A MAGLEV LOCAL ACTUATOR FOR HIGH SPEED ELECTRICAL DISCHARGE MACHINING

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ABSTRACT

This paper reports on a compact, 5-degrees-of-freedom (5-DOF) controlled maglev local actuator (MLA) for realizing high speed electrical discharge machining (EDM), comprising a magnetic coupling mechanism (MCM) to feed a discharge current to an electrode attached to a spindle, and to transmit a torque from a motor to the spindle. The spindle is supported by a 5-DOF controlled magnetic bearing and is rotated by following the rotation of a power supply ring, utilizing the magnetic coupling. Flexible wires between the power supply ring and the spindle feed the discharge current to the electrode, without transmitting disturbing forces, so that the spindle is free from the direct contact with brushes, used to feed the discharge current. Experimental positioning results show a prototype MLA possesses a positioning resolution of a few microns and several ten micro-radians, bandwidths greater than 100 Hz in the 5-DOF directions, and a positioning stroke of 2mm in the thrust direction. Moreover, the discharge current can be fed to the electrode attached to the spindle, rotating at 2,000min^{-1}.

INTRODUCTION

Electrical discharge machining (EDM) is an unconventional material removal process, based on the thermo-electric energy created between an electrically conductive workpiece and an electrode, submerged in a machining fluid [1][2]. In conventional electrical discharge machines, a combination of stacked 1-DOF lead screw mechanisms are normally used to position the electrode in three orthogonal directions. However, the positioning response of a lead screw is somewhat slow, due to the mass of stacked tables and the rotary inertia of the lead screws, so that the electrode cannot be re-positioned speedily and the debris around the electrode cannot be removed efficiently [3][4]. Therefore, the machining speed and accuracy are limited by the lower probability of the electrical discharges and abnormal electrical discharges caused by the debris.

To improve the machining speed and accuracy of EDM, the electrode should be speedily re-positioned in order to maintain a suitable distance from the workpiece. Furthermore, the debris around the electrode during EDM should be efficiently removed to avoid abnormal electrical discharges.

To realize high speed positioning of the electrode, combinations of the conventional electrical discharge machine and wide-bandwidth, high-precision, local actuators have been proposed [5-7]. For the local actuator, a positioning stroke of a few millimeters for the rapid retraction of the electrode in at least one direction of motion (for example, the thrust direction) is also necessary in order to remove the debris from around the electrode when micro holes with high aspect ratios are being machined.

To realize high speed positioning of the electrode with a stroke of a few millimeters, the authors have developed a 5-DOF controlled maglev local actuator (MLA) [8, 9]. The MLA not only has a wide-bandwidth and high-precision in 5-DOF, but also has a stroke of a few millimeters in the thrust direction, in order to realize the rapid retraction of the electrode. Using this MLA, micro holes may be machined in multi- directions and the machining speed is improved by 20 ~ 400% compared with a conventional EDM without the MLA. However, the brushes for feeding the discharge current to the electrode are in direct contact the levitated spindle, so that the motion of the spindle is disturbed by the friction between the spindle and the brushes.

In this paper, we propose an improved mechanism of a 5-DOF controlled MLA, in which the discharge current for EDM is fed to the electrode without the direct contact between the spindle and the brushes. The positioning, rotation and power supply performances for EDM have been evaluated using a prototype MLA.

