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PROBREMS ON THE SONIC BOOM SIMULATOR USING A BALLISTIC RANGE II: CONFIGURATION OF TEST SECTION

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Abstract

Abrupt pressure changes produced by supersonic projectiles in a ballistic range are investigated numerically. Unsteady Navier-Stokes and Euler equations are solved to simulate the flow fields around the projectiles in the range. The numerical data are compared with actual experimental results. Both Euler and Navier-Stokes calculations reproduce the peak overpressure of the abrupt pressure rise as the experimental value. Long flight-distances are required to obtain fully developed flow fields around the projectiles whose flight Mach number is close to unity.

Key Words: Supersonic Flow, Sonic Boom, Projectile, Pressure Measurement

1 INTRODUCTION

When an aircraft flies at supersonic speed, various pressure disturbances, which can be either compression or expansion waves, are generated around it. A family of the compression waves is collapsed to form a weak N-shaped shock wave called"sonic boom," which propagate from the craft toward the ground surface[1].

Aerodynamic facilities such as wind tunnels and ballistic ranges have been adapted to sonic boom generations and propagation studies in laboratory scale[2]. The ballistic ranges, of which a small projectile is launched into test section, are better instrument to investigate the properties of sonic boom than the wind tunnels, because the sonic boom can be obtained from the projectiles actually flying in the range.

Figure 1 shows a schematic diagram of the vertical ballistic range installed at Tokyo Noko Univ.[3][4] The ballistic range consists of a free-piston shock tube, a launcher and a test section. High-pressurized gas generated in the shock tube is used to drive the projectile. The pressure profiles against time are measured at several locations on the wall by using piezo-pressure transducers. At the same time, complicated flow fields around various projectiles are visualized by applying color schlieren photography to assure shock wave configurations as well as vortex generation around the projectile. Figure 2 shows a typical experimental result.

The present calculation is to design the test section of the ballistic range as a sonic boom simulator.

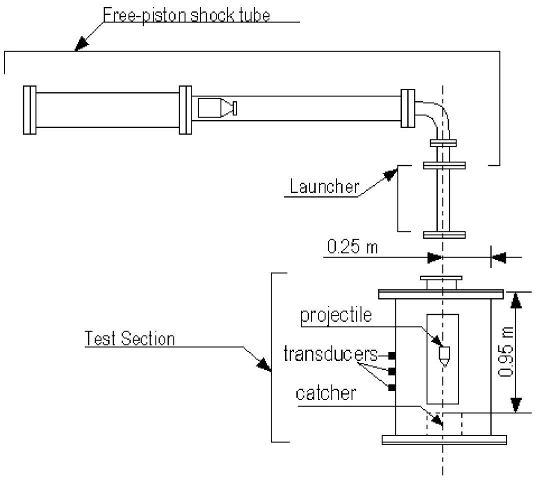

Fig.1: Vertical ballistic range at Tokyo Noko Univ.

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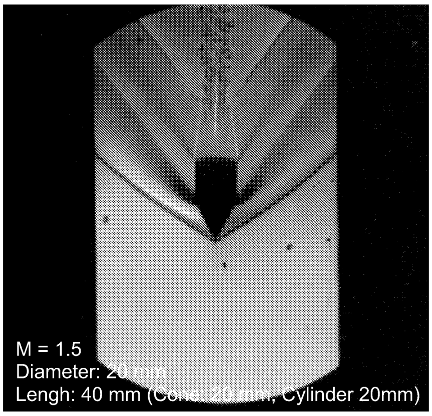
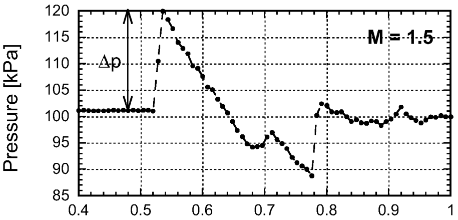


(a) Color Schlieren Photograph



(b) Pressure detected at side wall of the test section

Fig.2: Typical experimental result

The major aim is to clarify the adequate size of the test section for obtaining fully developed flow fields around the projectile in the range. Careful design should be required to obtain the fully developed flow fields. For example, blast wave exhausted from the launcher should be eliminated because it may interact with the flow fields around the projectile[3][5].

Firstly, steady solutions are obtained to examine viscous effects on the pressure signals, which is reflected on the sidewall of the ballistic range. The pressure distributions around flying projectiles are obtained with both Euler and Navier-Stokes equations. Adaptive grids are tested to capture weak pressure fluctuations such as sonic booms.

Secondly, unsteady calculation is conducted to estimate the flight distance to develop the flow field from the initial stage to the steady-state one.

The numerical results show that the effect of viscosity on pressure measurement is small. Long flight distances are required to develop the steady-state flow fields around the projectile when the flight Mach number is close to unity.

