Shock-Wave-Induced Flow Past a Circular Cylinder in a Dusty-Gas Shock Tube*

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An experimental investigation of a shock-wave-induced flow past a circular cylinder in a dusty-gas shock tube was made. Joint research was conducted between the Muroran Institute of Technology and the Institute of High Speed Mechanics, Tohoku University. The shock tubes used for the present research had test sections of identical geometry. For a frozen-shock Mach number of 1.3, flow visualization studies were conducted by the schlieren method, using an Imacon high-speed camera in Muroran and a pulsed-laser holographic interferometer in Sendai. The behavior of shock waves past a circular cylinder in a dusty gas, the development of dust-free regions and the formation of vortices behind a circular cylinder were observed in detail.

Key Words: Compressible Flow, Shock Wave, Shock Tube, Gas-Particle Flow, Multiphase Flow, Imacon Camera, Holographic Interferometer, Flow Visualization

1. Introduction

The present study of the shock-wave-induced flow past a circular cylinder in a dusty-gas shock tube has important engineering applications relating to estimation of the unsteady drag of blunt bodies (including small particles) and to the strength design and security of structures⁽¹⁾⁽²⁾.

There have been a number of experimental and numerical studies relating to the present study, for instance, experimental studies^{(3)~(7)} and numerical studies⁽⁸⁾⁽⁹⁾ on dusty-gas shock tube flows, and numerical analyses on dusty-gas supersonic steady flow past blunt bodies⁽¹⁰⁾⁽¹¹⁾. However, there have been few studies on body and shock-wave interactions in a dusty-gas shock tube⁽¹²⁾. Shirouzu⁽¹²⁾ observed the shock-wave-induced flow past a circular cylinder in a

dusty-gas shock tube and showed that a dust-free region existed behind the circular cylinder. To understand the flow better, it is necessary to take sequential, detailed photographs.

In this study, we observed the unsteady flow phenomena past a circular cylinder in a dusty-gas shock tube by sequential schlieren photographs taken at the Muroran Institute of Technology and by pulsed-laser holograms taken at the Institute of High Speed Mechanics, Tohoku University, and compared these results.

2. Experimental Apparatus and Method

Figure 1 shows the schematic diagram of the horizontal dusty-gas shock tube used in the present experiment⁽⁶⁾⁽⁷⁾. The shock tube consisted of a high-pressure chamber 1 m long and 50 mm in diameter and a 30 mm × 40 mm cross-sectional low pressure channel 4 m long. The flow around a circular cylinder was visualized by the schlieren method, an Imacon high-speed camera, and a pulsed laser holographic interferometer. The dust particles were fly ashes (JIS type 10), which had an almost spherical shape and an averaged diameter of 5 μm. The dust particles were

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supplied by a dusty-gas generator using a fluidized bed⁽⁶⁾. The high-pressure driver gases were nitrogen and helium at 0.34 and 2.02 MPa. The shock Mach numbers in the present experiment were 1.30 and 2.02 in terms of the sound speed of pure air. Two-dimensional circular cylinders (diameter $D=5, 10$ mm) were used for blunt body models.

3. Experimental Results and Discussion

3.1 Observation of flow field by high-speed schlieren photographs

To investigate the effect of the diameter of a circular cylinder in a dusty-gas shock tube, we alternated between $D=5, 10$ mm, and observed the passing shock-wave-induced flow. We will describe here the result for the case of $D=10$ mm, as the result for $D=5$ mm is virtually the same.

Figure 2 shows high-speed schlieren photographs of shock-wave-induced dusty-gas flows past a circular cylinder for the case of frozen shock Mach number $M_f=1.30$ and the initial dust loading ratio $\eta_0=0.01$. The framing speed of the photographs is $10 \mu\text{sec}/\text{frame}$, and the exposure time is $2 \mu\text{sec}$. Figure 2(a) presents a plane shock wave just before impingement on a circular cylinder in the first frame, a regular reflection of a shock wave in the second frame, and a Mach reflection of a shock wave in the third and fourth frames. In Fig. 2(b), the formation and development of a dust-free region are shown with the formation of a vortex in the dust-free region in the third and fourth frames. Figure 2(c) shows that the dust-free region elongates in addition to opening at the rear part. It is noted that there are no particles near the upper wall of the low-pressure channel of the present horizontal dusty-gas shock tube.

Figure 3 shows high-speed schlieren photographs

Fig. 1 Schematic diagram of dusty-gas shock tube apparatus

of the flow field for the case of $M_f=2.36$ and $\eta_0=0.01$. The photographs of Figs. 3(b) and (c) were taken 50 and $100 \mu\text{sec}$ after shock-wave impingement on the circular cylinder, that is, the time periods are the same as in Fig. 3(a). A regular reflection is observed in the third frame of Fig. 3(a), and a Mach reflection and a Mach stem are observed in the fourth and fifth frames. The symmetric dust-free region behind the circular cylinder can be seen clearly in the frame range from the sixth frame of Fig. 3(a) to the second frame of Fig. 3(b). The dust-free region becomes asymmetric after the third frame of Fig. 3(b). It is seen that the dust-free region oscillates horizontally and vertically because of vortices being shed from the cylinder.

