# 반복 레이저 펄스를 이용한 초음속 비행체의 항력저감

김재형* · Akihiro Sasoh** · 김희동***

# Wave Drag Reduction due to Repetitive Laser Pulses

Jae-Hyung Kim* · Akihiro Sasoh** · Heuy-Dong Kim***

## ABSTRACT

Wave drag reduction due to the repetitive laser induced energy deposition over a flat-nosed cylinder is experimentally conducted in this study. Irradiated laser pulses are focused by a convex lens installed in side of the in-draft wind tunnel of Mach 1.94. The maximum frequency of the energy deposition is limited up to 80. Time-averaged drag force is measured using a low friction piston which was backed by a load cell in a cavity as a controlled pressure. Stagnation pressure history, which is measured at the nose of the model, is synchronized with corresponding sequential schlieren images. With cylinder model, amount of drag reduction is linearly increased with input laser power. The power gain only depends upon the pulse energy. A drag reduction about 21% which corresponds to power gain of energy deposition of approximately 10 was obtained.

## 초 록

본 연구에서는 초음속 비행체의 조파저항을 감소시키기 위하여, 최대 주파수 80 kHz의 반복 레이저 펄스에 의해 야기된 에너지 부가법에 관한 실험적 연구가 수행된다. 기류 마하수 1.94의 흡입식 초음속 풍동의 바깥에 설치된 초점렌즈에 의하여 레이저 펄스가 실린더 모델 전단부에 집약된다. 시간변동 항력과 정체압력은 로드셀과 PCB 압력센서에 의해서 측정되며, 동시에 고속 카메라를 이용하여 가시화가 수행된다. 본 연구의 결과로부터, 레이저 펄스 에너지 부가에 의한 항력 저감량은 레이저 펄스 주파수가 증가할 때, 최대 21%까지 거의 선형적으로 증가하였다. 부가 에너지 효율은 레이저 펄스 에너지에만 의존하는 결과를 얻었으며, 최대 1000%까지 달성되었다.

Key Words: Wave Drag Force(조파 저항), Energy Deposition(에너지 부가), Shock Wave(충격파), Supersonic Flow(초음속 유동), Compressible Flow(압축성 유동)

## 1. Introduction

Repetitive-laser pulse energy depositions are contributed to reduce the wave drag of supersonic flight in this study. The intensive

* 일본 나고야대학 항공우주공학 전공
** 일본 나고야대학 공학연구과
*** 안동 대학교 기계공학부
† 교신저자, E-mail: xflying@daum.net

laser-heated gas generated by laser beam focusing is useful to control the supersonic flow field.When the laser energy is deposited into the air, blast waves and spherical laser heated gas interacts with bow shock wave in front of supersonic flight. Thereafter, laser-heated gas is transmitted to shock wave, and vortex is generated by baroclinic effects.

Tret'yakov et al.[1] conducted steady-state drag measurement in Mach-2 argon flow by irradiating CO2laser pulses at a repetition frequency of up to 100 kHz. A significant drag reduction of up to 45 % of the baseline drag was obtained. However, operation data with the efficiency of energy deposition being larger than unity was not presented.

Sasoh et al.[2] successfully measured the time-averaged drag reduction modulated with repetitive laser pulse energy depositions up to 10kHz. They used a load cell controlled by back pressure to estimate the drag reduction performance, and obtained drag reduction of 3% with energy deposition efficiency of 10. However, since laser pulses were irradiated from head of model, refraction problem of laser beam was occurred. Therefore, the disturbed shock layer degrades the effective laser power transmission performance at a high repetition frequency of around 10 kHz.

The main objective of this study is experimentally to investigate the drag reduction characteristics due to the energy deposition with high-repetitive laser pulses up to 80 kHz. Amount of drag reduction is verified by force balance system and associated the power gain of energy deposition is estimated. In high repetitive laser energy depositions, virtual spike which is featured as low density regime caused by baroclinic effects is presented remarkably.

