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Zero power levitation control of a magnetically levitated linear slider platform with non-contact power supply

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Abstract

A magnetically levitated linear slider platform with a non-contact power supply method is presented in this paper. The non-contact power supply was achieved using an open end generator with a plastic core. The objectives of this paper is to present FEM analysis of the open end generator and initial observations from the experimental prototype. The rotor of the open end generator was mounted on the stationary structure of the system and the rotor includes 6 magnetic pole pairs mounted on the surface of the rotor. The levitated platform was constructed by mounting four hybrid electromagnets on four corners of a single rigid rectangular steel plate. The cogging torques introduced by the open end generator on the levitated platform was investigated using FEM method and the results presented. Levitation of the platform was achieved while open end generator is producing electrical power. The performance of the levitated platform with the open end generator was experimentally measured and presented. The rotor of the open end generator was rotated at 1000rpm. The amount of total root mean square electrical power dissipated through 19Ω load resistors by an open end generator with plastic core was 35W. The levitated platform achieved less than 0.25W power consumption per hybrid electromagnet during steady state operation. Estimated power consumption by the sensors and the electronic control boards used in the experimental platform was approximately 15W. The results suggest that the open end generator can produce sufficient amount of power to support platform levitation and control.

Keywords : Magnetic levitation, Non-contact power supply, Zero power control, FEM analysis

1. Introduction

Regular machines such as conveyors and motors have a mover and a stator. The mover and the stator have mechanical connections between each other, achieved by utilizing mechanical machine elements such as bearings, guides ways, rollers, and gears depending on the nature of the machine. In order to avoid the mechanical connection between the mover and the stator, magnetic levitation can be used. Mechanical machine elements have contact surfaces with relative velocity between each other. Such movements are subjected to friction and therefore lubrication is essential when the mechanical machine elements are involved. When these machines are operated, friction between moving parts will break small particles from contact surfaces. The small particles broken from machines leads to wear of machine elements. Furthermore, lubrication chemicals are released into the operating environment of the machine. If the machines are operated in a clean room environment, these released particles could contaminate clean operating environment. Furthermore, mechanical machine elements could contribute to vibrations. Any power transfer between a mover and a stator achieved by utilizing commutators could contribute to electrical noise. Furthermore, these commutators are subjected to friction leading to particle release.

The machines which utilize magnetic levitation to separate the mover and the stator offers many advantages over regular machines which utilize mechanical machine elements. When the separation between the mover and the stator is achieved through magnetic levitation, there is no friction between the mover and the stator. Therefore, lubrication is not necessary and particles will not be released. The machine will not be subjected to wear and mechanical vibrations occurred from mechanical machine elements will be reduced. However, the levitated mover of the machine will require power to operate and therefore non-contact power transfer is essential. If continuous operation is not required, batteries can be used to supply power to the mover. The amount of time machine that the machine can be operated continuously, depend on the amount of energy stored in the batteries. Use of large batteries to increase continuous operation duration will also increase levitated weight and the physical size of the machine. By reducing the amount of power consumed by the levitated machine, the duration of continuous operation can be increased. Therefore, it is important to study magnetic levitation with non-contact power transfer methods.

The previous research by M. Morishita and T. Azukizawa suggests a use of linear quadric regulator with integral action to achieve zero power control of a magnetically levitated linear slider (MagLevLS) platform. The platform suggested by M. Morishita utilize 4 hybrid electromagnets (HEMs) as actuators and a platform consisting of two rigid plates with a pivot joint to achieve zero power control. The pivot joint is essential to introduce an extra degree of freedom to the levitated platform so that the zero power control can be realized. Previous research by Kim et al. uses a secondary suspension mechanism to achieve zero power control and reduce vibrations.

This paper presents a MagLevLS with an open end generator to address non-contact power problem. The results of FEM analysis of the open end generator and initial experimental results are presented. Furthermore, step response of the MagLevLS under cogging torques and forces of the open end generator is presented.

