論 文 内 容 の 要 旨

A magnetically levitated linear slider (MagLevLS) platform was designed, fabricated and experimental data was obtained. A novel non-contact power transfer system using an open end generator was purposed and custom designed to meet the requirements of the levitated platform. The proposed system is suitable to transport materials between short distances in a clean room environment. The main components of the system were designed separately and integrated into a single system. Main components of the system are the hybrid electromagnets (HEMs) used as levitation actuator and the open end generator used for non-contact power transfer.

A hybrid electromagnet was designed to use with a magnetically levitated linear slider platform and capable of generating approximately 65N force using 0A current. The existing designs of a hybrid electromagnet were improved to achieve better lateral aliment. The design of the HEM was analyzed using finite element method (FEM). The improvements made to the HEM was analyzed using FEM data and presented. The FEM analysis data was used to find the relationship between the attractive force, coil current and air gap using surface fitting techniques. A prototype electromagnet was fabricated and experimental data obtained by measuring attractive force, coil current and air gap. The analysis of experimental data and FEM data revealed that the experimental data has lower values than FEM analysis data. However, the experimental data showed a close match to FEM analysis data. The obtained data was used to derive a mathematical model describing the attractive force in terms of coil current and air gap. The linearized mathematical model was used in designing levitation controller.

A novel method of using an open end generator was suggested to transfer power to the levitated platform without using contacts. The open end generator was designed to meet three specific goals so that the open end generator can be used with the magnetically levitated platform. The first goal was to reduce the cogging forces generated by the open end generator to a limit that can be handled by the HEMs. The second goal was to transfer sufficient amount electrical power to the levitated platform. It is calculated that 35W of root mean square (RMS) electrical power is sufficient to achieve continuous operation of the system. The third goal was to achieve sufficient air gap between the stator and the rotor of the open end generator to achieve different zero power levitation air gaps under different load conditions. The design goal of air gap was to achieve air gap of at least 3.5mm when the rotor of the open end generator is at the center of the stator core of the generator. All three design goals are interconnected in such a way that changing one parameter affects all other parameters.

Even though a fairly large cogging force can be compensated using HEMs in the z-direction, it is not possible to compensate large forces in y direction because HEMs are not designed to generate large forces in the y direction. A several generator designs were analyzed using FEM to calculate cogging forces. The analysis revealed that the cogging forces generated by an open end generator with a soft magnetic steel core cannot be compensated by lateral direction forces of HEMs. The FEM analysis of open end generators with soft magnetic steel cores resulted in RMS electrical power larger than 100W while achieving 3.5mm air gap goal. Furthermore, analysis reviled that the cogging forces are generated regardless of the amount of power generated by the open end generator.

Due to the large cogging forces generated by soft magnetic steel stator cored generators, an open end generator was designed using ABS as the stator core material. After several refinements, the open end generator with ABS stator core resulted approximately 35W of RMS electrical power while having 4.25mm air gap. The cogging forces generated by the open end generator with ABS stator core depends on the current generated in the coils of the generator according to the FEM analysis results. When the current in coils of the open end generator is zero, the cogging force becomes zero. Since the cogging force is generated due to the induction of current in coils, the cogging force is a Lorentz force. The maximum amount of cogging force of the final design was approximately 1.1N at 3mm rotor eccentricity while having 19Ω external load per winding. Furthermore, FEM analysis revealed that the cogging force is a restitutive force supporting alignment of levitated platform in the y direction. The FEM analysis showed that the cogging torque generated by the open end generator was approximately 0.5Nm and fluctuations due to the rotor angular position are negligible. The change of electrical power generated due to the rotor eccentricity is negligible according to the FEM analysis results. Therefore, the open end generator can supply the same amount of power to the levitated platform regardless of the rotor eccentricity. This is an advantage for the levitated platform. Based on FEM analysis and experimental results, it is concluded that the open end generator with an ABS stator core can meet all design goals and suitable to supply power to the levitated platform. Since the open end generator was designed to use readily available cuboid shaped permanent magnets and due to the physical size constraints, a slight overlap between electrical coil windings was observed in the final open end generator design.

