Cooperative Control of a Maglev Local Actuator with a Conventional EDM Machine for High Speed Electrical Discharge Machining

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Abstract: During the process of electrical discharge machining (EDM), the distance between a work-piece and an electrode, which are submerged in dielectric machining fluid, changes as material is being removed from the work-piece and the electrode. In order to maintain a suitable distance to the work-piece to achieve a constant electrical discharge, a cooperative control system, consisting of a maglev local actuator and a conventional EDM machine, re-positions the electrode precisely and speedily.

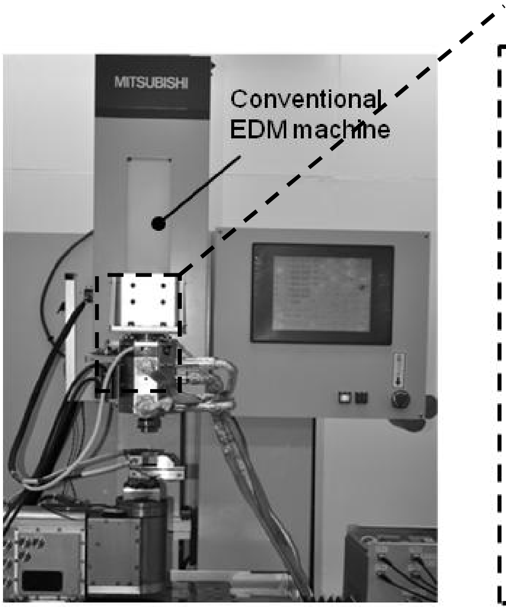
Keywords: Cooperative Control, Maglev Local Actuator (MLA), High-Speed, Electrical Discharge Machining (EDM), Magnetic Bearing (MB), Magnetic Coupling

Introduction

Electrical discharge machining (EDM) is a non-contact material removal process, based on the thermo-electric energy created between an electrically conductive work-piece and an electrode, submerged in a dielectric machining fluid [1,2]. During the process of EDM, the distance between the work-piece and the electrode changes as material is being removed from the work-piece. In order to obtain a high machining speed, it is required to re-position the electrode, precisely and speedily, to maintain a suitable distance to the work-piece. Furthermore, the debris which occurs during EDM should be removed efficiently to prevent abnormal electrical discharge, permitting improvement in both machining speed and machining accuracy.

In conventional EDM machines, to position the electrode in three orthogonal directions during the process of EDM, stacked one-degree-of-freedom (1-DOF) lead-screw mechanisms or linear positioning tables are normally used. However, the positioning response of such mechanisms is somewhat slow, due to the rotary inertia of the lead-screws and the mass of stacked tables, so the electrode cannot be re-positioned sufficiently quickly. Moreover, machining debris accumulating around the electrode cannot be removed efficiently by conventional EDM machines [3,4].

In order to improve the machining speed and accuracy, combinations of the conventional EDM machine and wide-bandwidth, high-accuracy local actuators have been proposed [5-7]. The local actuators can realize high-speed positioning of the electrode to maintain a suitable distance from the work-piece, and, compared to a conventional EDM machine, debris can be removed more efficiently by rotation, orbit motion or rapid retraction of the electrode, which may be facilitated by local actuators [8].



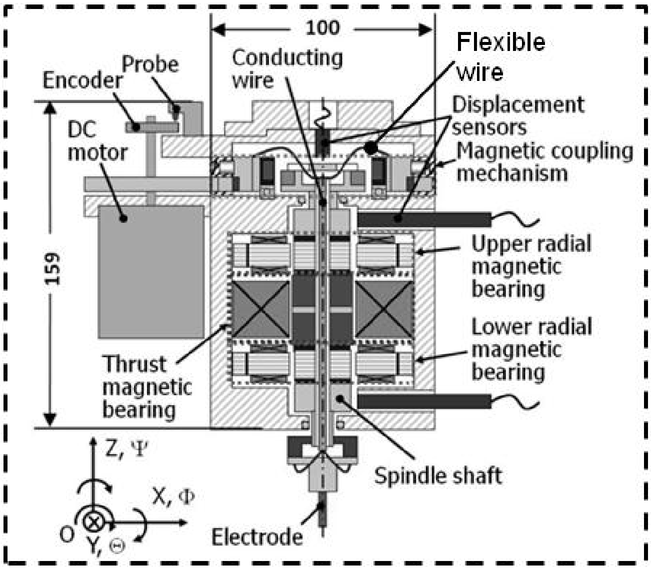


***Fig. 1** Cooperative EDM system*

***Fig. 2** Configuration of 5-DOF MLA*

To realize high speed and highly precise positioning for the electrode, the authors have developed a 5-DOF controlled maglev local actuator (MLA) [9,10]. The MLA not only has a wide-bandwidth and high-accuracy in 5-DOF, but also has a stroke of 2mm in the thrust direction to realize the rapid retraction of the electrode during EDM. Micro holes could be machined in multi-directions using the MLA, and the machining speed was improved by 20~400%, compared with a conventional EDM machine.