2. Basic design of the magnetically levitated linear slider platform.

Figure 1 shows the design of the MagLevLS platform. The platform uses 4 HEMs rigidly mounted at four corners of a single steel plate as shown. A linear motor is used to achieve linear movements of the platform. Laser air gap sensors were used to measure the air gaps between each HEM and the guide rails. Guide rails are installed on the stationary structure of the platform. An open end generator is mounted on the platform as shown. The open end generator has it's both sides open. A permanent magnet rotor mounted on the stationary structure of the platform is used to generate electricity in coils of the open end generator.

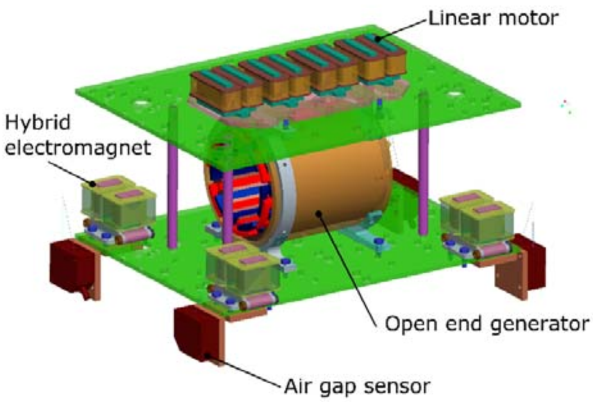

Fig. 1 Basic design of the magnetically levitated linear slider platform consisting of four hybrid electromagnets, air gap sensors, a linear motor, and an open end generator.

3. Mathematical model and the levitation controller

Figure 2 shows the forces generated by the HEMs and important dimensions of the MagLevLS platform. Equation 1 shows the mathematical model of the HEM. The constants a, b, and c were obtained by analyzing a 3D model of the HEM using FEM method.

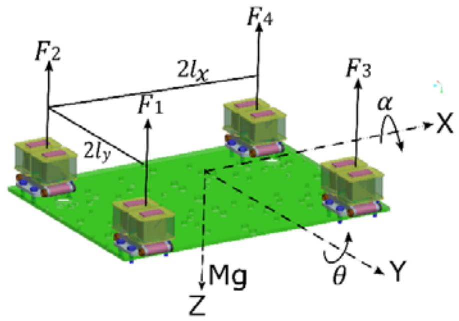

Fig. 2 Forces acting on the magnetically levitated linear slider platform and important physical dimensions referred in mathematical model

$$F = a\frac{(i+b)^2}{(z+c)^2} \quad (1)$$

Where,

$F =$ Force generated by a HEM in Newton.

$a = 1.747 \times 10^{-5}\,\mathrm{Nm^2A^{-2}}$

$b = 4.932\,\mathrm{A}$

$c = 1.343 \times 10^{-3}\,\mathrm{m}$

When the MagLevLS platform is levitated at the air gap z_0, the forces and torques acting on the platform can be described by the Eq. 2.

$$\begin{bmatrix} F_z \\ \Gamma_x \\ \Gamma_y \end{bmatrix} = T \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} Mg \quad (2)$$

Where,

$$T = \begin{bmatrix} -1 & -1 & -1 & -1 \\ -l_y & l_y & -l_y & l_y \\ -l_x & -l_x & l_x & l_x \end{bmatrix}$$

$F_z =$ Force in z direction.

$\Gamma_x, \Gamma_y =$ Torques around x and y axes respectively.

$M =$ Mass of the levitated platform.

The geometry of the MagLevLS platform yields Eq. (3) for small angles, assuming that the center of gravity of the levitated platform and the magnetic pole surfaces (perpendicular to z direction) of the HEMs are in the same XY plane.

$$\begin{bmatrix} \delta z_1 \\ \delta z_2 \\ \delta z_3 \\ \delta z_4 \end{bmatrix} = -T' \begin{bmatrix} \delta z \\ \delta \alpha \\ \delta \theta \end{bmatrix} \quad (3)$$

Where,

$\delta z =$ Distance between center of gravity of the platform and the guide rails in z direction

