Multi-use laser impulse pendulum and laser propulsion parameters measurement

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Received June 22, 2004

In order to investigate the mechanisms of both the air-breathing and the ablation modes of laser propulsion under laboratory conditions, a multi-use laser impulse pendulum (MULIP) is developed. The measurable impulse range is from 1.0×10^{-4} to 3.8×10^{-3} N·s. The experimental calibration data agree well with the theoretical calculated data. With MULIP, the ablation mode has been performed, in which a high power pulsed Nd:glass laser (λ= 1.06 μm, τ= 20 ns) and a gray PVC film sample are used. The experimental results show that the maximum momentum coupling coefficient $C_{\rm m}$ is 7.73×10^{-5} N/W, and the maximum specific impulse $I_{\rm sp}$ is 208.6 s.

OCIS codes: 140.3440, 350.5400, 120.0120, 000.2190.

It is known that the cost of launching a satellite into the low earth orbit (LEO) with the traditional chemical rocket is significant high. The conceived laser launching may reduce the cost to 1−2 orders of magnitude, which becomes very attractive. Laser propulsion (LP) has the unique features: (a) the work medium can be separated from the energy source located on the ground, and the energy obtained from work medium is not limited by the combustion heat for the chemical propellant, which result in high specific impulse; (b) the craft can be apart from the heavy energy system, so its weight is greatly reduced and the efficient load ratio is increased. Moreover, the ground-based laser launch system can be repeatedly used. Therefore, with the development of laser technology, the LP technique has become popular[1].

There are two main modes for laser launching mini-satellites: the air-breathing mode and the rocket ablation mode. The former is only applied in the atmosphere. It uses a mirror on the craft to reflect and focus the incident laser beam. The air at the focus is broken down, and high temperature and pressure plasma is generated to produce the propulsive impulse. This mode uses air as the propellant and does not consume any mass of the craft itself, however, it is not suitable in the highly rare atmosphere above the earth. The latter is an alterative way. Laser heats or ablates self-carried non-energetic propellant to generate backward ejecting plasma.

In order to quantitatively measure and analyze the efficiencies and mechanisms of these two LP modes and optimize various parameters, we have developed a set of multi-use laser impulse pendulum (MULIP), on which the rocket ablation mode experiment is performed.

The experimental setup comprises of the optical, mechanical, and measuring parts as shown in Fig. 1. For ablation mode, the beam from the laser is expanded, collimated, and focused on the target sample which is fixed on the pendulum. When power density at the laser spot exceeds the plasma ignition threshold of the sample material, the plasma is formed and produces the impulse to swing the pendulum. For the air-breathing mode, a parabolic reflector fixed on the pendulum focuses the collimated laser beam, which produces plasma explosion wave to swing the pendulum. The maximum deflection angle can be read out from the angle ruler.

The impulse pendulum contains a pendulum, an adjustable mechanical device, an append weight, a vacuum chamber, and a vacuum system etc.. The pendulum is made of light alloy. The corundum bearings and pinpoints made of tool steel are used to connect the pendulum and its suspension to greatly reduce the friction and deformation, and guarantee the pendulum rotating freely[2]. For greatly accessing to laser beam, the adjustable mechanical unit is used to move and rotate the pendulum in vertical direction and horizontal plane, respectively. To the advantage of observation, the windows of both sides of the chamber are large enough and made of highly transparent PMMA. The effectively internal volume of the chamber is 437 × 333× 160 mm^3. The vacuity can be adjusted between 1 Pa − 0.1 MPa, so the MULIP can be used to investigate the propulsion properties at different atmosphere pressures corresponding to different altitudes. In addition, the interaction between the laser and the material in vacuum can be performed.

A high speed CCD camera and a ordinary cinematograph are used to record the laser plasma and the pendulum rotation angle.

The MULIP can be used to study the relationships of propulsion characteristics with reflector shapes, laser parameters, environment pressures, and gas sorts, for the

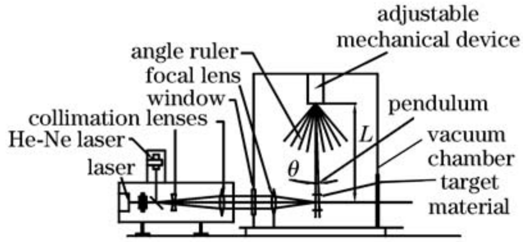

Fig. 1. Schematic of the MULIP.