However, the brushes feeding the discharge current to the spindle shaft contact the levitated spindle shaft directly, so that the rotation of the spindle shaft is disturbed by the friction between the spindle shaft and the brushes. However, the rotation of the electrode may be effective in increasing the flushing of the machining fluid during the machining of deep-small holes.

In this paper, firstly, a 5-DOF MLA with a magnetic coupling mechanism is introduced, feeding the discharge current to the electrode without any direct contact between the brushes and the levitated spindle shaft and its positioning performances are considered. The spindle shaft can rotate freely without any interference from the friction.

Secondary, a cooperative control system, consisting of the MLA and a conventional EDM machine (MEMH8N, Mitsubishi Electric Corporation.), has been constructed, as shown in Fig. 1.

Finally, the EDM of small holes using the EDM machine only and using the combination of the EDM machine and the MLA is tested and the machining speeds of the small holes are discussed.

5-DOF MLA

The configuration of the 5-DOF controlled MLA is shown in Fig. 2. The height of the MLA without an electrode and its attachment is 159mm and the width without the DC motor is 100mm.

It mainly comprises a 5-DOF controlled magnetic bearing (MB) system, a magnetic coupling mechanism and the spindle shaft.

The 5-DOF controlled MB system consists of an upper radial MB, a lower radial MB and a thrust MB, which are used to levitate and position the spindle shaft precisely and speedily in three orthogonal and two tilt directions. The weight of the spindle shaft, including the attachment of an electrode, is 0.53 kg.

The magnetic coupling mechanism, as shown in Fig. 3, is attached on the upper end of the MLA. It can transmit a torque from the DC motor to the spindle shaft through the magnetic coupling which consists of a permanent magnet ring comprising a Halbach permanent magnet array, a power supply ring and a toothed iron ring. The levitated spindle shaft can be rotated in synchronism with the rotation of the power supply ring. Discharge current can be fed from the power supply to power supply ring through the brushes, and thence to the electrode for EDM via flexible wires. Thus, the levitated spindle shaft is free from friction of brushes for the power supply.

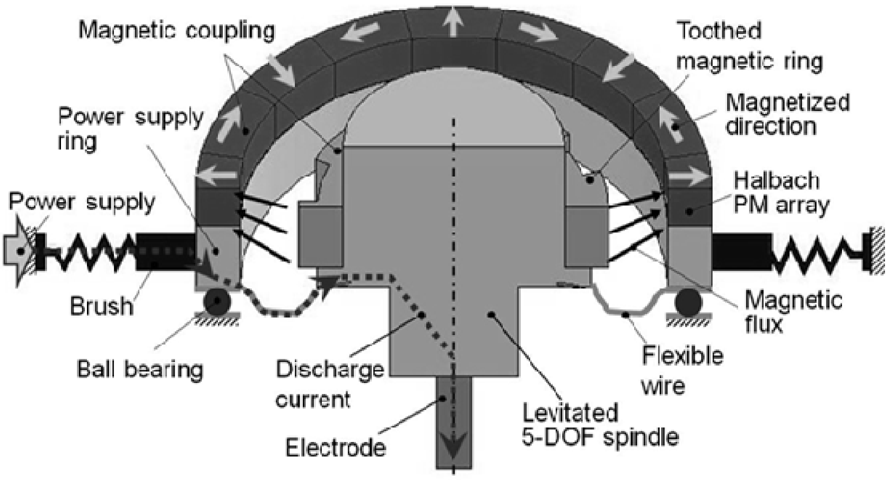


Fig. 3 *Configuration of magnetic coupling mechanism*

Table 1 *Positioning performances of MLA*

Direction	Positioning resolution	Bandwidth	Full stroke
X	0.3 μm	207 Hz	±80 μm
Θ	5 μrad	202 Hz	±1.5 mrad
Z	0.5 μm	230 Hz	±1 mm

Positioning and Rotational Performances

Positioning Performance. Table 1 shows the experimental positioning performances of the MLA in the X-, Θ- and Z-directions. The experimental results in the Y- and Φ-directions, which are not shown in the table, are almost the same as those in X- and Θ-directions.