## 2. Experimental Methods

Figure 1 shows a schematic diagram of experimental system with laser beam path. In-draft wind tunnel of Mach number=1.94 is connected to vacuum chamber of inner volume = 11.5m$^3$ . In supersonic wind tunnel, size of test section is 80mm×80mm square cross section. Further details on our experimental apparatus including the laser optics, drag measurement and visualization system refer to reference [3].

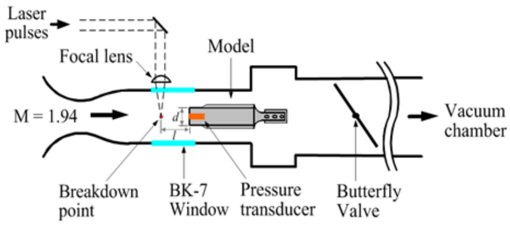



Fig. 1 Experimental apparatus and laser path

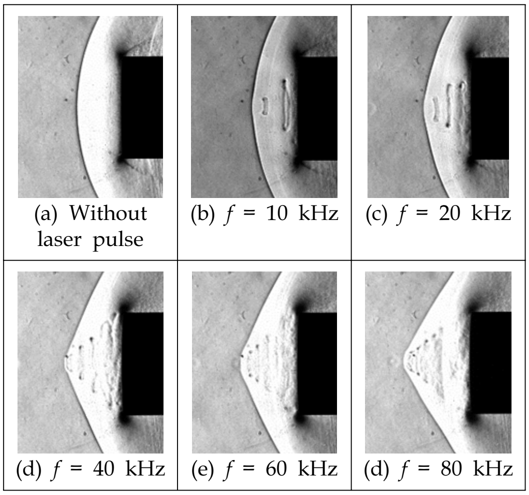


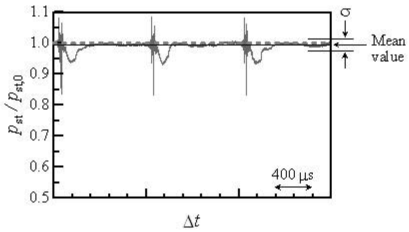

Fig. 2 Instantaneous schlieren image induced by high-repetitive laser pulses, $E$=5.0mJ/pulse

## 3. Results and Discussion

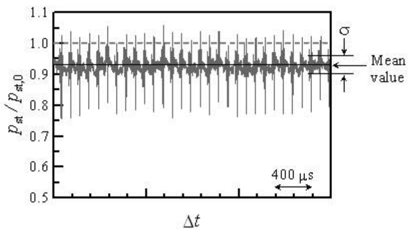
Schlieren images for a cylinder model

corresponding to repetitive laser frequency are shown in Fig. 2. In the steady-state supersonic flow without energy depositions, a standing bow shock wave is formed over the cylindrical model with a stand-off distance of about 0.45 *d*, see Fig. 2(a). Apex angle of distorted shock shape due to the interaction with laser-heated gases becomes smaller with frequency increasing. In Fig. 2(b), a couple of vortex ring can be found between bow shock wave and blunt body model, and vortex ring moves downstream axisymmetrically. When laser pulses of $f$=20kHz is irradiated, three vortex rings appear obviously in front of model. In this case, curvature of shock layer is smaller than that of $f$=10kHz. Over $f$=40kHz, clear vortex ring due to the effect of baroclinic could not be observed because vortex rings are broken rapidly, since vortices leads to the flow instability in front of the model. However, the bow shock layer which is composed of several vortices has cone shape like a virtual spike, and its effective apex angle decreases with increasing frequency.

