International Journal of Robotics and Automation, Vol. 32, No. 1, 2017

FINITE ELEMENT SIMULATION OF A PASSIVE MAGNETIC ROBOTIC SYSTEM

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Abstract

To realize the stability of the passive magnetic robotic system, a novel combination of permanent magnets is proposed. As we know, a single passive magnetic levitation is impossible to suspend all degrees of freedom of a rigid body; this article researches the combination of multiple passive magnetic bearings by the finite element method (FEM) simulation. Through changing the magnetization direction of permanent magnets, the radial force and axial force can be changed correspondingly. Various magnetization angles of permanent magnets are analysed, and the relationships are analysed among radial force, axial force, and axial displacement. Finally, the optimized magnetization angle of the permanent magnets and their arrangements are proposed. According to the analytic results, it is feasible to realize the stability using the proposed configuration.

Key Words

Passive magnetic bearing, magnetization angle, arrangement, stable, simulation, magnetic materials and devices, FEM

1. Introduction

As we all know, application of the robotic system is increasing more and more widely nowadays [1], [2]. In order to improve its accuracy, variable suspension systems are used in the robotic system [3], especially the electromagnetic suspension system [4]. The types of magnetic bearings in the electromagnetic suspension system are active magnetic bearing (including hybrid magnetic bearing) and passive magnetic bearing (PMB). PMBs [5]–[7] have several advantages over active magnetic bearings [8]–[10] because they require no input energy and no power consumption. So they have been used in the applications in flywheel [11], [12], control momentum gyro [13], high-speed motor [14], bearingless motor [15]–[17], and so on [18]. To the PMB, the typical form is consisted of two monolithic permanent magnetic rings with either axial magnetization or radial magnetization [19]. To realize higher displacement stiffness, layered PMB are widely used with Halbach magnetized array because it can use the arrangement of permanent magnets to increase the magnetic field on one side of the array while cancelling it on the other side [20]–[22]. The PMBs mentioned earlier can be adopted to provide force and few passive axial magnetic bearings are used to provide bigger gyro momentum in magnetically suspended control moment gyro (MSCMG) [23], [24]. More importantly, as stated in Earnshaw's theorem, passive magnetic levitation is impossible to suspend all degrees of freedom, so at least one degree of freedom (DOF) has to be active. Therefore, the magnetically suspended system mentioned earlier has one controlled DOF at least. Especially, a design for a PMB system that can stably levitate a rotor in all directions is described in the literature [25]. In the present system, the stability can only be realized in the lateral direction, but it still needs stabilization coils in the vertical direction whereas the permanent magnets with Halbach array can balance the gravity of the rotor.

In this article, the PMBs configuration is put forward. The relationship between axial force and axial displacement is analysed, as well as the radial force and radial displacement are measured. The various magnetization angles of permanent magnets are analysed by FEM in detail and the final magnetically suspended system is proposed with PMBs. Therefore, the proposed configuration can be realized stably when the movable part rotates.

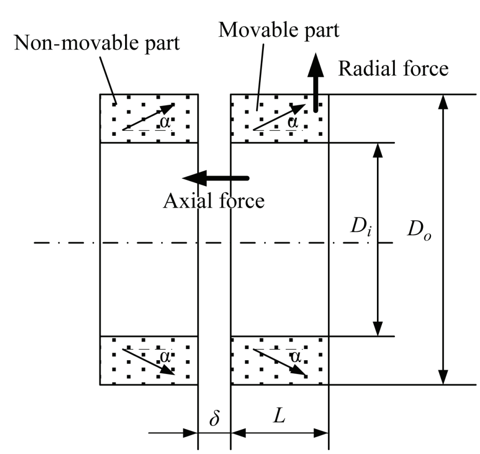

Figure 1. Structure of the PMB.