3.2 Effect of an incident frozen-shock Mach number on the development of a dust-free region

Figure 4 shows a time variation of the length of the dust-free region s obtained from the high-speed photographs of Fig. 2. The abscissa is the time after

Fig. 2 High-speed schlieren photographs of shock-wave-induced dusty-gas flow past a circular cylinder ($M_f=1.30$, $\eta_0=0.01$, Framing speed: $10 \mu\text{sec}/\text{frame}$)

the arrival of the incident shock wave at the center of the cylinder. The symbols in Fig. 4 denote experimental data for the frozen-shock Mach numbers of $M_f = 1.30, 1.48, 1.68$, and 2.36 . From Fig. 4, it is seen that the length of the dust-free region s increases faster with increasing M_f , and that s increases linearly with time t . The Reynolds numbers of the shock-wave-induced flow past the circular cylinder are $Re_D = 1.3 \times 10^5, 2.2 \times 10^5, 3.3 \times 10^5$, and 6.9×10^5 for $M_f = 1.30, 1.48, 1.68$, and 2.36 , respectively, where the reference length is the diameter of the circular cylinder $D = 10$ mm.

3.3 Observation of flow field by double-exposure laser holographic interferograms

In this section, we will observe in detail the behavior of the shock wave and the formation and development of vortices behind a circular cylinder in a dusty-gas shock tube. Figure 5 shows sequential double-exposure holographic interferograms of shock-wave-induced dusty-gas flows past a circular cylinder for the case of $M_f = 1.30$, and $\eta_0 = 0.01$. In Figs. 5(a)

Fig. 3 High-speed schlieren photographs of shock-wave-induced dusty-gas flow past a circular cylinder ($M_f = 2.36$, $\eta_0 = 0.01$, Framing speed: $10 \mu\text{sec/frame}$)

and (b), regular and Mach reflections of a shock wave can be seen. The symbols I, R, and T in the figures denote the incident shock wave, reflected shock wave and triple point. The incident shock wave propagates to the left, and t is the time, where the reference time is the same as that of Fig. 5(a). In Figs. 5(c) and (d), the refraction of the incident shock wave behind the circular cylinder and the reflection of R at the upper and lower shock tube walls can be seen. Figure 5(e) shows that the reflected shock wave RW reaches the circular cylinder surface and forms a pair of vortices. Figures 5(f) and (g) illustrate the development of the pair of vortices and the appearance of reflected shock wave N. Each of the shock waves propagates in the direction indicated in the figures by arrows. It is noted that an interference fringe shift is related to a density and pressure variation; thus the center of a vortex is a low-pressure region. In Figs. 5(h) and (i), we see that the vortices become asymmetric, are shed from the cylinder, and flow downstream. In Fig. 5(j), a Kármán vortex street can be seen, and it may be said that the flow becomes steady at this time.

3.4 Relation between the development of a dust-free region and the formation of vortices

In this section, we will investigate the relation between the development of a dust-free region and the formation of vortices behind a circular cylinder in the dusty-gas shock tube. Figure 6 shows the time variation of incident and reflected shock waves I and R, dust-

Fig. 4 Time variation of length of dust-free region

(a) $t=0$ (b) $t=9 \mu\text{s}$ (c) $t=41 \mu\text{s}$ (d) $t=54 \mu\text{s}$ (e) $t=77 \mu\text{s}$ (f) $t=97 \mu\text{s}$ (g) $t=135 \mu\text{s}$ (h) $t=223 \mu\text{s}$ (i) $t=417 \mu\text{s}$ (j) $t=1546 \mu\text{s}$

Fig. 5 Double-exposure holographic interferograms of shock-wave-induced dusty-gas flows past a circular cylinder ($M_f=1.30$, $\eta_0=0.01$, $D=10$ mm)

free region DFR and vortices V which were obtained from Fig. 5 and the other shadowgraphs. Figures 6(a) to (f) correspond to Figs. 5(c) to (h), respectively. In Fig. 6(a), it can be seen that the dust-free region appears behind the Mach stem. Figure 6(c), shows how a pair of symmetric vortices forms in the

dust-free region. From Figs. 6(d) to (f), the relation between the developments of a dust-free region and symmetric vortices can be seen quite well.

4. Conclusions

Shock-wave-induced dusty-gas unsteady flows

Fig. 6 Relation between development of dust-free region and formation of vortices
($M_f = 1.30$, $\eta_0 = 0.01$)

past a circular cylinder were observed in detail using high-speed schlieren photographs and laser holographic interferograms. The following results were obtained : (1) The development of the dust-free region behind a circular cylinder was clarified using high-speed schlieren photographs. (2) The behavior of a shock wave past a circular cylinder, the formation and development of vortices behind a circular cylinder and the transit process from the unsteady flows to the steady flows past the circular cylinder were clarified using laser holographic interferograms. (3) The relation between the development of a dust-free region and the formation and development of vortices was also clarified using shadowgraphs and holographic interferograms.

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