Measurement of unsteady shock standoff distance around spheres flying at Mach numbers near one

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Abstract

This paper reports the experiments on the shock standoff distance (SSD) around spheres flying at Mach numbers from slightly below 1.0. Spheres of the same diameter but three different densities were launched in a ballistic range by a light-gas gun, and the flow field around each sphere was measured by optical visualization. The purpose of this study is to investigate how projectile deceleration influences the SSD by comparing the results for projectiles of the same shape, size, and Mach number but different densities. The location history of the sphere center is obtained by fitting a formula derived from the equation of motion of a decelerating object, and the history of the instantaneous projectile Mach number is obtained by differentiating this formula. The SSDs of the projectiles with different densities are the same at higher Mach numbers, but different at lower Mach numbers, and the SSD decreases with decreasing projectile density. Seemingly, because projectile deceleration is related to the flow unsteadiness, steady flow cannot be assumed in the present range of Mach number with the different SSDs. At Mach numbers close to one, that of the propagating detached shock wave is higher than that of the flying projectile.

Keywords Shock standoff distance · Near-sonic · Unsteady flow · Ballistic range · Visualization

1 Introduction

The shock wave (SW) around a blunt-nosed object in supersonic flow is detached and located away from the object, and the distance between the object and the SW, namely the shock standoff distance (SSD), is determined by the shape and size of the object and the Mach number of the flow [1]. The SSD increases as the flow Mach number approaches one from above, becoming theoretically infinite at Mach number 1; there is no SW in subsonic flow. However, in visualizations of the flow field around a sphere moving at Mach numbers from 1.1 to slightly below 1, Kikuchi et al. [2] found that the SSD at Mach number 1 was not infinite, and the cause of this discrepancy between theory and experiment is yet to be clarified. To date, theoretical investigations [3,4] have assumed that the detached SW is relatively close to the object, mean-

ing that the speed range near Mach number 1 is yet to be considered. Some numerical results have also been reported [5–7].

The present paper reports experimental results in support of an explanation for the finite SSD at Mach numbers near one. The present results can also be used to validate previous numerical results. The finite SSD could be caused by (i) the ambient gas through which the detached SW propagates being neither static nor thermally uniform, (ii) the muzzle of the ballistic range that fires the projectile introducing a disturbance, or (iii) disturbances being reflected from the walls of the test tank in which the projectile flies. Moreover, while the theory assumes a steady flow (i.e., the projectile flies at constant speed), the projectile definitely decelerates in experiments. Therefore, investigated herein is the influence of projectile deceleration. The SSD is determined uniquely by the shape and size of the object and the Mach number of the flow, so any difference in SSD between projectiles of the same shape, size, and Mach number but different density is likely to be because of the projectile deceleration. The SSDs around spheres of three different densities flying near Mach number 1 were measured using optical visualization.

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2 Experiment

2.1 Facility, optical arrangement, and conditions

Figure 1 shows the experimental facility, which was a ballistic range at the Institute of Fluid Science at Tohoku University in Japan. The ballistic range accelerated and launched projectiles using pressurized helium gas, and the test tank in which the launched projectiles flew was 1.66 m in diameter and 12 m in length. The projectiles were 5/16-in ball bearings made of stainless steel (7.7 g/cm^3), aluminum (2.7 g/cm^3), or polyacetal (1.41 g/cm^3). Each projectile was installed in a sabot because the projectile diameter differed from the inner diameter of the launch tube. Figure 2 shows a projectile and a sabot, and Figure 3 shows the setup inside the test tank. The distance from the muzzle to the observation section was 5.4 m. The separated sabot parts were removed upon impact with a sabot stopper, and the precursor SWs released from the muzzle were attenuated forcibly by baffle plates located between the muzzle and the observation section. The optical arrangement was a basic shadowgraph method using 300-mm-diameter parabolic mirrors, the light source was a metal halide lamp (LS-M210; Sumita Optical Glass, Inc., Japan), and the recording camera was a high-speed video camera (HPV-X; Shimadzu Co., Ltd., Japan). The camera was triggered by the pressure of the detached SW as detected by a piezoelectric pressure sensor (603B; Kistler Instrument Corp., USA). The flight Mach number of the projectile in the observation section ranged from 1.2 to 0.95.

2.2 Image analysis

The projectile speed and the SSD were obtained from the high-speed images. The time history of the projectile's center location was obtained from the pixel coordinates of the projectile's front and end tips. Although the projectile speed could be directly obtained from the interframe time and the projectile traveling distance between next frames, the error due to reading error of 1 pixel was large. The speed error due

