Experimental Investigation of Normal Shock Wave-Counter Flow Interactions

T. Tamba, N.M. Tuan, A. Iwakawa, and A. Sasoh

Introduction

The interactions between a shock wave and various flows are important research subjects in various fields. Investigations of shock wave interaction with hot bubbles and that with turbulence lead to important applications in aerospace engineering. Energy deposition in supersonic flow has been investigated in recent years as the method to moderate a shock wave and reduce the wave drag. Previous results showed the drag was reduced by up to 21 % with laser-induced bubbles at Mach number of 1.92 flow [1]. Yet, if hot bubbles are connected with each other to form a long column, the drag reduction is expected to be much enhanced [2]. The shock wave-hot bubble column interaction was investigated using a single shock tube and a repetitive pulse laser; however the deformation of the shock wave was not observed because of the limitation of the facility performance [3]. Also, the interaction between a weak shock wave and turbulence has been investigated in order to understand basic processes of sonic boom propagating through the atmospheric turbulence. Some reports indicated that a weak shock wave is greatly modulated by the turbulence [4]; however the mechanisms of the modulation have not been well understood.

Many shock wave interaction experiments have been conducted in a shock tube. In a previous study, the interaction between a reflected shock wave and turbulent flow induced in the post-shock flow behind an incident shock wave was investigated using a single-driver shock tube [5]. However, in a single-driver shock tube, the conditions of the reflected shock wave and the post-shock flow are coupled with each other, cannot be controlled independently.

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In this study, a Counter-Driver Shock Tube (CD-ST) has been developed, which has two driver section to generate two shock waves and post-shock flows, respectively, and control each condition independently. Therefore the interaction of the shock wave and the post-shock flow can be investigated in various conditions. Using the CD-ST, the interactions between the shock wave and a column of bubbles generated by laser energy depositions was experimentally studied.

Counter-Driver Shock Tube (CD-ST)

Figure 1 shows the schematic of the CD-ST. The CD-ST has two Driver section (L-Driver and R-Driver) at the each end of the driven section (Fig. 1a). This configuration allows to generate Left- and Right-incident shock wave (L-iSW and R-iSW) independently, and Left- and Right-post-shock flow (L-PSF and R-PSF) are induced behind each shock wave. R-Driver is activated with proper delay so that the interaction occurs in test section (Fig. 1b). After the head-on collision of the two incident shock waves (Fig. 1c), Left- and Right-transmitted shock wave (L-tSW and R-tSW) are formed as new shock waves. R-tSW is used as an interacted shock wave and is propagating to left while interacting with L-PSF in the test section (Fig. 1d). The conditions of R-tSW and L-PSF are determined by the initial conditions of each driver. Therefore the investigation of shock wave-counter flow interactions can be conducted on the CD-ST while the condition of the interacted shock wave and the flow field are controlled independently. However the generation of each incident shock wave must be controlled temporally so that the interaction occurs in the test section. Therefore, in this study, the active rupture system using pneumatic cylinders is developed and the characteristics of the system are evaluated.

Figure 2 shows the whole system of the CD-ST. The shock tube is composed of a circular tube ($\phi = 70$ mm)

