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Technical Notes

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Wall-Propelled, In-Tube Propulsion with Repetitive-Pulse Laser Ablation

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Nomenclature

C_m = momentum coupling coefficient
E = laser pulse energy
f = laser pulse repetition frequency
L = side-body length of projectile, Fig. 1a
m = mass of projectile
N = number of laser pulses
P_0 = initial in-tube pressure
t = time originated in initiation of laser pulse irradiations
z = vertical coordinate along launch tube originated in initial projectile location
δ = wall thickness of projectile

I. Introduction

AT THE present, state-of-the-art aerospace launch technology does not have large flexibility in its thrust performance. On one hand, rockets have long (tens of minutes) yet modest (comparable to gravitational) acceleration characteristics. On the other hand, conventional ballistics have a short (less than a second) and excessively high (ten thousands of gravitational or even higher) acceleration. Hybridizing these technologies is not at all simple because their configurations are essentially different; a rocket is basically a free-flight vehicle, whereas ballistic range uses a confined in-tube space to enhance the propulsive pressure. So far, the most prominent concept of hybridizing them really examined is the ram accelerator [1–3], the idea of which was originated in the concept of "in-tube rocket" [3]. In the ram accelerator, premixed, combustible propellant gas is prefilled in a launch tube. After being accelerated to a supersonic speed of about Mach 3, a cone-nosed projectile is injected into an acceleration tube. A shock wave system is generated around the projectile, and assists the ignition of the propellant gas, thereby yielding a net thrust. The most important advantage of this device over conventional rockets is that the projectile does not need to carry propellant onboard, having much higher payload capability. From the viewpoint of ballistic range technology, the ram accelerator realizes a much longer acceleration period because, as long as the aforementioned shock system is sustained over the projectile, the highest pressure is kept immediately behind the projectile. After intensive studies of the ram accelerator, practically operational regimes using the existing materials and technologies were identified [3–5]. The most serious issues to bound the operation regime were the heat transfer and oxidation caused by the propellant gas. When the projectile increased an in-tube speed, the aerodynamic heating from the propellant gas increased almost in a cubic manner with respect to the projectile Mach number. The projectile, mostly made of aluminum or titanium alloy, lost its integrity due to the heating and the oxidation [6]. A couple of ideas to solve this problem were proposed and partially examined. An idea proposed in the review paper by Higgins [6] is to set segmented explosive layers and synchronize their ignition to the passage of the projectile. The launch tube is filled with inert gas at a much lower pressure, which is enough to ignite the explosive with the reflection of the oblique shock wave attached to the projectile. Another option is to completely evacuate the launch tube and electrically ignite the explosives. Although this idea definitely alleviates or even eliminates the aforementioned aerodynamic problems, technical hurdles to implement such an operation are considerably high, primarily from the viewpoint of safety.

Ablation, which is caused by electrical or optical discharge, is an option to propel a projectile in a ballistic range as is done in rail guns, the cylindrical electrode plasma accelerator [7], and the laser-driven, in-tube accelerator [8,9]. By using the ablation, the launch tube does not need to be prefilled with any gas, thereby realizing an aerodynamic-drag/heating-free device. Yet, in the devices so far examined, a projectile carries the propellant onboard; the aforementioned mass penalty of conventional rockets cannot be removed. In this paper, a novel ballistics range concept that is wall-propelled, in-tube propulsion, in which the propellant is supplied from launch-tube wall, has been developed, and proof-of-concept operation experiments have been conducted. The propellant is supplied using repetitive-pulse laser ablation.

II. Apparatus

Figure 1 shows schematic illustrations of the wall-ablative, laser-driven in-tube accelerator (WA-LITA) developed in this study. The launch tube has an outer brass frame and a 25-mm-side square inner cross section. A pair of opposing walls are made of polyacetal (POM) copolymer, which can act as volume ablators [10] suitable for impulse generation when using a laser of 10 μm wavelength [11–14]. The other sides are acrylic windows, on each of which a 3.0-mm-wide, 3.0-mm-deep projectile guide groove is machined. The projectile has a cross section fitted to the square launch-tube inner cross section. The clearance between the projectile and the tube wall, which was carefully adjusted to optimize the tradeoff of both lowering an effective wall friction and gas leakage through it, was made to be on the order of 200 μm. To realize a light mass, the projectile was made of high-tensile-stress aluminum alloy (A7075-T6) and had a small thickness. Two projectiles were manufactured: type A has a side-body length L of 20 mm, wall thickness δ of 1.0 mm, and mass m of 8.31 g; type B, $L = 10$ mm, $\delta = 0.5$ mm, and $m = 3.93$ g, respectively. The lower part of a projectile has