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Recommended by Dr. Peter Liu
(DOI: 10.2316/Journal.206.2017.1.206-4889)

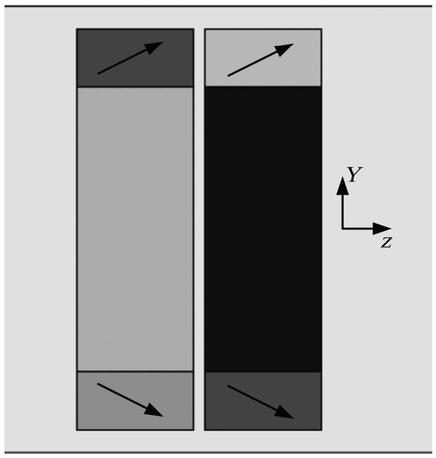


Figure 2. 2D FEM model of the PMB.

Table 1
Parameters of PMB

Parameter	Value
Outer diameter of permanent magnet, D_o/mm	35
Inner diameter of permanent magnet, D_i/mm	25
Length of permanent magnet, L/mm	10
Length of air gap, δ/mm	1
Remanence of permanent magnet, B_r/T	1.2
Coercive force of permanent magnet, H_c/(kA/m)	796

2. Structure and Finite Element Analysis Simulation of Passive Magnetic Bearings

The configuration and magnetization angle of the PMB are shown in Fig. 1. It consists of the non-movable part and movable part, which are made of permanent magnets.

In this figure, D_o denotes the outer diameter of non-movable part permanent magnet or movable part permanent magnet, D_i denotes the inner diameter of non-movable part permanent magnet or movable part permanent magnet, L denotes the length of non-movable part permanent magnet or movable part permanent magnet, α denotes the magnetization angle between non-movable part permanent magnet and movable part permanent magnet, and δ denotes the length of air gap between non-movable part permanent magnet and movable part permanent magnet.

The finite element 2D model is built by Ansys 14.0 for PMB as shown in Fig. 2. We can obviously see the permanent magnets and their magnetization direction. The parameters of the PMBs are illustrated in Table 1.

According to different magnetization angles of permanent magnets, the simulation results between forces and axial displacement are shown in Figs. 3 to 8 at 30°, 40°, 45°, 50°, 60°, and 75°, respectively.

All the results are summarized as shown in Table 2. From this table, it can be seen that the PMB system can be made stable when the magnetization angles of permanent magnets are 45° and 50°. The unit "m" means the length in the x direction, and it refers to the length of half circumference (as shown in Fig. 2).

The reason is seen from Figs. 4 to 6. From these figures, the axial force and radial force are all decreased when the axial displacement is increased. That is to say, the axial force and radial force will be large when the length of air gap δ is decreased, and the axial force and radial force will be small when the length of air gap δ is

