Development of a 2-DOF Controlled Magnetic Drive Actuator for Laser Beam Cutting*

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Abstract
Laser beam cutting (LBC) is a non-contact machining method that is widely used in industry. In order to improve cutting speed and reduce the consumption of assist gas, it is necessary to employ a machining method that applies a suitable eccentricity between the laser beam axis and the assist gas nozzle axis. This paper describes the development of a high-speed, high-precision, magnetic drive actuator, which can be attached to a conventional LBC machine to control the relative displacement between the laser beam axis and the assist gas nozzle axis in two orthogonal directions. First, a magnetic drive actuator is designed and fabricated. In the actuator, the motions of the lens in the radial directions are controlled by electromagnets, and the motions in the other directions are constrained by elastic hinges. Second, a compensation method for the zero point of the displacement sensors that are used to measure the displacements of the lens in the radial direction and an adaptive control method for the actuator are presented. Finally, the effectiveness of the presented control method is verified, and the positioning performance of the actuator is evaluated through experiments. The experimental results showed that the vibration of the lens was reduced using the presented control method, and the actuator had a positioning resolution of 0.75 µm, a bandwidth greater than 133 Hz, and a positioning stroke of 1 mm.

Key words: Laser Beam Cutting, Magnetic Drive Actuator, Adaptive Control

1. Introduction

The laser beams are widely used for cutting, drilling, marking, welding, sintering, and heat treatment. Laser beam cutting (LBC) is a non-contact machining method that is most widely used in industry to cut complex shapes with close tolerances from sheet material (1), (2). In the process, a high-energy laser beam is focused by a lens to melt and vaporize the work-piece material, and the molten material is blown away (3). In order to remove the molten material from the cutting front as soon as possible, assist gas is normally used in LBC (4). The ability of the assist gas to remove molten material from the cutting front is reduced as the work-piece becomes thicker. Insufficient gas flow to the cutting front
decreases the cutting speed, and generates burr, dross, and recast layers \(5, 6\).

In order to improve cutting speed and reduce the consumption of assist gas, a machining method with a suitable eccentricity between the axis of the laser beam and the axis of an assist gas supply nozzle was proposed \(7\). The eccentricity could be manually adjusted for each experiment, and the effect of the eccentricity was verified \(8\). However, real-time eccentricity control of the lens has not been realized in a conventional LBC machine. Particularly, in order to realize two-dimensional (2D) LBC, the relative displacement between the nozzle and the laser beam following the 2D reference cutting trajectory needs to be controlled. Therefore, a supplementary high-speed actuator with two degrees of freedom (2-DOF) is necessary for controlling the relative displacement between the gas nozzle axis and the laser beam axis.

In this paper, we report on the development of a high-speed, high-precision, magnetic drive actuator that can be attached to a conventional LBC machine to control the relative displacement between the gas nozzle axis and the laser beam axis in two orthogonal directions. First, the proposed magnetic drive actuator was fabricated. Then, a compensation method for the zero point of the displacement sensors and an adaptive control method for the actuator were developed. Finally, the positioning performance of the actuator was evaluated through experiments.

2. Magnetic drive actuator

To control the relative displacement between the gas nozzle axis and the laser beam axis in two orthogonal directions, a 2-DOF controlled magnetic drive actuator is proposed, as shown in Fig. 1. The lens is used to focus the laser beam, and it is fixed by a lens holder. The motions of the lens holder in the X and Y directions are controlled by a pair of electromagnets (EMs). In addition, the motions in the Z, Θ, Φ, and Ψ directions are constrained by elastic hinges.

![Fig. 1 Configuration of 2-DOF controlled magnetic drive actuator](image)

The desired specifications for the proposed actuator include a positioning resolution of less than 1 µm, a bandwidth greater than 100 Hz, and a positioning stroke of more than 1 mm. In order to realize the desired specifications, the EMs were designed based on a numerical analysis using static magnetic field simulation. The elastic hinges were also designed based on a numerical analysis.

