Downstream-facing shock wave/boundary layer interaction

Jiming Yang[1], Zhaoyuan Han[1], and Kazuyoshi Takayama[2]

[1] Department of Modern Mechanics, University of Science and Technology of China, Hefei, Anhui, 230026, China
[2] Shock Wave Research Center,Institute of Fluid Science, Tohoku University, Sendai 980, Japan

Abstract. An investigation of downstream-facing shock wave/boundary layer interaction was carried out experimentally and numerically. It was found that such an interaction is different from both the steady shock wave boundary layer interaction and the unsteady near wall interaction of a reflected shock at the end of the shock tube. Experimental and numerical results showed that after the interaction, the shock bends backward in the near wall region. The higher the flow speed ahead and the weaker the shock strength, the more serious the shock front curves. Meanwhile, a pressure peak is generated near the wall after the moving shock. A serial of pressure increases and decreases was found in the boundary layer when the flow speed ahead of shock is high and the shock is weak, for which the numerical examination showed locally transonic flow exists near the wall in the frame of reference attached on the moving shock. Mach-like and regular-like reflection structures were observed numerically.

1 Introduction

Shock wave/boundary layer interaction is a well-known subject. However, most of the past investigations were concentrated on the case of upstream-facing propagating shock waves, such as stationary oblique shock/boundary layer interaction, shock strains in internal gas flow, interaction of reflected shock wave from the end wall of a shock tube with the boundary layer induced by the incident shock etc.[1] The mechanism and flow configuration of the interaction between a downstream-facing moving shock and the boundary layer ahead are far from being well understood. Such kind of interaction may appear either in unstationary high-speed internal flow or when flying vehicle encounters a blast wave, for which the interests are often focused on the behavior of shock wave at the near-wall region[2]. Based on the simple expression of shock speed $Ws = Ma + U$ one can imagine that the shock front will be strongly deformed within boundary layer, and consequently there should be an interaction between shock wave and boundary layer as well as the wall. This type of interaction is different from the cases mentioned above since it is co-direction shock wave/boundary layer interaction, or in another word, a downstream-facing shock wave interacts with the boundary layer ahead. In this paper, an investigation was carried out experimentally and numerically to get some basic understandings of such kind of interaction phenomena.

2 Experimental and Numerical Methods

The experiment was conducted in a double driver shock tube, in which three sections, driver, middle and driven sections were used so that two shock waves can be generated. The first (precursor) shock wave is used for inducing flow, so the second shock wave becomes downstream-facing with flow ahead and consequently co-direction shock wave/boundary layer interaction occurs at the near wall region. The double driver shock tube, which has 94mm $\times$ 94mm square cross section, consists of 3 m driver section, 0.5 m middle section and 6.2 m driven section and is synchronized with rarefaction wave bursting technique which starts from the downstream diaphragm. Since the three sections as mentioned above are related to each other, the strengths of the two shock waves are not as freely chosen as that in a single driver shock tube, therefore the shock waves generated with mylar diaphragms and air in all the three sections do not change very much. Two pressure transducers 300 mm apart which were mounted upstream of the test section were used to measure the strengths of the shock waves. The interaction of downstream-facing shock wave (the second shock) with boundary layer were visualized with schlieren system, in which the spark light source was triggered with second shock wave.

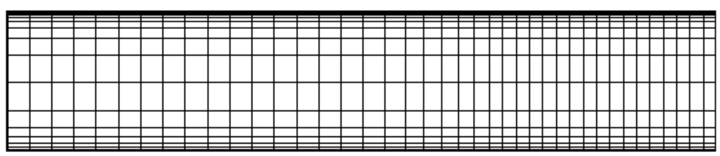
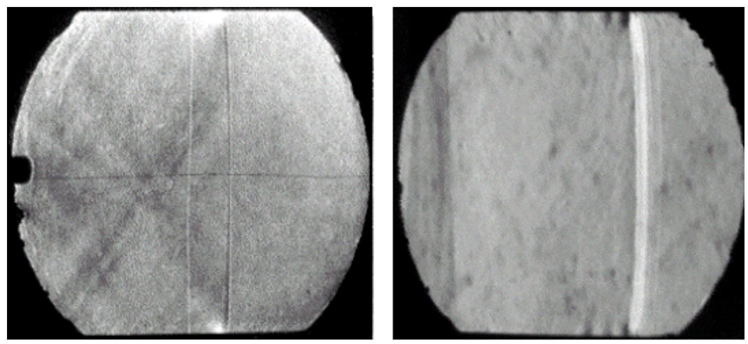


Fig. 1. Computational Domain and schematic mesh distribution.

