Experimental Investigation on CW Laser Microthruster

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Abstract: The micro-Newton thrust generation was observed through low-power continuous-wave laser and aluminum foil interaction without any remarkable ablation of the target surface. To evaluate the thrust characteristics, a torsion-balance thrust stand capable for the measurement of the thrust level down to micro-Newton ranges was developed. In the case of an aluminum foil target with 12.5 micrometer thickness, the maximum thrust level was 15 micro-Newtons when the laser power was 20 W. It was also found that the laser intensity, or laser power per unit area, irradiated on the target was significantly important on the control of the thrust even under the low-intensity level.

I. Introduction

THERE are growing interests in onboard 10-μN-class thrusters, which are compact and lightweight, for the utilization of precise attitude control of middle-scale or small/micro satellites. Although a large variety of micro-thruster concepts exist to achieve such a thrust level, a laser ablation thruster is one of the very interesting candidates because of the facts that its thrust level can be controlled by only changing the electric power of the laser. In addition, recent progress in compact high-intensity laser systems capable of the onboard thruster systems is significant.

A low-power laser ablation thruster was previously studied by Phipps[1] 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,[2-4] authors have been conducting a new approach utilizing a low-intensity continuous wave (CW) laser beam, whose output is 0.1 to 20 W, irradiated to a metallic target made of aluminum foil.[5] In order to evaluate the thrust performance of this novel laser propulsion system, the evaluation of the thrust characteristics was conducted with a newly developed torsion balance thrust stand with sub-micro-Newton sensitivity in a vacuum chamber.

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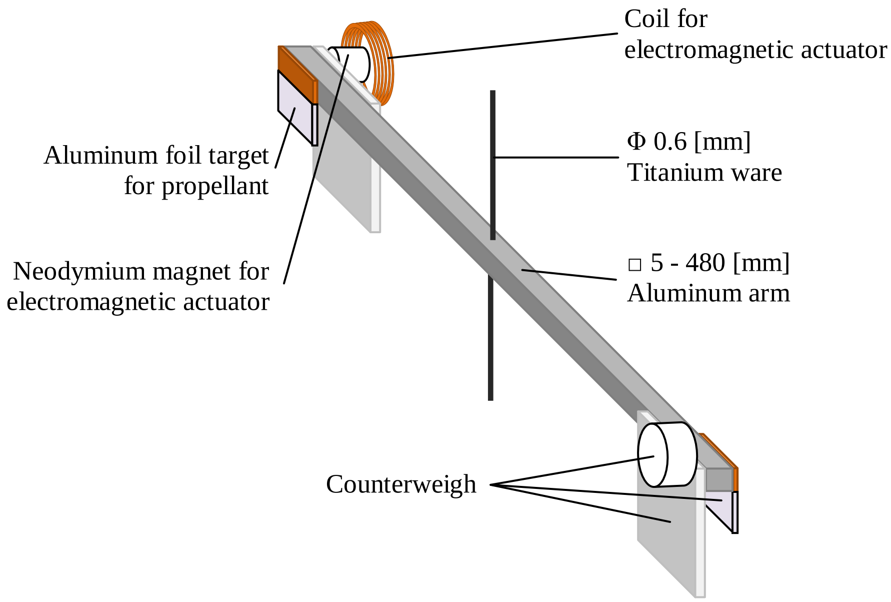
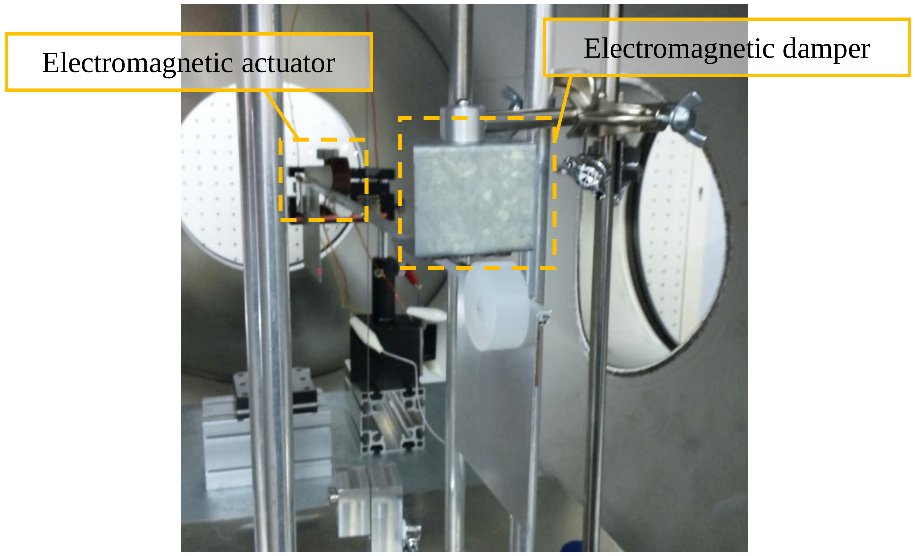
II. Experimental