Figure 2 shows a photograph of the experimental magnetic drive actuator. The length and width of the actuator are both 200 mm, its height is 30 mm, and its mass is 4.9 kg. The length and width of the lens holder are both 80 mm, and its inside diameter is 50 mm. The elastic hinge is a parallel leaf spring structure. In the X direction, the length, width, and
thickness of each leaf spring are 55 mm, 17 mm, and 1 mm, respectively. In the Y direction, the dimensions of the outside leaf springs are 55 mm in length, 14 mm in width, and 1 mm in thickness, and the dimensions of the inside leaf springs are 55 mm in length, 22 mm in width, and 1 mm in thickness. The lens holder and elastic hinges are an integral structure, and their material is brass. Additionally, each coil of the EM has 220 turns, and the initial air gap between the lens holder and the EMs is 0.6 mm.

The displacements of the lens holder in the X and Y directions are measured by a pair of differential eddy current displacement sensors (PU-05-489-401, AEC Corp., measurement range 2.0 mm, resolution 0.5 µm). The coil currents of the EMs are measured by multi-range current sensors (LA25-NP, LEM Corp., measurement range 7 A). The actuator is controlled by a digital signal processor (DSP; DS1103 PPC Controller Board, dSPACE Corp.), and the sampling rate is 10 kHz.

![Diagram of the experimental magnetic drive actuator](image)

**Fig. 2 Photograph of the experimental magnetic drive actuator**

### 3. Control system

#### 3.1 Nonlinear compensation of electromagnetic force

In the X direction, the motion of the lens holder is controlled by a pair of EMs. The equation of motion of the lens holder is given by:

\[
m_x \ddot{x} + c_x \dot{x} + k_x x = f_1 - f_2 = k_{i1f1} \frac{i_1^2}{(X_0 - x)^2} - k_{i2f2} \frac{i_2^2}{(X_0 + x)^2}
\]

where, \( x \) is the displacement of the lens holder in the X direction, \( m_x \) is the mass of the lens holder and the lens, \( c_x \) is the damping coefficient, \( k_x \) is the stiffness coefficient of the elastic hinges, \( f_1 \) and \( f_2 \) are the electromagnetic forces generated by EM1 and EM2, \( k_{i1f1} \) and \( k_{i2f2} \) are the coefficients of the gap-current-force of EM1 and EM2, \( i_1 \) and \( i_2 \) are the coil currents of EM1 and EM2, and \( X_0 \) is the initial air gap between the lens holder and the EMs. The motion equation in the Y direction is similar to Eq. (1), and not shown here.

In Eq. (1), the electromagnetic force is proportional to the square of the coil current. In order to achieve the linear electromagnetic force, a bias current is usually applied to the EMs (9). This linear method is limited to the following conditions: 1) the working range of the controlled object should be much smaller than the air gap between the object and EMs, and 2) the regulating current should be much smaller than the bias current. However, in the developed actuator, a stroke of the order of millimeters is necessary to control the relative displacement between the nozzle and the laser beam. Therefore, the bias current method is
applied to the actuator, the nonlinearity of electromagnetic force cannot be perfectly compensated, and vibration in the lens holder may increase at a long positioning stroke. Moreover, the copper loss caused by the bias current causes heat generation, which reduces positioning accuracy of the lens holder.

One simple solution for that is to drive the EMs with a zero bias current (10). In this method, when the lens holder is driven to the +X direction, the current only flows through the coil of the EM1, and the coil current of the EM2 is zero. In contrast, when the lens holder is driven to the −X direction, the current flows through the coil of the EM2, and the coil current of the EM1 is set to zero. In a general situation, only one of the two EMs is driven. Therefore, heat generation by the electromagnets can be minimized. However, in order to compensate the nonlinearity of the electromagnetic force in the full stroke of the lens holder, a nonlinear compensator is used as shown in the following (11):

\[
\begin{align*}
    i_{ref1} &= (X_0 - x) \sqrt{\frac{m_1}{k_{oi1}}} V_c \\
    i_{ref2} &= 0 & (V_c \geq 0) \\
    i_{ref1} &= 0 \\
    i_{ref2} &= (X_0 + x) \sqrt{\frac{m_2}{k_{oi2}}} V_c & (V_c < 0)
\end{align*}
\]

where \(V_c\) is the manipulated variable from the controller, and \(i_{ref1}\) and \(i_{ref2}\) are the references for the current feedback loops which are used to improve the response speed of the electromagnetic forces.