Numerical simulation was carried out based on two-dimensional unsteady compressible Navier-Stokes equations, in which laminar flow is considered. The computational scheme used to solve the equations is the explicit, upwind, finite difference TVD scheme. The computational domain, as schematically shown in Fig. 1, is 0.4 m long, which is supposed to be a part in the driven section covering the test section. A coarse and a fine spaced meshes up and down stream connected with a continuous transition part are used in the x-direction, while an exponentially stretched mesh spacing is used in the y-direction to match the viscous effect near the wall. Grid points of 2561$\times$101, in x- and y-direction, respectively, were used for most of the present computations. To simulate the experimental condition, the flow parameters after the first shock wave are introduced initially. After a certain steps of calculation, the second shock wave is input from the inlet of the domain.

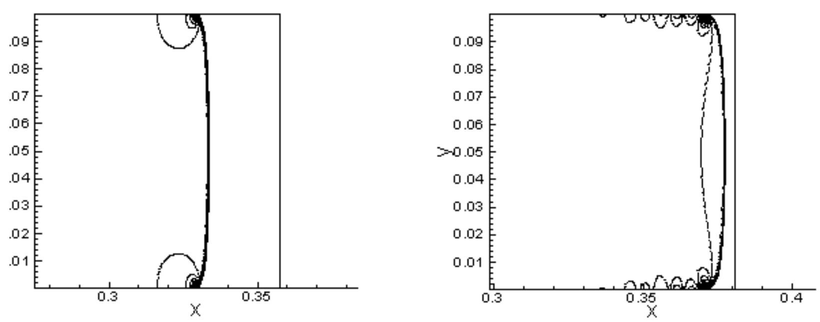
3 Results and Discussions

Two experimental conditions were operated during the study: one with 500kPa, 245kPa and 80kPa in driver, middle and driven sections, respectively, and the generated shock Mach numbers are Ms1=1.22 and Ms2=1.2, respectively; the other with the same pressure in driver section, 275kPa in the middle and 30kPa in driven section, so the first shock is stronger, Ms1=1.51 and second shock is weaker, Ms2=1.15, compare to the former.



Ms1=1.22, Ms2=1.2   b Ms1=1.51, Ms2=1.15

Fig. 2. Schlieren photos of down stream-facing shock wave/boundary layer interaction



a. Ms1=1.22, Ms2=1.2   b. Ms1=1.51, Ms2=1.15

Fig. 3. Numerical results of down stream-facing shock wave-boundary layer interaction.

Figure 2 shows the schlieren photos of the second shock when it passes the test section. Note that the first shock is only used to induce the flow and Ms1 can be considered to be a reference of the flow speed ahead of the second shock which is what we are interested in. Both pictures show obviously that the shock front bends backward when it approaches the wall. Although such a distortion is less serious for relatively stronger shock wave and slower flow ahead as shown in Fig. 2a, the white spot at the foot of shock wave demonstrates strong density change caused by the curved shock-wall interaction. For a little weaker shock wave and faster flow ahead as shown in Fig.2b, the shock front curves more. This can be found not only at the near-wall region but also from the thicker shock front in the photo comparing to the other, which is because of the boundary layer effect from the side-wall of windows. Another interesting phenomenon is, through a careful observation from Fig. 2b, that one can find a series of wavelets follow the moving shock close to the wall. For better understanding, it will be helpful to get more information from numerical simulation.

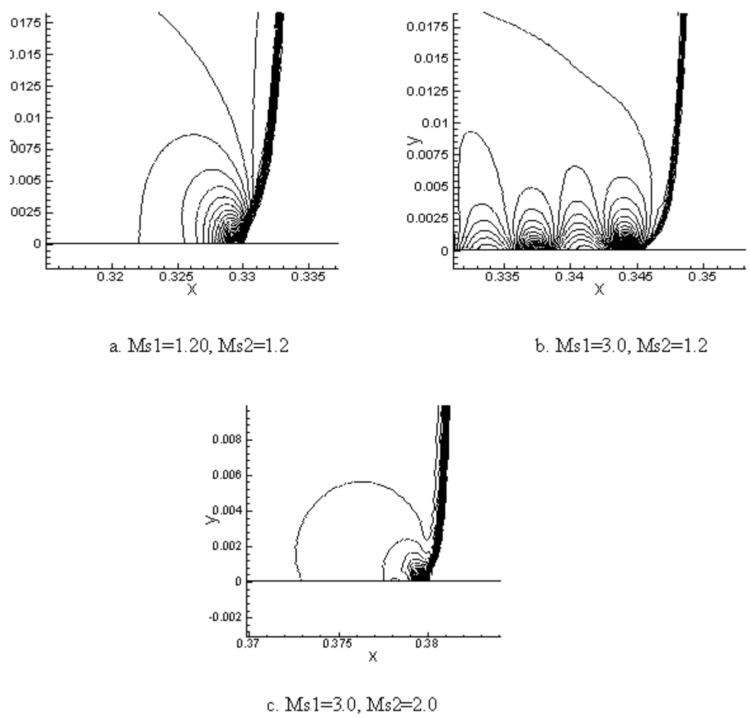
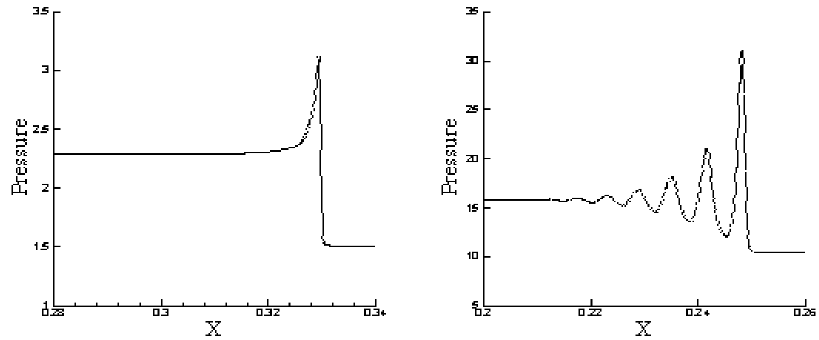