2 NUMERICAL METHOD

2.1 Governing Equations

Unsteady and steady calculations are conducted to simulate flow field around a supersonic projectile in a ballistic range. The governing equations are Navier-Stokes or Euler equations. The flow is assumed to be axisymmetric and to obey the perfect gas law. Thermal conduction is neglected not only in the gas phase but also between the gas and solid surface.

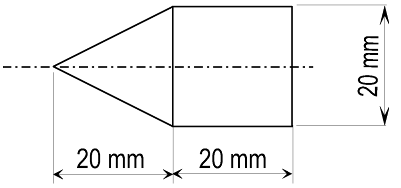


Fig.3: Projectile

2.2 Numerical Schemes

A finite volume method is employed to discretize a two-dimensional axisymmetric form of the governing equations[5].

Roe's flux difference splitting scheme[6] is used to evaluate the inviscid part of the numerical flux. An improved Chakravarthy-Osher TVD scheme[7][8] is used to obtain higher-order upwind-biased approximation for the flux.

A local time stepping is applied to improve convergence to the steady solutions.

Boundary-fitted, structured grids are used in the present calculation. The two-boundary technique[9], a kind of algebraic mapping, is applied to generate the grids. Solution adaptive-grids[8] are also tested in the steady calculation.

3 CONFIGURATION OF TEST SECTION, COMPUTATIONAL DOMAIN, BOUNDARY CONDITIONS

The numerical conditions are determined to reproduce the experimental data obtained in the ballistic range at Tokyo Noko Univ.(Fig. 1)

Figure 3 shows the projectile used in the experiments. The projectile is a circular cylinder with a conenose. The diameter, total length, and nose length are 20 mm. The projectile is launched into the test section with atmospheric pressure and room temperature conditions at rest.

Figure 4 shows the configuration of the test section with the computational domain for the present calculation. The projectile is launched into the test section from an inlet, and is shot at a catcher. The section has an inner diameter of 250 mm. The flight distance from the inlet to the catcher is 950 mm. The inlet is opened to atmospheric air with room temperature conditions.

Figure 5 shows the boundary conditions applied to the calculation. Notice that the wall conditions for

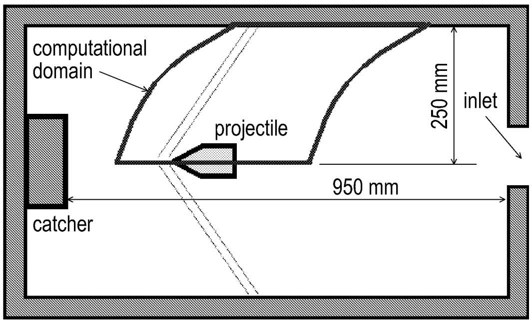


Fig.4: Configuration of test section and computational domain

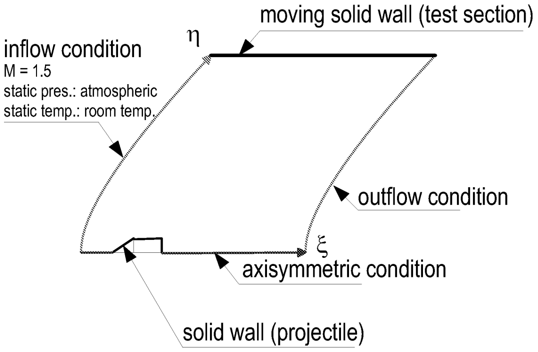


Fig.5: Boundary conditions

the outer boundary in the Navier-Stokes calculation. The wall should be a moving wall whose speed is the same as the projectile, in order to reproduce the exact experimental conditions in the ballistic range.

4 VISCOUS EFFECTS ON PRESSURE MEASUREMENTS

4.1 Numerical Conditions

Steady solutions are obtained by solving unsteady Navier-Stokes or Euler equations.

The test section is in atmospheric pressure and room temperature at rest.

The speed of projectile is chosen at M = 1.5, although the present ballistic range can launch projectiles at several speeds. The peak overpressure Δp, defined in Fig. 2(b), detected at the sidewall of the test section is 18.3 kPa.

4.2 Navier-Stokes Equations

Figure 6 shows the numerical result obtained by solving the Navier-Stokes equations. Grid and pressure contour are displayed in Fig. 6. In the pressure contour, some pressure profiles at specific locations are also indicated. The number of grid points is 216×216.

N-shaped pressure profiles are generated around the projectile. The peak overpressure detected on the sidewall of the test section is computed as 17.0 kPa, which is slightly smaller than the actural experimental value (18.3 kPa).

