Control of thrust measurement system for cw laser thrusters

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Keiji Hagiwara[1], Hitoshi Yonamine[2], and Hideyuki Horisawa[3]
Dept. Aeronautics and Astronautics, Tokai University, Hiratsuka, Kanagawa, 259-1292, Japan

and

Yuya Oshio[4], Hiroki Sato[5] and Ikkoh Funaki[6]
JAXA/ISAS, Sagamihara, Kanagawa, 252-5210, Japan

Abstract: To estimate the thrust characteristics of a low-power CW laser thruster, a single-wire torsion balance thrust stand was developed. To suppress the displacement of the arm of the torsion balance during the thrust generation, a PID control system was developed. As a result, suppression and control of the displacement of the arm was achieved and its position on the origin, or a focal point of the focusing lens, was successfully maintained. Moreover, from the control signal, the thrust could be estimated. Some preliminary thrust characteristics were also obtained.

Nomenclature

H	=	magnetic field
n	=	winding number of coil
z	=	distance between coil and magnet
l	=	length of coil
d	=	thickness of magnet
q_m	=	magnetic charge
K_U	=	limit sensitivity
P_U	=	period of vibration
K_P	=	proportion gain
K_I	=	integral gain
K_D	=	differential gain

I. Introduction

THE current trend towards smaller spacecraft, which is not only mass-limited but also power-limited, has produced a strong interest in the development of micropropulsion devices[1-4]. The significance in reducing launch masses has attracted growing interests in regard to a decrease in mission cost and an increase launch rate. Although, in the past, many very small spacecraft lacked propulsion systems altogether, future microspacecraft will

[1] Graduate Student, Department of Aeronautics and Astronautics, keiji19880421@gmail.com
[2] Graduate Student, Department of Aeronautics and Astronautics, 0bmjm027@mail.tokai-u.jp
[3] Professor, Department of Aeronautics and Astronautics, horisawa@keyaki.cc.u-tokai.ac.jp
[4] Graduate Student, Department of Space and Astronautical Science, y-oshio@ac.jaxa.jp
[5] Graduate Student, Department of Space and Astronautical Science, satoh.hiroki@jaxa.jp
[6] Associate Professor, Institute of Space and Astronautical Science, Member AIAA, funaki@isas.jaxa.jp

require a significant propulsion capability in order to provide a high degree of maneuverability and capability in terms of thrust, specific impulse, or efficiency. The benefit of using electric propulsion for the reduction in spacecraft mass will likely be even more significant for mass-limited microspacecraft missions[2-4]. Feasibility studies of microspacecraft are currently under development for a mass less than 100 kg with an available power level for propulsion of less than 100 watts. Various potential propulsion systems for microspacecraft applications have been proposed and are under significant development for primary and attitude control applications[4].

On the other hand, small onboard laser thrusters are also under significant development along with the rapid evolution of novel compact laser systems. One of the advantages of such laser thrusters is that they can use any solid materials as their propellant. Therefore, the system can be very simple and compact with significant controllability of thrust[5-9]. A low-power laser ablation thruster was previously studied by Phipps[5] using ms-duration laser pulses with a multi-mode laser diode to exceed an ablation threshold fluence in the smallest focal spot available with conventional optics. The best result was 680 μN thrust with 2.1 W of average optical power. Unlike the approach by Phipps and others [10-12], authors have been conducting a new approach utilizing a low-intensity continuous wave (CW) laser beam with output of 0.1 to 20 W irradiated to a metallic target made of aluminum foil, as shown in Fig.1[13]. In order to evaluate the thrust performance of this novel low intensity laser propulsion system, development of a new torsion balance thrust measurement system with sub-micro-Newton sensitivity is conducted in this study.

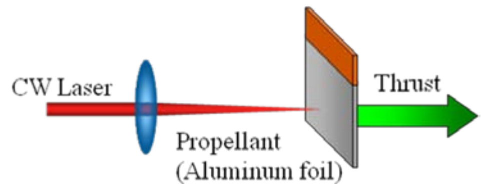

Figure 1. Low intensity CW laser thruster.

