Hypersonic wave drag reduction performance of cylinders with repetitive laser energy depositions

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Abstract. It has been widely research that wave drag reduction on hypersonic vehicle by laser energy depositions. Using laser energy to reduce wave drag can improve vehicle performance. A second order accurate scheme based on finite-difference method and domain decomposition of structural grid is used to compute the drag performance of cylinders in a hypersonic flow of Mach number 2 at altitude of 15km with repetitive energy depositions. The effects of frequency on drag reduction are studied. The calculated results show: the recirculation zone is generated due to the interaction between bow shock over the cylinder and blast wave produced by energy deposition, and a virtual spike which is supported by an axis-symmetric recirculation, is formed in front of the cylinder. By increasing the repetitive frequency, the drag is reduced and the oscillation of the drag is decreased; however, the energy efficiency decreases by increasing the frequency.

1. Introduction
In recent years, due to the rapid development of hypersonic vehicles [1-3], drag reduction of demand on more and more strongly, which attracted researchers attention. Drag reduction using laser energy deposition is a new way of drag reduction. America, Russia, Japan and other countries have carried out research on laser energy deposition drag reduction using numerical simulation and experiment methods [4-6]. Riggins team studied the influence of laser parameters on drag reduction by numerical simulation on the condition of continuous wave laser [7-8], Knight team simulated the interaction between the low density region produced by single pulse laser and bow shock over the blunt body [9-10], Sasoh team further studied the effect of laser energy deposition on different shapes of blunt body [11-12]. Literature results show that laser energy deposition is a very effective way to reduce hypersonic wave drag and pulsed laser is usually choose as energy source. So the choice of frequency is an important component of the research. Based on previous work, this paper studies the interaction between high-repetitive laser energy deposition and bow shock over the cylinder, and the effect of frequency on drag reduction. The condition of stable drag reduction is proposed under the conditions of this research.

2 Numerical method
Two-dimensional axisymmetric inviscid flow over a cylinders is assumed to be a idea gas with the constant specific heat ratio of 1.4. Mass, momentum and energy conservation equations are discretized using a finite-difference method. The MUSCL approach is employed with a min-mod limiter, and computed flow properties are second-order accurate in space. The discretized equations are
numerically integrated in time by using a second-order Runge-Kutta method. From reference [13] we know that this CFD method can describe the process of laser plasma reducing wave drag.

Two-dimensional planar graph of the blunt body used in the present study is in figure 1. The diameter of cylinder \(D\) is 2cm, the distance \(L\) between the stationary point of the body and energy deposition position is equal 2\(D\), that is \(L=4\)cm. For all cases in the present study, the Mach number is set to 2, and the static pressure and temperature of the freestream flow are set to \(1.2 \times 10^4\)Pa and 216.65K respectively. The computational zone is divided into two zones-zone 1 and zone 2 which can be seen in figure 1. The grids of the two zones are 200\(\times\)200 and 100\(\times\)70 respectively. A heating source term for a periodic laser energy deposition is added to energy equation, the energy is deposited during the period of the order of the laser pulse duration at constant volume and that the deposited energy is injected instantaneously. The energy of single laser is 3mJ.

![Figure 1. Two-dimensional planar graph of blunt body.](image)

3 Results and discussion

Hypersonic wave drag reduction performances of cylinder at frequency \(f\)=10kHz, 20kHz, 50kHz, 100kHz and 200kHz are studied in this paper.

3.1 Unsteady flowfield at \(f=10\)kHz

Figure 2 shows the density contours and instantaneous streamlines between \(t=410\)µs and \(t=549\)µs. The blast wave and low density region produced by laser energy deposition are appear in figure 2(a1). From the streamline shown in figure 2(a2), one can see vortices near the frontal surface of the body. This implies the low density region created by the previous energy deposition still stays near the corner of the cylinder surface.

We can see from the density contour in figure 2(b1) at \(t=449\)µs that the blast wave reaches at the frontal surface of the cylinder. This feature makes the drag increase. The low density region starts to interact with the bow shock at \(t=464\)µs and the bow shock is deformed one can see in figure 1(c1). This distortion is called lens effect [14].

