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Technical Notes

Wave Drag Reduction with Acting Spike Induced by Laser-Pulse Energy Depositions

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Introduction

DEPOSITING a reasonable amount of power ahead of a body, so-called energy deposition, is recognized as a promising scheme for drag reduction in high-speed flows. However, so far, experimental validation of the usefulness of this scheme was insufficient; the drag-reduction performance was estimated by measuring pressure modulation induced by a single-pulse energy deposition, or steady-state drag reduction was obtained only by supplying an excessive amount of power that was higher than the saved propulsion power. This Note experimentally demonstrates that by repetitively depositing laser-pulse energies up to 80 kHz a quasi-steady-state acting spike is built up in the bow shock layer, and up to 21 % drag reduction with an efficiency of energy deposition of 5 (500 %) is obtained. Even with strong pulse-to-pulse, fluid-dynamic interactions, the drag decreases almost linearly with laser-pulse repetition frequency.

The efficiency of energy deposition [1,2], η, is defined as the ratio of a saved propulsion power to a deposited laser power by

$$\eta = \frac{U_\infty(-\Delta D)}{fE} \tag{1}$$

where E, f, U_∞, and ΔD designate a laser-pulse energy, pulse repetition frequency, upstream flow speed, and increment or decrement in drag due to energy deposition (negative for drag reduction), respectively. For useful energy deposition, two conditions, $\eta > 1$ and $0 < -\Delta D/D_0 (<1)$, in which D_0 designates the baseline drag without energy deposition, must be satisfied.

Most of the experimental work on the energy deposition have investigated flow modifications and associated drag-reduction impulse performance caused by a single laser energy deposition [3–5]. From single-pulse experiments, drag reduction as a linear function of f can be predictable only in a low-pulse-repetition-frequency regime in which pulse-to-pulse interaction is negligible.

Tret'yakov et al. [6] generated a train of CO_2/laser-pulse-heated gases ahead of a conical nose in supersonic argon flow with a Mach number of 2.0; $-\Delta D/D_0 = 0.45$ was obtained with $f = 100$ kHz, yet with $\eta < 1$. Sasoh et al. [7] obtained $-\Delta D/D_0 = 0.03$ over a flat-head circular cylinder with $\eta = 4.5$ at $f = 10$ kHz. Drag-reduction performance was modest for the low f level and unfavorable optical interference. The latter occurred because the laser pulses were sent through a lens on the cylinder head. With increasing f the laser beam transmission performance past the disturbed shock layer was degraded, and then η decreased. In this Note, these problems are solved by introducing a laser device of a much higher f of up to 80 kHz and side-through optics for better laser beam transmission.

Apparatus

Figure 1 shows the schematic diagram of experimental setup. Except for the laser device and its optical path, the setup is identical to that of [7]: the model is a 20-mm-diam flat-head cylinder in Mach 1.94 airflow in the 80 mm × 80 mm in-draft wind tunnel. A time-averaged drag force is measured by the force-balance system using a load cell. Its drag resolution is 15 mN and response time is better than 90 ms. Framing Schlieren visualization is done using a high-speed framing camera (HPV-1, Shimadzu Company, 312 × 260 pixels, 10^6 frame/s maximum, 100 frames) with exposure time of 1 μs. A xenon flash lamp (SA-200F, Nissin Electronic Company, duration of 2 ms) is used as the light source. Laser pulses are irradiated through the BK-7 side window (90 mm in diameter, 15 mm in thickness, and better-than-99% transmittance) so that they do not suffer optical interference with the shock layer. In addition to the Nd:YLF laser (wavelength of 1047 nm, pulse duration of 10 ns, repetition frequency of 10 kHz maximum, and average power of 85 W maximum), an Nd: YVO_4 laser (wavelength of 1064 nm and pulse duration of 10 ns) with an even higher repetition frequency ($f = 100$ kHz at a maximum) and power ($fE = 400$ W at a maximum) yet with a smaller pulse energy (maximum $E = 8$ mJ at $f = 50$ kHz) is used for $f \geq 10$ kHz. The output laser beam has a square cross section of 5 mm × 5 mm with the Nd:YLF laser and of 6 mm × 6 mm with the Nd: YVO_4, respectively. The beam is reflected against three 45 deg mirrors, then focused with a convex lens with a focal length of 60 mm set right before the BK-7 side window. The focal spot is on the center axis at a separation distance of 40 mm ahead of the model. The time-averaged laser power is measured using a power meter (1000W-SH-V2 ROHS, Ophir). Hereafter, the value of E will equal a laser-pulse energy effectively sent on to the focal spot.