The experimental results indicate that the MLA possesses sub-micron positioning resolution in the radial directions and several micro-radians positioning resolution in the tilt directions; bandwidths greater than 200 Hz in all the 5-DOF directions, positioning strokes of ±1mm in the thrust direction, ±80μm in the radial directions and ±1.5mrad in the tilt directions [11].

Rotational Accuracy. Utilizing the magnetic coupling mechanism, the spindle shaft of the MLA can be rotated at up to 2,000rpm. However, due to the unbalance force of the spindle shaft and the unbalance magnetic pull of the magnetic bearings, the rotational run-out increases as the rotational speed increases.

Therefore, space domain repetitive controllers comprising a low-pass-filter (LPF) and an integral delay [12] have been adopted in the X-, Y-, Θ- and Φ-directions for the suppression of run-out. The thrust motion suffers but little from the unbalances, so no repetitive controller is added to the control system in the Z-direction.

Fig. 4 shows that, utilizing the repetitive controller, the rotational vibration amplitudes of the spindle shaft decrease from ±3.5μm to ±0.7μm in the radial directions and from ±61μrad to less than ±15μrad in the tilt directions at 2,000rpm.

High Speed Motion. The electrode can realize high-speed thrust jump motion, rotation, high-frequency orbital motion and combinations of these [11]. All these motions of electrode may be effective in increasing the flushing of the dielectric fluid during EDM. The increased flushing is expected to increase the material removal rate, decrease tool wear rate and improve surface finish.

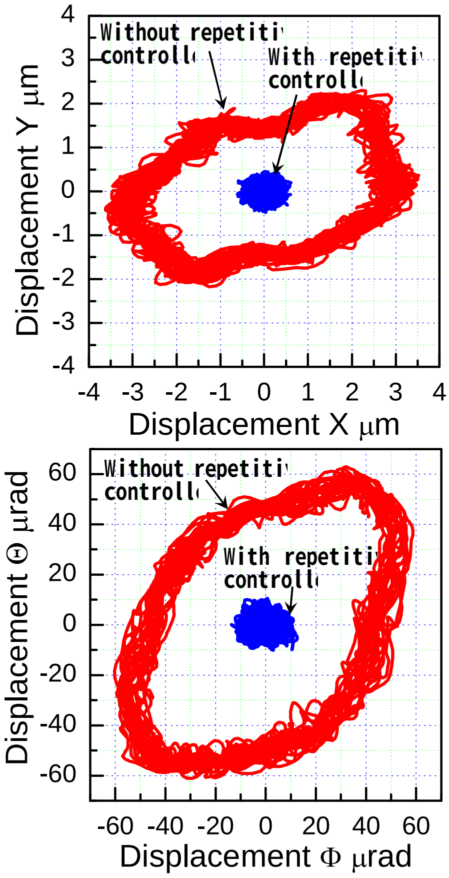


Fig. 4 Rotational vibration of spindle shaft at 2,000rpm

Cooperative EDM

In order to realize not only high positioning response, but also positioning stroke greater than that of the MLA, a cooperative control system has been adopted for EDM. In the cooperative EDM, the MLA is mounted on a positioning stage of a conventional EDM machine, which has a large stroke with high positioning accuracy but low positioning response.

Fig. 5 shows the cooperative control system in the Z direction. During EDM, the discharge voltage V between the electrode and work-piece was monitored through a LPF with a cut-off frequency of 300Hz and was used as a feedback signal. The EDM controller generated the reference position of the electrode in the thrust direction according to the feedback voltage V_{fb} and a reference EDM voltage V_r.

