AIAA JOURNAL
Vol. 44, No. 5, May 2006

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Shock-Tube Operation with Laser-Beam-Induced Diaphragm Rupture

Akihiro Sasoh,* Toru Takahashi,† Keiko Watanabe,‡
Hiroyuki Torikai,§ and Qian-Suo Yang¶
Tohoku University, Sendai 980-8577, Japan

Nomenclature

d = side of square channel cross section
E = effective laser energy incident on diaphragm
t = time
x = distance from diaphragm along the low-pressure channel; see Fig. 1
ΔP = pressure increment from initial pressure
δ = diaphragm thickness
σ = tensile stress of Mylar diaphragm

Introduction

A SHOCK tube is a fundamental experimental tool for research on shock waves and compressible fluid dynamics. The low- and high-pressure channels in a shock tube are usually separated from each other by a diaphragm. For operations in a moderate pressure range, plastic material, such as Mylar or cellophane, is used for the diaphragm. In ideal shock-tube operation, the separation should be instantly and completely removed so that a plane shock wave is generated immediately. However, in practice it takes a finite time for the diaphragm to be ruptured before the flow past the diaphragm reaches the full channel value.[1,2] If only a partial area of the diaphragm is ruptured or the time required for the rupture is too long, the shock formation distance cannot be neglected, and/or the postshock pressure deviates from the ideal value. This problem becomes significant when the fill pressure difference between the high- and low-pressure channels is small because the thrust onto the diaphragm is not large enough to remove it within a reasonably short period of time.

A free-piston driver or fast-acting valve[3–5] is often used as an alternative to the diaphragm separation in shock tubes. In this case, the effective shock formation distance should be considered carefully because the mass of the piston or its equivalent is not at all negligible; the usefulness of this technique is limited by this aspect. Yang et al.[6] have developed a diaphragm-less shock tube using a much lighter component for the separation, a rubber membrane. The system also had the practical advantage that the low- and high-pressure channels did not need to be disconnected to replace the ruptured diaphragm with a new one. However, the connection is shaped as an annular bend. When the postshock flow speed is high, the pressure loss through the bend becomes large. Although the uncertainty in the local shock Mach number was reduced to 0.25%, the postshock pressure might not necessarily remain constant for the required test period.

Rupturing the diaphragm using an electromagnetic repulsive force has been examined in an expansion tube operation.[7] However, the effect of this active rupture was not clear, presumably because the opening time was not at all negligible. Moreover, electromagnetic interference to surrounding instrumentation caused by the large current to the coil and electrical insulation of the electrical coil circuit from metal tubes are not trivial issues.

Remote and/or temporal control of diaphragm rupture would be useful, for example, in expansion tube operation and in small-scale machineries in which an ordinary device cannot fit. Thus, with the objective of improving shock-tube performance, we have carried out trials of shock-tube operation initiated by rupturing the diaphragm with laser-beam irradiation to determine the usefulness and the eventual drawbacks of this new technique.

Apparatus and Experimental Conditions

Figure 1 shows the experimental setup used in the present study. The shock-tube passage has an 80×80 mm square cross section. The length of the high-pressure channel is 2 m, and that of the low-pressure channel is 4 m. A diaphragm made of a sheet of Mylar separates the low- and high-pressure channels. The diaphragm thickness was varied from 5 to 50 μm. The gas contained in the channels is air. The inlet for the laser beam to the shock tube, that is, the left-hand end of the high-pressure channel in Fig. 1, could be sealed with a ZnSe window. However, for simplicity, it was left open to the atmosphere (initial pressure; 101.0 ± 0.5 kPa) in this study. This condition does not affect the general nature of the present study. The low-pressure channel is evacuated to an initial pressure of 81.0 ± 0.5 kPa. The corresponding value of M_s and

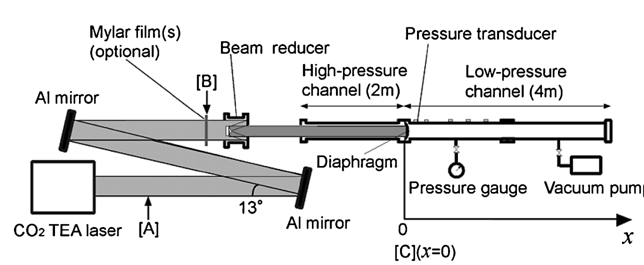

Fig. 1 Experimental setup.

Presented as Paper 2004-1352 at the AIAA 42nd Aerospace Sciences Meeting, Reno, NV, 5–8 January 2004; received 15 April 2004; revision received 3 March 2005; accepted for publication 25 November 2005.

*Professor, Institute of Fluid Science; currently Professor, Department of Aerospace Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan; sasoh@nuae.nagoya-u.ac.jp. Associate Fellow AIAA.

†Graduate Student, Institute of Fluid Science.

‡Graduate Student, Institute of Fluid Science; currently Research Associate, Department of Mechanical Engineering, Ritsumeikan University, 1-1-1 Noji-Higashi, Kusatsu 525-8577, Japan.

