Experimental investigation of the effects of laser parameters on laser propulsion

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The effects of main laser parameters, such as pulse energy, pulse duration, frequency, and work time on laser propulsion of "air-breathing mode", are investigated experimentally with a high power and high repetition frequency TEA-CO_2 pulsed laser. The results show that the momentum coupling coefficient C_m decreases with increasing the pulse energy for single pulse tests and pulse duration of about 1 μs. Either higher or lower frequency will reduce C_m in multi-pulse tests, which suggests an optimal frequency for the maximum C_m. As to the work time, the longer the work time is, the less the C_m will be.

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In 1972, Kantrowitz[1] proposed an idea to launch a spacecraft into the low earth orbit (LEO) with a ground-based laser, and opened a new era for laser propulsion study. In 1989, Myrabo[2] presented the concepts of "lightcraft" and "air-breathing mode" of laser propulsion. Since the air-breathing mode used air as propellant in atmosphere, it can increase the effective weight ratio of payload of a lightcraft launched into LEO greatly. In October 2000, Myrabo[2] successfully lifted a disk-like lightcraft model of 51 g vertically to 71 m high. Recently, Tang *et al.*[3] lifted a paraboloid type lightcraft of 4.6 g to a height over 1 m with TEA-CO_2 laser and the air-breathing mode. In this letter, the effects of laser parameters on laser propulsion are investigated experimentally.

Figure 1 is the schematic of the horizontal propulsion experiments. The laser used in the experiments is a high repetition frequency TEA-CO_2 laser (located at the Electronics Research Institute, Chinese Academy of Sciences). The pulse duration is about 1 μs, wavelength is 10.6 μm, and the maximum frequency is 180 Hz. Figure 2 shows the typical experimental record of laser pulse. An air-cushion slide track of 1.5-m length was used in the tests.

The parabolic reflectors (i.e. the lightcraft models) are made of aluminum alloy and manufactured with a digital controlled lathe. The measured reflection coefficient of the laser beam at the internal surface is greater than 0.9. Two types of the parabolic cones were used in the tests: type A with $f = 10$ mm, $D = 65$ mm, and $W = 16.3$ g; and type B with $f = 15$ mm, $D = 65$ mm, and $W = 8.5$ g, where f is the focus, D is the diameter of the reflector at the open side, and W is the mass. In the horizontal tests, the parabolic reflectors are fixed on an air-cushion slider, then the total mass plus the slider becomes 78.5 g for type A, 67.5 g for type B1, and 181 g for type B2. Single pulsed horizontal experiments with various pulse energy were conducted for all types. Each test was repeated for 2–3 times for checking the repeatability of the experiments. The experimental data are listed in Table 1. In the table the momentum coupling coefficient C_m is defined as the ratio of the gained impulsion of the reflector to the energy of the incident laser pulse. The experimental error was mainly due to the pulse energy of laser and the displacement readout of the high speed camera records. The total error was estimated about 7%.

The data in Table 1 show that C_m of higher pulse energy is less than that of lower pulse energy for the same

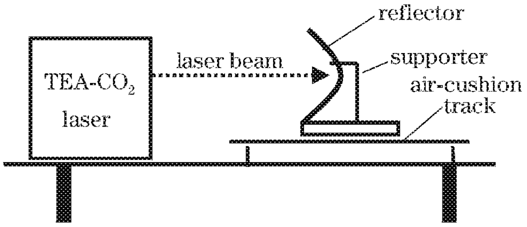

Fig. 1. Schematic of the horizontal propulsion.

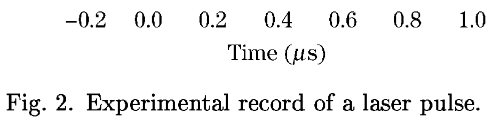

Fig. 2. Experimental record of a laser pulse.