The streamline at \(t=449\)µs shown in figure 2(b2) indicates that the vortices began to break down. By judging with the density contour in figure 2(b1), one can find that the vortex flow structure cannot keep in the frontal region over the body until the low density region produced at the next deposition reaches near the bow shock under this repetitive frequency condition. As shown in figure 2(c2), new vortices are produced in the region where the low density region interaction with the bow shock. The deformed low density region moves downstream as shown in figure 2(d2) and (e2). In figure 2(f1), the density contour at \(t=549\)µs is returns to the contour at \(t=449\)µs. One can know that at \(f=10\)kHz, the interaction between low density region and bow shock is independence in different laser depositions.
Figure 2. The density contour and streamlines at $f=10\text{kHz}$. 

L: Low density region; B: blast shock.
3.2 **Quasi-steady state flowfield at different frequencies**

The calculated quasi-steady flowfields at different frequencies are presented in figure 3. The flowfields are different between the lower repetitive frequency at \( f = 10\text{kHz} \) and 20kHz, and the higher frequencies at \( f = 50\text{kHz} \), 100kHz and 200kHz. In figure 3(c), one can see an oblique shock wave in the frontal region of the cylinder. The oblique shock wave is formed through the interaction of the low density region with the bow shock. In contrast to the lower repetitive frequency, the oblique shock wave is strongly due to the multiple density regions incoming into the forebody region of the body. A large vortex flow region is produced due to the successive interaction of the low density regions with the bow shock. The flowfield shows a recirculation zone, as shown in the streamlines in figure 3(c) to 3(e), the recirculation zone is maintained in the frontal region of the body, the recirculation zone serves as virtual conical geometry in the flowfield, blocking the hypersonic flow incoming to the body [12]. Because the low density region flows through the recirculation zone in the forebody region, the pressure on the surface is kept lower as compared with the case at \( f = 10\text{kHz} \) and 20kHz. From the comparison of the density contours between \( f = 100\text{kHz} \) and 200kHz, as shown in figure 3(d) and 3(e), the angle of the oblique shock wave for \( f = 200\text{kHz} \) is shallower that that for \( f = 100\text{kHz} \). This trend is due to the fact that the size of the recirculation zone is larger for \( f = 200\text{kHz} \) as compared with the one for \( f = 100\text{kHz} \). As a result, the forebody region over cylinder is maintained at a lower pressure level, and the collision of the blast wave contributes to the increase of the drag only slightly.
Figure 3. Quasi-steady state flowfield at different frequencies.

3.3 The influence of frequency on drag reduction

The wave drag curves at different repetitive frequencies of $f=10\text{kHz}$, $20\text{kHz}$, $50\text{kHz}$, $100\text{kHz}$ and $200\text{kHz}$ are given in figure 4. In each of the cases, the drag asymptotically approaches to a quasisteady
state, showing periodical fluctuations. The averaged drag value is 13.4N, 13.2N, 9.4N, 6.1N and 2.5N, for the case of $f=10$kHz, 20kHz, 50kHz, 100kHz and 200kHz, respectively. The normalize drag which the ratio of averaged drag value to the one without energy deposition is about 91.7%, 90.9%, 64.8%, 42% and 17%. The oscillation becomes weaker with the repetitive frequencies increasing. Figure 5 shows the trend of the power efficiency $S$ with frequencies $f$. One can see that $S$ first increase and then decrease, the peak of $S$ appear at $f=50$kHz and $S$ is about 20. At $f=200$kHz, $S$ is the minimum, but $S>>1$.

![Figure 4. Drag curves at different frequencies.](image)

![Figure 5. power efficiency vs. frequency.](image)

4 Conclusions

In this paper, the influence of repetitive frequency on drag reduction is studied by numerical simulation. The numerical simulation results show that recirculation zone over blunt body is formed due to laser energy deposition, and the formation of recirculation zone reduces the wave drag of hypersonic vehicle. Frequency is an important parameter of influencing drag reduction, the higher frequency, the more drag reduction. When the frequency increases to 200kHz, the drag is least and only about 2.5N. However, power efficiency is not the best at $f=200$kHz, the maximum power efficiency is obtained at $f=50$kHz. Therefore, we should choose appropriate frequency according to the need of task. By increasing the repetitive frequency, the oscillation of the drag is decreased; At $f=100$kHz, the drag is steady.

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