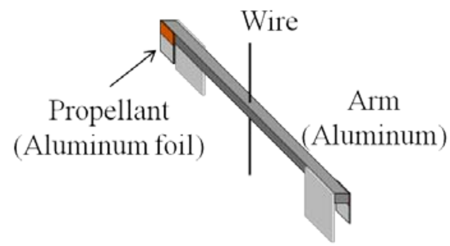

Figure 2. Thrust stand.

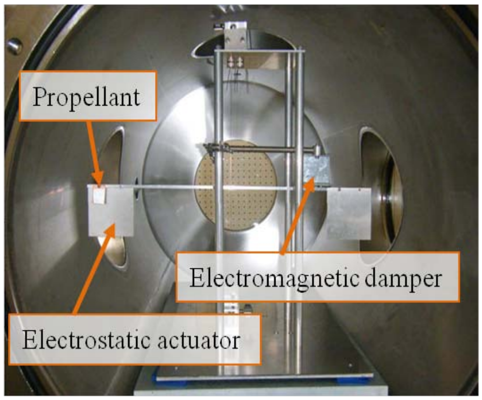

Figure 3. Photo of thrust stand.

II. Development of Thrust Measurement System

A. Torsion balance thrust measurement system

Thrust levels of our thruster are down to some micro-newtons. To measure the low thrust, torsion balance thrust measurement systems are being developed to estimate the propulsive performances. A schematic diagram and photo of thrust stand are shown in Figs. 2 and 3, respectively. As shown in these figures, this thrust stand consists of a pair of a wire and an aluminum arm suspended at its center horizontally. A propellant target and an electromagnetic actuator were placed at one side and a counter weight was placed at another side the arm. To reduce mechanical vibrations and oscillations of the arm, an electromagnetic damper, or eddy current damper, consisting of eight SmCo magnets was placed above the arm.

Measuring torsional displacements of the arm caused by the thruster, thrusts can be estimated. Because of the displacement, a distance between a

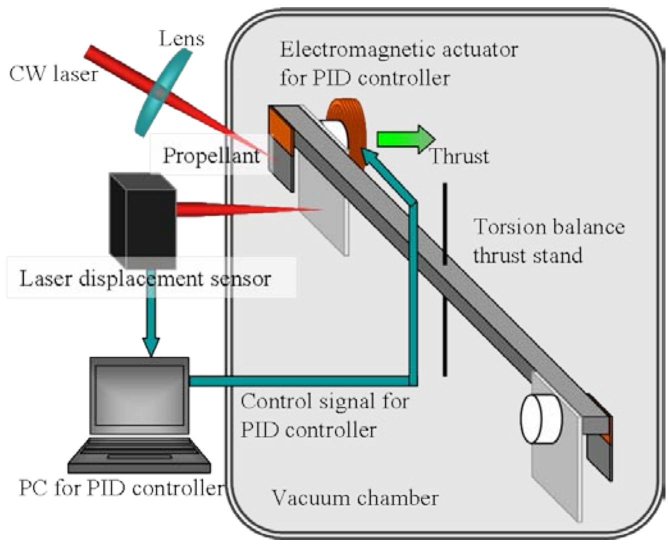

Figure 4. Experimental setup.

propellant target and a focusing lens, or focal length, cannot be kept constant while the thrust measurement. In laser thrusters in general, a power density of the laser on the target is one of the most important parameters which determine thrust performances. Therefore, to keep the focal length constant is also important to obtain the constant power density in estimating thrust performances of laser thrusters. To suppress the displacement of the arm, a PID control system was developed in this study. Suppression of the displacement was done by applying a controlled force generated by an actuator against a thrust through the PID controller. From the calibrated output signals from the controller, thrusts generated from the thruster can be estimated.

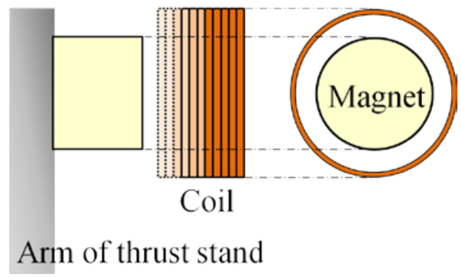

Figure 5. Electromagnetic actuator.