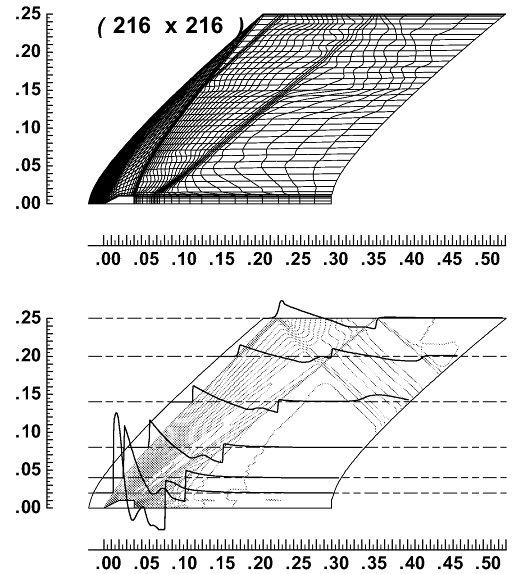


Fig.6: Steady flow field around a supersonic projectile at M = 1.5 (1) Navier-Stokes code

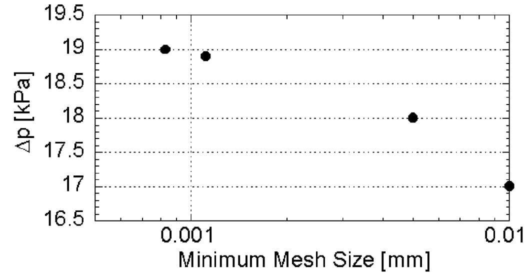


Fig.7: Peak overpressure versus minimum mesh spacing. Navier-Stokes code

Better results can be obtained by minimizing mesh spacing close to the outer boundary. The Navier-Stokes calculation requires sufficiently small mesh spacing to avoid numerical dissipation. Figure 7 shows the peak overpressure versus the minimum mesh spacing. As the mesh spacing decreases, the peak overpressure reaches 19 kPa, which is approximately the same as the experimental value.

4.3 Euler Equations

Figure 8 shows the numerical result obtained by solving the Euler equations. Solution adaptive procedure is applied to obtain this result. The number of grid points is 193×184.

The peak overpressure at the outer boundary is 19.4 kPa, which is approximately the same as the numeri-

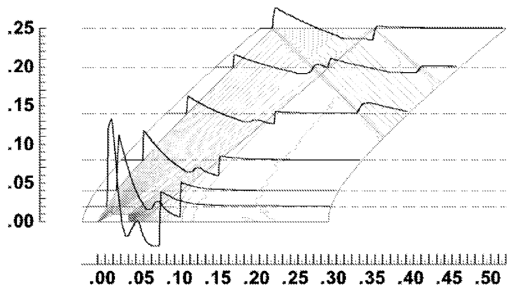


Fig.8: Steady flow field around a supersonic projectile at M = 1.5 (2) Euler code

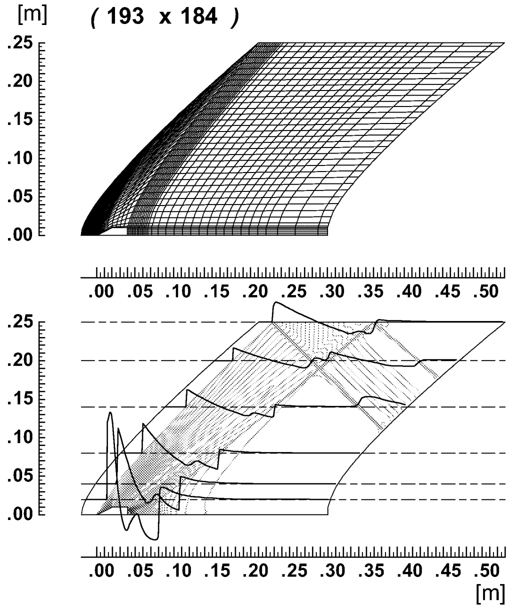


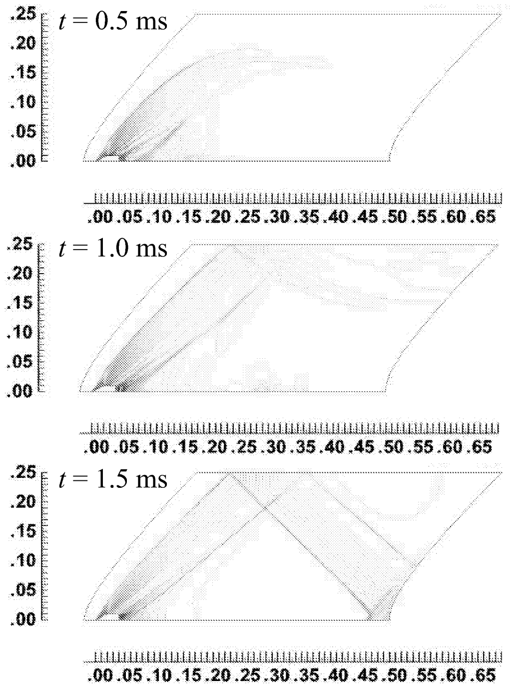
Fig.9: Steady flow field around a supersonic projectile at M = 1.5 (3) Euler code, non-adaptive grid

cal result by the Navier-Stokes code. This agreement indicates that viscous effect is not important for detecting the peak overpressure in the present ballistic range, though it has considerable influences on the flow behind the projectile.