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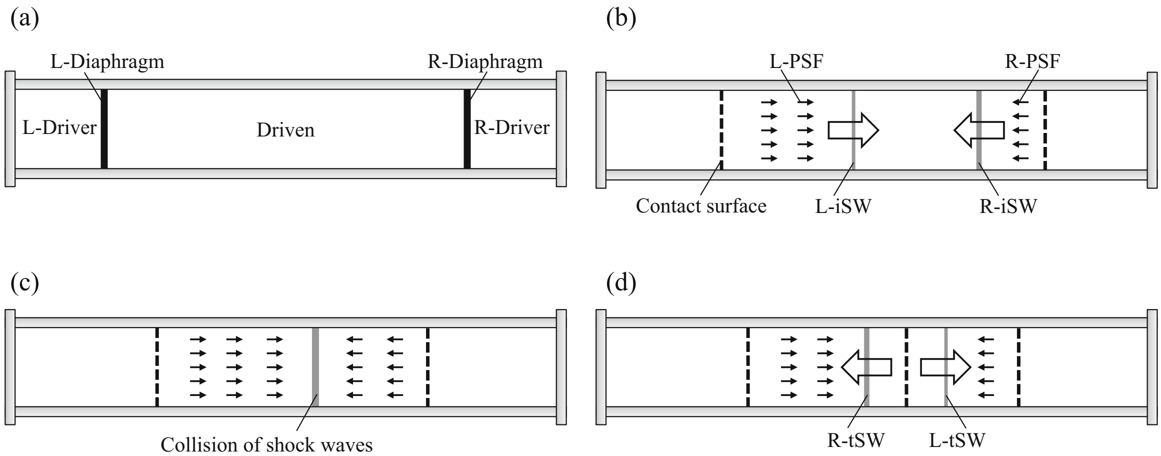


Fig. 1 Schematic of CD-ST. (**a**) Initial condition; (**b**) generation of shock waves and flows; (**c**) collision of shock waves; (**d**) interactions between shock waves and flows

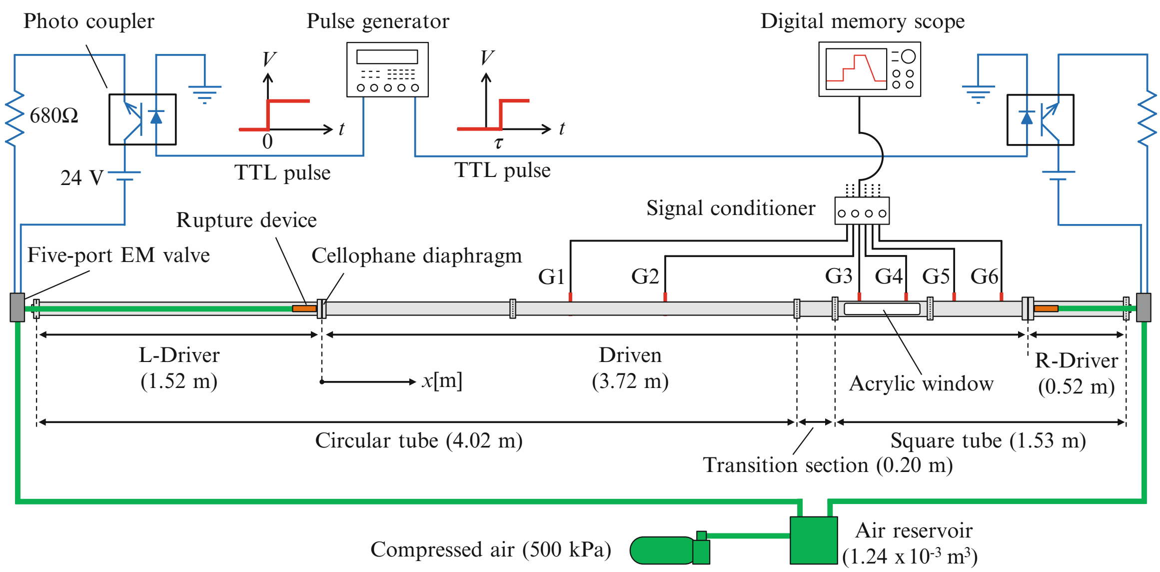


Fig. 2 System of CD-ST

and square tube (62 × 62 mm). Each section is connected by transition section as the cross section is not changed. The test section is located in the square tube and the interactions can be visualized through acrylic windows. To obtain pressure histories, six pressure transducers are installed on the inner wall of the driven section. The pneumatic cylinders are driven by compressed air (0.5 MPa) provided by the electromagnetic valves. Therefore the ruptures in each drivers is controlled by the time difference of the TTL signals from a pulse generator to the electric circuit of the electromagnetic valves. The delay time of the generation of each shock wave is calibrated in advance since the active rupture system using a pneumatic cylinder drives in finite time.