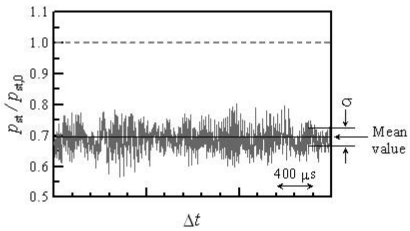
The histories of $p_{st}/p_{st,0}$ with various values of $f$ are shown in Fig. 3. With $f$=1kHz, the pressure modulation is repeated in an almost independent manner; the pressure ratio restores to unity after each laser pulse irradiation. However, with higher $f$, the baseline value does not go back to unity. With $f$=10kHz, pressure fluctuations caused by laser pulses interaction is significantly affects to pressure history. In this case, vortex ring generated by another pulse influence the pressure field in front of the model before former vortex ring induced pressure disturbance is not perfectly recovered. These pressure characteristics make new steady flow field after laser irradiation and time-averaged stagnation pressure is decreased by around $p_{st}/p_{st,0}$=0.93 with standard deviation, σ, of about 5%. Time-averaged stagnation pressure is more significantly decreased as repetitive frequency becomes higher. It can be observed that the stagnation pressure ratio has 0.7 for $f$=50kHz. With high-repetitive laser pulse, next vortex is arrived to the distorted shock before shock shape is restored to the original form. Therefore, apex angle of shock layer becomes smaller with time, and transition of shock layer is maintained during short time.




(a) $f$=1kHz




(b) $f$=10kHz




(c) $f$=50kHz

Fig. 3 Stagnation pressure histories, $E$=6.2–6.6mJ/pulse

In this experiment, laser pulses are irradiated during one second. For $f$ = 1kHz to 10kHz, the Nd:YLF laser is used with $E$ = 6.6mJ for higher $f$ the Nd:$YVO_4$ laser with $E$ = 6.2mJ. Figure 4 presents the drag reduction characteristics with varying $f$. With a constant value of $E$, $\Delta D/D_0$ almost linearly increases with $f$. The coefficient in the linearity is slightly larger with the Nd:$YVO_4$ laser presumably due to better beam quality. If same laser energy per pulse is irradiated into the flow field, laser induced laser-heated gas of same size and strength has influence on the drag reduction. Consequently, it is indicated that increase of repetitive frequency might affect linearly to drag reduction, and amount of drag reduction can be predicted if pulse energy is known. With the cylinder model, drag reduction is realized by about 21% at $f$=50kHz and $E$=6.2mJ.

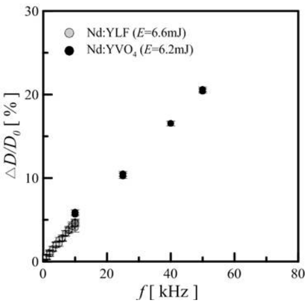


Fig. 4 Drag reduction performance vs laser frequency

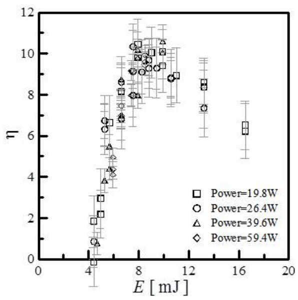


Fig. 5 Power gain vs energy per pulse

The power gain of energy deposition, $\eta$, is defined as the ratio of a saved propulsion power to a deposited laser power by,

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

From Eq. (1) for constant $E$ and $\eta$, $\Delta D$ scales with $f$. Therefore, this linearity is equivalent to that $\eta$ depends only on E. As seen in Fig. 5, $\eta$ depends primarily on the value of $E$ irrespective to a laser power $fE$. With the Nd:YLF laser, $\eta$ has a maximum value of around 10 at about $E$ = 8.0 mJ. Decreasing $E$ from this 'optimum' value results in sharp decrease in h to vanish at 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 .

## 3. Conclusions

Experimental study had been performed to investigate the drag reduction performance due to laser induced energy deposition. It is remarkably concluded that pulse-to-pulse interaction in stagnation pressure history becomes significant with increasing the laser pulse repetition frequency, yet the drag reduction ($\Delta D/D_0$) scales almost linearly with $f$. Time-averaged drag force decreased up to 21 % and the power gain is a function of only laser pulse energy. In our laser optic system, the power gain had a peak value(1000%) at $E$=8.0mJ.

## 참 고 문 헌


1. Tret'yakov, P. K., et al. Physics-Doklady, Vol.41, Issue11, pp.566-567, 1996.
2. Sasoh, A., et al. AIAA Journal, Vol. 48, No. 12, pp. 2811-2817, 2010.
3. Kim, J-H., et al. 40th AIAA Fluids Dynamic s Conf. and Exhibit, AIAA 2010-5104, 2010.