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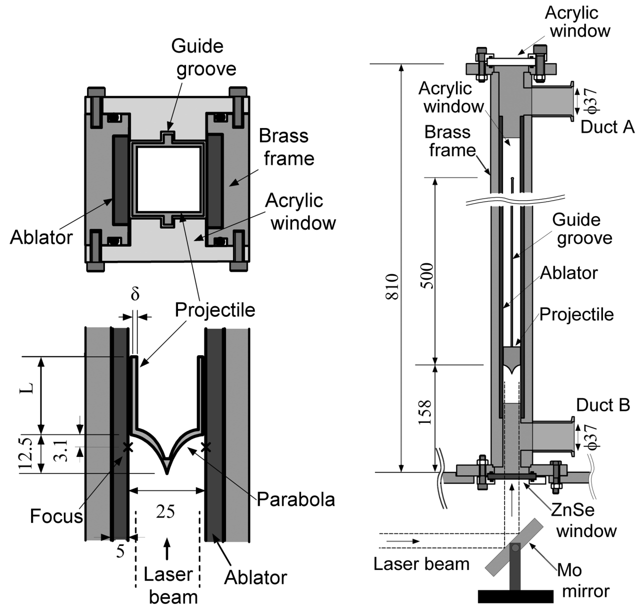

a) b)

Fig. 1 Schematic illustrations of wall-ablative, laser-driven, in-tube accelerator: a) zoomed-up cross sections over projectile, b) launch-tube system, length unit in millimeters.

two-dimensional, symmetric parabolas with the respective focuses on the same side ablator walls. A collimated laser beam is sent into the launch tube through a ZnSe window that plugs the launch-tube bottom, reflected on the projectile parabolas, and then focused onto the ablator walls (see Figs. 1a and 1b). This configuration is also mechanically favorable for momentum coupling because, in principle, the ablation jet and an induced shock wave radiating from a focus reflect against the corresponding parabola, and are then directed down along the launch-tube axis [15].

As seen in Fig. 1b, the effective length of the guide grooves equals 500 mm. The upper end of the launch tube is plugged with an acrylic window. On a side wall, two circular ducts of an inner diameter of 37 mm, duct A (above the guide grooves) and duct B (below) are connected. Duct A is connected to a vacuum chamber that has an inner volume of 0.8 m^3. Using a rotary pump, the vacuum chamber pressure is kept lower than 20 Pa. Duct B is either connected to the same vacuum chamber through a separate path or is plugged with a blind flange. The former simulates operation through an infinitely long tube in vacuum; the latter, a ballistic range operation within a finite length.

Laser pulses were irradiated from a transversely excited atmospheric (TEA) CO_2 laser (ML205E, Selective Laser Coating Removal Co., wavelength 10.6 μm), reflected from a concave (focal length 5 m) and two planar Mo mirrors. The laser energy effectively incident to the projectile, which was measured using an energy meter (Gentec EDL-500LIR), ranged from 3.7 to 6.3 J/pulse. The laser pulse was composed of a primary power peak of the full width at half-maximum, 170 ns, and a following tail for about 3 μs. The incident laser beam had an ellipticlike shape of effective axes of 19 ± 3 mm.

The launch trajectory of a projectile on z-t coordinates was captured with either a high-speed framing camera (96×600 pixels, framing rate 5000 frames/s) or eight sets of a diode laser and a photo diode combination. The effective friction force on the projectile and the tube-wall interfaces was estimated from the projectile free-fall motion through the launch tube in vacuum. Both the gravitational and friction forces were taken into account in estimating the momentum coupling coefficient C_m, in the same manner as in [8].

III. Results and Discussions

Vertical launch experiments were conducted in two modes: One was a "closed-breech" mode in which duct B was plugged. The other was "open-breech" mode in which duct B was connected to the

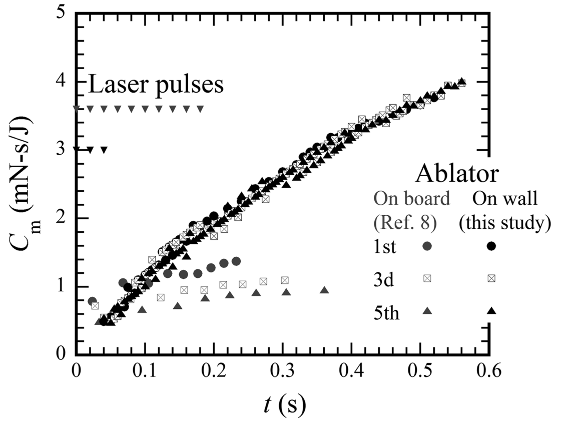

Fig. 2 C_m histories, $f = 50$ Hz, closed-breech mode; projectile A, $E = 3.77 \pm 0.05$ J/pulse, $N = 3$ (black symbols); onboard ablator, $E = 3.78 \pm 0.05$ J/pulse, $N = 10$ [8] (gray symbols).

vacuum chamber, which simulated operation through an infinitely long launch tube that was initially in vacuum. Figure 2 shows the variations of measured momentum coupling coefficient C_m obtained in the respective modes.