Results

Figure 3 shows the *x-t* diagram of the operation test of the CD-ST. Based on the delay time obtained by the calibrations, the rupture TTL signal to R-driver was sent 24 ms after the signal to L-driver. Each incident shock waves (L- and R-iSW) collided at $x = 3.3$ m, then formed transmitted shock waves (L- and R-tSW) propagating in the shock tube. In the test section, the interaction between R-tSW and L-PSF induced by L-iSW was realized. The Mach numbers of L-iSW and R-tSW obtained from the pressure histories were $M_s = 1.04$ and $M_s = 1.30$, therefore

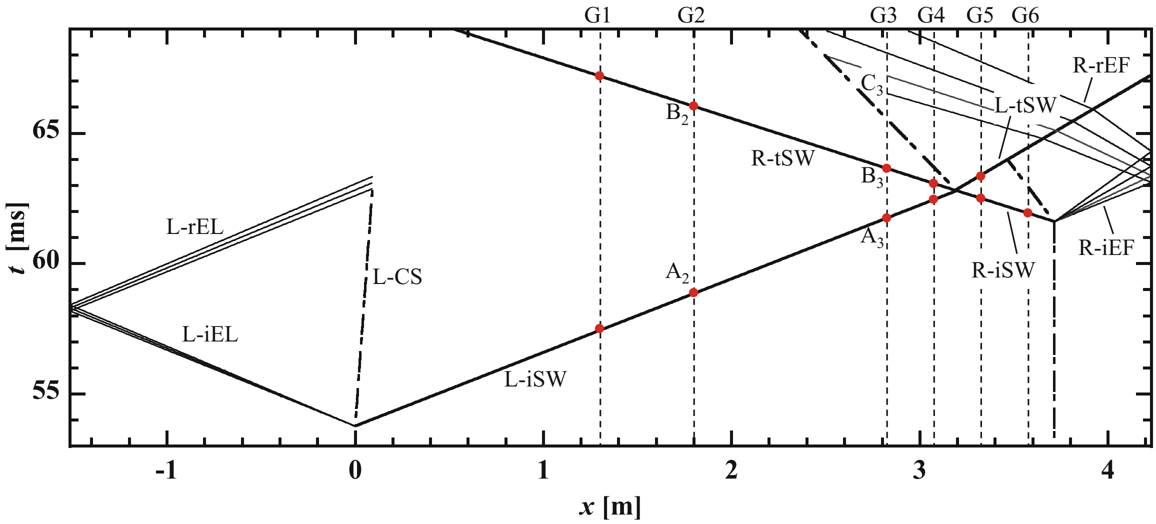


Fig. 3 *x-t* diagram

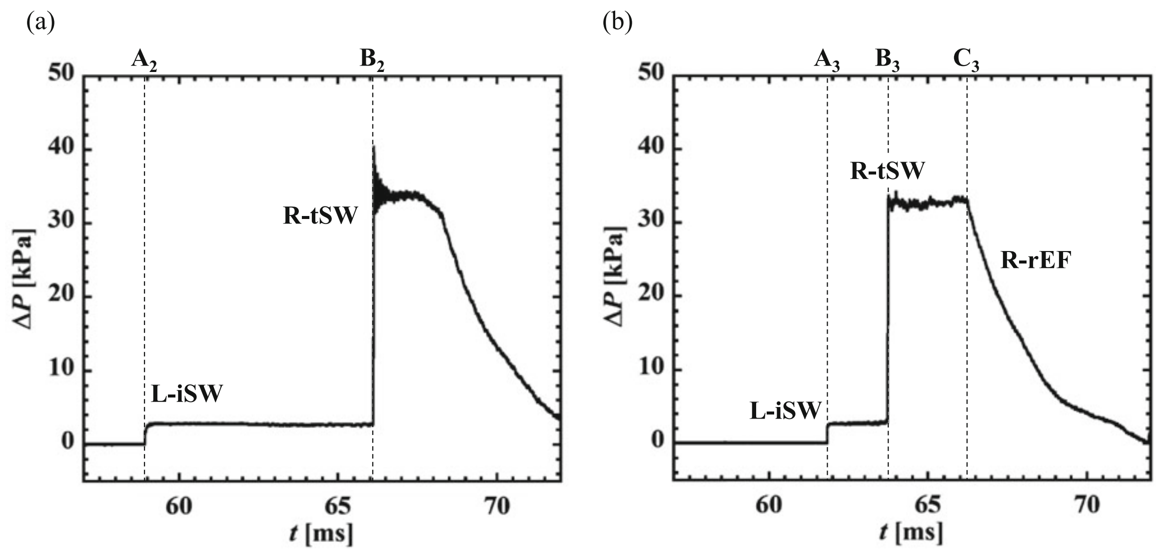


Fig. 4 Pressure histories correspond to Fig. 3. (**a**) G2 ($x = 1.8$ m); (**b**) G3 ($x = 2.8$ m)

the interacted shock Mach number (of R-tSW) and counter flow speed decided by L-iSW were controlled independently by the CD-ST. Also, since the collision point of the shock waves was less than 34 mm in 5 shots in the demonstration, the CD-ST has an enough accuracy for the interaction experiments.