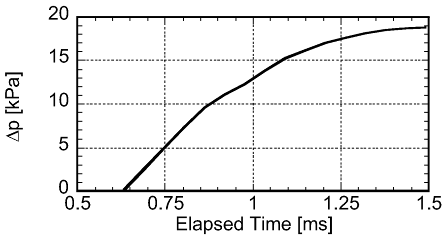
The solution adaptive procedure is not needed in the Euler calculation to capture the peak overpressure. Figure 9 shows the numerical result in which the adaptive grid is not used. The peak overpressure is computed as 18.8 kPa, which is close to the experimental value.

5 FLIGHT DISTANCE

Unsteady computation is conducted to clarify developing process of the flow fields around a supersonic projectile. In order to use a ballistic range as a sonic boom simulator, it is necessary to obtain the fully developed flow fields around the projectile within the range. Euler equations with non-solution adaptive grids are used to simulate the unsteady process.



(a) Pressure contours



(b) Peak overpressure

Fig.10: Development of flow field around a projectile at M = 1.5. Euler code

Figure 10 shows three instantaneous pressure fields at different time levels. A line graph associated with the pressure contours displays the time history of the first peak overpressure detected on the sidewall of the test section (see Figs. 1 and 2). The flight Mach number is 1.5. The configuration of the projectile is the same as that shown in Fig. 3.

Pressure waves generated around the projectile gradually propagates thorough the surrounding air ($t = 0.5$ ms). Then, the waves reach the sidewall of the test section, and reflect at the wall ($t = 1.0$ ms). Finally, the flow field is developed into steady state ($t = 1.5$ ms). The peak overpressure increases during the development of flow field around the projectile.

Figure 11 shows duration to develop the flow fields to steady state at several different flight-Mach num-

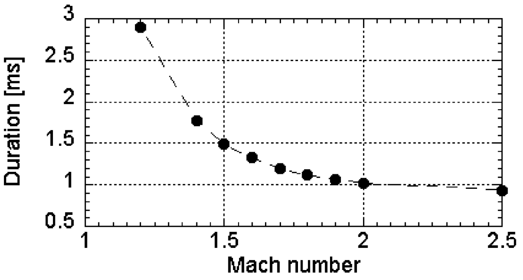


Fig.11: Duration vs. Mach number

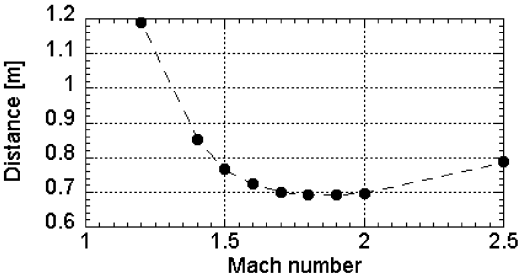


Fig.12: Flight distance vs. Mach number

bers. The duration decreases as the Mach number increases. Since the pressure disturbance is strong at large flight Mach number conditions, the propagation velocity of pressure waves becomes larger as the Mach number increases.

Figure 12 shows the flight distance required to obtain the fully developed flow field around the projectile. The distance is defined as the flight speed of the projectile multiplied by the duration, which is shown in Fig. 11. The minimum flight distance is obtained at M = 1.8. The distance substantially increases when the Mach number is close to unity. This implies that large test section should be needed to capture the sonic boom generated by the supersonic projectile with the flight speed close to sonic one.

6 CONCLUSIONS

Numerical simulation is conducted to design a ballistic range as a sonic boom simulator. The numerical conditions are determined to simulate the actual experimental data obtained in the ballistic range at Tokyo Noko Univ.

In order to examine viscous effects on the pressure measurements in the ballistic range, steady solutions for pressure fields around a supersonic projectile are calculated by Navier-Stokes and Euler codes. Solution adaptive-grids are used to capture abrupt pressure changes produced by the projectile. The peak overpressure in an abrupt pressure rise detected on the sidewall of the test section is compared with the numerical results.

The steady calculation indicates that the viscous effect on the peak overpressure is small. Sufficiently small mesh spacing should be required to obtain the reliable pressure field by the Navier-Stokes code.

Unsteady calculation is performed to estimate the flight distance for achieving fully developed pressure fields around the projectile. The results show that the distance depends on the flight Mach number. Substantial distance should be required when the flight Mach number is close to unity.

The numerical simulation based on CFD is an effective tool to develop experimental facilities such as the ballistic range.

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