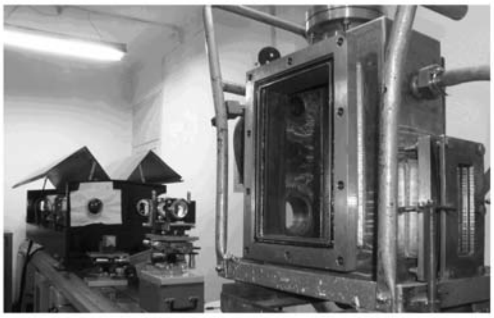

Fig. 2. Photograph of experimental setup.

air-breathing mode. For the ablation mode, the relationships of propulsion features with target materials, laser parameters, and circumstance pressures can be studied. Cooperating with the shadowgraph apparatus and spectrometer, the plasma forming and the evolution of the laser-supported plasma explosion flow field can be further studied so as to explore the laser propulsion physical mechanisms.

According to conservation of momentum and energy, we can get

$$p = \frac{2}{L}\sqrt{mgJl_{\rm c}}\sin\frac{\theta_0}{2}, \tag{1}$$

where p denotes the coupling impulse on the target, L is the arm length of p, J is the moment of inertia of the pendulum rod and target sample, θ_0 is the maximum deflection angle of the pendulum, m is the pendulum mass, and $l_{\rm c}$ is the distance from the mass center to the rotation center of the pendulum. For the current MULIP, $L = 0.2085$ m, $m = 1.198\times10^{-2}$ kg, $l_{\rm c} = 7.706\times10^{-2}$ m, $J = 1.52\times10^{-4}$ kg·m^2, and the maximum θ_0 is 40°. Substituting the above parameters into Eq. (1) yields

$$p = 1.12\times10^{-2}\sin\frac{\theta_0}{2}. \tag{2}$$

The unit of p in Eq. (2) is N·s. The momentum coupling coefficient $C_{\rm m}$ and the specific impulse $I_{\rm sp}$ are two important parameters to evaluate the efficiency and performance of propulsion, and they are defined as the coupling impulse of unit incident laser energy and the generated impulse of unit consumed propellant, respectively[3],

$$C_{\rm m} = p/E, \tag{3}$$

$$I_{\rm sp} = p/g\Delta m, \tag{4}$$

where E is the laser energy on the target sample, g is the gravity acceleration, Δm is the ablated mass of the target sample. Let $Q = E/\Delta m$ be the heat of unit consumed target material, the relationship among $C_{\rm m}$, Q, exhaust velocity V_E, and $I_{\rm sp}$ is

$$C_{\rm m}Q = V_{\rm E} = gI_{\rm sp}. \tag{5}$$

The above equations show that the faster the V_E is, the larger the $I_{\rm sp}$ is, and the smaller the Δm is when p is constant. From Eq. (1), the experimental error of coupling impulse Δp can be deduced as

$$\Delta p = \frac{\sqrt{mgJl_{\rm c}}}{L} \times\left[\cos\frac{\theta_0}{2}\Delta\theta_0 + 2\sin\frac{\theta_0}{2}\left(\frac{\Delta L}{L}+\frac{\Delta m}{2m}+\frac{\Delta J}{2J}+\frac{\Delta l_{\rm c}}{l_{\rm c}}\right)\right], \tag{6}$$

where $\Delta\theta_0 = 0.5° = 8.72\times10^{-3}$ rad, $\Delta L = 5\times10^{-4}$ m, and $\Delta m = 2.5\times10^{-4}$ kg are the reading errors, $\Delta l_{\rm c} = 1.0\times10^{-3}$ m and $\Delta J = 5\times10^{-6}$ kg·m^2 are the calculation errors

$$\Delta p = 5.62\times10^{-3} \times\left(8.72\times10^{-3}\cos\frac{\theta_0}{2} + 7.14\times10^{-2}\sin\frac{\theta_0}{2}\right). \tag{7}$$