Figure 4 shows the pressure history obtained by the pressure transducers G2 and G3 correspond to Fig. 3. On these sensors, two step pressure jumps were observed. The first jump was caused by L-iSW and L-PSF induced by the shock wave. The second jump corresponds to R-tSW propagating through the counter flow L-PSF. After that, the pressure decreased since the expansion fan from the R-driver reached the gauges.

As one of the example using the CD-ST, Fig. 5 shows the experimental schematic of the shock wave-a laser induced bubble column interaction. A repetitive pulse laser (Nd:YLF laser, Edgewave, $\lambda = 1064$ nm, repetitive frequency $f = 4$ kHz, pulse energy $E = 7.0$ mJ) was focused at $x = 3.1$ m. The Mach number of L-iSW was set in 1.02 so that L-PSF induced by L-iSW was low enough to generate a hot bubble column by a repetitive pulse laser. In L-PSF, a hot bubble was generated at a focal point after the previous bubble has been drifted by the flow, therefore a hot bubble

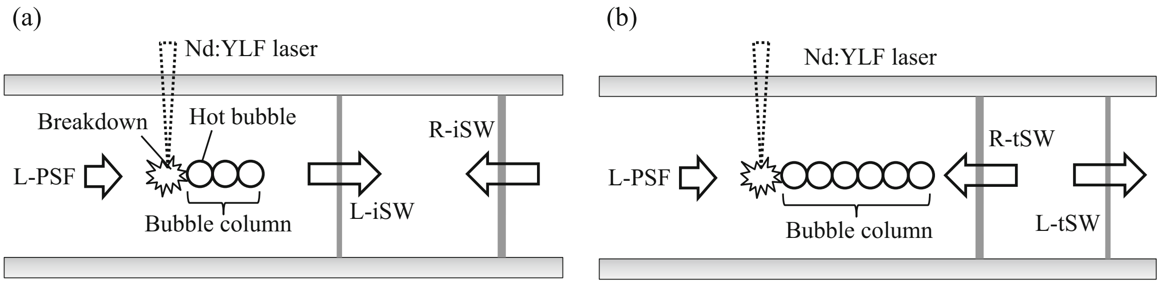
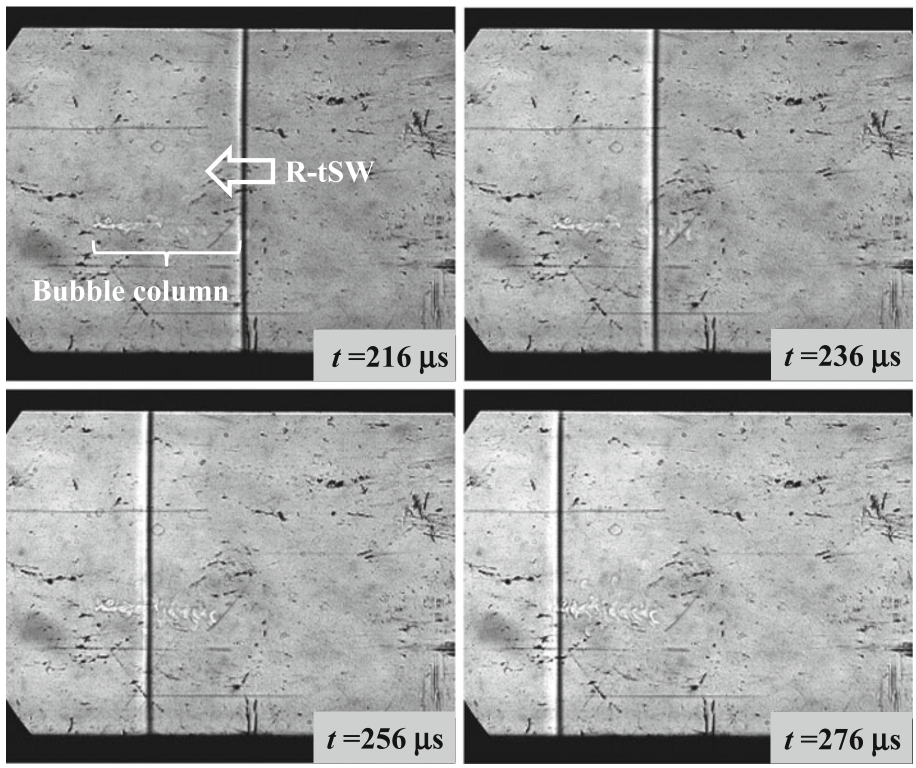