A. Micro-Newton-Class Thrust Stand

Since the goal of our thruster was the minimum thrust level of below 1 μN, the new thrust stand was required to show the accuracy corresponding to the sub-micro-Newton class thrust. Figures 1 (a) and (b) show a schematic image and photo of the thrust stand developed in this study. As shown in these figures, a propellant target and a set of counter weights were fixed at each side of an aluminum arm hung by one wire.



(a) Schematic image of torsion balance thrust stand



(b) Photo of torsion balance thrust stand installed in vacuum chamber

Figure 1. Schematic and photo of torsion balance thrust stand including its damper and calibration system

To remove the mechanical noise from the outside of the vacuum chamber, a passive eddy current damper was used. As for the electromagnetic damper, samarium cobalt magnet was used. The calibration of the thrust stand was carried out by an electromagnetic actuator comprised of coil and magnet, and displacement through the electromagnetic force to occur between a magnet and a coil were measured by a laser displacement sensor.

B. Experimental Setup

A schematic of the experimental apparatus is shown in Fig.2. In thrust measurement the thrust was measured when the laser beam was continuously irradiated to a solid metallic propellant. As for the propellant, an aluminum foil target was used. 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. In addition, to elucidate effect of wavelength, a CW laser diode (JENOPTIK, JOLD-30-CPXF-1L) with wavelength of 808 nm and maximum output of 30 W was also used. The thrust measurement was carried out in a vacuum chamber. To focus the laser beam, convex lenses with focal length of 15 mm and 60 mm were used. As illustrated in the figure, the propellant was fixed to a planar holder on the thrust stand, and the displacement of the holder was measured with a laser displacement sensor. Using the result of calibration, the thrust was estimated from the displacement. A typical thickness of the aluminum foil was 12.5 μm.

To evaluate the effect of laser defocusing distance, or laser intensity, on the thrust performance, thrust measurements for various defocusing conditions were carried out, where the effect of variation of the distances between the aluminum target and focusing lens were investigated. Laser output power was also changed from 0.3 to 20 W. A typical output signal of the thrust stand displacement with the CW fiber laser irradiation is shown in Fig.3.

