A Study on the Unsteady Aerodynamics of Projectiles in Overtaking Blast Flowfields

C.K.Muthukumaran* · G.Rajesh* · Vincent Lijo** · Heuy Dong Kim**†

ABSTRACT

A projectile that passes through a shock wave experiences drastic changes in the aerodynamic forces. These sudden changes in the forces are attributed to the wave structures produced by the projectile-shock wave interaction. A computational study using moving grid method is performed to analyze the effect of the projectile-shock wave interaction. Cylindrical and conical projectiles have been employed to study such interactions. This sort of unsteady interaction normally takes place in overtaking blast flow fields. It is found that the overall effect of overtaking a blast wave on the unsteady aerodynamic characteristics is hardly affected by the projectile configurations. However, it is noticed that the projectile configurations do affect the unsteady flow structures and hence the drag coefficient for the conical projectile shows considerable variation from that of the cylindrical projectile. The projectile aerodynamic characteristics, when it interacts with the secondary shock wave, are analyzed. It is also observed that the change in the characteristics of the secondary shock wave during the interaction is different for different projectile configurations.

Key Words: Aerodynamic(공기역학), Projectile(발사체), Shock Wave(충격파), Launch Tube(발사관), Numerical Method(수치해석 방법)

1. Introduction

Launching of a projectile is associated with many complicated fluid dynamic processes such as the shock wave diffraction at the exit of the launch tube [1], secondary shock wave development [2], generation of contact discontinuities and associated instabilities [3]. When the projectile leaves the launch tube, there are various types of interactions between the projectile and the unsteady flow structures [4]. The shock wave dynamics of a moving projetile in the unsteady flow field is computationally studied previously by Jiang and Takayama [4]. They noticed that the interaction between precursor shock wave and bow shock wave are strongly dependent on the projectile speed. They observed that when the bow shock wave catches up to the precursor blast wave, the interaction of these two shock waves produces a contact surface. Though the fluid dynamics of the flow field was fairly explained in their work, the aerodynamics associated with the flying

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projectile in the near field has not been addressed. Watanabe [5] studied the projectile arodynamics when it overtakes the blast wave using numerical methods. They used the one-dimensional theory to analyse the various overtaking criteria. They argued that the possible overtaking can be either subsonic or supersonic depends on projectile relative mach number.

A computational study on the projectile overtaking a blast wave was performed by Rajesh et al [6]. Their results show that the projectile flow field cannot be catagorized based on the relative projectile mach number as the Mach number of the blast wave is continuously changing. It is also shown that the the aerodynamic characteristics of the projectile are hardly affected by the overtaking process for smaller blast wave Mach numbers as the blast wave will become weak by the time it is overtaken by the projectile. They noticed that the projectile drag coefficient is greatly affected by the unsteady flow structures than the overtaking process.

In this paper, a computational study is performed using moving grid method, to analyze the effect of the configuration of the projectile on the overtaking process. It is also planned to study the effect of the projectile configuration on its interaction with the secondary shock wave. Cylindrical and conical projectile configurations are employed to perform this study for various initial blast wave Mach numbers which in turn decides the projectile mach numbers.

2. Computational method

The computational study has been performed using a commercial software CFD-Fastran, which makes use of density-based finite volume method that solves the two-dimensional axi-symmetric Euler equations. It employs chimera mesh scheme for the structured grids. For simulating the projectile motion, this chimera mesh scheme allows the overlapping of one zone over the other. The communication between the chimera cells and the overlapping cells is established through trilinear interpolation. The projectile is identified as the moving body with six degrees of freedom. The projectile motion is modeled with Euler''s equations of motion which is numerically solved at every time step and it requires the physical informations of the projectile such as mass, moment of inertia.

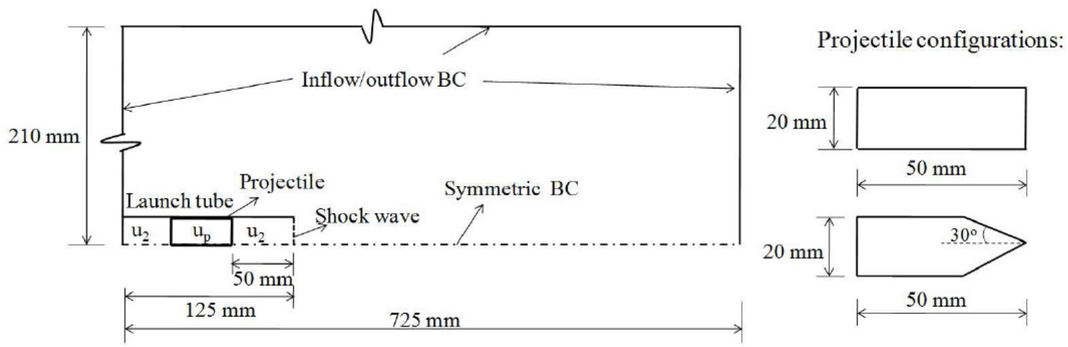


Fig. 1 Computational domain, boundary conditions and Projectile configurations.