### 3.2 Compensation for the zero point of displacement sensors

For the machining accuracy of the actuator and the assembly accuracy of the displacement sensors, the lens holder center, which is fixed by the elastic hinges, does not coincide with the zero point of the displacement sensors, as shown in Fig. 3. In this case, if the lens holder center is set to the zero point of the displacement sensors, the elastic hinges produce a restoring force. The restoring force is a disturbance force on the lens holder, and it will reduce the positioning accuracy of the lens holder. Moreover, in order to control the disturbance force produced by the elastic hinges, one of the two EMs installed in both sides of the lens holder should always work. Consequently, the heat generated by the EMs reduces the positioning accuracy of the lens holder. In order to prevent the generation of the disturbance force and heat, the zero point of the displacement sensors is compensated by the integral of the coil currents until it coincides with the lens holder center, as shown in Fig. 3.

![Fig. 3 Compensation for the zero point of the displacement sensors](image-url)
3.3 Adaptive controller of actuator

To compensate for the nonlinearity of the electromagnetic force, a nonlinear compensator is used, as shown in Eqs. (2) and (3). In the nonlinear compensator, the coefficients of the gap-current-force $k_{ix1}$ and $k_{ix2}$ are included; $k_{ix1}$ and $k_{ix2}$ are changed depending on the length of the air gap between the EMs and the lens holder. In a larger working range, $k_{ix1}$ and $k_{ix2}$ cannot be considered as constants. To compensate perfectly for the nonlinearity of the electromagnetic force, real-time estimation of $k_{ix1}$ and $k_{ix2}$ is necessary.

Figure 4 is a block diagram of the adaptive control system of the actuator in the X direction. The block diagram of the control system in the Y direction is identical; therefore, it is not shown here. In the control system, the coefficient of the gap-current-force is estimated in real-time from the displacement of the lens holder. The positioning controller is composed of an integrating compensator and a regulator, obtained from a transfer function consisting of a 2nd-order numerator and 2nd-order denominator. To improve the response speed of the electromagnetic force, the local current feedback loops, using a proportional-integral (PI) compensator, are added.

Additionally, a compensator for the zero point of the displacement sensors is used to coincide with the center of the lens holder, which is fixed by the elastic hinges. However, when the reference position of the lens holder is only equal to zero, the integration switches for the coil currents are turned on to compensate for the zero point of the displacement sensors.

The model parameters in the X direction are identified in Table 1 where $k_{ix0}$ is the coefficient of the gap-current-force of the EMs at the initial air gap. When the bandwidth of the current feedback loop is set to 500 Hz, the parameters of the PI compensator are determined, where the proportional gain $k_p$ is 45, and the integral gain $k_i$ is 2500. Moreover, the motion controller parameters $\gamma_x$, $a_{0x}$, $a_{1x}$, $b_{0x}$, $b_{1x}$, and $b_{2x}$ can be automatically defined such that the denominator of the transfer function $(X'/X_r)$ approaches $m_xL_x(s + \alpha)^6$ after determining only the value of $\alpha$. This controller-design approach is easier than experimental parameter-tuning of the proportional-integral-derivative controller, because any positive real number value of $\alpha$ always satisfies the condition for system stability.
When the value of $\alpha$ is set to $2\pi \times 250$ rad/s, the parameters of the motion controller are determined according to Table 2.

Table 1 Identified model parameters in the X direction

| Parameter | Value |
|-----------|-------|
| $m_x$     | 0.90kg |
| $k_x$     | $1.03 \times 10^5$ N/m |
| $c_x$     | 3.94 Ns/m |
| $L_x$     | $1.45 \times 10^{-2}$ H |
| $R_x$     | 3.6 $\Omega$ |
| $k_{ixf0}$ | $2.226 \times 10^{-6}$ Nm$^2$/A$^2$ |

Table 2 Determined parameters of the motion controller

| Parameter | Value |
|-----------|-------|
| $\gamma_x$ | $3.00 \times 10^3$ |
| $b_{0x}$  | $1.13 \times 10^{11}$ |
| $a_{0x}$  | $1.66 \times 10^7$ |
| $b_{1x}$  | $3.52 \times 10^8$ |
| $a_{1x}$  | $6.29 \times 10^3$ |
| $b_{2x}$  | $4.66 \times 10^6$ |

4. Experimental results

4.1 Zero point compensation of displacement sensors

One second after starting the experiment, the zero point compensation for the displacement sensors was initiated. The compensation value, the output of the displacement sensors, and the coil currents of EM1 and EM2 in the X direction were measured as shown in Fig. 5. The experimental results in the Y direction, which are not shown, are nearly the same as those in the X direction.