§Postdoctoral Fellow, Institute of Fluid Science; currently Associate Professor, Faculty of Science and Technology, Hirosaki University, 3 Bunkyo-cho, Hirosaki 036-8561, Japan. Associate Fellow AIAA.

¶Visiting Scholar, Institute of Fluid Science; currently Associate Professor, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, People's Republic of China.

overpressure ΔP calculated form the shock-tube relations are equal to 1.048 ± 0.003 and 9.37 ± 0.06 kPa, respectively. The histories of inner wall pressures are measured using piezoelectric pressure transducers (PCB 113A21, rise time 1 μs).

The diaphragm is ruptured using a CO_2 transversely excited atmospheric laser (TC-300, General Physics Institute, Moscow, Russia; wavelength 10.6 μm; laser energy 380 J; 90% of the pulse energy is emitted in 2.5 μs). The beam output from the laser has a cross-sectional area of 150×150 mm. However, the intensity inside the central 80×80 mm^2 area is negligible because the laser has an unstable resonator. The output beam from the laser is reflected on two plane aluminum mirrors and is introduced into a beam reducer that is composed of two conical, diamond-cut aluminum (A1050) mirrors, one concave and the other convex. The size-reduced laser beam is introduced into the shock tube; the local fluence outside of the central 72×72 mm square is negligibly small. The laser-beam energy incident onto the diaphragm is varied between 30 and 300 J with an error of $\pm 2\%$ using one or more sheets of Mylar film of various thicknesses placed before the beam reducer, at location [B] in Fig. 1.

Usually, the length of the low-pressure channel of a shock tube necessary for the shock-wave formation from compression waves[8] to become complete is of the order of 50 to100 times the characteristic dimension of the channel cross section.[9] However, in this study the locations of the overpressure measurements in the low-pressure channel are very close to the diaphragm: $x/d = 1.4$, 4.0, 11.5, 16.5, and 21.5. Moreover, shock-tube operation with such a small pressure difference as that of the present study usually necessitates a long shock formation distance.[8,9] Therefore these two experimental factors give a strong impact to the role of diaphragm rupture processes on the shock formation characteristics in the following experiments.

Results and Discussion

In the experiments, we examined the use of Mylar and cellophane as diaphragm material. Cellophane was not found suitable for laser rupture because it melted and became stiff after laser pulse irradiation and pressure fluctuation induced by laser ablation of the diaphragm was much larger than for Mylar of the same thickness. In the following, only results obtained using Mylar films will be presented.

In the square section channel, the lasting pressure difference $\Delta P_{\max} = 4\delta\sigma/d$, with a diaphragm of thickness $\delta = 5$ μm, is 59 kPa, which is only three times higher than the initial pressure difference set in the experiment, 20 kPa. Considering the margin for local tension concentration and mechanical distortion which are to some extent unavoidable in practical shock-tube operation, this thickness is practically the smallest limit for the experiment.

Figure 2 shows pressure histories measured on the inner wall in the low-pressure channel for a laser energy of 70 J. The response time in the side-on pressure measurement is determined as (diameter of the pressure transducer = 5.5 mm)/(shock speed = 360 m/s) + (pressure transducer rise time = 1 μs), which, in the present condition, equals 16 μs. For a diaphragm thickness of 5 μm and $x/d \leq 4.0$, the measured pressure rise time is one order of magnitude longer than the just-mentioned response time. At $x/d = 16.5$, the overpressure reaches the value for an ideal shock tube[9,10] within the response time with less than 2% error. The overpressure histories are affected by 9% fluctuations.

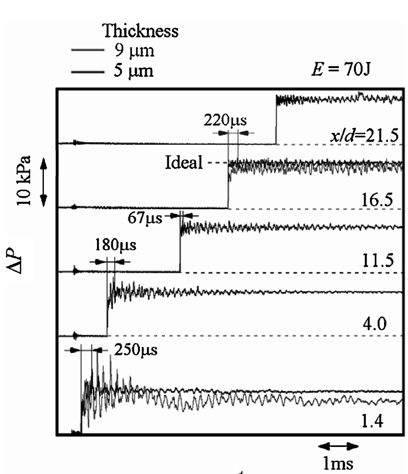

Fig. 2 Typical pressure histories for $E = 70$ J.

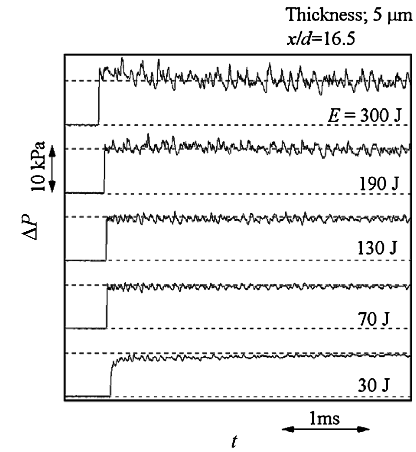

Fig. 3 Pressure histories with various values of E, diaphragm thickness of 5 μm and $x/d = 16.5$.