$\delta z_n = z_n - z_0$

$z_n =$ Air gap between nth HEM and the guide rail. n = 1…4

The linearized mathematical model of the MagLevLS platform in linear z direction, around the x axis and around the y axis obtained from Eq. (1), Eq. (2) and Eq. (3) can be represented as Eq. (4)

$$\begin{bmatrix} M\ddot{z} \\ I_x\ddot{\alpha} \\ I_y\ddot{\theta} \end{bmatrix} = -\left(\frac{\partial F}{\partial z}\right)_{z0,i0} TT' \begin{bmatrix} \delta z \\ \delta\alpha \\ \delta\theta \end{bmatrix} + \left(\frac{\partial F}{\partial i}\right)_{z0,i0} T \begin{bmatrix} \delta i_1 \\ \delta i_2 \\ \delta i_3 \\ \delta i_4 \end{bmatrix} \tag{4}$$

Where,
I_x = Moment of inertia of the platform around the x axis
I_y = Moment of inertia of the platform around the y axis
δi_n = (n=1…4) current in nth HEM.
z_0, i_0 = Zero power operating point
i_0 = 0A

Assuming that a force δF_z in the z direction, a torque $\delta\tau_x$ around the x axis and a torque $\delta\tau_y$ around the y axis are used to achieve levitation around the operating point z_0, i_0, the state space realization of the platform can be shown as in Eq. (5)

$$\dot{X} = \begin{bmatrix} 0_{3\times3} & I_{3\times3} \\ -\left(\frac{\partial F}{\partial z}\right)_{z0,i0} TT' & 0_{3\times3} \end{bmatrix} X + \begin{bmatrix} 0_{3\times3} \\ I_{3\times3} \end{bmatrix} \begin{bmatrix} \delta F_z \\ \delta\tau_x \\ \delta\tau_y \end{bmatrix} \tag{5}$$

Where,
$0_{3\times3} = 3\times3$ Zero matrix
$I_{3\times3} = 3\times3$ Identity matrix
$X = [\delta z \quad \delta\alpha \quad \delta\theta \quad \delta\dot{z} \quad \delta\dot{\alpha} \quad \delta\dot{\theta}]'$

The system shown in Eq. (5) can be controlled with 3 separate proportional and derivative (PD) controllers. The controlled variables δF_z, $\delta\tau_x$ and $\delta\tau_y$ are transformed into four controlled currents as shown in Eq. (6). An integrator was used to reach levitating air gap z_0 under different load conditions. Two integrators were used to reach $\alpha = 0$ and $\theta = 0$ during operation of the platform. Figure 3 shows the implementation of the controller used to levitate experimental platform.

$$\begin{bmatrix} \delta i_1 \\ \delta i_2 \\ \delta i_3 \\ \delta i_4 \end{bmatrix} = \frac{-T^{-1}}{\left(\frac{\partial F}{\partial i}\right)_{z0,i0}} \begin{bmatrix} \delta F_z \\ \delta\tau_x \\ \delta\tau_y \end{bmatrix} + \frac{\left(\frac{\partial F}{\partial z}\right)_{z0,i0}}{\left(\frac{\partial F}{\partial i}\right)_{z0,i0}} T' \begin{bmatrix} \delta z \\ \delta\alpha \\ \delta\theta \end{bmatrix} \tag{6}$$

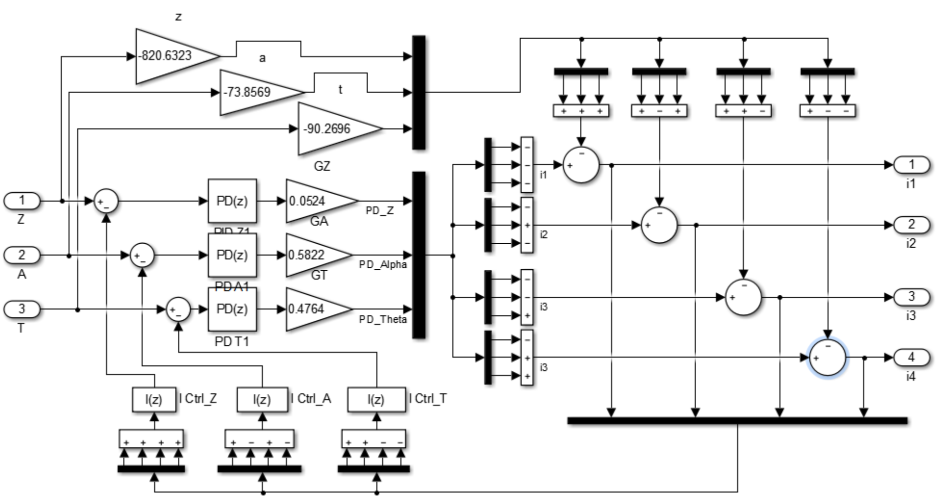

Fig. 3 Controller used to levitate magnetically levitated linear slider platform. The figure shows 3 input ports receiving difference between set value and measured value of the state variables z, α and θ in left side and four output ports sending controlled currents in right side.

