Optimization of a hybrid magnetic bearing for a magnetically levitated blood pump via 3-D FEA

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ABSTRACT

In order to improve the performance of a magnetically levitated (maglev) axial flow blood pump, three-dimensional (3-D) finite element analysis (FEA) was used to optimize the design of a hybrid magnetic bearing (HMB). Radial, axial, and current stiffness of multiple design variations of the HMB were calculated using a 3-D FEA package and verified by experimental results. As compared with the original design, the optimized HMB had twice the axial stiffness with the resulting increase of negative radial stiffness partially compensated for by increased current stiffness. Accordingly, the performance of the maglev axial flow blood pump with the optimized HMBs was improved: the maximum pump speed was increased from 6000 rpm to 9000 rpm (50%). The radial, axial and current stiffness of the HMB was found to be linear at nominal operational position from both 3-D FEA and empirical measurements. Stiffness values determined by FEA and empirical measurements agreed well with one another. The magnetic flux density distribution and flux loop of the HMB were also visualized via 3-D FEA which confirms the designers’ initial assumption about the function of this HMB.

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1. Introduction

In this paper, a hybrid magnetic bearing (HMB) that is used in an axial flow pump is introduced. Three dimensional finite element analysis (3-D FEA) was used to optimize the design of the HMB as the previous design did not allow the pump to function over an adequate operational range because of insufficient axial forces generated by the HMB. Radial, axial and current stiffness of HMB were calculated for systematic variations of geometric variations of the HMB by 3-D FEA and verified by empirical testing. The HMB optimized via 3-D FEA presented a better system performance and met the design objective.

1.1. Magnetic bearings in blood pumps

Over the past few decades, great developments have been made in the field of advanced bearings. Bearings must be capable of supporting high-speed flexible rotors found in new rotating machinery applications and magnetic bearings are emerging as a promising solution to meet the demanding requirements found in these applications [1–5]. Magnetic bearings are used to support and control rotors or other loads by means of contact-free electromagnetic forces, thereby eliminating mechanical friction between the stator and rotor. Advantages of contact-free magnetic bearings over mechanical bearings are: low localized heat generation, quiet operation, no lubrication requirements, and very low vibration due to the active control feature of magnetic bearings. Additionally, in the particular application of rotary blood pumps, the contact-free configuration has the potential advantage that blood cells can flow freely through the pump without being exposed to stresses induced by mechanical bearings. Due to these advantages, magnetic bearings have been used in the most current generation of artificial blood pumps [6–9] as a means to extend pump life by eliminating material wear, decreasing heat generation, and minimizing both red cell damage and the formation of blood clots, both of which are physiological phenomena associated with elevated fluid shear stress and heat generation.

Magnetic bearings are inherently nonlinear electromagnetic actuators. With bias current supplied to coils, the control force and current relationship can be linearized over small displacement of rotor. This electromagnetic force $F$ applied to the rotor can be expressed as a function of control current $i$ and rotor displacement $s_d$:

$$F_d = k_d s_d - K_{dsd} d = x, y, z$$

(1)

where $k_d$ is the force-current factor (referred to here as current stiffness) and $K_{dsd}$ is the force–displacement factor (also referred to as position stiffness, radial or axial stiffness). The second term on the right hand side of Eq. (1) represents the passive magnetic force due to the rotor displacement. In our magnetic bearing configuration which will be introduced later, the axial component of $K_{dsd}$ has a positive sign (like springs), so that the bearing is inherently stable axially.

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