A mathematical model for the MagLevLS platform describing three degrees of freedom motion was developed. The forces of the HEMs was described using the model obtained by FEM analysis and experimental testing. The linearized mathematical model was used to develop three PD controllers to control vertical levitation position, roll, and pitch. The gains of three PD controllers was obtained to meet selected system performance. The experiments revealed that the initial gains of the PD controllers were not accurate enough to maintain stable levitation of the experimental system. Subsequently, a nonlinear system was modeled, and the initial controller was tuned. The nonlinear system was modeled to closely match components of the experimental system. The controller was improved to achieve zero power operation by adding three integral controllers to the initial levitation controller. The levitation system was simulated to observe different real world operation scenarios and results were presented. The simulations revealed that the levitation controller with zero power control loop can achieve and maintain stable levitation under step inputs while the cogging torque of the open end generator is active. Furthermore, the effect of cogging torque on levitated platform was clearly visible in the simulation results.

A prototype platform with an open end generator was fabricated to experimentally validate simulation results. The levitated system was constructed as a four-point suspended single rigid rectangular platform. Therefore achieving zero power operation of all four HEMs was not possible in the experimental system. The controller was designed to achieve near zero power operation of the experimental platform. The experimental system has a DSP board with 1 kHz sampling rate, four laser air gap sensors, and four hybrid electromagnets. The con-contact power transfer was achieved by operating the open end generator. Experiments were performed to evaluate the levitation system under a step load input applied at the center of the levitated platform and applied at one side of the platform. Experiments revealed that the MagLevLS system can achieve and maintain stable levitation under cogging forces and torque introduced by the open end generator. Furthermore, slightly increased vibrations were observed due to the operation of the open end generator. The experiments revealed that the prototype open end generator can generate approximately 35W RMS electrical power at 1000rpm rotor speed. Furthermore, experiments confirmed that the change of generated electrical power due to the rotor eccentricity was negligible. The experimental observations of the open end generator was a close match to the FEM analysis results.

The effect of the cogging torque was clearly visible in the experimental results. However, the zero power levitation controller managed to reach near zero power operation point under step input within approximately 2.5s time. The power consumption per HEM was increased to 35W during the transient state of step input. However, the power consumption reduced to less than 1W per HEM within 0.5s of step input and reduced to 0.25W per HEM within 5s of step input. The power measurements were recorded under the influence of cogging forces and torque of the open end generator. Therefore, it is concluded that the MagLevLS can be powered through open end generator and stable near zero power operation can be achieved while disturbances introduced by the cogging forces are acting on the levitated platform.

During the experiments, lateral vibrations were observed due to the application of step load. The major reason for the lateral vibrations is because of application of step load, which is not perfectly vertical at the time of application. Furthermore, if the platform is not perfectly orthogonal to the direction of gravity at the time of application of the step load, the application of vertical step load leads to force components in vertical, lateral and horizontal directions. Lateral vibrations are not controlled and not actively damped. Therefore, it is observed that the lateral vibrations due to the application of step load take about 60s to disappear. However, MagLevLS platform managed to return to lateral position due to the improvements made to HEM and guide rail design.

During the manufacturing of prototype, it is observed that the manufacturing process of the rotor is complicated and fairly expensive compared to other mechanical elements of the system. Furthermore, all major components manufactured using SS400 was galvanized to avoid corrosion. The HEMs were made using laminated soft magnetic steel to reduce eddy currents.

As a result of the research work carried out, a magnetically levitated linear slider system was designed, analyzed and stable near zero power levitation was achieved. The suggested novel non-contact power transfer system was designed, analyzed and a prototype was fabricated. The complete system was controlled using a DSP controller and observed experimental results were a close match to the simulation and FEM analysis results.