Abstract The effect of the hydraulic force on magnetically levitated (maglev) pumps should be studied carefully to improve the suspension performance and the reliability of the pumps. A maglev centrifugal pump, developed at Ibaraki University, was modeled with 926,376 hexahedral elements for computational fluid dynamics (CFD) analyses. The pump has a fully open six-vane impeller with a diameter of 72.5 mm. A self-bearing motor suspends the impeller in the radial direction. The maximum pressure head and flow rate were 250 mmHg and 14 l/min, respectively. First, a steady-state analysis was performed using commercial code STAR-CD to confirm the model’s suitability by comparing the results with the real pump performance. Second, transient analysis was performed to estimate the hydraulic force on the levitated impeller. The impeller was rotated in steps of 1° using a sliding mesh. The force around the impeller was integrated at every step. The transient analysis revealed that the direction of the radial force changed dynamically as the vane’s position changed relative to the outlet port during one circulation, and the magnitude of this force was about 1 N. The current maglev pump has sufficient performance to counteract this hydraulic force. Transient CFD analysis is not only useful for observing dynamic flow conditions in a centrifugal pump but is also effective for obtaining information about the levitation dynamics of a maglev pump.

Key words Computational fluid dynamics (CFD) analysis · Transient analysis · Magnetically suspended pump · Rotary blood pump · Centrifugal pump

Introduction

Many computational fluid dynamics (CFD) studies have focused on rotary blood pumps and their biocompatibility, e.g., their hemolytic properties and antithrombogenicity. Recently, studies using CFD analysis for rotary blood pumps have been accelerated thanks to improved computing power. We have worked in this field and have revealed the relationship between hemolysis and the hydrodynamic conditions in a rotary blood pump with a systematic research approach using CFD analysis, visualization techniques, and in vitro hemolysis tests conducted with a commercially based rotary blood pump. The usefulness of CFD analysis to develop biocompatible blood pumps is well known, and CFD analysis is used around the world for the design of rotary blood pumps.

Magnetically levitated (maglev) blood pumps have been developed in several institutes because of their high durability, low hemolytic properties, and antithrombogenic characteristics. The levitated impeller of the maglev blood pump is exposed to the dynamic changes of the hydraulic force in the pump, unlike the case for traditional shaft-driven pumps. The magnetic suspension system, which has lower suspension stiffness than normal shafts, must suspend the impeller against the dynamic changes of the hydraulic force. The effect of hydraulic forces on the levitated impeller in a maglev pump should be studied carefully to improve the suspension performance and the reliability of such pumps.

We have already reported the possibility of estimation of the radial hydraulic force on the levitated impeller by using the levitation control information of a maglev system. However, it is still difficult to reveal detailed phenomenon of the levitated impeller movement experimentally because the Reynolds number of the blood pump is so large and the
flow speed in the blood pump is too fast to observe with current visualization techniques. We believe that CFD analysis can provide useful information about hydraulic forces on the impeller for evaluating the stability of a maglev blood pump. The purpose of this study was to reveal the hydraulic force on the levitated impeller in a magnetically suspended blood pump using transient CFD analysis.

Methods

Magnetically suspended centrifugal blood pump as a target pump for analysis

A schematic of the magnetically suspended pump which has been developed by Ibaraki University is shown in Fig. 1.25-27 The pump consists of the upper and lower pump casing, a fully open six-vane impeller, and a maglev stator. A rotor with four permanent magnets and a magnet yoke is embedded in the impeller. The outer diameter of the impeller is 72.5 mm and the inner diameter is 55 mm. The pump size and weight are \( \phi 78.5 \times 41.5 \) mm and 512 g, respectively. The pump is small enough for use as an implantable left ventricular assisted device. The maglev stator is set at the center of the pump and the ring-shaped rotor is set radially around the stator. The maglev stator has electromagnet coils for levitation and rotation control. The stator suspends the impeller using radial magnetic forces and rotates the impeller directly with a rotating magnetic field. The gap sizes around the impeller are shown in Fig. 2. The minimum gap size is 0.4 mm between the stator and the impeller inner surface. The other gap sizes around the impeller are 1 mm or more.

Radial displacement of the levitated impeller is controlled actively with the maglev stator. Axial displacement and tilt of the levitated impeller is restricted with passive stability so as to simplify the control system by reducing the control axes. The pump can produce a flow rate of 5 l/min against a pressure head of 100 mmHg with a rotation speed of 1400 rpm. The maximum pressure head and flow rate are 250 mmHg and 14 l/min, respectively. The levitated impeller position of the maglev pump is regulated by a zero-power controller.29 The zero-power controller regulates the impeller position to minimize the power consumption. The mechanism of the zero-power controller is shown in Fig. 3. The levitated impeller of the maglev pump has permanent magnets on its inner circumference. The impeller position is controlled at the center of the pump in the usual control method. In this usual control method, the attractive force between the permanent magnets is balanced and can be

![Fig. 1](image1.png)

Magnetically suspended centrifugal pump developed at Ibaraki University, Hitachi, Japan. A self-bearing motor that can suspend and rotate the impeller with one stator is set at the center of the pump. The rotor, which has permanent magnets, is embedded in the levitated impeller

![Fig. 2](image2.png)

Gap sizes around the impeller. The magnetically suspended pump has narrow gaps between the impeller and the casing in which to suspend the impeller

<table>
<thead>
<tr>
<th>Stator &amp; impeller (inner)</th>
<th>0.4 mm</th>
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<tr>
<td>Casing &amp; impeller (outer)</td>
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<td>Casing &amp; impeller (downside)</td>
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