Before compensation, the lens holder center does not coincide with the zero point of the displacement sensors, and the difference is 76.8 $\mu$m. EM2 works all the time, and its coil current is 1.61 A to control the lens holder center so it coincides with the zero point of the displacement sensors. The compensation modifies the zero point of the displacement sensors from 0 to $-76.8$ $\mu$m, and the average values of the coil currents are close to zero.

![Fig. 5 Compensation results of the zero point of the displacement sensors in the X direction](image)

4.2 Estimation of the coefficient of the gap-current-force

Figure 6 describes an experimental setup for estimation of the coefficient of the gap-current-force. The EM installed with a load cell (LUR-A-100NSA1, Kyowa Electronic...
Instruments Co., Ltd.) is fixed on a beam supported by two pillars. The target of the EM is fixed on an XYZ stage that can move up and down to set the air gap between the EM and its target. The load cell is used to measure the electromagnetic force generated by the EM, and 2 eddy current displacement sensors (PU-05, AEC Corp.) are used to measure the length of the air gap. Additionally, a current sensor (LA 25-NP, LEM Corp.) is used to measure the coil current of the EM.

When the measured electromagnetic force, air gap length, and coil current are substituted into Eq. (1), the coefficient of the gap-current-force can be estimated. Figure 7 shows the relationships between the coefficient of the gap-current-force $k_{ix}$ and the air gap $X_0'$ for 3 trials. From the results, it can be seen that the coefficient of the gap-current-force decreases with an increase in the length of the air gap. The average value of the 3 trials follows the exponential function described in Eq. (4), and it is used for the adaptive control system shown in Fig. 4. The estimation results of the other EMs, which are not shown, are nearly the same as this EM.

$$k_{ix} = (2.226 + 1.278e^{-\frac{X_0'}{0.26x10^{-6}}}) \times 10^{-6} \text{ Nm}^2 / A^2$$  \hspace{1cm} (4)

![Fig. 6 Experimental setup for estimation of the coefficient of the gap-current-force](image1)

![Fig. 7 Relationship between the coefficient of the gap-current-force and the air gap](image2)

### 4.3 Efficacy of adaptive control

When the lens holder was moved to the full stroke of 0.5 mm in the +X direction, the vibrations of the lens holder were measured as shown in Fig. 8. The standard deviations ($\sigma$) of the vibrations of the lens holder without and with the adaptive control were 0.25 µm and 0.19 µm, respectively. Using the adaptive control, the vibration of the lens holder was reduced by 31.6%. Moreover, when the lens holder was moved 0.5 mm in the +Y direction, the vibrations of the lens holder were also measured, as shown in Fig. 9. Using the adaptive control, the standard deviation of vibration of the lens holder was reduced from 0.32 µm to 0.29 µm, and the vibration of the lens holder was reduced by 10.3%.

![Fig. 8 Vibrations of the lens holder at the full stroke of 0.5 mm in the +X direction](image3)

(a) Without adaptive control  \hspace{1cm} (b) With adaptive control
4.4 Positioning performance of actuator

Figure 10 shows that the actuator has a full stroke of 1 mm at 1 Hz in the X and Y directions. Using the actuator, the relative displacement between the nozzle and the laser beam can be controlled in two orthogonal directions. Figure 11 shows the positioning resolutions in the X and Y directions. It can be seen that the actuator has a positioning resolution of 0.75 µm. Moreover, the frequency responses in the X and Y directions were measured by a frequency response analyzer (FRA 5095, NF Corp.), as shown in Fig. 12. The bandwidths of the actuators were 141 Hz in the X direction and 134 Hz in the Y direction.
5. Conclusions

In LBC, to improve cutting speed and reduce the consumption of assist gas, a high-speed, high-precision, magnetic drive actuator, which can be attached to a conventional LBC machine to control the relative displacement between the laser beam axis and the assist gas nozzle axis in two orthogonal directions, was designed and fabricated. In this actuator, the motions of the lens in the radial directions are controlled by electromagnets, and the motions in the other directions are constrained by elastic hinges.

