanent magnets and the thrust force in the axial direction. The movements in the radial and angular directions are passively supported by the restoring force and torque generated by the permanent magnets. The geometry of the pump and dimensions of the permanent magnets were designed so that the mechanism had positive stiffness in all directions. The levitation of the impeller in the axial direction was confirmed in the experiment by the pump prototype.

Keywords: *Passive bearing, Passive levitation, Thrust force, Magnetic bearing, Blood pump*

1. Introduction

The durability of a blood pump has been enhanced owing to the development of magnetic bearings. In this system, an impeller is levitated by using magnetic force to enhance the durability and hemocompatibility. According to Earnshaw’s law(Earnshaw, 1839), 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(Hoshi, Shinshi and Takatani, 2006). 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, Masuzawa and Osa, 2022)(Hijikata *et al.*, 2015), thrombus detection(Hijikata *et al.*, 2020) and thrombus prevention(Murashige and Hijikata, 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. Therefore, in this study, we developed a novel hybrid levitation mechanism with a large gap without any active control system by combining thrust force and passive magnetic bearings.

2. Principle of thrust force hybrid levitation system

The proposed hybrid levitation mechanism installing in an axial blood pump is shown in Fig. 1(Magari and Hijikata, 2022). The mechanism consists of a housing, impeller, flow straightener, diffuser, direct-drive motor, and passive magnetic bearing. The housing used in the proposed mechanism has a unique shape with a larger diameter in the center of the pump. 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 system, which 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 exhibits a positive stiffness around it.

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

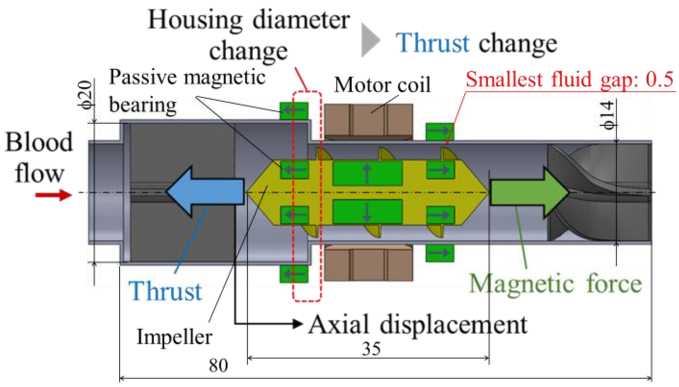


Figure 1 Configuration and dimension of the hybrid levitation mechanism installed in the blood pump.

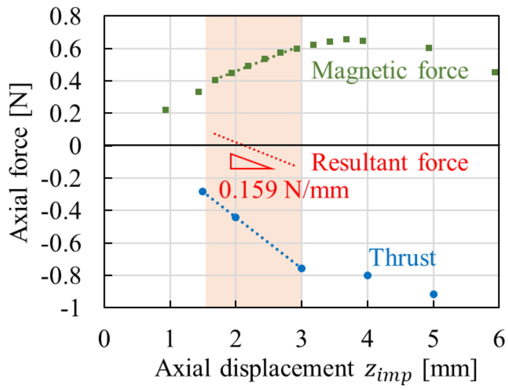


Figure 2 Concept and simulated axial force acting on the impeller.

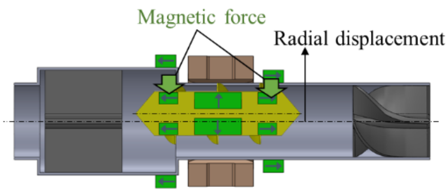


Figure 3 Levitation principle in the radial direction.

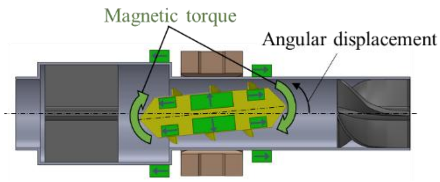


Figure 4 Levitation principle in the angular direction.

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

Conditions (ii) and (iii) can be satisfied by a normal passive magnetic bearing as shown in Fig. 3 and Fig. 4, respectively. However, under these conditions, axial stiffness becomes negative. In the proposed levitation system, thrust force is utilized to overcome this negative stiffness in the axial direction to levitate the impeller. We found that the thrust force increases as the cross-sectional area of the flow path at the end of the impeller (indicated with red-dashed rectangle in Fig. 1) increases. Owing to this feature, the proposed pump can have a positive stiffness in the thrust force against the displacement of the impeller and hence, the total stiffness in the axial direction can also be positive, that meets the condition (i).