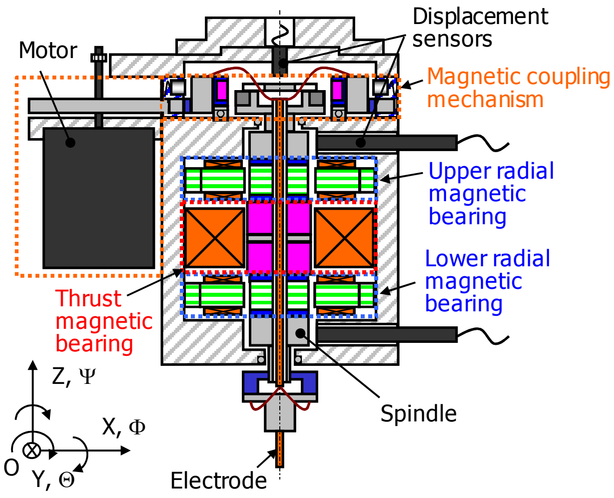

FIGURE 1: Schematic of the MLA

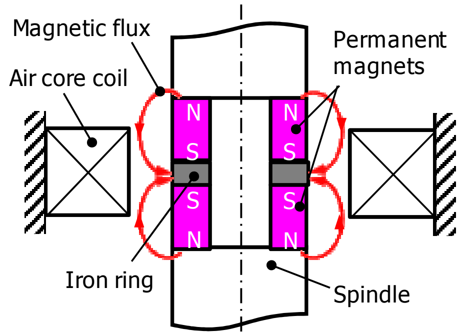

FIGURE 2: Schematic of the thrust magnetic bearing

PRINCIPLE OF MLA

5 DOF Controlled MLA

Figure 1 shows a proposed 5-DOF controlled MLA. The MLA primarily consists of a thrust magnetic bearing, upper and lower radial magnetic bearings, and a magnetic coupling mechanism (MCM). Using the thrust and the radial magnetic bearings, the spindle can be levitated and positioned in 5-DOF (X, Y, Z, Θ and Φ) directions. Also, using the MCM, a torque can be transmitted from a motor to the spindle to rotate the spindle around the Z-axis, while the discharge current can be fed to the electrode attached to the spindle, for EDM.

During EDM of micro holes with high aspect ratio, a voice coil motor type of thrust magnetic bearing is used to realize a positioning stroke of a few millimeters for the rapid retraction of the electrode in the Z direction, as shown in Figure 2. This consists of an air core coil, located in the stator, and a pair of oppositely magnetized permanent magnets (PMs) sandwiching a ring made of pure iron, located in the spindle.

The sandwiched iron ring is used in order to concentrate magnetic flux in the air core coil. Thus, the Lorentz force in the thrust direction, generated between the air core coil and the PMs, can be comparatively increased. Moreover, since the repulsion between the PMs is changed into attraction by inserting the iron ring, the assembly of the spindle is more easily achieved and the problem of demagnetization of the PMs is also reduced.

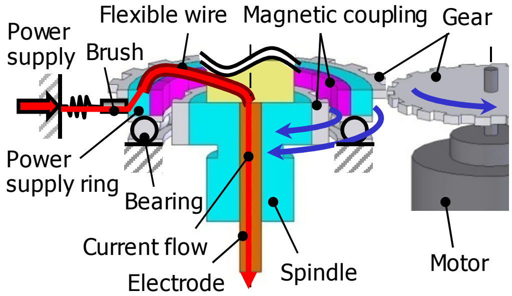

FIGURE 3: Configuration of the MCM

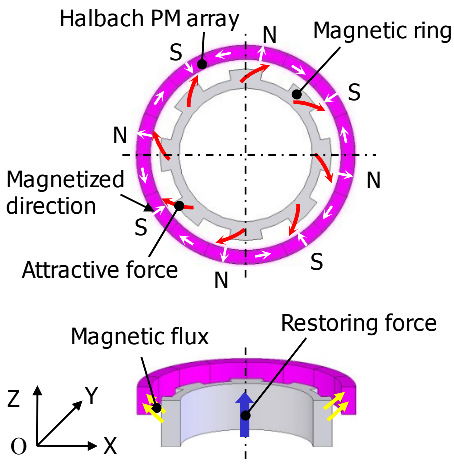

FIGURE 4: Configuration of the magnetic coupling

Configuration of MCM

Figure 3 shows a configuration of a MCM in order to feed a discharge current to the electrode and to transmit a torque from a motor to the spindle. The main components comprise four brushes, a power supply ring, a ball bearing, a magnetic coupling, a levitated spindle, four flexible wires, a gear and a motor. The power supply ring, contacting with the brushes, is arranged on the outer circumference of the spindle, and it is supported by the ball bearing. The flexible wires are used to connect the power supply ring and the electrode attached to the spindle, so that the spindle is free from the direct contact with the brushes. The magnetic coupling consists of a PM ring comprising a Halbach PM array, and a toothed magnetic ring, as shown in Figure 4. The Halbach PM array is located in the power supply ring, while the magnetic ring is located in the spindle.