For a diaphragm thickness of 9 μm, the diaphragm rupture was not sufficiently complete. Even at $x/d = 16.5$, the transition to a shock wave is not complete, the pressure rise time is 220 μs, the postshock overpressure is smaller than the ideal value by 13%, and the amplitude of the pressure fluctuation is 17% of the ideal overpressure. The pressure history at $x/d = 1.4$ exhibits pressure fluctuations of much larger amplitude. This increase of pressure fluctuation is caused by stronger laser ablation of the diaphragm. The laser energy that is absorbed in the diaphragm increases with its thickness. According to our calibration measurement, the effective reflectivity and absorption coefficient of Mylar films against the CO_2 laser pulse is 0.20 ± 0.01 and 0.142 ± 0.005 $(\mu\text{m})^{-1}$, respectively. Using these values, the laser energy absorbed in a 5-μm-thick Mylar film is estimated to be 5.5% of the incident energy. For an incident energy of 70 J, the absorbed energy is 3.9 J, which corresponds to the static enthalpy of a layer of 1.7 mm of driver air in the channel. Because of the exponential dependence of the absorbed energy on the diaphragm thickness, the energy absorbed in a 9-μm-thick diaphragm is 1.75 times that absorbed in a 5-μm-thick one, thereby causing much larger pressure fluctuations.

Figures 3 shows pressure histories measured using a 5-μm-thick Mylar diaphragm for various laser energies. When the incident laser energy was small ($E = 30$ J), the pressure immediately after the incident shock wave did not reach the ideal shock-tube value. The laser energy was so small that only a fraction of the diaphragm was ruptured. When the laser energy was too large ($E = 130$ J and larger), pressure fluctuations induced by ablation became large. The best conditions were achieved with a laser energy of 70 J: the postshock pressure was close to the ideal shock-tube value, remained almost constant, and had a relatively small fluctuation amplitude.

Conclusions

Our experiments demonstrated that shock-tube operation with active diaphragm rupture using laser-beam irradiation is possible. A shock transition distance of the order of 10 times the channel side is obtained. Because the amount of energy absorbed in the diaphragm affects pressure fluctuations, the material and thickness of the diaphragm and the incident laser energy should be carefully set. On one hand, an excessively small laser energy results in insufficient diaphragm opening and decreasing postshock pressure; on the other hand, with an excessively large laser energy the postshock flow is contaminated with pressure fluctuations induced by laser ablation of the diaphragm.

Acknowledgments

The authors are grateful for valuable technical help from Kikuo Takahashi, Makoto Kato, Kazuo Asano, Toshihiro Ogawa, and Hidenori Ojima from the Technical Service Division, Institute of Fluid Science.

References

[1]White, D. R., "Influence of Diaphragm Opening Time on Shock-Tube Flows," *Journal of Fluid Mechanics*, Vol. 4, 1958, pp. 585–599.

[2]Oertel, H., *Stossrohre*, Springer-Verlag, Vienna, 1966, p. 670.

[3]Oguchi, H., Funabiki, K., Sato, S., and Hatakeyama, M., "A Free-Flight Experiment of Projectiles Ranging from High Subsonic to High Supersonic Mach Numbers," *Shock Waves*, Vol. 1, No. 3, 1991, pp. 233–236.

[4]Stalker, R. J., "The Free Piston Shock Tunnel," *Aeronautical Quarterly*, Vol. 17, No. 4, 1966, pp. 351–370.

[5]Ikui, T., Matsuo, K., and Yamamotor, Y., "Fast-Acting Valves for Use in Shock Tubes. II. Formation of Shock Waves," *Bulletin of the Japan Society for Mechanical Engineers*, Vol. 22, No. 167, 1979, pp. 693–699 (in Japanese).

[6]Yang, J., Sasoh, A., and Takayama, K., "The Reflection of a Shock Wave over a Cone," *Shock Waves*, Vol. 6, No. 5, 1996, pp. 267–273.

[7]Miller, C. G., "Expansion Tunnel Performance with and Without an Electromagnetically Opened Tertiary Diaphragm," *AIAA Journal*, Vol. 15, No. 7, 1977, pp. 1045–1047.

[8]Shapiro, A. M., *The Dynamics and Thermodynamics of Compressible Fluid Flow*, Vol. 2, Ronald, New York, 1953, Chap. 24.

[9]Glass, I. I., and Sislian, J. P., *Nonstationary Flows and Shock Waves*, Clarendon, Oxford, 1994, Chaps. 4 and 13.

[10]Nishida, M., "Shock Tube Theory," *Handbook of Shock Waves*, edited by G. Ben-Dor, O. Igra, and T. Elperin, Vol. 1, Academic Press, San Diego, CA, 2001, Chap. 4, pp. 563–581.

M. Sichel
Associate Editor