3. Design and Prototyping

By using computational fluid dynamics (CFD) analysis and magnetic field analysis, dimensions of the mechanism and each stiffness were calculated. The designed dimensions were shown in Fig. 1 and stiffness was shown in Fig. 2, respectively. In this calculation, flow rate of the pump and rotational speed of the impeller were considered as 1.5

L/min and 10000 rpm. The equilibrium point was at z_{imp} = 2.1 mm, and the resultant thrust and magnetic force exhibited a positive stiffness of 0.159 N/mm around the equilibrium point. The calculated stiffness in the radial and angular directions by the passive magnetic bearing was 9.5 mN/mm and 0.08 mNm/deg., respectively. These results satisfied the conditions of levitation (i) - (iii).

To validate the CFD and magnetic field analyses, we experimentally measured the axial force as well as observe the axial levitation. Fig. 5 shows the configuration of the pump used for validation and Fig. 6 shows photographs of the experimental prototype. Note that radial motion of the impeller was supported by the shaft and bearings because this experiment aimed to validate the levitation in the axial direction. The thrust force generated on the impeller can be transmitted to load cells via a shaft that supports the impeller. The shaft was supported by linear bearings, and the position of the impeller was adjusted by turning the screws on both ends of the experimental apparatus. As shown in Fig. 7, the prototype pump was connected to the mock circulatory loop consisting of a reservoir, pressure gauges and flow meter. As a working fluid, porcine blood was filled in the loop. The viscosity of the blood was measured with a viscometer (SV-10, A&D Co., Ltd, Tokyo), and it was 5.12 mPa·s (21.9°C).

After measuring the thrust force, axial levitation was demonstrated. In this demonstration, load cells were removed so that the impeller could be displaced in the axial direction and working fluid was replaced to water to measure the axial displacement of the impeller by using a laser displacement sensor. The smallest gap between the impeller and housing was 500 µm.

4. Results

Fig. 8 shows the experimental results of the thrust force measurement. Although the target flow rate was set to 1.5 L/min, the flow rate at 5000 rpm did not reach the target value. Hence, the thrust at maximum flow was recorded, that is, the flow rates were 0.72 L/min, 0.89 L/min, 0.98 L/min, 1.1 L/min, 1.2 L/min, 1.2 L/min, 1.3 L/min, and 1.2 L/min at the axial displacement of the impeller z_{imp} = 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0 mm, respectively. At other speeds, the flow rate was set as 1.5 L/min. Simulated results of the CFD analysis with the viscosity of 3.6 mPa·s was also indicated in the plots. As expected, the magnitude of the thrust increased with impeller displacement, indicating positive stiffness. The trend was also in good agreement with the CFD analysis.

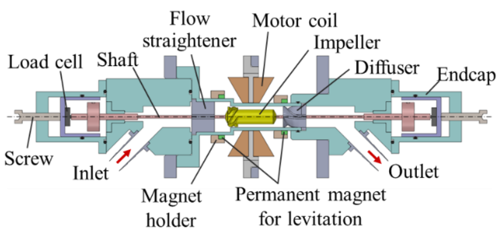


Figure 5 Configuration of the prototype mechanism.

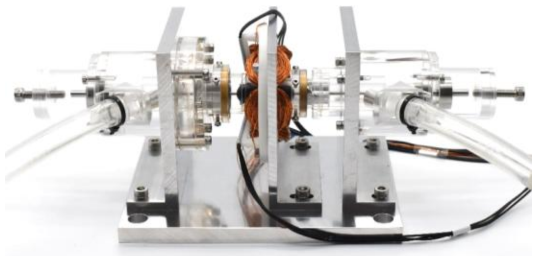


Figure 6 Photograph of the prototype.