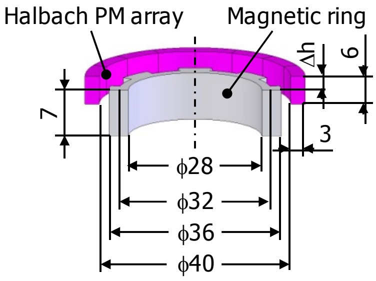

FIGURE 5: Dimensions of the magnetic coupling

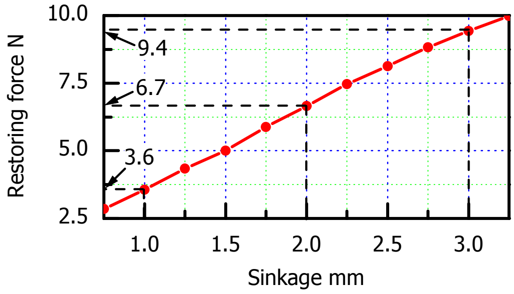

FIGURE 6: Relationship between the sinkage of the magnetic ring and the restoring force

Using the magnetic coupling, the torque generated by the motor can be transmitted from the power supply ring to the levitated spindle. Therefore, the spindle can be rotated in synchronism with the rotation of the power supply ring, and the flexible wires between the power supply ring and the spindle can feed the discharge current to the electrode for EDM, without the effect of brushes providing friction or the entanglement of the flexible wires. Additionally, the power supply ring is rotated by the motor and the gear.

The magnetic coupling has a positive stiffness characteristic in the thrust direction. As the magnetic ring is moved in the thrust direction in relation to the PM ring, an axial restoring force is generated, as shown in Figure 4. Therefore, the magnetic coupling also can balance the weight of the spindle, to reduce the power consumption of the thrust magnetic bearing.

The MCM is attached to the upper end of the MLA, as shown in Figure 1. The reasons for this are as follows. Firstly, by attaching this mechanism to the middle of the MLA, the replacement of the flexible wires would be troublesome when the wires are broken. Secondly, by attaching it to the lower end of the MLA, the motion control of the electrode would become difficult, because it would then be hard to measure a true vibration of the electrode, due to the increase in the distance between the displacement sensors and the electrode.

DESIGN OF MAGNETIC COUPLING

Design Objective

For the design of the magnetic coupling, it is necessary to consider the transmission torque and the axial restoring force. Firstly, to avoid breaking the magnetic coupling, it is desirable to generate a large transmission torque with a small relative angle between the PM ring and the magnetic ring. Secondly, since the transmission torque can be reduced by the sinkage of the magnetic ring, it is also desirable to generate a large restoring force with only a little sinkage. However, a little change in the restoring force is expected to be generated when the spindle is moved in the thrust direction, since this change becomes the load of the thrust magnetic bearing. The two demands for the restoring force are thus contradictory.

The desired specifications for the magnetic coupling are decided as follows. The permitted sinkage is set to 2mm or less, to reduce the influence of the sinkage on the transmission torque. The restoring force is set to 4.9N, assuming that the mass of the spindle is 0.5kg. The desired change in the restoring force is set to be less than 10% of the electromagnetic force of 55N, generated by the thrust magnetic bearing, assuming that the maximum displacement of the spindle in the thrust direction is ±1mm during EDM. Moreover, the desired transmission torque is set to 7.6×10^{-2}Nm at a sinkage of 2mm [10], assuming the maximum rotational speed of the spindle of 5,000min^{-1}.

Design

Based on the numerical analysis, using static magnetic field simulation, the magnetic coupling is designed as shown in Figure 5. The Halbach PM array of the magnetic coupling is composed of sixteen PMs and the magnetic ring with eight teeth is made of electromagnetic soft iron. The detailed geometrical dimensions are also denoted in the Figure 5.

