Computational Fluid Dynamics (CFD) of Drag Force for Bullet’s Shape Design

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Abstract. The factors in bullet’s shape design which affect the drag force of bullets are important in aerodynamics, especially in ballistics. In this paper, based on traditional researches about different bullet shape designs, nose cone design of the bullet is mainly discussed, as well as the hollow tip and the rifling on the appearance of the bullet are also included. This paper adopts Fusion360 and Ansys fluent to calculate and model. This research verifies the similarity of the drag coefficient of different bullet shape design at a low speed and figures out the best shape characteristic coefficient in Haack series design, while some problems still exists in the influence of hollow tips of the bullet to the drag force.

1. Introduction
The aerodynamic analysis of the nose cone design is very important for objects moving in a compressible fluid. Therefore, the most important issue is to describe the geometry of the nose cone in order to obtain the best aerodynamic performance. The geometric classification of the nose cone design has been discussed by Gary A. Crowell Sr. et al, in 1996[1]. Gary A. and Crowell Sr. adopted different diameter equations to describe the geometric characteristics of different nose cone designs, such as double cones, cones, and power series. In 1941, Wolfgang Haack[2] deduced HAACK series based on mathematics, and obtained the nose cone design with the least air resistance. Von Kamen also gave the design of the least resistance to a given length and diameter based on the design of the HAACK series[3].

Since Carvalho and Geovanio employed computational fluid dynamics, CFD, to analyze the resistance of different nose cone designs, traditional fluid mechanics research and design methods were changed,
and this method also promoted technological progress in fluid mechanics. Since three mathematicians, R. Courant, K. O. Friedrichs and H. Lewy pioneered the study of computational fluid dynamic in 1928[7]. This method has been well developed and recently some studies that combine computational fluid dynamics with deep learn and neural networks have also appeared to deal with large scale problems[8]. As a mature commercial application software, ANSYS Fluent software is a convenient and efficient choice to conduct some simple fluid calculation problems.

This paper will set out to verify the design of different nose cones under high-speed condition in air. It focuses on considering the bullet resistance at the actual speed of movement, which is the drag within the transonic speed region. In addition, there is possible effect of the rifling produced in the actual shooting of the bullet on the resistance of the bullet, thus this research will also discuss the influence of two different shapes of rifling on the resistance of bullets’ movement. This paper also hopes to verify the impact of hollow point in recent trend of competition bullet design. Meanwhile in the simulation of different nose cone designs, the method of finite element analysis is mainly used to carry out computational fluid dynamics on the produced model, and the simulation result of bullet drag flow will be discussed.

2. Mathematical model methodology
To simulate actual bullets, a cylinder behind each nose cone is necessary as the part where the bullet contacts the rifle. Meanwhile, the establishment of different models in this paper is mainly used to study the resistance of different nose cone designs under the condition of the same bullet quality and caliber, so the cylinder is also necessary to control the total volume. Moreover, to reduce the number of variables in future analysis, the aspect ratio of the nose cone will also remain the same in the modeling.

According to the normal bullet shape with caliber of 5.56mm in Optimum Bullet Study and some real bullets from a bullet manufacturer, SIERRA, the aspect ratio in the characteristic size of the bullet cone of the bullet manufacturer is usually between 2.5-3[4]. In order to make the conclusion more practical, caliber of all models will be 6.5mm(diameter = 6.71mm) and the length of nose cones will be 2.5 times of the diameter, 16.775mm. Moreover, according to some studies by Dave Emary, Sidra I. Silton and Paul Weinacht, effects of rifling and hollow point were also considered in the design of nose cones[4, 9]. Therefore, in this study, different geometric shapes will be produced to verify the influence of the rifles and hollow points. Here is a series of models established in Autodesk Fusion 360.

2.1. PARABOLIC Series
As Gary A. and Crowell Sr. summarized, “The Parabolic Series nose shape is generated by rotating a segment of a parabola around a line parallel to its Latus Rectum.” [1] By using their definition as equation.1, models include four different $K'$ in following values: $K'=0.25$, $K'=0.5$, $K'=0.75$, $K'=1$. The plan view of the bullet is shown in Figure 1-4. Here $y$ is equal to the radius of the nose cone of each x bullet.

\[
y = R \left( \frac{\frac{2}{3} (\frac{y}{R}) - K' (\frac{y}{R})^2}{2-K'} \right) \tag{1}
\]

2.2. HAACK Series
The geometry of the nose cone is defined by HAACK series (equation.2) from Gary A. and Crowell Sr.[1]. The models include four different $C$ in following values: $C=0$, $C=1/6$, $C=1/3$, $C=1/2$. For a given length and diameter, when $C = 0$, this shape (also called Von Karman Ogive) has the least resistance, and for a given length and volume, this shape has minimum drag when $C=1/3$. The plans of the bullets are Figure 5-8 shown below and $y$ equals to the radius of the bullet nose cone for each $x$. 
\[ \theta = \cos^{-1} \left( 1 - \frac{2z}{L} \right) \quad ; \quad y = \frac{R \left[ \frac{\sin(\theta)}{2} + \cos^2 \theta \right]}{\sqrt{\pi}} \] (2)