Results and Discussion

Without energy deposition, Fig. 2a, a bow shock wave is formed ahead of the flat head of the cylinder with a shock standoff distance of $0.45d$ (where d is the diameter of the cylinder). According to [8], laser-pulse energy depositions induce significant pressure fluctuations. In particular, with laser-pulse energy depositions of $f >$ 10 kHz pulse-to-pulse interactions become significant. As seen in Fig. 2b, an "acting spike" composed of several baroclinically generated vortices is formed; the shock standoff distance is increased up to $0.62d$. This quasi-steady-state flow structure is confirmed also from the history of a stagnation pressure, p_{st}, in Fig. 3; with $f =$ 50 kHz the stagnation pressure is decreased in a quasi-steady-state manner.

Figure 4 shows histories of measured drag D normalized by the baseline value $D_0 = 21.5\ \mathrm{N} \pm 0.045\ \mathrm{N}$ (root mean square, rms = 0.2%), which is obtained without laser-pulse irradiation. In each run, laser pulses are irradiated during 1 s. For $f = 1$ kHz to 10 kHz, the Nd:YLF laser is used with $E = 6.6$ mJ ± 0.2 mJ; for higher f the Nd: YVO_4 laser with $E = 6.2$ mJ (±0.19 mJ). Before and after the laser-pulse irradiations, D exhibits a steady-state value

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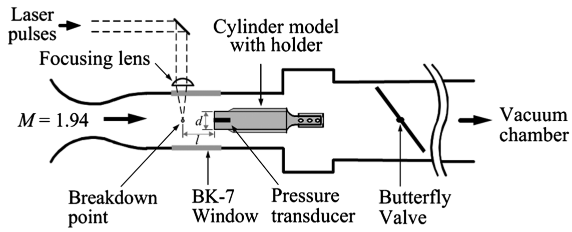
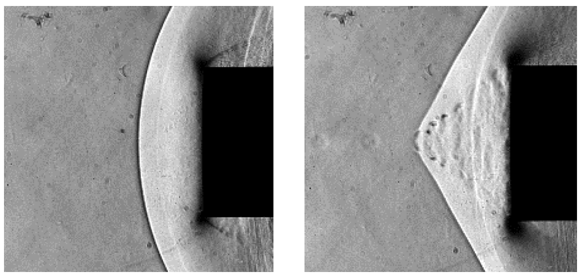


Fig. 1 Schematic diagram of experimental setup, top view.



a) Without laser pulse **b) *f*=80kHz, *E*=5.0mJ/pulse, Nd:YVO$_4$ laser**

Fig. 2 Schlieren images.

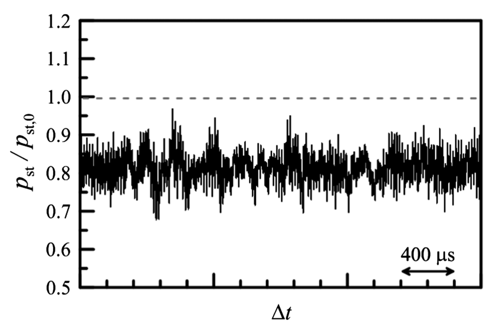


Fig. 3 Stagnation pressure histories, $E = 5.0$ mJ, $f = 50$ kHz, Nd: YVO$_4$ laser, $p_{st,0}$; stagnation pressure without energy deposition.