4. FEM analysis of the open end generator

Figure 4 shows the basic design of the open end generator. The rotor of the open end generator is mounted on the stationary structure of the system. Six magnetic pole pairs are mounted on the surface of the rotor as shown in fig 4. The stator of the open end generator is mounted on the levitated platform. The platform and stator can travel along the rotor while the platform is levitated. The rotor was rotated using an electric motor and the winding on the stator generates electric power for the levitated platform. When a regular generator is operated, it is expected that the axis of the stator and the rotor are identical. Any non-identical rotor and stator axes introduce unbalanced cogging forces and torques. A regular generator has its rotor and stator axes maintained in identical axes using bearings which mechanically connect stator and rotor assembly. In the presented platform design, rotor axis is fixed on the stationary structure of the system. However, the stator of the open end generator has to move with the levitated platform in the z direction to reach zero power levitation position. Zero power levitation position in z direction depends on the load on the platform. Therefore, it is impossible to maintain identical axes for the rotor and the stator of the open end generator. Furthermore, the air gap between the rotor and the stator should allow the motion of the levitated platform.

The stator of the open end generator has two windings and each winding has 120 turns. The internal resistance of each winding was 19Ω. The diameter of the rotor measured between surfaces of permanent magnets at opposite side of the rotor was 60.5mm.

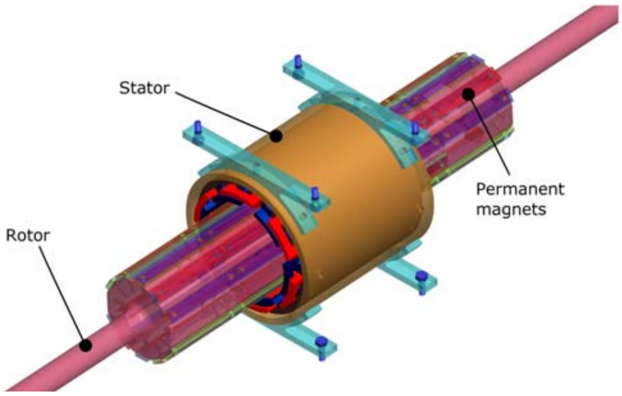

Fig. 4 Basic design of the open end generator. The long permanent magnet rotor is mounted on the stationary structure of the system and the stator was mounted on the levitated platform

Figure 5 shows the cogging torques obtained through FEM analysis. According to the results, when the stator was manufactured using SS400 soft magnetic steel, the cogging torque has an oscillation which can be described using a sine wave. For the analysis, each winding of the open end generator was connected to a separate 19Ω external resistor. The rotor speed was 800rpm. The maximum and the minimum of the cogging torque are approximately 6.7Nm and 5.4Nm respectively. A HEM is rated to produce a maximum of 65N force at approximately 1.2mm air gap and with zero coil current. In order to achieve 6.7Nm torque, the force difference required between F_1 HEM and F_2 HEM is approximately 37N. Even though it is possible to achieve this force difference, a large coil current will be required to maintain platform $\alpha = 0$ condition.

A plastic core was used to replace SS400 core and the FEM analysis was performed. According to the results shown in Fig. 5, the plastic core produces approximately 0.5Nm cogging torque. The cogging torque waveform similar to the SS400 core was observed in the plastic core. However, the observed peak to peak torque fluctuation was within 0.015Nm. Therefore, use of a plastic core leads to better torque characteristics for the levitated platform.

Figure 6 shows the root mean square (RMS) of the electrical power produced by the open end generator. When the SS400 core was used, total RMS power dissipated through 19Ω load resistors was approximately 280W. When the plastic core was used, the amount of total RMS electrical power dissipated through 19Ω load resistors was approximately 25W.