**Figure 1.** The plan view of the bullet of PARABOLIC series

2.3. **Hollow bullet tip**

As mentioned in previous study, the increasing drag of hollow point or exposed lead style designs are not as obvious as normal shape of bullets and more researches are required to give answer to this phenomenon[5]. Meanwhile, bullet manufacturers tend to hollow out the bullet’s head and claim that this can effectively reduce air resistance, just as shown Figure 17. Thus, by hollowing out the bullet’s head, eight new shapes based on the above designs are given. One example of the bullets are Figure 9 corresponded to figure 5.
Figure 2. The plan view of the bullet of Haack series

Figure 3. Bullet with hollow tips
2.4. Rifling
Sidra I. Silton and Paul Weinacht concluded that smooth rifling had few effects on normal moving condition of bullet with wind tunnel data[9]. Thus, rifling is added to each model of the hack series in this paper to compare the air resistance of the two series of models by using the computational fluid dynamics. Two examples of the bullet with riflings are Figure 10, 11, which are round and square riflings, and others' are similar to them.

![Figure 4. Bullet with round rifling](image)

![Figure 5. Bullet with square rifling](image)

3. Theoretical analysis

3.1 Fluid condition
According to Fluid Mechanics by Zhou, et al[10], the branch of hydrodynamics in which the effect of compressibility cannot be ignored and is usually called aerodynamics or compressible hydrodynamics. It usually researches on compressible flow at high speed in a small space. For such flows, the following assumptions can be made:
(1) The density of the fluid is not constant;
(2) The viscous effect of fluid is negligible;
(3) The flow is isentropic;
(4) The effect of gravity is negligible;
Considering the above assumptions, this paper uses the continuity equation and the motion equation of the inviscid compressible fluid motion and the gas equation to describe the dynamic problem.
This study only considers the steady state condition of the bullet drag problem, so there is no initial condition. In addition, the speed conditions and temperature conditions have to be given on the solid wall as the boundary conditions. For velocity conditions, it is generally necessary to give the normal phase velocity component of the wall and the velocity circulation around the solid surface. For temperature conditions, a common consideration is non-temperature jump conditions, that is, the temperature gradient on the solid surface is zero.
Even though an analytical solution can be given to some simple geometry models according to flow equations and solving conditions, this method can not solve most complex problems especially the actual problems. Therefore, this research turns to the computational fluid dynamics to analyze the nose cone design.

3.2 Dimensioned analysis
Dimensioned analysis is employed in this paper to analyze variables appearing in the experience. The density of the fluid($\rho$), the flow speed($v$), the sound speed($a$) and the viscous effect($\mu$) are considered as the variables of the fluid. Meanwhile, the length of the bullet, the caliber of the bullet and the characteristic coefficient like $K'$ and $C$ in equation 1&2 are considered as the variables of the bullet. Drag force of the bullet($F_d$) is the main variable in this problem. At the same time, length, time
and the dimension of mass are three basic variables. Therefore, five variables have to be considered in this experiment according to the dimensioned analysis. Three of these variables are listed below, while the characteristic coefficient (K' or C) and the aspect ratio of the nose cone ($\lambda' = \frac{L}{\pi}$) are two constants in this problem.

Drag coefficient:

Reynolds number:

Mach number:

Among these variables, drag coefficient and the characteristic coefficient are the variables that have to focus on figuring out the relationship between the drag and the shape design.

3.3 Simulation analysis

The simulation in this paper will consider three speed of bullet, about 100 m/s, that the Mash number is about 0.3, as well as about 310m/s, that the Mash number is about 0.9, and about 1000m/s, that the Mash number is about 3. In these three different situation, theoretical analysis is also needed for different fluid conditions.

When the Mash number is about 0.3, the velocity is about 100m/s. The fluid can be considered to be incompressible, so Mash number or the velocity of the sound will not be considered as a variable in experiences. At the same time, in computational fluid dynamics, pressure condition is needed to calculate the drag in the simulation. Some studies by Gary A. and Crowell Sr. and Chin SS., show that the drags of difference nose cones are close in low speed according to experiences[1, 11]. Thus, this research uses CFD to verify this conclusion.

As the summary about ballistics[12], the speed of normal rifle bullets used in rifle is 3-4 times of the velocity of the sound. Therefore, when the Mash number is about 3, the velocity is about 1000m/s, and the fluid have to considered to be compressible and the Mash number have to be a variable in experience or simulation. At the same time, because of air resistance, the bullet speed will decline after moving for a long distant. Therefore, it is meaningful to pay attention to the air resistance of bullets at the transonic speed.

