Title:
External Ballistics for an Anti-Aircraft Gun with Flow Simulations around a Bullet

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Introduction:
External ballistics has been researched for a long time because it is one of key factors in the design process for an anti-aircraft gun. The trajectory of a bullet from artillery is affected by many parameters such as mechanical and environmental conditions. The main parameters include the traverse and elevation angles of a gun barrel, muzzle velocity, rotational speed and mass of a bullet, wind velocity, etc.

External ballistics has been established and developed with the point mass trajectory model. Ignoring the Magnus force and pitching force of a bullet referring to the study of Lieske and Reiter [1], a modified point mass model is dependent only the drag and the lift of a bullet and can be expressed as the following equation.

$$\frac{\partial \vec{u}}{\partial t} = -\frac{\rho C_D S}{2m} v\vec{v} + \frac{\rho C_L S}{2m}\left[\vec{v}\times\left(\vec{x}\times\vec{v}\right)\right] + \vec{g} \qquad (1)$$

Here, $\vec{u}$ is velocity of a bullet with respect to ground, $\vec{v}$ velocity with respect to wind, $\vec{x}$ unit vector along the longitudinal axis of a bullet, $\vec{g}$ the gravitational vector , C_D drag coefficient, C_L lift coefficient, S cross-section area of a bullet, and m mass of a bullet. In particular, drag and lift coefficients play an important role to determine the trajectory of a bullet and two parameters are affected by mainly the shape, velocity and yaw angle of a bullet. Therefore, this study is focusing on the mechanical phenomena and the trajectory of a real bullet with different velocity and yaw angle.

Test Case and Numerical Method:
A bullet used in this study has a real geometry made by a company in South Korea for an anti-aircraft gun. The mass and diameter of a bullet are 0.235kg and 30mm respectively. The initial speed and elevation angle of a gun barrel are fixed as listed in Table 1. The flow simulations have been conducted for three different yaw angles to obtain the drag and lift coefficients. The yaw angle is an angle between the longitudinal axis and the center of a bullet as shown in Fig. 1. Then, the trajectories of a bullet have been computed for two different cross winds.

Parameter	*Mass*	*Diameter(D)*	*Initial speed*	*Elevataion angle*	*Yaw angle(α)*	*Cross wind*
Value	0.235kg	30mm	1000m/s	30°	0°, 2°, 4°	0m/s, 5m/s

Tab. 1: Parameters for computing trajectories of a bullet.

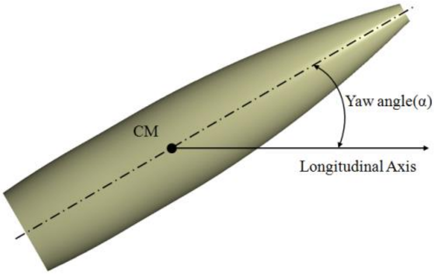


Fig. 1: Definition of yaw angle.

Steady flow simulations for bullets with different yaw angles and speeds have been conducted using a commercial flow solver, Ansys CFX-14 [2] to obtain the drag and lift coefficients. High resolution scheme was applied to capture a shock around a bullet and the k-ω SST (Shear Stress Transport) model was employed to obtain the turbulent viscosity. The computational domain has a size of 20D×20D×60D with a least effects of boundaries as shown in Fig. 2. The computational mesh has about 700,000 nodes and y+ value is equal to or less than 3. The flow velocity has been varied from 50m/s to 1000m/s and the yaw angle has been changed to be 0˚, 2˚ and 4˚. The outlet boundary condition is specified as an ambient static pressure.