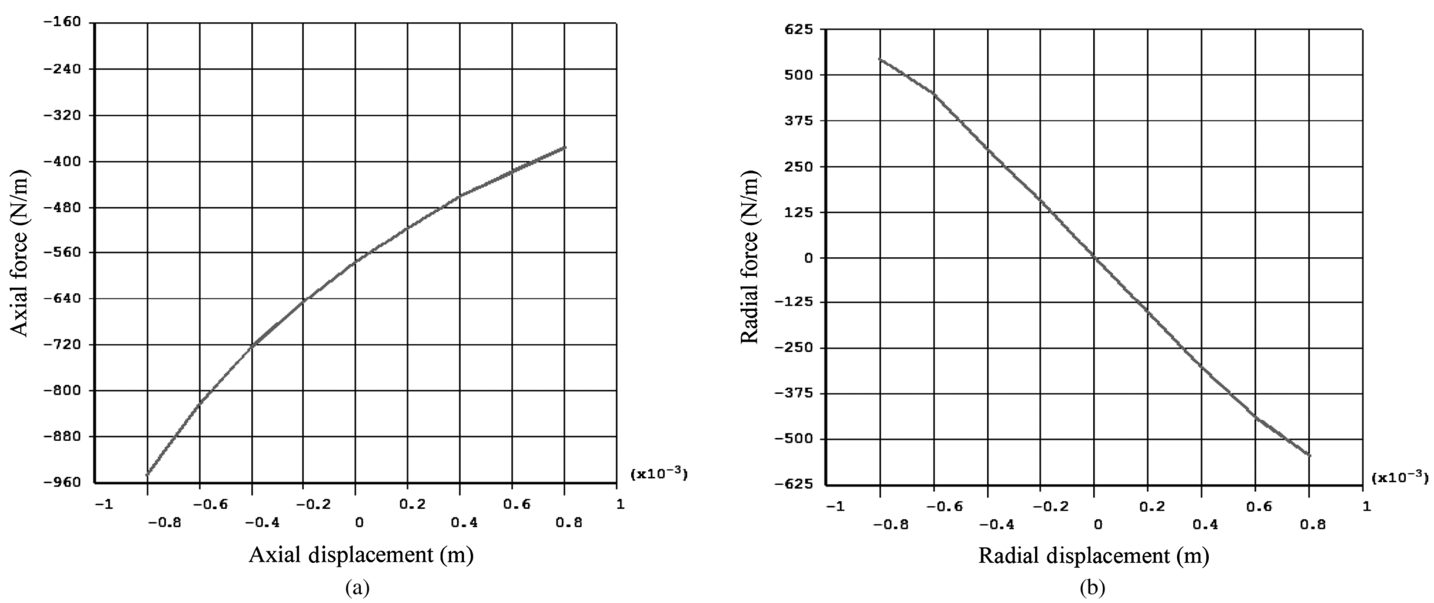
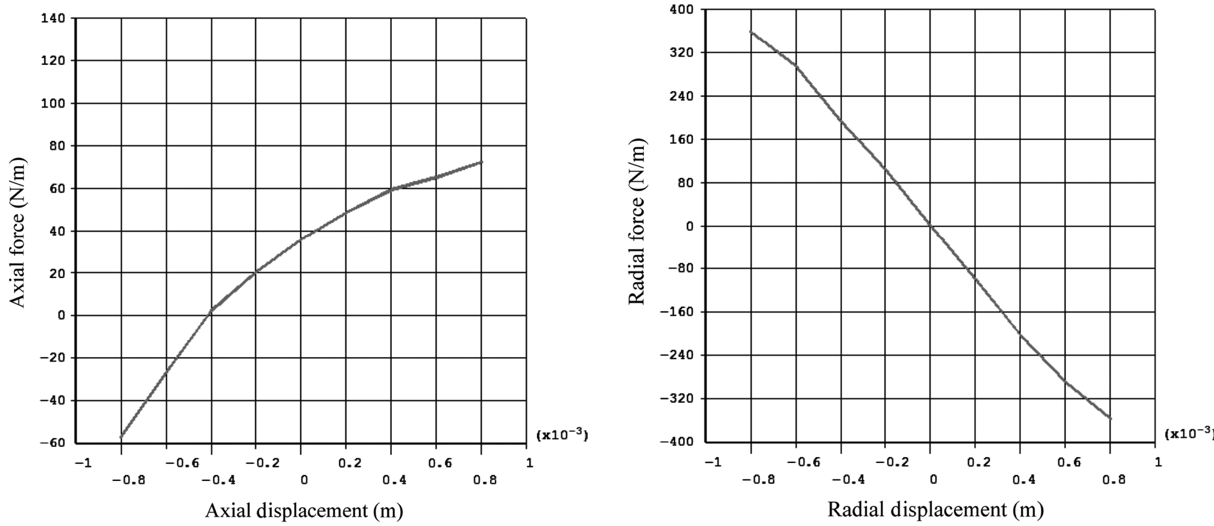
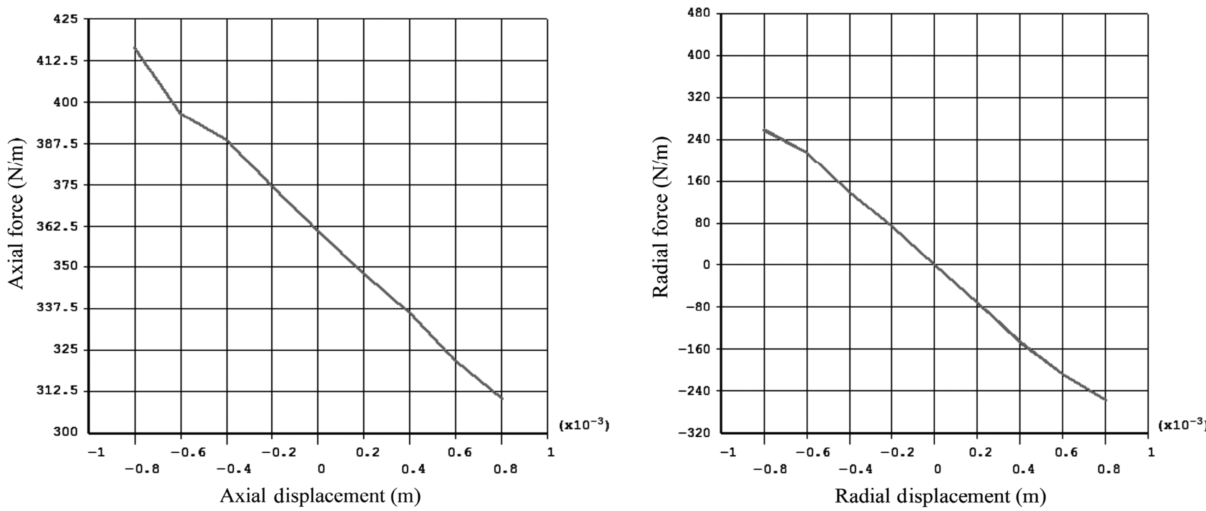