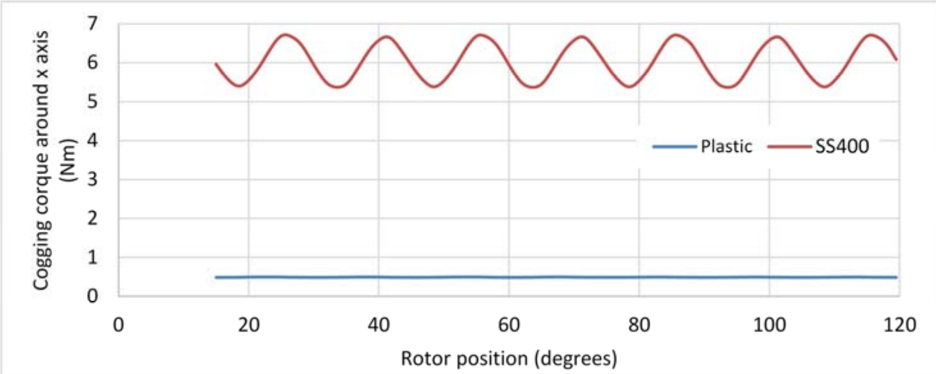

Fig. 5 Cogging torque around the x axis of the open end generator obtained by FEM analysis. Each coil of the generator was loaded with 19Ω resistor and rotor was rotating at 800rpm. The data obtained at 0.5^0 rotor increments.

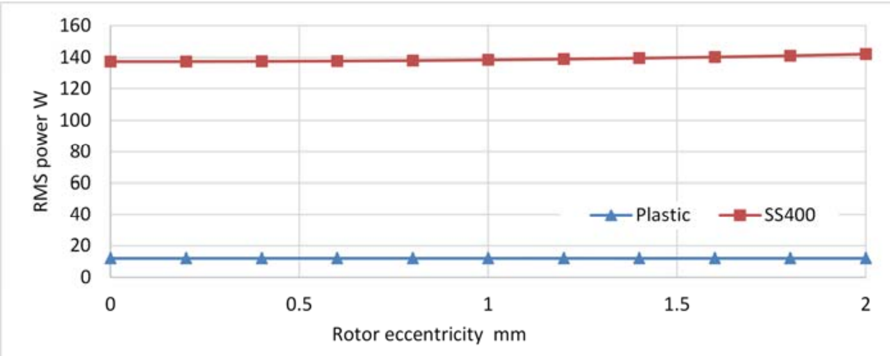

Fig. 6 Root mean square (RMS) power dissipated through 19Ω load resistor. Each coil of the generator was loaded with 19Ω resistor and rotor was rotating at 800rpm

5. Experimental results.

The MagLevLS platform and the open end generator was constructed and experiments were performed to observe the effect of open end generator on the MagLevLS platform. Figure 7 shows a picture of the prototype MagLevLS platform used for the experiments and the open end generator. Table 1 shows the parameters of the HEMs used. Discrete PD controllers with a sampling time of 1ms were used to control the platform. The air gaps of the HEMs was measured using laser distance sensors. Four PWM motor controllers were used as current controllers to supply power to HEMs.

Table 1 Hybrid electromagnet parameters

Parameter	Value
Number of coils per HEM	2
Number of turns per coil	360
Magnetic pole surface size	10mm×20mm
Permanent magnet	12mm×21mm×25mm N50
Approximate lamination factor	0.94

To observe responses to an added mass on to the MagLevLS platform, a mass of 1.1kg was placed on the levitated platform and results was recorded. The experimental controller can record only up to 3 variables at a time. Therefore, 3 variables recorded per each experiment. The measured values of the state variables z, α and θ are shown in the fig. 8. During the experiment, open end generator was producing approximately 17.5W of electrical power. The rotor of the open end generator was rotating at 1000rpm. The effect of the open end generator can be observed from the fig. 8 by the data of the state variable α.