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Table 1. Experimental Data for Single Pulse Horizontal Tests

Type	Mass (g)	Laser Pulse Energy (J)	Speed (m/s)	C_m (10^{-5} N·S/J)	
A	78.5	18	0.05952	25.96	26.09
			0.06050	26.37	
			0.05945	25.93	
		23.2	0.07440	25.18	24.39
			0.06975	23.60	
B1	67.5	18	0.0765	/	20.71
B2	181	23.2	0.0287	22.35	21.78
			0.0272	21.20	
		18	0.0203	/	22.15

type. Since the peak duration of the laser pulse (Fig. 2) is less than 200 ns, it could be considered as a point explosion. According to Sedov's theory of point explosion[4], the intensity of explosion wave is proportional to 2/5 order of the pulse energy, then C_m should decrease with the increase of the pulse energy. The present data are consistent with Sedov's prediction and the simulated results are based on the theory of point explosion[5]. However, the data of Schall *et al.*[6] show that C_m increases with the pulse energy. We noticed that in their tests the pulse duration was about 10 μs, which was much longer than ours, hence Sedov's theory may not be suitable in their case. The preliminary simulation of Gong *et al.*[5] shows the effect of the pulse duration on C_m.

The average C_m of type A with $f = 10$ mm is greater than that of type B with $f = 15$ mm at the same pulse energy. Since the diameters of two types of parabolic reflectors A and B are same at the open side, this difference is caused mainly by the focus, i.e., C_m increases with smaller focus in the present experimental range. For type B, C_m of B2 with heavier slider is greater than that of B1 with lighter slider.

It has been reported in Ref. [3] that C_m of the single pulse tests was greater than that of the multi-pulse tests. C_m of multi-pulse tests is the final momentum of the reflector divided by the total energy of all laser pulses. The multi-pulse tests were examined further in the present study at frequencies of 20, 50, and 80 Hz for type B2 with the pulse energy of 23.2 J. The experimental data are listed in Table 2 and shown in Fig. 3.

The data show that C_m of 50 Hz is the greatest in the tests and drops slowly at 20 Hz but rapidly at 80 Hz. The phenomenon may attribute to two mechanisms. One is the flow field interference between two successive laser pulses and another is the aerodynamic resistance of the reflector. For the experiments with frequency of 80 Hz, the first mechanism may dominate since the time interval is short. For the case of 20 Hz, the second one may be the main factor since the time interval is much longer. It seems that there exists an optimal frequency to get maximum C_m if other parameters are fixed. With these two mechanisms, C_m of multi-pulse test will be always less than that of single pulse test, which is consistent with the experimental observation.

Table 2 and Fig. 3 also show that C_m for tests with work time of 0.3 s is greater than that of the tests with work time of 0.6 s. It is because that the ultimate velocity of the reflector with 0.6 s is larger than that with 0.3 s, then the momentum loss for tests with 0.6 s will be greater than that with 0.3 s due to the aerodynamic resistance. It means that C_m will decrease with the

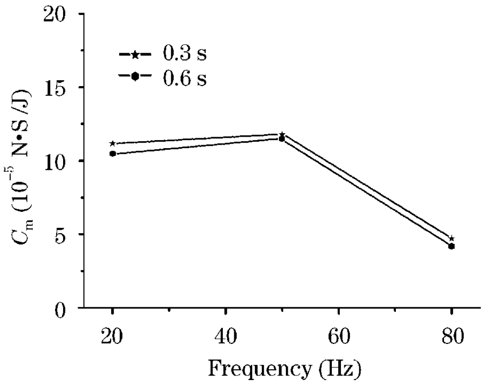

Fig. 3. C_m versus laser frequency.

Table 2. Experimental Data of Multi-Pulse Tests

Frequency (Hz)	Work Time (s)	Pulse	Speed (m/s)	C_m (10^{-5}N·S/J)	
20	0.6	14	0.1791	9.98	10.48
		14	0.1970	10.98	
	0.3	7	0.1003	11.178	11.18
		6	0.0860	11.182	
50	0.6	30	0.4669	11.77	11.49
		30	0.4310	11.21	
	0.3	16	0.2425	11.80	11.79
		20	0.3017	11.77	
80	0.6	44	0.2328	4.128	4.190
		46	0.2507	4.252	
	0.3	25	0.1592	4.968	4.720
		30	0.1719	4.471	

increase of the velocity of the lightcraft during launching process.

In summary, it has been found in this study that for a laser pulse with very short duration, the momentum coupling coefficient C_{m} decreases with the increase of the pulse energy. However, for longer pulse C_{m} may increase with the increase of the pulse energy, as shown in Ref. [6]. Hence, there must be a certain rule between the utilization of the pulse energy and the pulse profile for laser propulsion. It is also found that the pulse frequency affects C_{m} dramatically.

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