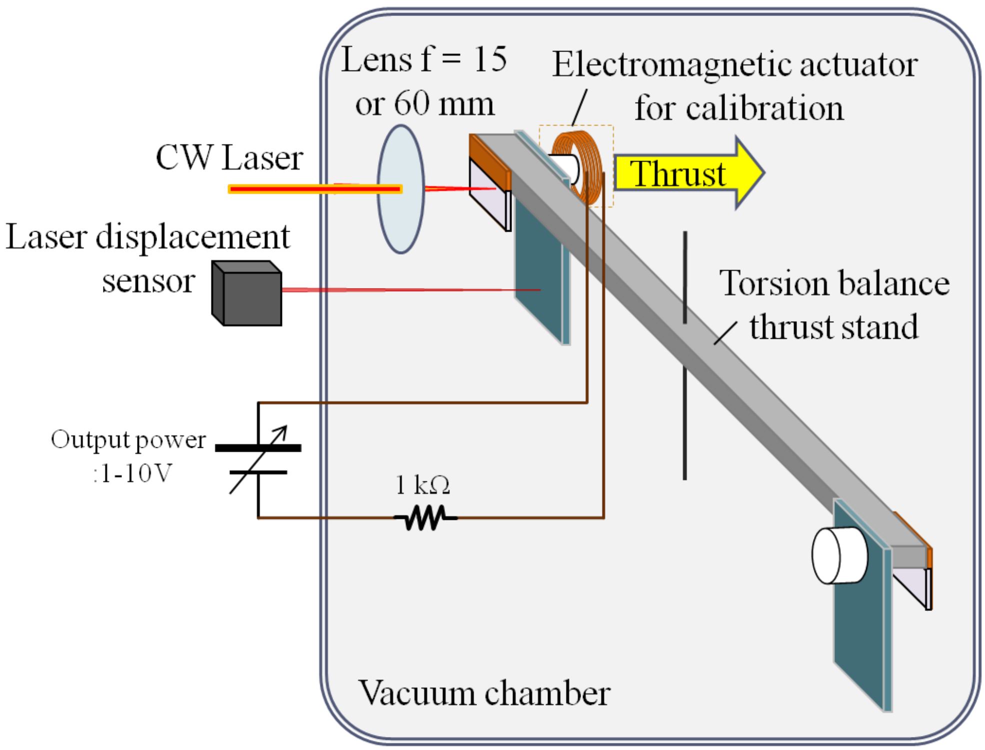


Figure 2. Experimental setup

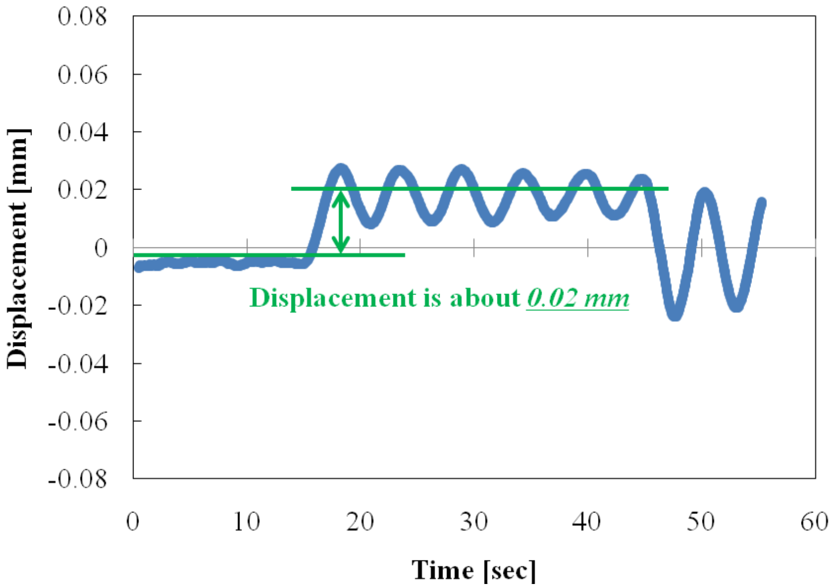


Figure 3. Typical output signal of thrust stand displacement with CW fiber laser irradiation.