Figure 3. Relationships between forces and displacement at $\alpha = 30°$: (a) axial force versus displacement and (b) radial force versus displacement.



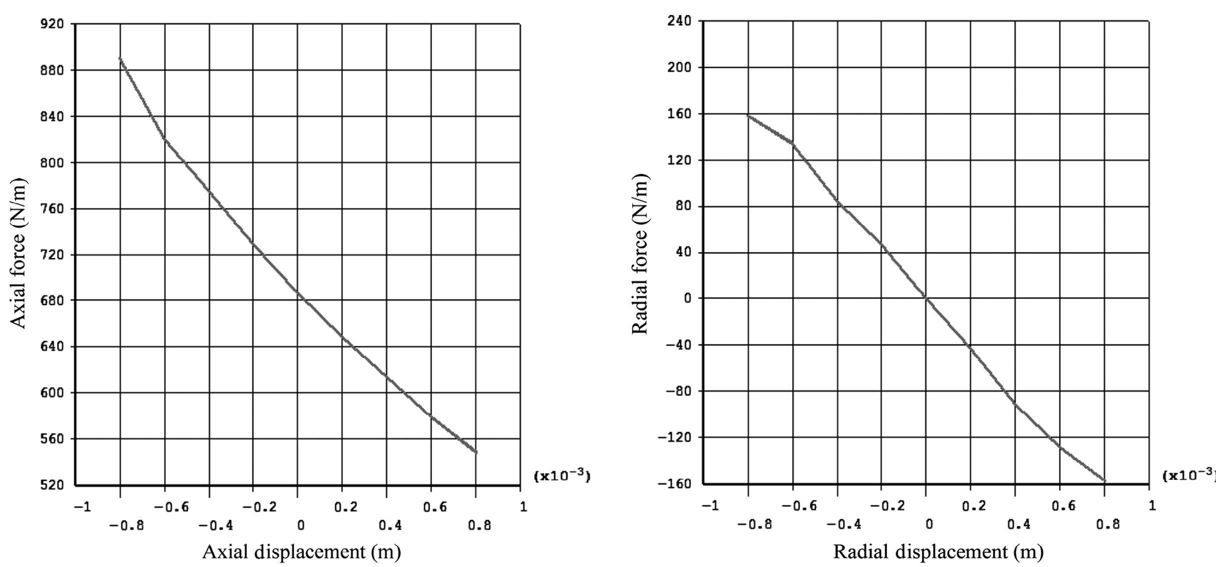
(a) (b)

Figure 4. Relationships between forces and displacement at $\alpha = 40°$: (a) axial force versus displacement and (b) radial force versus displacement.