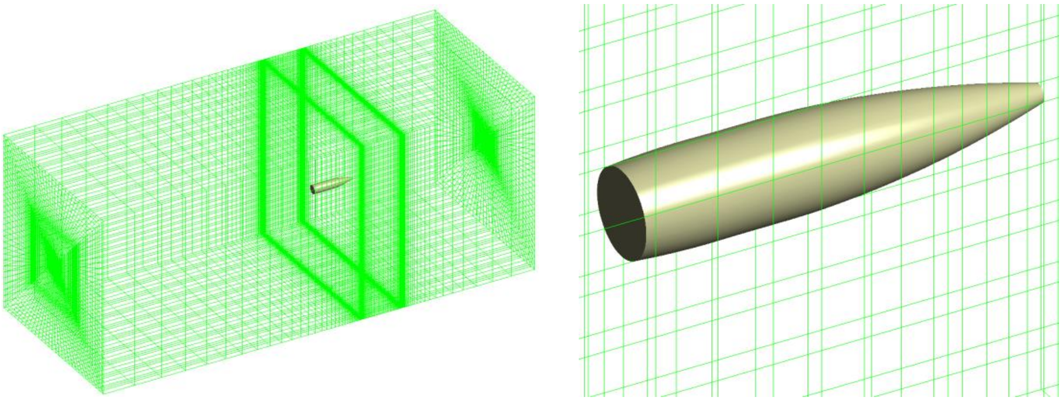
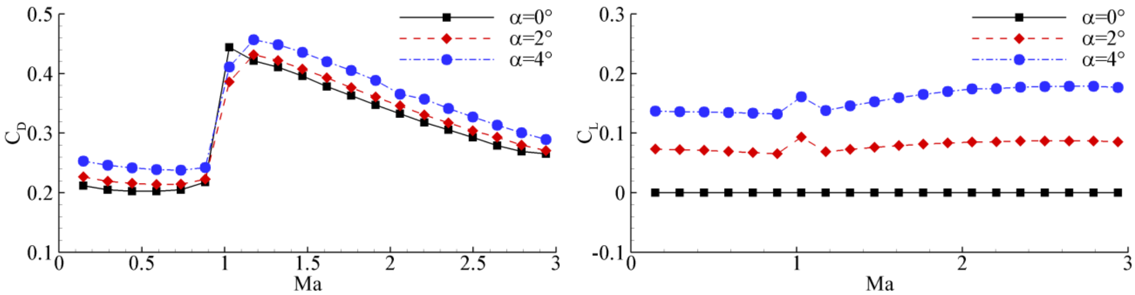
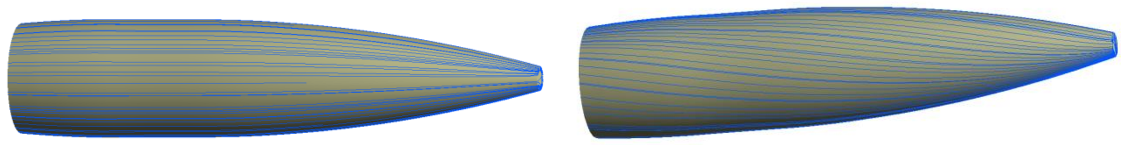


Fig. 2: Computational mesh and a bullet.



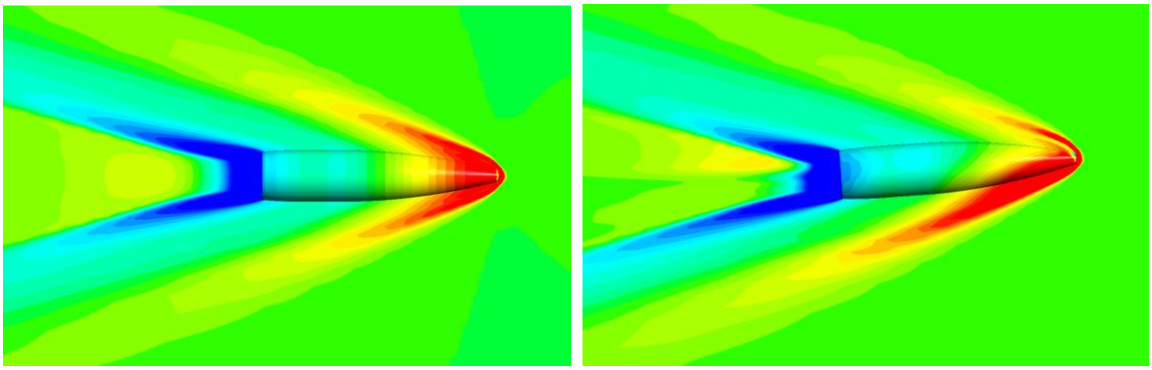
(a) Drag Coefficient (b) Lift Coefficient

Fig. 3: Effects of Mach number and yaw angle on a bullet.