Figure 6 shows the relationship between the sinkage of the magnetic ring and the restoring force. At a sinkage Δh=2mm, the restoring force is 6.7N. Thus, the weight of the spindle can be balanced when the sinkage is less than the designed value of 2mm. Furthermore, when the spindle is moved by ±1mm in the thrust direction, based on the sinkage position of Δh=2mm, the change in the restoring force is about ±3N, which is also less than 10% of the electromagnetic force.

Moreover, the relationship between the relative angle and the transmission torque is calculated at a sinkage Δh=2mm. At the relative angle of 10.5°, the max torque of 9.3×10^{-2}Nm can be transmitted, which is more than the desired value of 7.6×10^{-2}Nm.

EXPERIMENTAL MLA

Figure 7 shows an experimental MLA and its spindle. The height of the MLA was 159mm, the width was

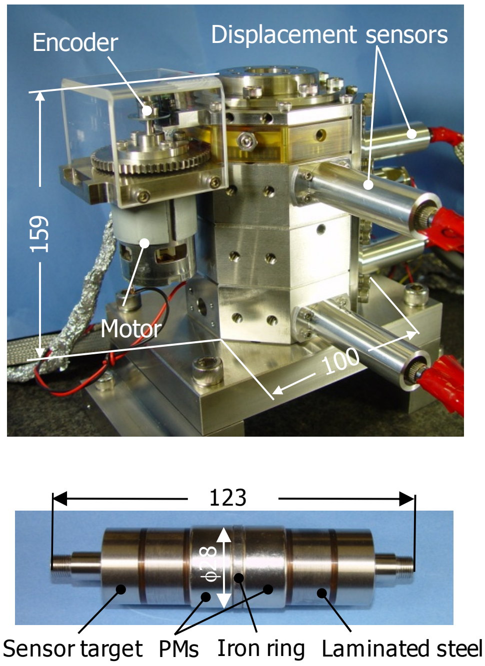

FIGURE 7: Experimental MLA and its spindle

100mm, and the mass was 10kg. The length of the spindle without its attachments was 123mm, its diameter was 28mm, and the mass was 0.35kg.

The displacement of the spindle in the thrust direction was measured using an eddy current displacement sensor (PU-05, AEC Corp., measurement range ± 1.0mm, resolution 0.5μm), and the displacements in the radial directions were measured using four capacitive displacement sensors (MicroSense 5502, ADE Corp., measurement range ± 0.1mm, resolution 20nm). The power supply ring was driven by a DC motor (RS-755WC-8017, Mabuchi motor Corp.) and a gear (Gear ratio 1:1.5), and the rotational speed of the spindle was measured by an encoder (MG-20-1200, Microtech Laboratory Inc., resolution 1200ppr). The MLA was controlled via a digital signal processor (DS1005, dSPACE Corp.) and the sampling rate was 10kHz.

The controller for each directional motion was simply composed of an integrating compensator and a regulator, obtained from a transfer function consisting of a 2nd order numerator and 2nd order denominator, without any consideration of the interference between each directional motion. To improve the response speed of the electromagnetic force for the thrust and radial magnetic bearings, local current feedback loops, using PI compensators, were also added.