(a) (b)

Figure 5. Relationships between forces and displacement at $\alpha = 45°$: (a) axial force versus displacement and (b) radial force versus displacement.



(a) (b)

Figure 6. Relationships between forces and displacement at $\alpha = 50°$: (a) axial force versus displacement and (b) radial force versus displacement.

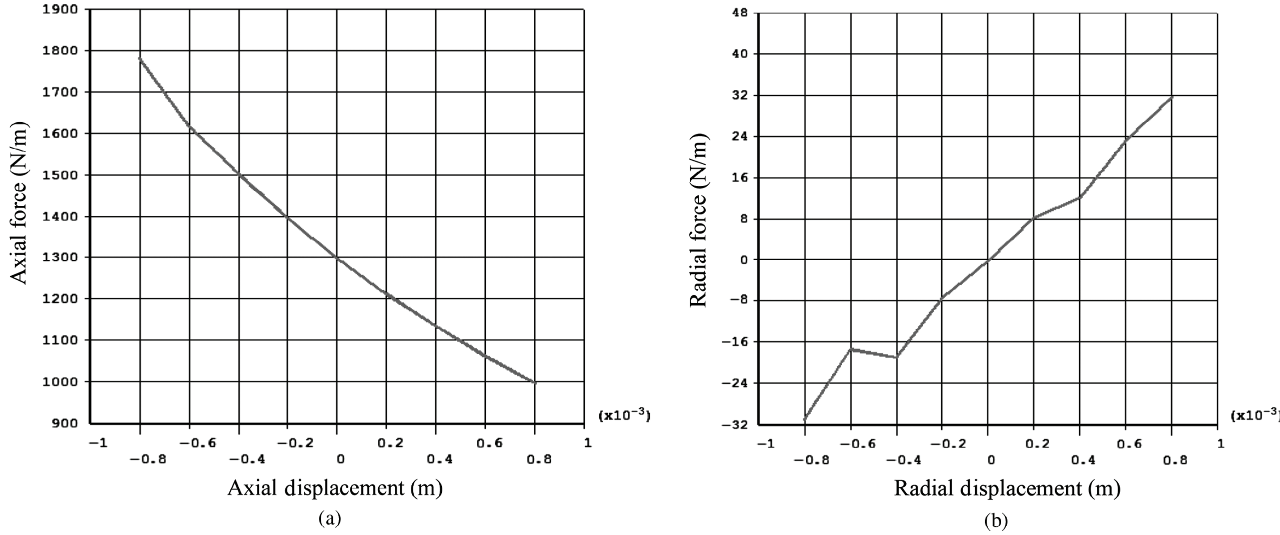


Figure 7. Relationships between forces and displacement at $\alpha = 60°$: (a) axial force versus displacement and (b) radial force versus displacement.