Fig. 5 The interaction with a laser-induced bubble column. (**a**) Generation of a bubble column; (**b**) Interaction between R-tSW and the bubble column

Fig. 6 Schlieren images of the interaction with a laser-induced bubble column



column was formed in L-PSF (Fig. 5a). After the collision of the shock waves, R-tSW propagated to left and interacts with the bubble column (Fig. 5b). In the experiment, the Mach number of R-tSW was 1.27 and the velocity of L-PSF was 11.9 m/s.

Figure 6 shows the Schlieren images of the experiment. The distance between bubbles is calculated as 3.0 mm by the velocity of L-PSF and the repetition frequency of laser pulses. Since the distance is calculated shorter than the diameter which is 1.8 mm from Schlieren images, the bubbles connected each other and formed a dense bubble column. Then, R-tSW propagated through the bubble column. Using the CD-ST, the strong shock wave R-tSW could be adopted for the interaction while the counter flow speed was kept in slow speed to form a dense bubble column. Although more experiments need to be done in the CD-ST, the usefulness of CD-ST on the shock wave-counter flow interactions has been demonstrated.

Conclusions

The Counter-Driver Shock Tube (CD-ST) has been developed, in which the interaction of the shock wave and the post-shock flow can be investigated in various conditions has been developed. Using the CD-ST, the interactions between a shock wave and a laser induced bubble column was experimentally studied and the availability of the CD-ST was demonstrated.

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References

1. Kim, J.H., Matsuda, A., Sakai, T., Sasoh, A.: Wave drag reduction with acting spike induced by laser-pulse energy depositions. AIAA J. **49**, 2076–2078 (2011)
2. Kremeyer, K., Sebastian, K., Shu, C.W.: Computational study of shock mitigation and drag reduction by pulsed energy lines. AIAA J. **44**, 1720–1731 (2006)
3. Takeya, K., Yokota, S., Sasoh, A.: In: Proceedings of 44th Fluid Dynamics Conference, 1A12 (JSASS–2012–2015–F/A)
4. Kane, E.J.: Some effects on the atmosphere on sonic boom. Proceedings of a conference on sonic boom research, pp. 49–64, (1967)
5. Agui, J.H., Briassulis, G., Andreopolos, Y.: Studies of interactions of a propagating shock wave with decaying grid turbulence: velocity and vorticity fields. J. Fluid Mech. **524**, 143–195 (2005)