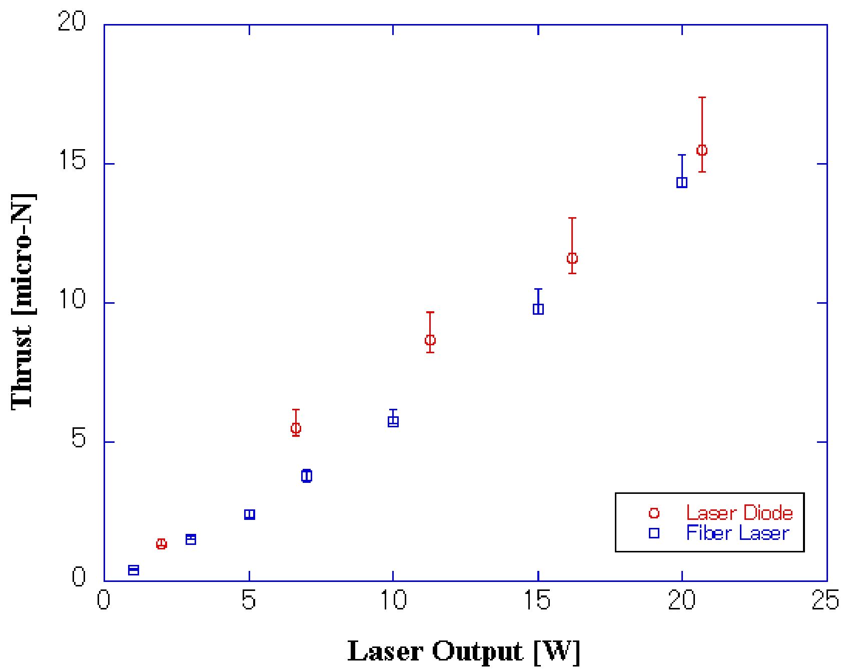


Figure 4. Dependence of thrust on laser power
(distance between lens and target: 60mm (focal point), Al foil propellant).

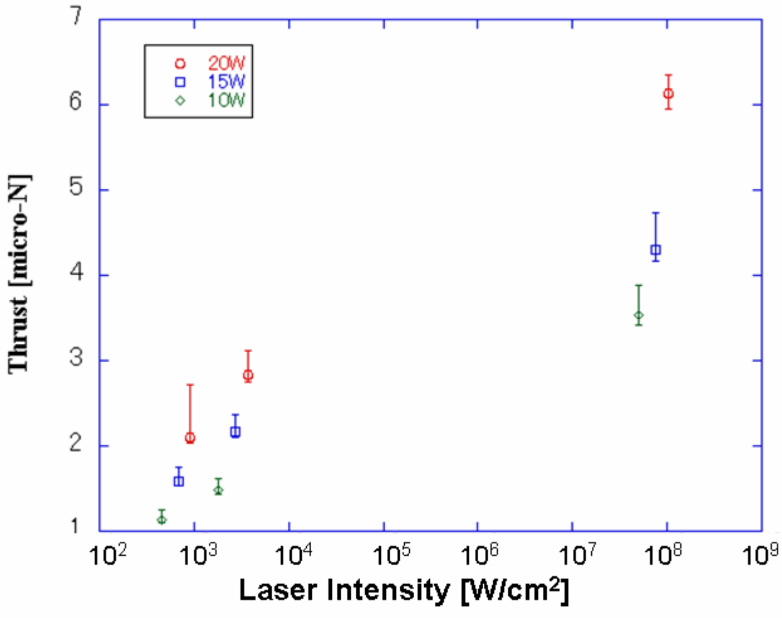


Figure 5. Influence of laser intensity on thrust for Al foil propellant target (focal length of the lens: *f* = 60 mm)