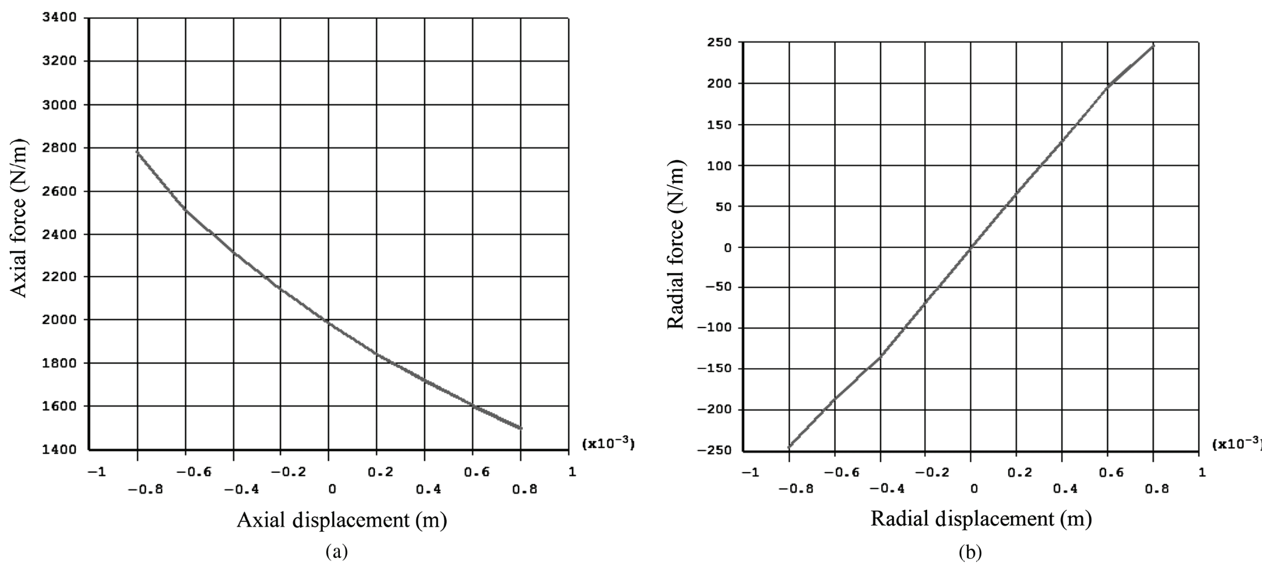


Figure 8. Relationships between forces and displacement at $\alpha = 75°$: (a) axial force versus displacement and (b) radial force versus displacement.

Table 2
Analytic Results Summary of PMBs using FEM

α	Axial Stiffness (N/m/mm)	Radial Stiffness (N/m/mm)	Effect
30°	356	−650	Axial unstable, radial stable
40°	81	−437	Axial unstable, radial stable
45°	−66	−312	Axial stable, radial stable
50°	−212	−200	Axial stable, radial stable
60°	−500	40	Axial stable, radial unstable
75°	−812	312	Axial stable, radial unstable

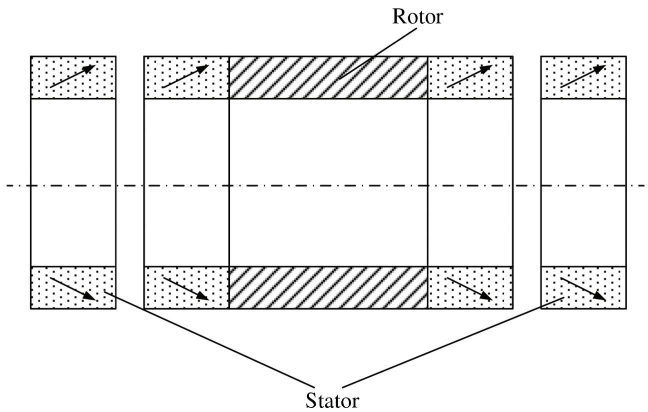


Figure 9. Stable magnetically suspended system with two pairs of PMBs.

increased. Therefore, when two pairs of PMBs are used, as shown in Fig. 9, the whole system can be realized as stable.

3. Conclusion

In this article, a magnetically suspended system with PMBs is proposed for stability, which is applicable for the robotic system. The magnetization angle of PMBs is analysed by FEM simulation in detail. The relationships among axial force, radial force, and axial displacement are analysed by using 2D FEM. The finite element analytic results show that the axial force changes from unstable to stable and the radial force changes from stable to unstable due to an increase in the magnetization angle. When the magnetization angles of permanent magnets are 45° and 50°, the magnetically suspended system with two PMBs can be realized stable when the movable part rotates.

Acknowledgement

This work was supported by National Natural Science Foundation of China (Grant Nos. 51575025, 51405322), by the Foundation for the Author of National Excellent Doctoral Dissertations of China (Grant No. 201330), the Fundamental Research Funds for the Central Universities (Grant No. YWF-16-BJ-Y-23), and the Singapore Academic Research Fund (Grant No. R-397-000-173-133).

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Biographies

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