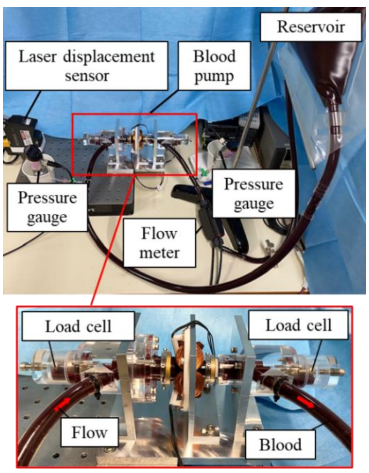


Figure 7 Configuration of the prototype mechanism.

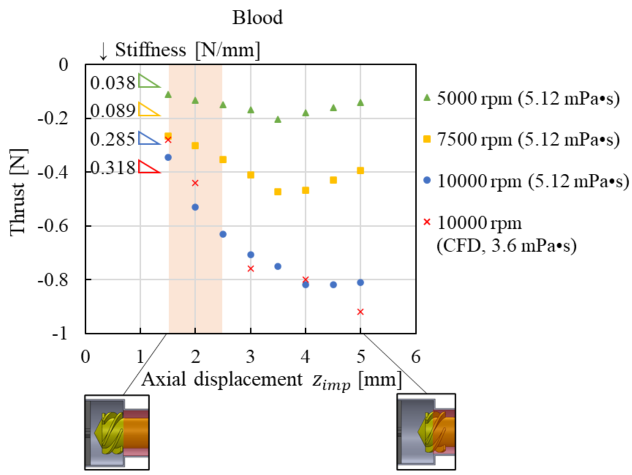
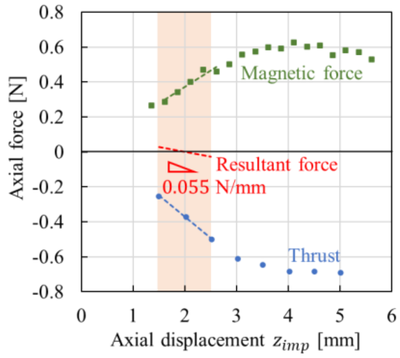


Figure 8 Measured and simulated thrust force.



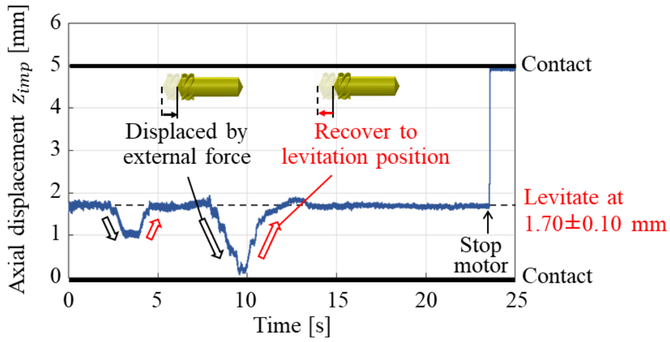


Figure 9 Resultant force measured in the experiments.

Figure 10 Result of the levitation verification in the axial direction.

Fig. 9 shows the resultant force experimentally obtained from the measured thrust (water, 10000 rpm) and magnetic force. The resultant force had a positive stiffness of 0.055 N/mm, and the equilibrium point existed at z_{imp} = 2.0 mm. Therefore, it is considered to satisfy the axial levitation condition and can levitate in the axial direction. Then, we removed load cells and validate the levitation. As the measured axial displacement shows in Fig. 10, the impeller could levitate at the center position of z_{imp} = 1.70 mm with the rotational speed of 10000 rpm. At approximately 3 and 7 s, the impeller was pushed using a screw installed at the end of the pump to verify the stability of the levitation. The impeller returned to the levitation position after the displacement. These results show that the impeller levitated in the axial direction with the smallest gap of 500 µm without any active control.

5. Conclusion

In this study, hybrid passive levitation mechanism utilizing thrust force and magnetic force was developed to realize blood pumps with large gaps without an active control system. The axial magnetic force and thrust acting on the impeller were experimentally measured, and the results showed that the stiffness of the resultant axial force was positive value of 0.055 N/mm. Furthermore, the demonstration showed that the impeller could levitate in the axial direction with the smallest gap of 500 µm without any active control. The results of this study indicate there is possibility to realize fully passive levitation principle by combining the thrust force and magnetic force. The verification of levitation, including the radial and angular directions, will be examined in a future study.

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