The time variations of C_m obtained in the closed-breech mode are shown in Fig. 2. The black symbols show variations of C_m in this study. It should be noted that, in each experiment, only three laser pulses were irradiated with a repetition frequency f of 50 Hz; the last irradiation was terminated at $t = 0.04$ s. The ablated gas was confined in the in-tube space between the projectile and the tube bottom, keeping a high pressure, contributing to a thrust even after terminating the laser pulse irradiations. C_m kept increasing in the available test periods. The gray symbols are C_m variations in [8], in which a projectile has a POM ablator rod onboard a projectile; to obtain comparable performance, 10 laser pulses were irradiated in each shot. Because the clearances between the projectile peripheral and the tube wall are 16.2 mm^2 in the present study and 51.5 mm^2 in [8], respectively, the sealing performance against the propellant gas leakage through the clearance is much improved, obtaining much higher impulse performance. In this operation condition, a C_m of 4.0 $mN \cdot s/J$ was obtained. With increasing the total number of laser pulses N, the projectile speed and C_m would be increased. However, to avoid damage to the acrylic windows, N was limited to 3 in this operation mode.

Another important aspect is the effect of ablator erosion. On one hand, in the case of the onboard ablator operation, the thrust performance was degraded with increasing the number of shots, because the ablator rod was rapidly eroded to form a crater. On the other hand, as shown in Fig. 2, the thrust performance was not degraded with accumulating the shot numbers. In the WA-LITA operation, the location z of ablation moved with the projectile motion, and was not as localized as in the former case.

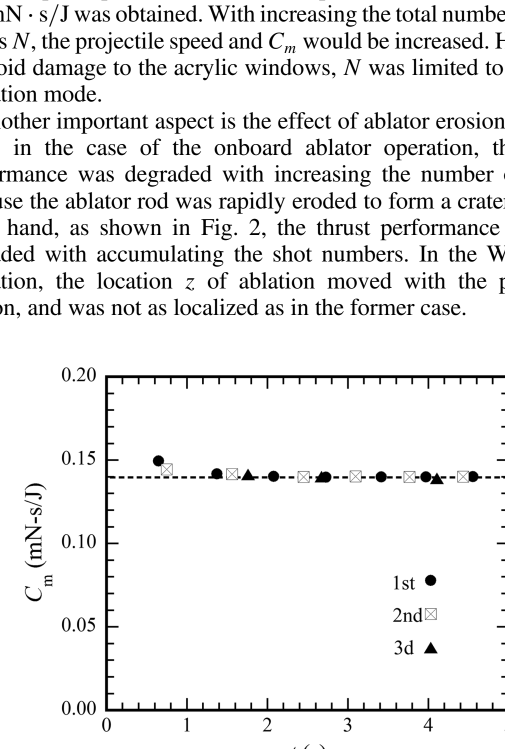

Fig. 3 C_m histories, $f = 50$ Hz, open-breech mode, three shots displayed, projectile B, $E = 5.55 \pm 0.05$ J/pulse, $N = 250$, $f = 50$ Hz.

Figure 3 shows C_m variations obtained in the open-breech mode. In this case, a propulsion impulse is obtained as a reaction momentum of the ablation gas particles reflecting against the projectile parabolas. Except for the startup period of $t < 1$ s, C_m became an almost constant of 0.14 ± 0.00 mN · s/J irrespective to the location of the projectile. Even if the launch tube was longer, this value is expected to be kept as long as the constant laser energy is irradiated onto the projectile. The ablation mass rate, which was separately measured under the same condition, was on the order of 85 ± 13 μg/J. From these representative values, the effective exhaust velocity is estimated to be 1.7 ± 0.3 km/s. This is on the same order as the laser ablation impulse against the same TEA CO_2 laser generated onto a flat surface of POM ablator [16].

IV. Conclusions

In this study, proof-of-concept demonstrations of wall-propelled, in-tube propulsion have been conducted using repetitive-pulse laser ablation. The aluminum alloy projectile was vertically launched even in the open-breech mode which simulated launch operation through an infinitely long tube, yielding a constant C_m of 0.14 mN · s/J. This value corresponds to an effective exhaust velocity of 1.7 ± 0.3 km/s, which is comparable to that obtained in the laser ablation plume from the ablator surface. As is suggested by Higgins [6], by using an explosive as a wall ablator, the thrust performance would be much improved. Because the constant-momentum coupling operations are demonstrated in the open-breech mode, this device is proved to be applicable even in space. Increasing available laser and/or chemical power will enhance the usefulness of this high-payload launch scheme.

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