EXPERIMENTAL RESULTS

Magnetic Levitation

Figure 8 shows the responses of the spindle in the

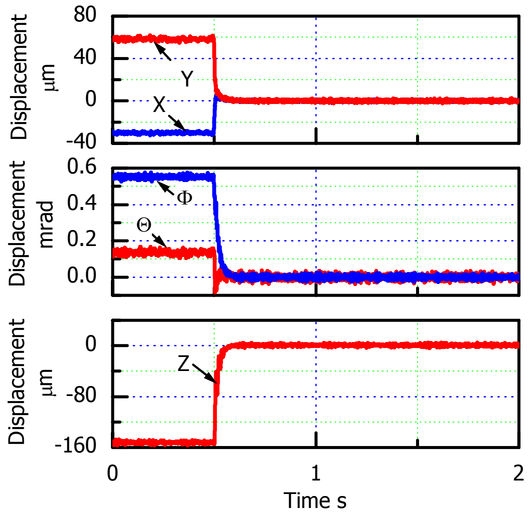

FIGURE 8: Responses of the spindle at start up

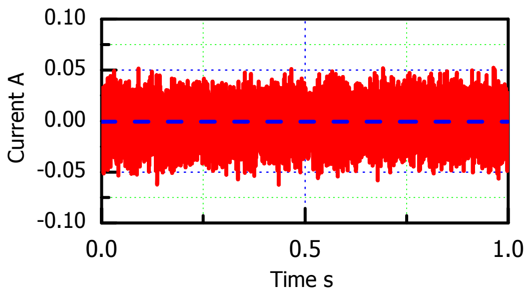

FIGURE 9: Coil current in the thrust magnetic bearing

5-DOF at a start up. From these results, it can be seen that the spindle of the MLA can be levitated stably. Defining the position in which the restoring force balances the weight of the spindle as a zero position of the displacement sensor of the thrust direction, the measured coil current of the thrust magnetic bearing is shown in Figure 9, indicating that its average value was 0A. Using the restoring force generated by the magnetic coupling, the weight of the spindle could be balanced, so the power consumption of the thrust magnetic bearing could be reduced.

Positioning Performance

The positioning resolution and bandwidth of the MLA are summarized in Table 1. The MLA possessed a few microns and several ten micro-radians positioning resolution, bandwidths greater than 100 Hz in the 5-DOF directions. However, compared with the resolution of the displacement sensors employed, the positioning resolution of the MLA was insufficient. We intend to make improvements in the future work. Figure 10 shows that the thrust magnetic bearing had a full stroke of 2.0mm at 1Hz for the rapid retraction of the electrode, required to remove the debris during EDM.

TABLE 1: Positioning performances of the MLA

	X, Y directions	Θ, Φ directions	Z direction
Positioning resolution	2.0μm	0.04mrad	1.5μm
Bandwidth	115Hz	110Hz	150Hz

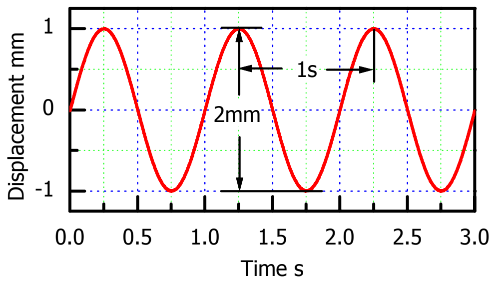

FIGURE 10: Stroke in the thrust direction

Rotational Accuracy

The spindle supported by the 5-DOF controlled magnetic bearing was rotated to 2,000min^{-1}, following the rotation of the power supply ring via the magnetic coupling. Figure 11 shows the vibrational amplitude of the spindle at various rotational speeds, in the X, Θ and Z directions. The experimental results in the Y and Φ directions, which are not shown, were almost the same as those in the X and Θ directions. As the rotational speed increased, the vibration of the spindle became severe. At 2,000min^{-1}, the vibrational amplitude of the spindle was 8.4μm, 0.2mrad and 3.0μm in the X, Θ and Z directions, respectively. In the future, the vibration of the spindle will need to be suppressed by the improvement in the control technique for the MLA.

Transmission Torque of MCM

The transmission torque of the MCM was experimentally examined. In this experiment, the magnetic ring attached to the spindle was fixed and the current impressed to the motor was increased, gradually, to rotate the PM ring attached to the power supply ring. The relative angle between the PM ring and the magnetic ring was measured by the encoder, installed on the motor axis. The transmission torque of the MCM was calculated from the measured motor current.

Figure 12 shows the relationship between the relative angle and the transmission torque. When the torque was less than 0.07Nm, the relative angle did not change, and its value was almost zero. It is thought that the torque of 0.07Nm was caused by the friction of the brushes and the gear. On the other hand, when the