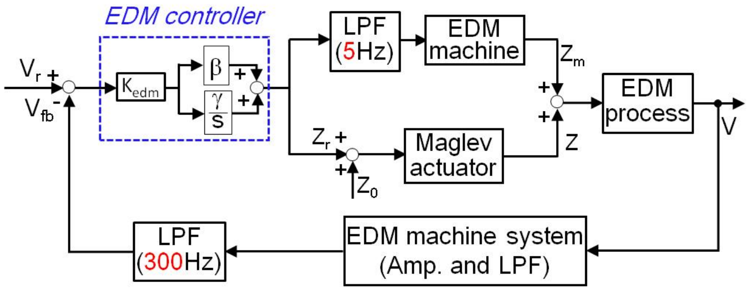


Fig. 5 Cooperative EDM control system

The reference position was entered into the maglev actuator system directly and into the conventional EDM machine through a LPF with a cut-off frequency of 5Hz. Following the reference position, the MLA adjusted the electrode speedily and precisely to maintain a suitable distance from the work-piece, and the conventional EDM machine fed the mounted MLA with the electrode, slowly and continuously in the machining feed direction, to avoid the saturation of the positioning stroke of the MLA.

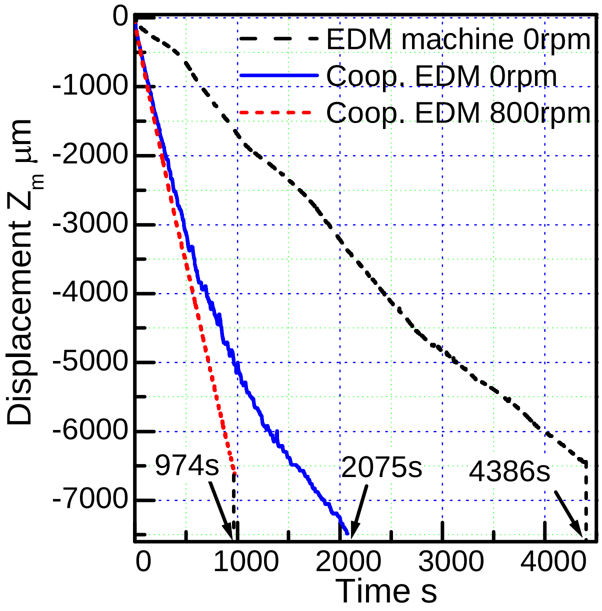
Experimental Machining

To evaluate the effectiveness of high-speed and high-accuracy re-positioning and rotation of the electrode by the MLA, small holes were machined using the cooperative EDM, with and without electrode rotation, and the conventional EDM machine, only, without electrode rotation. Cylindrical shaped copper electrodes with diameters of ϕ0.5mm were used and the machining was continued until the electrode penetrated a work-piece to a thickness of 4mm.

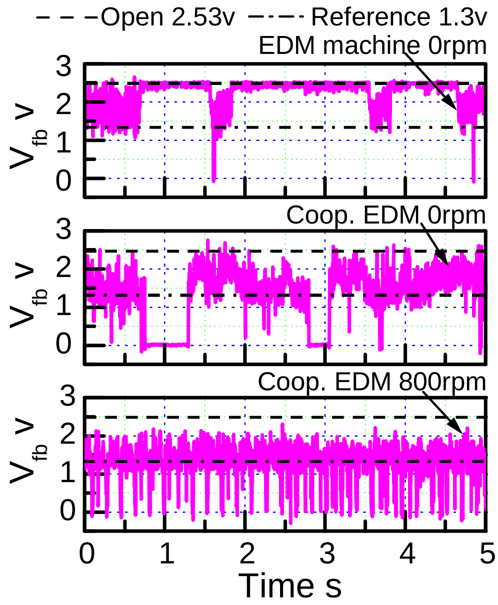
Fig. 6 (a) shows the displacement of the stage of the conventional EDM machine in the Z direction. According to the machining results, the cooperative EDM without electrode rotation increased the machining speeds, defined as the ratio of the machining time and the depth of the machined hole, by 111% compared with machining using the conventional EDM machine only without electrode rotation, while the electrode rotated at 800rpm in cooperative EDM increased the machining speed by 350% compared to the conventional EDM machine only.

Fig. 6 (b) shows the feedback voltage V_{fb} for 5 seconds during EDM in each machining case. In the experimental machining, the open voltage between the electrode and the work-piece was set as 2.53V and the reference voltage V_r was 1.3v.

During machining, V_{fb} around 0-0.5V means a short circuit, and V_{fb} around 2.0-2.53v means an open circuit, in these cases, the electrical discharge would stop and the position of the electrode needed to be adjusted to re-start the electrical discharge. When the V_{fb} was around 1.3v, electrical discharge was eroding continually and a high machining efficiency was obtained.