A compensation method for the zero point of the displacement sensors using the integral of the coil currents was presented to prevent generation of the disturbance force produced by the elastic hinges. Moreover, in order to achieve a high-precision long stroke of the actuator, an adaptive control method that applies estimation of the coefficient of the gap-current-force in real-time was presented.

The effectiveness of the presented control method was verified, and the positioning performance of the actuator was evaluated through experiments. The experimental results showed that the coefficient of the gap-current-force decreased exponentially with an increase in the length of the air gap, and the standard deviations of the vibrations of the lens holder in the X and Y directions were reduced by 31.6% and 10.3%, respectively, using the adaptive control. The magnetic drive actuator showed a positioning resolution of 0.75 μm, a bandwidth greater than 133 Hz, and a positioning stroke of 1 mm. Future work will apply the actuator to laser cutting.

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References

(1) Kumar Dubey, A. and Yadava, V., Robust Parameter Design and Multi-objective Optimization of Laser Beam Cutting for Aluminium Alloy Sheet, International Journal of Advanced Manufacturing Technology, Vol.38, No.3-4 (2008), pp.268-277.
(2) Kumar Dubey, A. and Yadava, V., Multi-objective Optimisation of Laser Beam Cutting Process, Optics & Laser Technology, Vol. 40, No.3 (2008), pp. 562-570.
(3) Radovanovic, M. and Dasic, P., Research of Surface Roughness by Laser Cut, Tribology, Fascicle VIII, The Annals of University “Dunarea de Jos” of Galati, ISSN 1221-4590, (2006), pp. 84-88.
(4) Kumar Dubey, A. and Yadava, V., Laser Beam Machining—A Review, International Journal of Machine Tools and Manufacture, Vol. 48. No. 6 (2008), pp. 609-628.
(5) Golnabi, H. and Bahar, M., Investigation of Optimum Condition in Oxygen Gas-assisted Laser Cutting, Optics & Laser Technology, Vol. 41 No. 4 (2009), pp. 454-460.
(6) Kovalev, O. B., Yudin, P. V. and Zaitsev, A. V., Modeling of Flow Separation of Assist Gas as Applied to Laser Cutting of Thick Metal, Applied Mathematical Modeling, Vol. 33, No. 9 (2009), pp. 3730-3745.
(7) Ketting, H.O. and Olsen, F.O., High Pressure Off-axis Laser Cutting of Stainless Steel and Aluminum, Proceedings of International Conference on Laser Advanced Materials Processing (Science and Applications), No. 7-12 (1992), pp. 607-612
(8) Quintero, F., Pou, J., Fernandez, J.L., Doval, A.F., Lusquinos, F., Boutinguiza,M., Soto, R. and Perez-Amor, M., Optimization of An Off-axis Nozzle for Assist Gas Injection
in Laser Fusion Cutting, *Optics and Lasers in Engineering*, Vol. 44, No. 11 (2006), pp. 1158-1171.

(9) Setiawin, J. D., Mukherjee, R. and Maslen, E. H., Adaptive Compensation of Sensor Runout for Magnetic Bearings with Uncertain Parameters: Theory and Experiments, *Transactions on the ASME, Journal of Dynamic Systems, Measurement, and Control*, Vol. 123, No. 6 (2001), pp. 211-218.

(10) Maslen, E. H., Allaire, P. E., Noh, M. D. and Sortore, C. K., Magnetic Bearing Design for Reduced Power Consumption, *Transactions of the ASME on Journal of Tribology*, Vol. 118, No. 10 (1996), pp. 839-846.

(11) Zhang, X., Shinshi, T., Li, L. and Shimokohbe, A., Precision Control for Rotation About Estimated Center of Inertia of Spindle Supported by Radial Magnetic Bearing, *JSME International Journal, Series C*, Vol. 47, No. 1 (2004), pp. 242-250.

(12) Hao, S. H., Yang, Z. J. and Tsuji, T., Adaptive Nonlinear Control for a Magnetic Levitation System, *Transactions of the SICE*, Vol. 32, No. 1 (1996), pp. 87-96. (In Japanese)