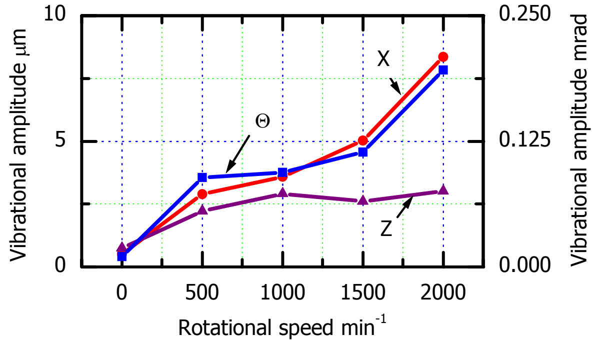

FIGURE 11: Amplitude of the spindle vibration at various rotational speeds

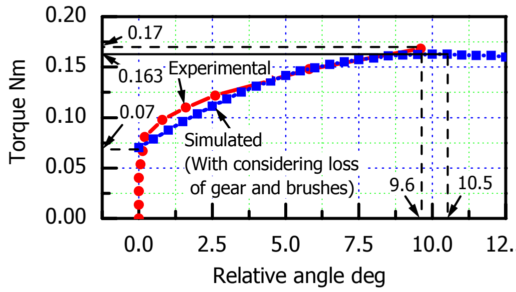

FIGURE 12: Relationship between the relative angle and the transmission torque

torque was more than 0.17Nm, the magnetic coupling was broken. The experimental result indicated that the maximum transmission torque was 0.1Nm and the relative angle was 9.6° with this system. Comparing the experimental result with the simulation, considering the friction of the brushes and the gear, it can be seen that the measured transmission torque was almost the same as the calculated value.

Power Supply

To confirm whether a discharge current could be fed to the electrode when the spindle was rotating, a simulated experiment was carried out. One terminal of a 5V supply was connected to the brushes, and the other terminal was brought into contact with the electrode, via a copper leaf spring, through a resistance of 60Ω and a switch. At a rotational speed of 2,000min^{-1}, the switch was activated and the current fed to the electrode was measured, as shown in Figure 13. The experimental result confirmed that the simulated discharge current could be fed to the electrode whilst the spindle was rotating.

The simulated discharge current was also measured at various rotational speeds, as shown in Figure 14. The current did not depend on the rotational speed of the spindle.

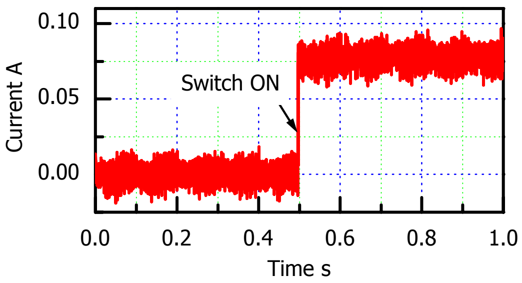

FIGURE 13: Simulated discharge current at 2,000min^{-1}

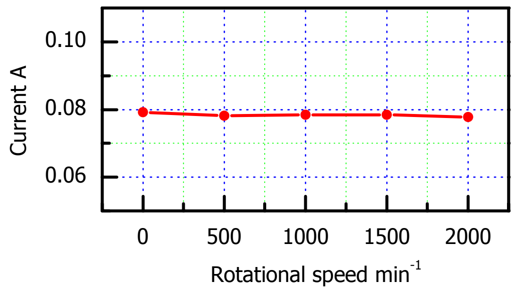

FIGURE 14: Relationship between the rotational speed and the simulated discharge current

CONCLUSIONS

To realize high speed EDM, a compact 5-DOF controlled MLA with a novel MCM has been proposed. The MCM can feed the discharge current to the electrode, and can also transmit the torque from a motor to the spindle. The spindle can be rotated, synchronized with the rotation of the power supply ring, and the flexible wires between the power supply ring and the spindle can feed the discharge current to the electrode without the effect of the friction associated with brushes, or the entanglement of the flexible wires.

Experimental results show the MLA has a few microns and several ten micro-radians positioning resolution, bandwidths greater than 100Hz in the 5-DOF directions, and a positioning stroke of 2mm in the thrust direction. Moreover, the spindle can be rotated smoothly to 2,000min^{-1}, without breaking the magnetic coupling, and the discharge current can be fed to the electrode whilst the spindle is rotating.

In future work we plan to improve the positioning performances and the rotational accuracy of the MLA, and then apply the MLA to EDM.

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