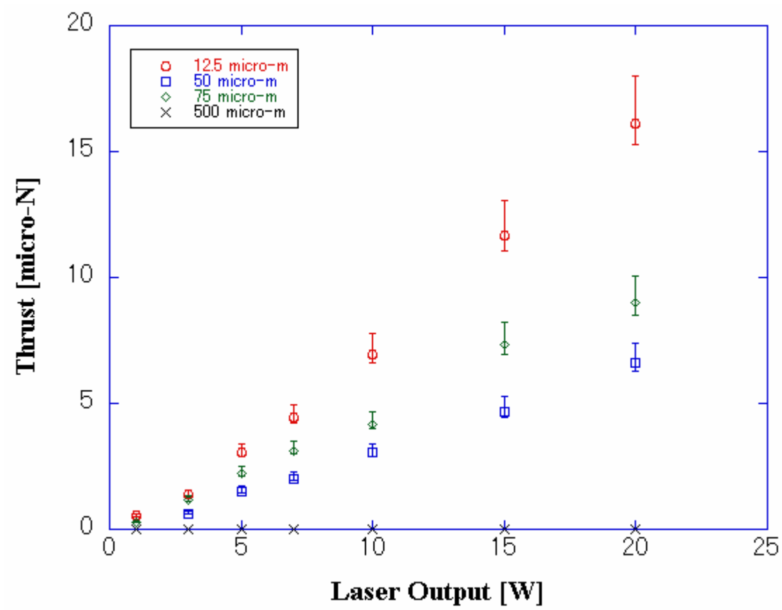


Figure 6. Relations of propellant thickness and thrust.

III. Results and Discussion

Thrust characteristics for the aluminum foil target are shown in Fig.4, in which the laser power changed from 0.3 to 20 W for both fiber laser and laser diode cases. From the figure, it was shown that with increasing the laser output power for both laser cases the thrust increased and reached the maximum thrust of about 15 μN at 20 W, or about 0.75 N/MW. As shown in this figure, the error level of the thrust was within about 20 % probably due to the mechanical fluctuation of the relative position of the propellant target to the focal point, and also due to the optical fluctuation of the laser beam. Although slightly higher thrust values were obtained with the laser diode case, difference of thrusts for both laser cases were insignificant.

Figure 5 shows the relation between thrust and laser intensity, measured by changing the defocusing length, or the distance between focal lens and target for a fixed focal length (60 mm), for various laser power conditions. Although large scatter of the data can be seen due to the difficulty to identify the spot sizes, thrust is increasing with laser intensity. Also from the result, it should be emphasized that the generation of the thrust could be confirmed even under the intensity of 10^3 W/cm^2.

Influences of propellant target thickness on thrust are shown in Fig.6.It can be seen that a target with thickness of 12.5 μm, or the thinnest target, showed the highest thrust among several thickness cases. As can be seen, with thicker targets lower thrusts were observed. Namely, there is a strong dependence of thrust on the thickness. In particular, for thick target cases, more than 500 μm for example, thrust could not be obtained.

At current stage of our study, a mass removal rate from the propellant surface is too small to measure. In addition, an irradiated spot is quite hard to identify, or even undamaged in most of the cases. Therefore, it is quite hard to identify and measure an amount of any substances ejected from the surface, which include target material (aluminum), surface contamination, surrounding gas in the vacuum chamber, etc. From this reason, the mechanism of thrust generation of this regime is still unknown. Further investigation on the mechanism and improvement of the thrust performance should be conducted in the future study.

IV. Conclusion

The micro-Newton thrust measurement was conducted for the low intensity CW laser beam ablation thruster for an aluminum foil propellant target. To evaluate the thrust characteristics, a torsion-balance thrust stand capable for the measurement of the thrust level down to micro-Newton range was developed. In the case of the aluminum foil target, the maximum thrust level was 15 μN when the laser power was 20 W, or about 0.75 N/MW. It was also found that the laser intensity, or laser power per unit area, irradiated on the target was significantly important on the control of the thrust even under the low-intensity level. The generation of the thrust could be confirmed even under the intensity of 10^3 W/cm^2. In addition, a target with thickness of 12.5 μm showed the highest thrust among several thickness cases which were more than 50 μm-thick.

Since a mass removal rate from the propellant surface is still unknown at this stage, the mechanism of thrust generation of the CW laser thruster of this type is also unknown.

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