The amount of RMS power generated by the open end generator was 35W and was achieved at a rotor speed of 1000rpm. According to the obtained data, each HEM consumed less than 0.25W power during the steady state operation. Peak power demand per HEM was approximately 40W when the 1.1kg mass placed on top of the levitated platform. The peak power demand was observed for less than 20ms duration and the power demand per HEM was reduced to less than 1W after 0.5s from the step input. The electronic components and the sensors were rated at approximately 15W. Therefore, the open end generator can generate sufficient amount of power to achieve continuous levitation. To supply peak power demand, a rechargeable battery can be used. The excess power from the open end generator can recharge the battery during the steady state operation. Furthermore, to move the platform in the x direction, a linear motor is required. Since the open end generator can produce 35W of continuous power, it is possible to use a linear motor up to 15W power while having 5W for recharging the battery.

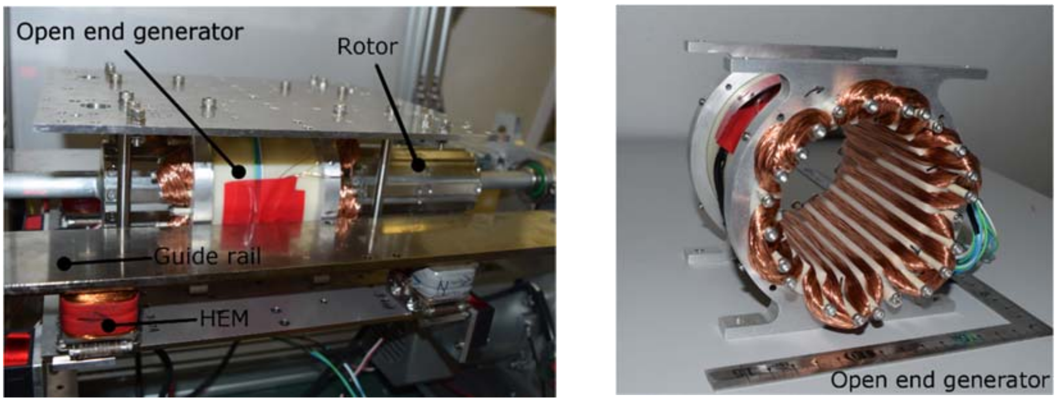

Fig. 7 Prototype magnetically levitated platform and open end generator

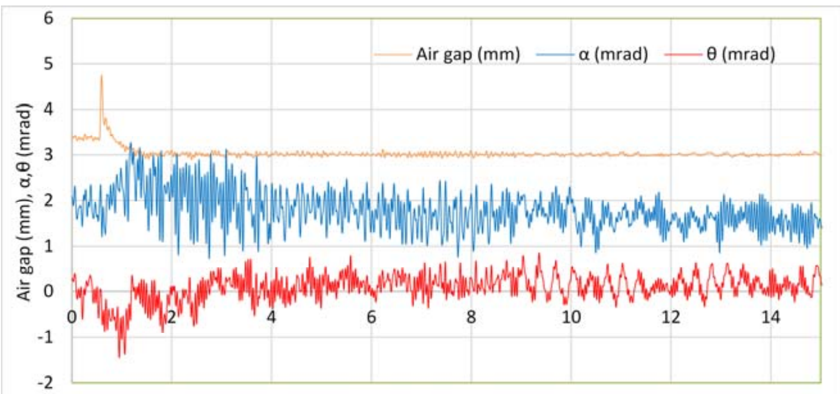

Fig. 8 Step response of MagLevLS platform when a 1.1kg mass was placed on the platform. The open end generator was producing approximately 17.5W power during the experiment

6. Conclusion

A prototype MagLevLS platform with a non-contact power supply was built and performance of the levitation system and non-contact power transfer system was investigated. The experiments have shown that the open end generator can generate sufficient amount of power to levitate and control the MagLevLS platform. The FEM analysis revealed that the use of SS400 soft magnetic steel as core material can generate 280W of electric power. However, the SS400 core produced large cogging forces and torques which were excessive for the HEMs. Therefore, a plastic core was used and according to the experimental results, 35W of RMS electrical power can be generated when a plastic core was used. According to the experiments, MagLevLS can levitate while open end generator was producing power and 0.25W per HEM achieved during steady state operation.

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