4. Computational approach

4.1 Mesh setting

To make object meshed, this research used the analysis system in Ansys Fluent, Fluid Flow(fluent). After importing .step document which includes information of the models, the element size is 0.01m and the element order is linear. At the same time, the export format is set to be standard. Finally, the mesh has to be attached to the solid body.

4.2 Calculation condition

Several calculation conditions also have to be set. These conditions will be listed as below.

General setup: solver type is Density_Based and solver is steady.

Models: the energy equation option is needed and viscous model is Spalart-Allmaras.

Boundary Conditions: Far-field pressure flow conditions have to be set; the option of Mash number depends on the velocity of the bullet; flow direction is y-axis; wall of the bullet has to be smooth.

Material Conditions: the air has to be set as ideal-gas.

Report Definitions: a drag-monitor is needed to feedback drag-coefficient.
5. CFD simulation result

(1) As the simulation result in low flow speed, the drag coefficients of different appearances is about 0.148(0.141-0.155), and the influence of hollow tips and rifles is not obvious. Since the flow speed is about 100m/s, a low velocity, the friction effect not the pressure plays main roles in causing the drag. Therefore, as the boundary condition of the wall is set to be smooth, the drag effect is small at the low speed. Here will also give the pressure field of the flow in Figure 6.

![Figure 6. Pressure field of the flow at low speed](image)

(2) At a low flow speed, by using the k-epsilon equation, the astringency of the result is excellent, and further discussion is meaningless. While at a high flow speed, by utilizing the Spalart-Allmaras models, the astringency of the result is uncertain and more iterations are needed to calculate the result. Therefore, this research gives the relationship between several variables and iterations whose results have good astringency in Figure 13, to insure the model equations and the solver conditions are reasonable.

![Figure 7. Residuals of different variables](image)

(3) By comparing the drag coefficient of bullets in different Haack series shape, the best shape design in high flow condition can be given according to the Figure 8.

(4) The pressure fields of the flow of two different hollow tips situations of a same bullet appearance at about 340m/s are given in Figure 15-(1,2) as the compare and drag coefficients of them are also shown in Figure 14.

(5) Figure 16-(1,2,3) shows the flow pressure field of three asynchronous guns (no rifling, round rifling and square rifling) with the same bullet appearance, and drag coefficients of Von Karman Ogive design with different rifling are also shown in Figure 8.
Figure 8. Drag coefficient of different shape situations

Figure 9. Pressure field of flow with different hollow tips

Figure 10(1). Pressure field of flow with normal shape
6. Discussion
(1) As the simulation rustle in a low flow speed, the bullet shapes do not play a big role in flow drag. Meanwhile, in the same situation, the hollow tip of the bullet and the rifle have little effect.
(2) The bullets of Haack series design can indeed reduce the air resistance about three times of the speed of sound when moving at high speeds. The best design among the bullets of Haack series can reduce the resistance by 1/6 more than the simplest design of parabolic series. Moreover, in Haack series design, the Von Karman Ogive, C=0 in equation 2, performs the best. It reduces the drag by about 1/8 more a normal design, C=0.5 in equation 2.
(3) Observing the pressure field and the change of the drag coefficient of different hollow tips situations, it can be found that it is nearly the same at both high and low flow speeds. While since a different situation appeared in Dave Emary’s research, further studies have to be conducted. This study assumes that it is the precision in modeling affects the calculation fluid dynamics process, because when calculating the models with hollow tips, the astringency of the calculation process is not as good as other models.
(4) Observing the pressure field and the change of the drag coefficient of different rifle situations, it can be found that it is nearly the same at a high flow speed but it is quite different at a low speed. This paper assumes that rifle on the bullet increases the total area of the bullet, so that the drag caused by friction increases as well. On the other hand, when the bullet is moving at high speed, its effect is small, because the pressure difference between the front and rear surfaces has a much greater impact than friction.

7. Conclusion
This paper uses a more advanced method, namely, computational fluid dynamics. It is mainly used in aerospace engineering and aircraft design, to analyze the drag force for different bullet shape designs. The study calculates drag coefficients of different bullet shapes at both high and low velocity and compares them with each other. The result verifies the similarity of the drag force of bullet at low speed, and figures out the best shape characteristic coefficient in Haack series design. Meanwhile, the influence of riflings and hollow tips are also shown in the result. According to the simulation and the calculation, riflings on the surface of bullets affect little to the part of drag force which is caused by pressure difference. However, since the flow in the hollow space is complex, the influence of the hollow tips is not revealed notably in the result.
In the process of computation, the degree of refinement of the models sometimes affects the astringency of the equation, especially at the place with huge gradient. However, limited by the computing power of the computer, this article can not increase the refinement of models and meshes. Moreover, most factors of bullet shape design have been discussed in this article except the tail of the bullet. More discussion about it, especially by using CFD, will be appreciated in future researches.
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