with fluctuation of a rms of 0.24 %. During the laser-pulse irradiations, $0 < t < 1$ s, D is decreased by $-\Delta D$. The higher f, the larger $(-\Delta D)$ becomes. Figure 5 shows drag-reduction characteristics with respect to varying f with constant values of E. With each value of E from a specific laser device, $-\Delta D/D_0$, almost linearly increases with f even in the regime of strong interactions, $f > 10$ kHz. From Eq. (1) for constant E and η, $-\Delta D$ scales with f. Therefore, this linearity is equivalent to that η depends only on E. As seen in Fig. 6, η depends primarily on the value of E irrespective to a laser power fE. With the Nd:YLF laser, η has a maximum value of around 10 at about $E = 8.0$ mJ. Decreasing E from this optimum value results in a sharp decrease in η, with drag reduction finally vanishing at a threshold value of about 4.0 mJ for optical breakdown. Irradiating an excessive amount of energy over the optimum value also leads to inefficient energy deposition [2]. With the Nd: YVO$_4$ laser, $\eta = 5.4 \pm 0.6$ and 7.2 ± 0.5 with $E = 5.0 \pm 0.2$ mJ and 6.2 ± 0.2 mJ, respectively; due to device performance limitation, E is too low to maximize η. As long as the pressure modulation is done independently pulse to pulse, drag reduction should be in proportion with f. However, as reported in [8] and shown in Figs. 2b and 3, with f higher than 30 kHz pulse-to-pulse interaction becomes so significant that a quasi-steady-state flow structure (that is, an acting spike) is established [9]. Nevertheless, such a linear relation is experimentally obtained.

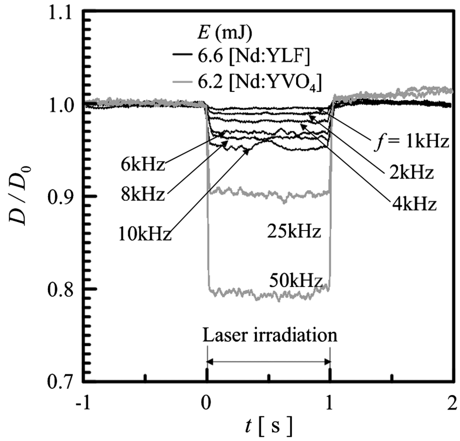


Fig. 4 Drag histories with $E = 6.2$–6.6 mJ, time, *t*, is originated in the initiation of laser-pulse irradiations.

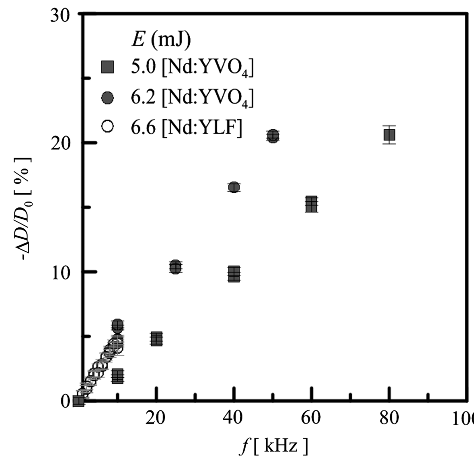


Fig. 5 Drag-reduction characteristics with constant pulse energies.

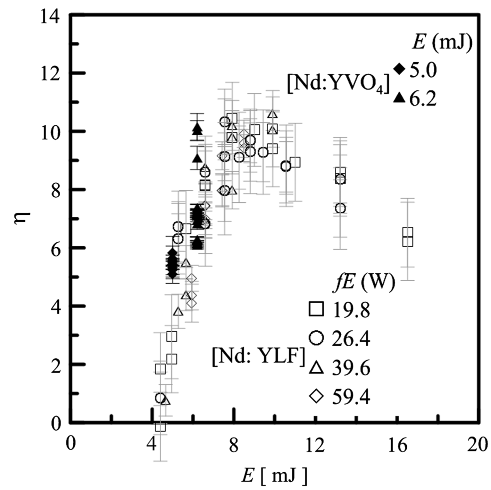


Fig. 6 η vs *E*, the error bars in η are evaluated from rms in *D*. Data of Nd: YVO$_4$ laser with two laser-pulse energies, *E*; data of Nd:YLF laser with four time-averaged laser powers, *fE*.

Conclusions

In conclusion, in this Note, efficient wave drag reduction by highly repetitive laser energy depositions is experimentally demonstrated. Even with the strong pulse-to-pulse interactions, drag reduction scales with a laser-pulse repetition frequency. This result is promising for applying this scheme to a more sophisticated model shape such as a truncated cone. Definitely, drag-reduction performance with even higher repetition frequencies warrants further investigations.

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