The solver uses Van Leer''s flux vector splitting scheme with higher order spatial accuracy with Osher-Chakravarthy flux limiter. The time integration is carried out using point Jacobi fully implicit scheme.

2.1 Computational domain, Grid system and Boundary conditions

The computational domain, the boundary condition and the configuration of the projectile for the present study are illustrated in Fig. 1. The projectile has a length of 50 mm, diameter of 20 mm and the half-cone angle for the conical projectile is 30°. The computational domain and the conditions that are used here is same as that used by Rajesh and Kim [6]. Based on a grid independent study performed [6], the number of cells that have been chosen here is 300000. When the computation starts, the moving shock wave is assumed to be at the exit of the launch tube in which the projectile is kept inside at a distance of 50 mm behind the shock wave. The flows ahead and behind the projectile are assumed to be in the same condition as that of the flow behind the moving shock wave that is at the exit of the launch tube, and the projectile also is moving with the velocity of the flow behind the moving shock wave when the computation starts.

3. Results and Discussion

The acceleration histories of the cylindrical and the conical projectile are compared in Fig. 3a. Various state points are marked in the figure based on the interactions. The acceleration histories of the cylindrical projectile passing through unsteady flow structures is discussed in [6]. Till state b, where the projectile starts interacting with the secondary shock wave, the cylindrical and conical projectiles shows similar features in acceleration histories. At state b, there is a sudden drop in the acceleration of both the projectile configurations. This is the point, where the projectile interacts with the secondary shock wave and enters into a flow field, where the relative Mach number becomes supersonic. From the state c to d, there is a fluctuation in the acceleration of the cylindrical projectile. This can be attributed to the formation of the bow shock wave infront of the cylindrical projectile [6].

From the acceleration history of the conical projectile, as shown in Fig. 3a and Fig. 4a, the fluctuation corresponds to the interaction with the secondary shock wave is not observed. This shows that the interaction between the projectile and the secondary shock for the case of cylindrical projectile and conical projectile is quite different from each other. This is due to the difference in the configuration and its effect on the flow field. The smooth interaction between the conical projectile and the secondary shock wave reflects the fact that during the formation of bow shock wave, the excursion of expansion wave does not occur. To investigate the aerodynamic characteristics of the projectile, the drag coefficient histories of the projectiles are plotted in Fig. 3b and Fig. 4b, where the drag coefficient is defined in [6]. The same trends as those of the acceleration history can be seen for the C_d curves of both the cases of M_{p1}.

As the projectile passes through the secondary shock wave, the relative projectile Mach number increases to supersonic state. The detached bow shock wave develops in front of the conical projectile, as shown in Fig. 2d, since the relative projectile Mach number is less than the critical Mach number for this half cone angle. The relative projectile Mach number increases gradually due to changes in the flow conditions behind the attenuating primary blast wave. From the state e onwards, the drag coefficient of the conical projectile is significantly less than that of the cylindrical projectile, as shown in the Fig. 3b and Fig. 4b. This verifies the strength of the bow shock wave develops infront of the conical projectile is weaker than that of the cylindrical projectile. As the projectile overtakes the blast wave, the bow shock wave interacts with the blast wave and forms a triple point on the either side of the projectile. This corresponds to state g in Fig. 3, where there is only a slight fluctuation in the drag and the overtaking phenomena hardly affects the unsteady drag of the projectile irrespective of its configurations.

It is also noticed that during the interaction, the dynamics of the shock wave depends on the configuration of the projectile. This can be clearly seen from the Fig. 2b and Fig. 2c, for the case of cylindrical projectile, the shock wave preserves its shape till the interaction. But for the conical projectile, the characteristics of the secondary shock wave changes as it is approached by the conical face of the projectile. This mainly due to the turning of the flow field in the vicinity of the conical face of the projectile. This causes the normal shock wave to evolve as oblique shock wave to meet the downstream flow conditions.

To identify the overtaking process, the x-t relation of the projectile and blast wave is shown in Fig. 5a. It can be seen that the speed of the projectile in the near field region is constant due to its high inertia. But the blast wave attenuates with space and time.