Fig. 1 Ballistic range

Fig. 2 Projectile and sabot

Fig. 3 Setup inside test tank

to 1 pixel reading error of this experiment, where the inter-frame was $15 \mu\text{s}$ and 0.66 mm of 1 pixel, corresponded to 44 m/s . The time history of the projectile speed was obtained by fitting between the equation of motion and these experimental data. The equation of motion of a decelerating projectile is

$$m \frac{d^2x}{dt^2} = -\frac{1}{2} \rho \left(\frac{dx}{dt} \right)^2 C_D S \quad (1)$$

where m is the projectile's mass, x is the projectile's location, C_D is the drag coefficient, S is the projectile's cross-sectional area, and ρ is the ambient gas density. Defining $\alpha = \frac{1}{2m} \rho C_D S$, (1) becomes

$$\frac{d^2x}{dt^2} = -\alpha \left(\frac{dx}{dt} \right)^2 \quad (2)$$

and thus, the projectile's speed v and location x are given by

$$v = \frac{dx}{dt} = \frac{v_0}{1 + v_0 \alpha t} \quad (3)$$

$$x = \frac{1}{\alpha} \ln \{ 1 + \alpha v_0 t \}. \quad (4)$$

The value of the coefficient α in (4) was obtained by least-squares fitting the time history of the projectile's center location to (4), whereupon the time history of the projectile's speed was derived by substituting α into (3). The location of the detached shock front was obtained from the pixel coordinates of the images, and the SSD was obtained as the

difference between the shock front and the projectile's front tip.

3 Results and discussion

3.1 Visualizations and projectile speed histories

Figure 4 shows examples of the visualization images. In this case, the projectile material was polyacetal and the average flight Mach number in the observation section was 1.03. Figure 5 shows an enlarged image of the projectile in flight. The error in reading the projectile's tip coordinate was one pixel, given that the projectile edge was not very sharp. Figure 6 shows the results of fitting (4) to the measured projectile center locations, as well as the projectile speed derived from (3). The fitted curve agrees well with the experimental data. In this experiment, as the projectile passed through the observation section, its speed dropped by around 7 m/s. This speed drop which was equivalent to around 0.02 in Mach number was small. It is well known that the drag coefficient changes significantly approaching Mach number one. In previous experiment reported by Charters and Thomas [8], the difference of 0.02 in Mach number was equivalent to the difference of 0.02 in the drag coefficient. Even if the drag coefficient changed 0.02 during passing through the observa-

Fig. 4 High-speed images of polyacetal projectile flying at an average Mach number of 1.03

Fig. 5 Enlarged image of projectile

Fig. 6 Time histories of projectile center (left axis) and projectile speed (right axis)

tion section, the derived Mach number changed only 0.003. Thus, the drag coefficient through the observation section was assumed as constant.

3.2 Shock standoff distance

Figure 7 shows a plot of the unsteady SSD obtained for a polyacetal projectile flying at a Mach number of 1.03. Here, the abscissa is the Mach number M and the ordinate is the normalized SSD δ/d . The Mach number M was instantaneous velocity v , which was derived from Eq. (3) using the coefficient α by fitting between Eq. (4) and the time history of the projectile's center location, divided by the sound speed. The normalized SSD δ/d was SSD δ divided by the projectile diameter d . The SSD of the right-end mark was corresponding to the first frame of high-speed video images. The SSD increased considerably in the observation section. Figure 8 shows the curves obtained from all the experimental results, where the abscissa and ordinate are the same as those in Figure 7. For the projectiles of a given density, the average value of α was calculated from those of all the experiments because α was not constant for a given density, and the projectile speed history for that density was derived from the average value of α for that density. Meanwhile, the SSDs for a given density were the same at higher Mach numbers but not at lower ones, and the SSD decreased with decreasing projectile density. The curves branched out in this range of Mach numbers, and the Mach number at which the curves branched out was presumed to be the critical Mach number at which deceleration influenced the flow field. The deceleration was related to the unsteadiness of the flow, so it was seemingly impossible to assume a steady flow lower than this critical Mach number.

Fig. 7 Unsteady shock standoff distance around polyacetal projectile flying at an average Mach number of 1.03

Fig. 8 Unsteady SSD (all data)

Fig. 9 Comparison of Mach numbers between projectile and propagating detached shock wave

3.3 Mach number of propagating detached shock wave

Figure 9 shows the relationship between the average Mach numbers of the projectile and the propagating detached SW. Projectile average Mach number M_p was the projectile average velocity, which was calculated from location and timing on end to end of the observation section, divided by the sound speed. Shock average Mach number M_s was the detached SW average propagating velocity which was calculated same as the projectile average velocity was divided by the sound speed. Each Mach number is the average value for the various experiments. The dashed line represents equality between the two Mach numbers, so a result above the dashed line means that the shock Mach number exceeds the projectile Mach number. Interestingly, the shock Mach number exceeds the projectile Mach number in a range near Mach number 1. Starr and Varner [9] suggested that the SSD does not respond instantaneously as the Mach number decreases, and instead, they suggested a response time corresponding to the time taken for a disturbance from the projectile to reach the detached SW. The difference between the Mach numbers of the projectile and the detached shock may be due to this response time.

4 Conclusion

The SSDs around spheres of the same diameter but three different densities were obtained experimentally. The SSD around a decelerating sphere increased as the sphere passed through the observation section. At higher Mach numbers, the SSDs did not differ despite the different projectile densities. At lower Mach numbers, the SSDs around spheres of lower density and thus higher deceleration were less than those around spheres of higher density. Comparing the Mach numbers of the propagating detached SW and the sphere in flight showed the former to be higher than the latter near Mach number 1.0.

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Declarations

Availability of data and material The data that support the findings of this study are available from the corresponding author upon reasonable request.

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