Since the control system is based on an input from a thrust, or a displacement of the arm, versus an output to a displacement of the arm, or a force induced by the actuator, the PID control system is utilized as shown in Fig.4. The PID control system consists of a laser displacement sensor (KEYENCE, LK-G400), an electromagnetic actuator (Fig.5), and a controller (PC with AD/DA convertor, ADA16-8/2 (LPCI) L).

B. Electromagnetic actuator

In our previous study, an electrostatic actuator has been used for the actuator. This actuator consisted of a pair of parallel and planar electrodes, and electrostatic forces were induced by applying voltages between the electrodes. Although relatively high voltages were necessary, i.e. up to 600 V depending on the size of electrodes, it took over tens of seconds to wait for the oscillation being suppressed down to a target level. Moreover in this system, a tendency of drifts of the origin of the arm was also confirmed. These are probably due to the non-linear relationship between a force generated by the electrostatic actuator and an output voltage from the controller, and also to the impossibility of generation of a repulsive force by the actuator in our previous system.

To overcome these issues, an electromagnetic actuator was designed and developed. A schematic diagram of the electromagnetic actuator is shown in Fig.5, which consists of a solenoid coil and a cylindrical magnet.
A magnetic field, *H*, induced by the coil is expressed from the Biot-Savart law as follows,

$$H = \frac{nj}{2}\left[\frac{z+\frac{l}{2}}{\sqrt{a^2+\left(z+\frac{l}{2}\right)^2}} - \frac{z-\frac{l}{2}}{\sqrt{a^2+\left(z-\frac{l}{2}\right)^2}}\right] \quad (1)$$

where *j* is the current in the coil, *n*: number of turns of the coil, *z*: distance between the coil and magnet, *l*: length of the coil, and *a*: coil radius. An electromagnetic force *F*, is generated by an interaction of the magnetic field *H*, induced by the coil and a cylindrical magnet of the length *d*, with a magnetic charge of q_m, and is expressed as follows,

$$F = q_m H_{\left(z+\frac{d}{2}\right)} - q_m H_{\left(z-\frac{d}{2}\right)} \quad (2)$$

From Eqs.(1) and (2), it can be confirmed that the relation between the electromagnetic force *F* and the input voltage, or the current *j*, from the PID controller is linear. Although depending on the current, magnetic charge, and configuration of the coil, the electromagnetic force can be relatively large compared to those generated by our previous electrostatic actuator. In our actuator, typical applied voltages, to the coil were low enough coming directly from the PID controller, or AD/DA convertor of the PC, i.e. between -10 to +10 V, or currents of -10 to +10 mA.

III. Experimental setup

A schematic of the experimental setup is shown in Fig.4. For a laser oscillator, a CW fiber laser (SPI Lasers, SP-25C-0001) with wavelength of 1,090 nm for variable output power from 0.1 to 20 W was used. To elucidate effects of wavelength, a CW laser diode (JENOPTIK, JOLD-30-CPXF-1L) with wavelength of 808 nm and maximum output power of 30 W was also employed. As described in the previous session, the thrust measurement system consists of a torsion balance with a pair of a wire and an arm, a laser displacement sensor, an electromagnetic actuator, and a PID controller (PC).

Specifications of the electromagnetic actuator, consisting of a solenoid coil and a cylindrical magnet, developed in this study (Fig.5) are listed in Table 1. As described in the above session, this actuator is designed to be driven by the currents of -10 to +10 mA. Since the output voltages from the AD/DA converter of the PC were about -10 to +10 V, a series resistor of 1 kΩ was inserted in the circuit. Since the maximum electromagnetic force can be obtained with the relative distance between the coil and magnet of 10 mm, the distance between the magnet and coil attached to the arm of the torsion balance was set to 10 mm. In addition, using Eqs.(1) and (2), this actuator was also used for calibration of the thrusts.