The overtaking process is identified as the point, where the x-t curve of projectile and

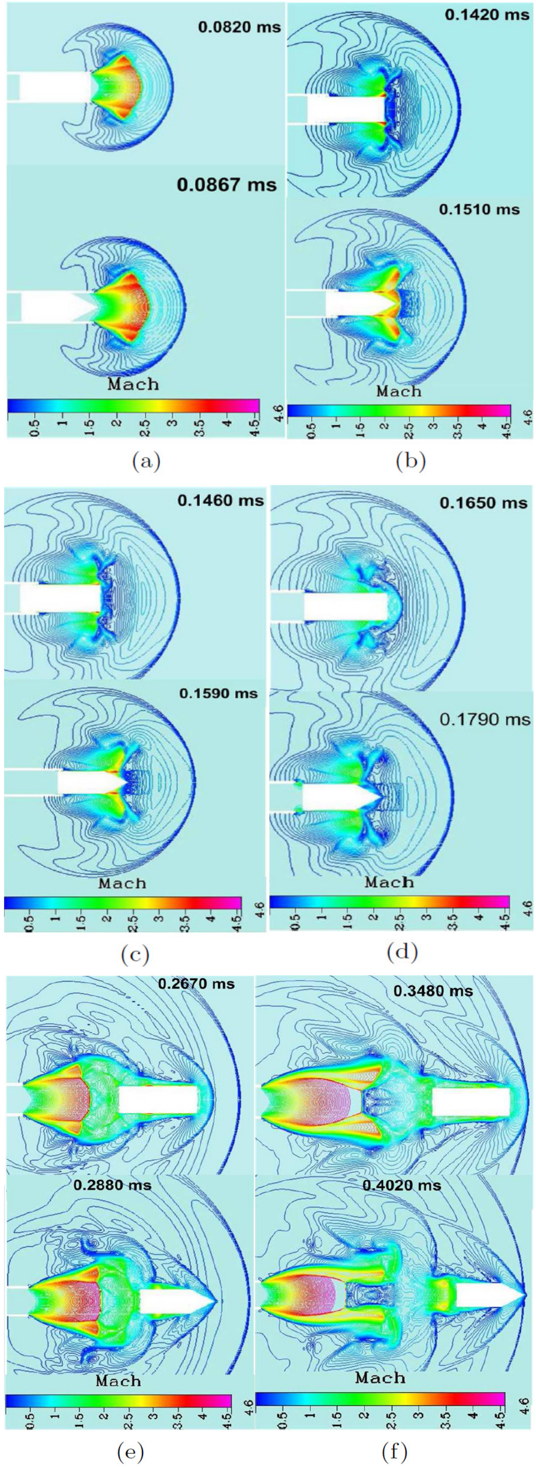
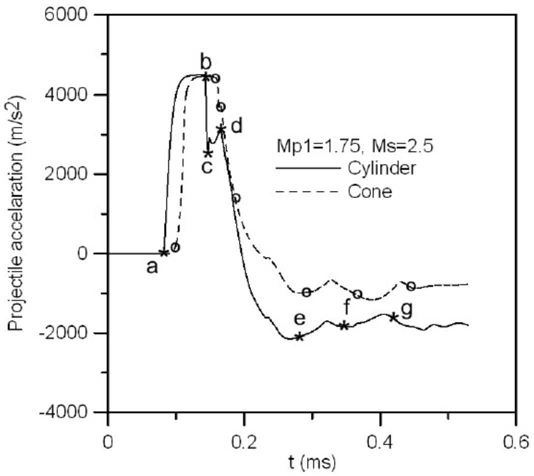


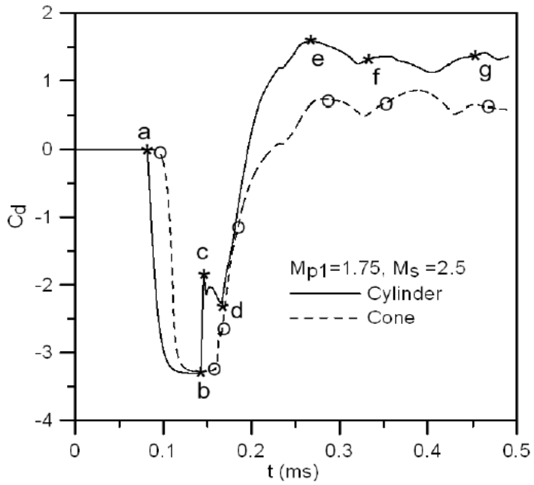
Fig. 2 Mach contours of the cylindrical projectile for M_{P1}=1.75 and M_s=2.5

blast wave meets. The overtaking time and distance are being same for both the projectile configurations.

The variation of M_s and M_{p2} of the conical projectile with time is shown in fig. 5b. It clarifies the effect of the attenuating blast wave on the overtaking process. It can be seen that during the whole overtaking process, the blast wave Mach number is varying from seen that during the whole overtaking process, the blast wave Mach number is varying from an impossible overtaking ($M_{p1}<M_s$) condition to possible one ($M_{p1}>M_s$). The overtaking is impossible until time t_1 for the case of $M_{p1}=3$ and time t_2 for the case of $M_{p1}=2.5$, since the blast wave travels faster than the projectile, and above this time the overtaking becomes possible due to the blast wave attenuation.