(a) Displacement of EDM machine stage



(b) Feedback voltage

***Fig. 6** Experimental machining of 4mm-through-holes*

Regarding the results in Fig. 6 (b), in the case of using EDM machine only without electrode rotation, electrical discharge would increase the distance between the electrode and work-piece, then the V_{fb} would increase and cause an open circuit, however, due to the slow response speed of EDM machine, it took a long time to adjust the position of electrode to re-start an electrical discharge, resulting in low machining speed.

In the case of cooperative EDM without electrode rotation, the MLA could position the electrode much more speedily than the EDM machine, so an open circuit seldom occurred; even if there were short circuits, mainly caused by debris accumulating around the electrode, the high response of the MLA could adjust the position of electrode in a short time, so the machining speed was higher than that using EDM machine only.

Finally, in the case of cooperative EDM with electrode rotation, the rotation of electrode increased the flushing during EDM, which removed the debris efficiently and decreased the incidence of short circuits, therefore, electrical discharge was eroding continually and a much higher machining speed was obtained.

Conclusion

In this paper, a high-speed, high accuracy, 5-DOF controlled MLA with sub-micron and several-micro-radian positioning resolutions, bandwidths greater than 200 Hz in the all 5-DOF, and smooth rotation was demonstrated for high speed EDM. The cooperative EDM using the combination of the MLA and a conventional EDM machine was tested. Compared to the conventional EDM machine, the cooperative EDM with electrode rotation possessed much higher response speed for maintaining the suitable discharge voltage, and facilitated an increased machining speed.

References

[1] M. Kunieda, B. Lauwers, K. Rajurkar, B. Schumacher: Advancing EDM through Fundamental Insight into the Process, CIRP Ann 54, 2 (2005) pp.599-622

[2] K. H. Ho, S. T. Newman: State of the Art Electrical Discharge Machining (EDM). International Journal of Machine Tools and Manufacture 43, 13 (2003) pp. 1287-1300

[3] K. Varanasi, S. Nayfeh: The Dynamics of Lead-screw Drives: Low-Order Modeling and Experiments, Trans ASME J Dyn Syst Meas Control. 126, (2004) pp. 388-396

[4] Y. Zhao, X. Zhang, X. Liu, K. Yamazaki: Geometric Modeling of the Linear Motor Driven Electrical Discharge Machining (EDM) Die-sinking Process, International Journal of Machine Tools & Manufacture, 44, (2004) pp. 1-9

[5] Y. Imai, A. Satake, A. Taneda: Improvement of EDM Machining Speed by Using High Frequency Response Actuator, International Journal Electrical Machining, 1, (1996) pp. 21–26

[6] T. Masuzawa, K. Tanaka, M. Fujino: Study on the High Speed Machining by EDM Using a Moving Coil Head Type Feed Control, Proc. of the 19th International MTDR Conference, (1978) pp. 543-549.

[7] T. Imai, T. Nakagawa, H. Miyake, H. Hidai, H. Tokura: Local Actuator Module for Highly Accurate Micro-EDM, Journal of Materials Processing Technology, 149, 3 (2004) pp. 328-333

[8] M. Ghoreishi, J. Atkinson: A comparative experimental study of machining characteristic in vibratory, rotary and vibro-rotary electro-discharge machining, Journal of Material processing Technology, 120, (2001) pp. 374-384

[9] X. Zhang, T. Shinshi, G. Kajiwara, A. Shimokohbe, Y. Imai, H. Miyake, T. Nakagawa: 5-DOF Controlled Maglev Local Actuator and its Application to Electrical Discharge Machining, Precision Engineering, 32, (2008) pp. 289-300

[10] X. Zhang, T. Shinshi, A. Shimokohbe, T. Sato, H. Miyake, T. Nakagawa: High-speed Electrical Discharge Machining By Using a 5-DOF Controlled Maglev Local Actuator, Journal of Advanced Mechanical Design, Systems, and Manufacturing, 2, 4 (2008) pp. 493-503

[11] D. He, H. Morita, X. Zhang, T. Shinshi, T. Nakagawa, T. Sato, H. Miyake: Development of a Novel 5-DOF Controlled Maglev Local Actuator for High Speed Electrical Discharge Machining, Precision Engineering, 34, 3(2010) pp. 453-460

[12] X. Zhang, T. Shinshi, L. Li, A. Shimokohbe: A combined Repetitive Control for Precision Rotation of Magnetic Bearing, Precision Engineering, 27, (2003) pp. 273-282