Before conducting thrust measurements of the thruster, it was necessary to tune the gains of the PID controller by the ultimate sensitivity method. In this method, proportional gains, K_Ps, increased up to a stable limit, or an ultimate gain K_U, and from the oscillation period, an ultimate period P_U can be determined. From these values, gains were tuned as listed in Table 2. Since the gains obtained through these procedures in our actual control system were too large, actual gains used in our system were tuned to smaller values than those by the ultimate sensitivity method.

After the gain tuning, thrust measurements were conducted with maintaining the position of the arm of the torsion balance at the origin. Thrusts were estimated by calculating theoretical forces from Eqs.(1) and (2) generated by the actuator using the controlled variables sent to the actuator from the PID controller. The theoretical reaction forces were defined as the thrusts generated by the thruster in this study.

One of the benefits of controlling the displacement of the arm of the torsion balance is to maintain the relative distance between the focusing lens and target. From the benefit, effects of lens-target distance on thrust, or influences of laser intensity on thrust performance, can be investigated.

IV. Results and Discussion

An example from results of gain tuning is shown in Fig.6. As can be seen, target positions of the arm of the torsion balance were controlled sequentially from -0.08 mm, 0.08 mm to 0 mm (the origin) without remarkable deviations. In addition, it can also be seen that the controlled variables are not exceeding the ultimate values of ± 10 V. Although the tuned gains obtained from the ultimate

Table 1. Specifications of the electromagnetic actuator

	Parameter	Value	Unit
Coil	Total number of turms	10	turns
	Radius	15	mm
	Wire diameter	1.5	mm
	Thickness	14	mm
Magnet	Surface inductive flux	280	mT
	Radius	7.5	mm
	Thickness	10	mm

Table 2. Parameter regulation law of ultimate limit sensitivity method.

Controller	K_p	T_I	T_D
P	$0.5K_U$	–	–
PI	$0.45K_U$	$P_U/1.2$	–
PID	$0.6K_U$	$0.5P_U$	$P_U/8$

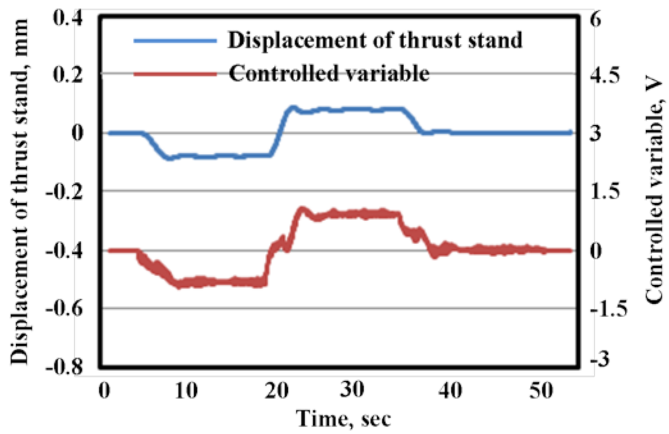

Figure 6. Result of gain tuning.

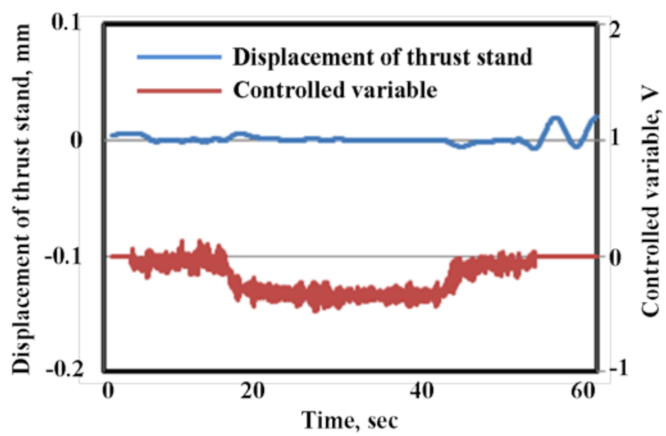

Figure 7. Temporal variations of displacement of the arm and controlled variables for the actuator in thrust measurement.

sensitivity method were $K_P = 1$, $K_I = 2.4$ and $K_D = 3.75$, the gains employed in the thrust measurements were suppressed as $K_P = 1$, $K_I = 0.6$ and $K_D = 0.6$ to keep the controlled variables not to exceed ultimate values.