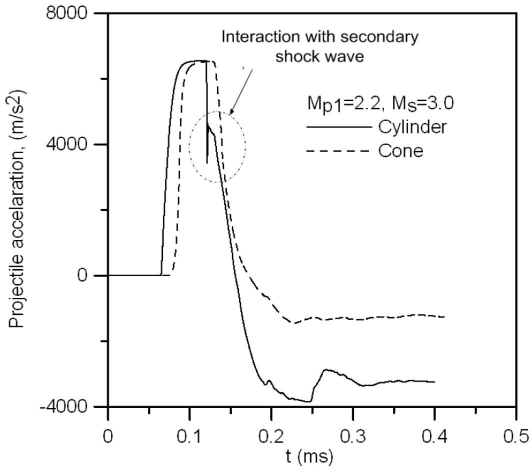


(a)

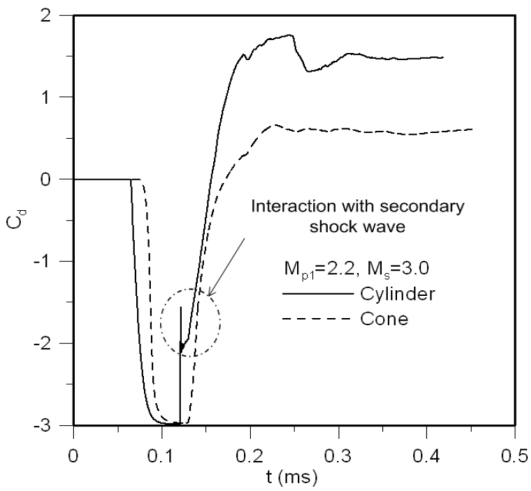


(b)

Fig. 3: a: Acceleration history of the projectile. b: Drag coefficient history of the projectiles, for M_{P1}=1.75 and M_s=2.5



(a)



(b)

Fig. 4: a: Acceleration history of the projectile. b: Drag coefficient history of the projectiles, for M_{P1}=2.2 and M_s=3

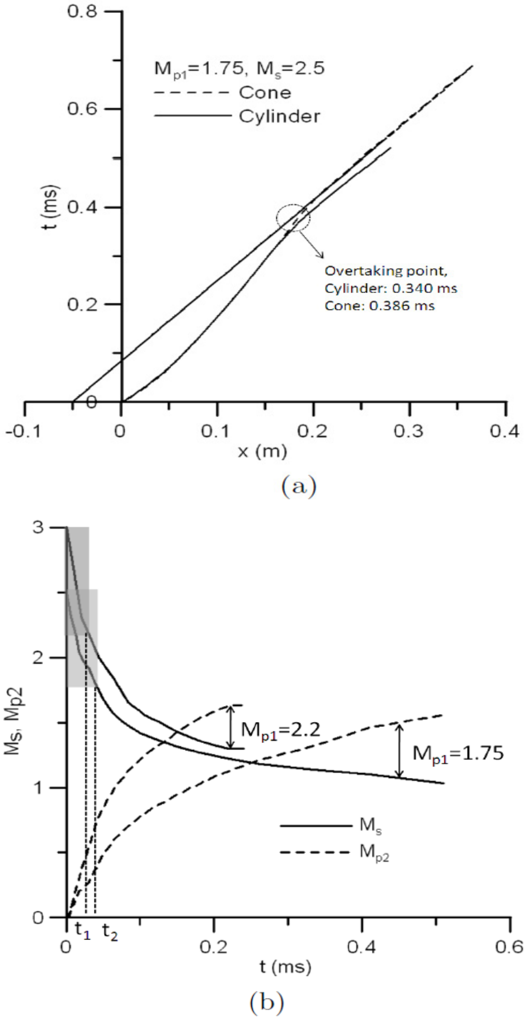


Fig. 5: a: x-t diagram of projectile and blast wave. b: variation of M_s and M_{p2} of conical projectile with respect to time

4 Conclusion

A computational study was performed to analyse the effect of the configuration of the projectile on overtaking blast flow field as well as its interaction with secondary shock wave in the unsteady flow field. The study shows that the aerodynamic characteristics of both the projectile configurations is unaffected during overtaking process as they undergo only supersonic overtaking. But the projecile configurations determines the aerodynamic characteristics, when it travels in unsteady flow field, especially when it interacts with the secondary shock wave. This interaction between the projectile and the secondary shock wave is highly transient, since the projectile relative Mach number becomes supersonic as it passes through the secondary shock. It is also observed that the shock wave dynamics of the secondary shock wave is characterized by the configuration of the projectile it interacts.

Acknowledgment

"This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MEST) (No. 20110027283)."

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