Equations (6) and (2) give the relative error expression as

$$\frac{\Delta p}{p} = \frac{4.36\times10^{-3}}{\tan\frac{\theta_0}{2}} + 3.57\times10^{-2}. \tag{8}$$

It can be seen from Eqs. (7) and (8) that if p and θ_0 are small, the absolute error are mainly caused by the reading errors of θ_0, and the relative error is larger. As p and θ_0 increase, the relative error decreases. The calculated error data with θ_0 for the present MULIP based on the above error analysis are listed in Table 1. The measurable p ranges from 1.0×10^{-4} to 3.8×10^{-3} N·s.

In order to verify the above analysis, a calibration experiment is designed and conducted as shown in Fig. 3. A small steel ball (mass between 0.26–3.4 g) is launched horizontally with the velocity between 0.8–2.1 m/s to impact the pendulum target sample. The ball will be stuck on the sample surface by a layer of vacuum grease and swings with the pendulum together. The velocity of the

Table 1. The Calculated Error Data of the MULIP

θ_0(deg.)	p (N·s)	Δp (N·s)	$\Delta p/p$ (%)
1	1.0×10^{-4}	5.3×10^{-5}	50
10	9.8×10^{-4}	8.4×10^{-5}	8.6
20	2.0×10^{-3}	1.2×10^{-4}	6.1
30	2.9×10^{-3}	1.5×10^{-4}	5.2
40	3.8×10^{-3}	1.8×10^{-4}	4.8

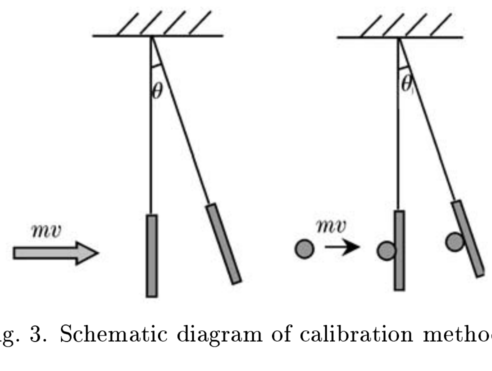

Fig. 3. Schematic diagram of calibration method.

Table 2. Experimental Parameters and Results (Material: Gray PVC with Same Size)

Experimental No.	1	2	3	4	5	6	7
Vacuity (Pa)	19	21	22	30	40	17	20
Single Pulse Energy (J)	16.63	19.25	8.38	19.75	16.88	23.5	21.25
θ_0 (deg.)	10.8	12.2	6.3	10.9	8.8	13.6	13.5
Power Densities (GW/cm^2)	1.46	1.70	1.40	3.74	3.19	2.07	1.87
p ($\times 10^{-4}$ N·s)	10.54	11.90	6.15	10.64	8.59	13.26	13.16
$C_{\rm m}$ ($\times 10^{-5}$ N/W)	6.67	6.51	7.73	5.67	5.36	5.64	6.19
Δm ($\times 10^{-7}$ kg)	8.67	5.52	11.53	10.74	15.0	17.6	19.84
Q ($\times 10^4$ J/g)	1.72	3.14	0.66	1.66	1.13	1.34	1.07
$V_{\rm E}$ (m/s)	1147.2	2044.4	510.2	941.2	572.3	754.6	662.5
$I_{\rm sp}$ (s)	117.1	208.6	52.1	96.0	58.4	77	67.7

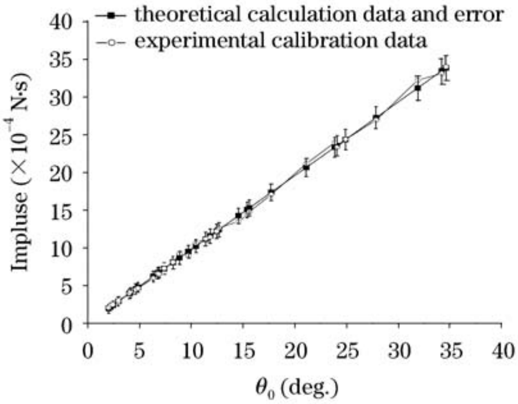

Fig. 4. Experimental calibration data compared with theoretical calculation data.