Temporal variations of displacement of the arm and controlled variables for the actuator in thrust measurement are shown in Fig.7. From the figure, it is shown that the displacement is suppressed and the position of the arm of the torsion balance is maintained at the origin. In this case, a controlled reaction force was generated by the actuator driven by the controlled variables from the PID controller. Since a theoretical electromagnetic force generated by the actuator using the controlled variable was 2.64 μN, a thrust generated by the thruster could be estimated as 2.64 μN.

Relations of laser power and measured thrust are plotted in Fig.8. It can be seen that the thrust linearly increased with the increase of laser power. Figure 9 shows relations of lens-target distance and measured thrust. The maximum values of the thrust can be obtained at lens-target distance of 17 to 18 mm. When the lens-target distance varies, a spot size of the irradiated laser beam, or a laser intensity, changes on target surface. Although including some scatters of data, it can be seen that the thrust is dependent on the laser intensity.

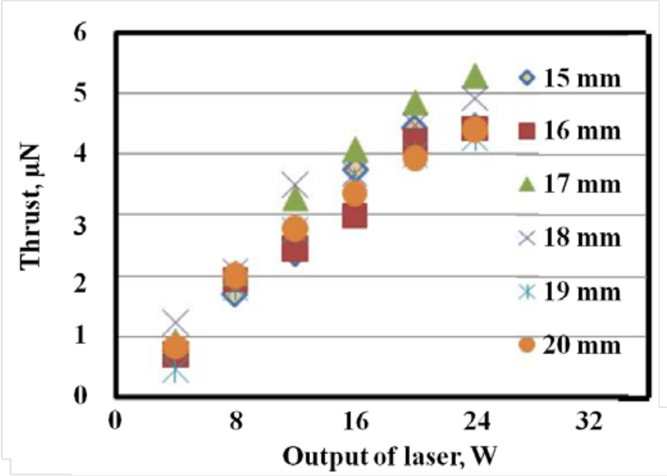

Figure 8. Relationship of output of laser and thrust.

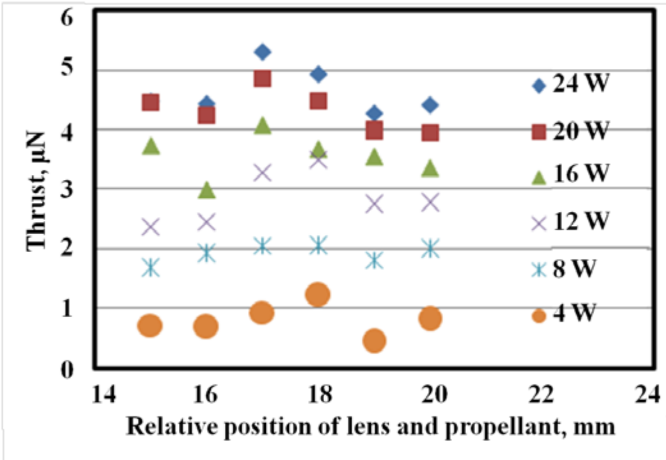

Figure 9. Relationship of focal distance of laser and thrust.

V. Conclusion

To suppress the displacement of the arm of a torsion balance during the thrust generation, a PID control system, which consisted of an electromagnetic actuator, a laser displacement sensor and a PID controller, was developed for a single-wire torsion balance thrust stand. Conclusions are as follows.

1) Target positions of the arm of the torsion balance were controlled sequentially from -0.08 mm, 0.08 mm to 0 mm (the origin) without remarkable deviations. The gains employed in the thrust measurements were suppressed as $K_P = 1$, $K_I = 0.6$ and $K_D = 0.6$.
2) The displacement is suppressed and the position of the arm of the torsion balance is maintained at the origin. In this case, a thrust generated by the thruster could be estimated as 2.64 μN.
3) The thrust linearly increased with the increase of laser power. The maximum values of the thrust can be obtained at lens-target distance of 17 to 18 mm. Finally, it was confirmed that thrust is dependent on the laser intensity.

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