Fig. 4. Close-up view of near-wall wave pattern

Fig. 3 shows numerically the pressure contours with flow conditions close to the experimental ones shown in Fig. 2. The agreements with the visualizations are good for both cases through the comparison of wave patterns. For the case of relatively stronger shock and slower flow ahead (Fig. 3a), the numerical simulation also shows the pulling back at the shock foot due to the boundary



a. Ms1=1.2, Ms2=1.2 **b.** Ms1=3.0, Ms2=1.2

Fig. 5. Pressure distribution along the wall surface.

layer. Furthermore, an increase of nearly 50% in pressure was observed numerically after the curved shock is reflected on the wall. When the shock strength is decreased and the flow speed ahead is increased to the condition shown in Fig. 3b, the shock front at the near-wall region bends backward more seriously, behind which pressure starts oscillation along the wall. Some close-up views of the wave structure near the wall are given in Fig. 4, in which parameters are free of experimental limitations. In Fig. 4a and Fig. 4b, the shock strengths are the same (Ms2=1.2) but the flow speeds ahead are different. The pressure distributions along the wall surface for these cases are shown in Fig. 5a and Fig. 5b, respectively. It can be clearly seen that when the flow ahead is slow, the shock deformation is less (Fig. 4a) and only one pressure peak exists immediately behind the reflecting point (Fig. 5a). As the flow ahead becomes faster, not only the shock front is strongly distorted (Fig. 4b), but also the pressure behind starts oscillation (Fig. 5b). A natural question is how does the pressure oscillation come from? One explanation might be reasonable through an analysis with steady flow concept. Since the growing speed of the boundary layer is almost negligible compare to the shock wave propagation, it is acceptable to attach a frame of reference on to the shock front and make the flow in the vicinity of shock wave nearly steady in the moving frame of reference. It is well known that the flow behind a normal shock in steady flow is subsonic and pressure waves can only exist in supersonic flow. Based on a coordinate transfer calculation through numerical data it was found that, although the outer flow behind the shock is subsonic as expected, the flow speed increases when approaches to the wall and indeed it becomes supersonic near the wall for the cases when the pressure oscillation occurs.

Another combination of Fig. 4b and Fig. 4c demonstrates the variation of wave pattern when shock strength changes, since the flow speeds ahead are the same (Ms1=3.0). The pressure oscillation can only exist for weak shock cases and disappears when the shock becomes strong enough. As shown in Fig. 4c, although flow ahead of the shock is fast, since the moving shock wave is fairly strong the wave structure looks similar to the case of slow flow with weak shock shown in Fig. 4a. It needs to be mentioned that the wave patterns in Fig.4a and Fig. 4c are Mach-like reflection, while Fig. 4b is regular-like reflection.

4 Conclusions

Downstream-facing shock/boundary layer interaction is different from both the steady shock wave boundary layer interaction and the unsteady near wall interaction of a reflected shock at the end of the shock tube. The shock front bends backward in the near wall region. The higher the flow speed ahead and the weaker the shock strength, the more serious the shock front curves. Meanwhile, a high-pressure region is generated near the wall after the moving shock. A serial of pressure increases and decreases was found in the boundary layer when the flow speed ahead of shock is high and the shock is weak, for which the numerical examination showed locally transonic flow exists near the wall in the frame of reference attached to the moving shock.

Acknowledgements. The authors would like to thank Mr. Nan Zong for his contribution to the research. This work was supported by Chinese Academy of Science.

References

1. Takayama K (ed) (1995) Shock Wave Handbook (in Japanese), Springer-Verlag, Tokyo, PP195-250
2. Han ZY, Wang ZQ, Yin XZ et al. (1985)A method for performing oblique shock-bow shock interaction in double driver shock tube (tunnel). Proc. 15th Int. Symp. On Shock Wave and Shock Tube, In: Bershader D, Hanson R (ed) Berkeley, California, pp533-540