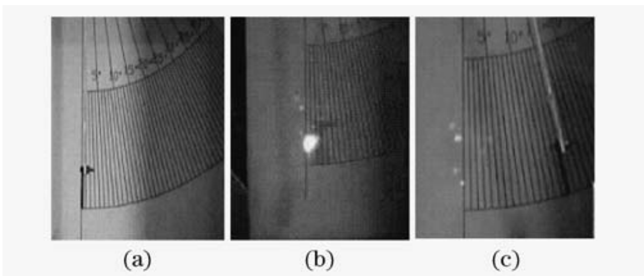

Fig. 5. Pendulum positions at three typical moments. (a) The initial angle of the PVC target; (b) the produced plasma at the moment of the ablated PVC; (c) the maximal angle of the PVC target.

ball and θ_0 can be recorded by the high speed camera. Subtracting the coupling impulse of the steel ball and grease, the calibrated data (circle symbols) between p and θ_0 are obtained when θ_0 is between $2°-34.6°$ in Fig. 4. The calibration data of p versus θ_0 are almost linear and fits well with the theoretical calculation data (square symbols) within the range of experimental error. The calibration results indicate that the bearings friction loss between the pendulum and abutment, and the air resistance can be neglected in the present experiment.

Using a Nd:glass high power pulsed laser (1.06-μm wavelength, 20-ns pulse width, single pulse energy adjustable) as the energy source and a gray PVC as target material, the rocket ablation mode experiment is conducted on the MULIP. Figure 5 shows the pendulum positions at three typical moments. The primary experimental parameters and results of 7 shots are listed in Table 2.

For the ablation mode, Phipps *et al.* summarized a great deal of experimental data to draw an empirical parameters scale law of solid target in vacuum[4],

$$C_{\rm m} = b(I\lambda\sqrt{\tau})^n, \quad (9)$$

where I is the laser power density, λ is the laser wavelength, τ is the laser pulse width, b and n are the constants related to the target materials, for C-H polymers, $b = 6.5$, $n = -0.3$. Figure 6 shows our experimental results (circle points) compared with the Phipps' C-H data (square points)[5] and the predicted model (line) in Eq. (9), in which Phipps' data are based on 1-W diode laser. It can be seen that our experimental data agree with the Phipps' data and the predicted model. In addition, Fig. 6 shows that $C_{\rm m}$ trends to decrease with the increase of the laser power density I if λ and τ keep constant.

As a summary, the MULIP for measuring the laser propulsion characteristic has been developed. The calibrated coupling impulse has linear relationship with the deflection angle and agrees with the theoretical calculation. The present pendulum apparatus can measure the coupling impulse between $1.0\times10^{-4} - 3.8\times10^{-3}$ N·s, furthermore, it can extend the upper limit by adding append weight to the pendulum. The relative error of the apparatus is about 4.8% as the coupling impulse is 3.8×10^{-3} N·s. The rocket ablation mode experiments have been

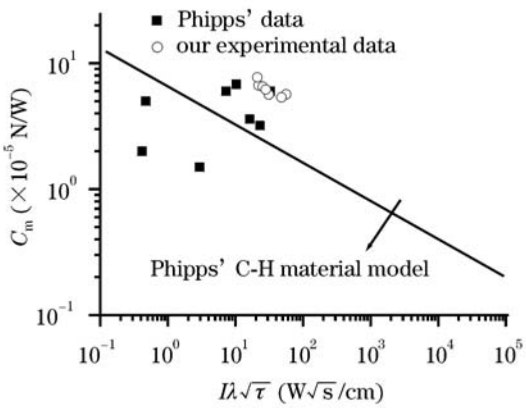

Fig. 6. Comparison between our experimental data and foreign data.

conducted to measure the propulsion parameters of materials in vacuum. The incident laser power densities (λ= 1.06 μm, τ = 20 ns) on the gray PVC sample are 1.40–3.74 GW/cm^2, the measured coupling coefficient C_m is (5.36–7.73)$\times 10^{-5}$ N/W, and the specific impulse I_{sp} is 52.1–208.6 s, which agree basically with Phipps' data and model.

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