(a) α=0° (b) α=4°

Fig. 4: Limiting Streamlines on the surface of a bullet.



(a) α=0° (b) α=4°

Fig. 5: Static pressure distribution.

Computational Result and Trajectory of a Bullet:

Figure 3 shows the drag and the lift coefficients of a bullet with different speeds and yaw angles. For the reference case with 0° of yaw angle, the drag coefficient is nearly constant for subsonic flow (Ma<1) and has a value of 0.2. The drag coefficient increases rapidly around Ma=1 but decreases steadily and slowly for a higher supersonic flow. The lift coefficient for the reference case remains constant independently of a bullet speed. For other two cases with higher yaw angles, the variation of the drag coefficient looks similar to the reference case, but the value of the coefficient is larger at each speed of a bullet than that of the reference case. It is worth noting that the drag coefficient at a fixed speed grows parabolically with the increase in the yaw angle. Unlike the reference case, non-zero yaw angles generate lift force around a bullet and the lift coefficient is linear to the yaw angle. It is necessary to analyze the flow field around a bullet to understand the variation of two coefficients.

The limiting streamlines and the static pressure distribution on the surface of a bullet are shown in Figs. 4 and 5 for two different yaw angles. The speed of bullet for these figures is 950m/s equal to Ma=2.8. The limiting stream lines are parallel to the center axis of a bullet for the reference case, but the limiting streamlines move from the bottom-right to the top-left and envelop the bullet with 4° of yaw angle. In the static pressure distribution on the surface of a bullet, the strong shock is formed in front of a bullet but the strong expansion wave at the rear part. The static pressure increases through the shock rapidly but decreases through the expansion wave. Consequently, high pressure region is formed at the front part but low pressure region at the rear part. This pressure difference is the main cause of drag and lift force of a bullet. For the reference case, the static pressure is axisymmetric about the center of a bullet so that the drag force is large but the lift force is negligible. With non-zero yaw angles, the static pressure at the front part is also larger than at the rear part and the static pressure at the bottom-right much larger than the top-right. For a bullet with non-zero yaw angles, therefore, both drag and lift forces are important.

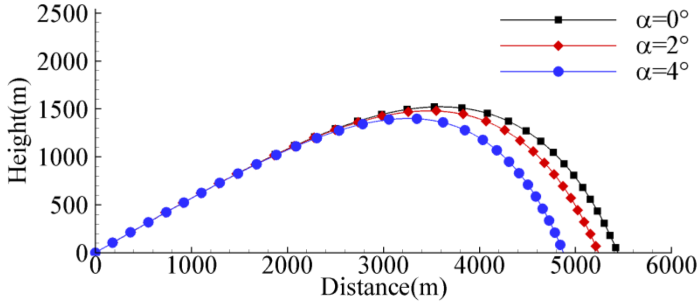


Fig. 6: Trajectories of a bullet without wind.

Finally, the drag and lift coefficients obtained from the numerical flow simulations are applied to the trajectory model and the results without cross wind are shown in Fig. 6. The trajectory with different yaw angles is calculated using the 4th Order Runge Kutta method. After being fired from a gun, a bullet is traveling to 2000m regardless of yaw angles but the difference in drag and lift coefficients caused by yaw angles affects the trajectories of each bullet thereafter. With increasing yaw angles, the maximum height and distance decrease due to the increased drag coefficient. Within the effective range of an anti-aircraft gun, usually 3000m, the difference in the point of impact varies within approximately 50m and can decrease hit probability significantly.

Conclusion:

This work analyzed the effect of yaw angle on the drag and lift coefficients and the corresponding trajectory of a real bullet. It is found that the trajectory of a bullet can be affected significantly by yaw angle. Although there is no result in the abstract for different cross winds and different shapes of a bullet, effects of other parameters have already been investigated and will be presented in the conference.

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[1] Lieske, R. F.; Reitter, M. L: Equations of motion for a modified point mass trajectory, BRL Report No. 1314, 1966.
[2] Ansys CFX-14 Manual, http://www.ansys.com, ANSYS, INC.