Accuracy Analysis of Aerodynamic Calculation of Two-dimensional Ballistic correction Projectile based on Missile Datcom

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Abstract. Missile Datcom (hereinafter referred to as Datcom) is an aerodynamic engineering calculation software developed by the US Air Force Research Laboratory. It is commonly used in the preliminary design of the shape scheme of missiles, aircraft and other aircraft. In this paper, Datcom is used to calculate the aerodynamic parameters of a two-dimensional ballistic correction projectile (D2BCP), and the calculated data is compared with the wind tunnel test data. The analysis results show that Datcom calculates the axial force coefficient (CA) of the projectile with large system deviation, however, the deviation can be eliminated by a certain compensation, thereby obtaining a more accurate CA of the projectile. Datcom calculates the normal force coefficient (CN) with high Mach number accuracy, but there is an unacceptable deviation of the projectile CN calculated at small angle of attack (α). The calculation of pitching moment coefficient with α (CMα) is higher, but the error is larger under individual Mach numbers.

1. Introduction

The aerodynamic shape of the modified component of the two-dimensional ballistic correction project has a great influence on the flight stability, range, and dispersion of the projectile. Mastering the influence law of the aerodynamic characteristics and ballistic characteristics of the D2BCP under different modified component shape schemes is the basis for correcting the aerodynamic scheme design of the component [1]. A. Dupuis et al. conducted a wind tunnel test on a 155 mm projectile with four long straight wings mounted around the center of mass. The experimental data were compared with the calculation results of PRODAS and Datcom software, and the applicable conditions of different software were obtained, which provided a basis for the analysis of the aerodynamic characteristics of the projectile in the future [2]. Nicolas Hamel et al. used FLUENT software, Datcom software and semi-empirical formula to obtain the aerodynamic parameters of the projectile under different conditions [3]. The accuracy of the calculation results was not confirmed due to the lack of reliable test data. Qu Xianlin used the wind tunnel test to study the difference of aerodynamic parameters between the traditional projectile and the D2BCP with different modified components. The variation law of the CN, CD and rolling torque coefficient of each model was analyzed [4]. Ji Xiuling and Wang Haipeng used the
implicit TVD numerical format to study the influence of the modified component on the aerodynamic characteristics of the rotating projectile. The feasibility of the numerical calculation method was verified, and the variation of the aerodynamic parameters of the projectile with the fixed azimuth angle was obtained [5]. Wu Ping and Hao Yongping studied the aerodynamic characteristics of D2BCP modified ammunition by wind tunnel test and aerodynamic numerical simulation. The effects of different aerodynamic layouts on the aerodynamic characteristics of the projectile were analyzed [6-7]. It provides a basis for the aerodynamic shape design and research of the D2BCP. Xue Ming, Chen Shaosong and others used numerical simulation method to study the influence of the installation position of the rudder blade on the rolling characteristics of the projectile. It was pointed out that the rudder was installed in the cone section of the projectile, and the rolling moment coefficient of the projectile was improved in the transonic stage. In the supersonic phase, it is basically unchanged [8].

On the whole, due to the high cost of wind tunnel test, there are few literatures on wind tunnel test to study the aerodynamic characteristics of D2BCP. The researchers use numerical simulation software to perform aerodynamic simulation calculation. Compared with the numerical simulation software, Datcom has the characteristics of short calculation cycle, comprehensive acquisition of aerodynamic data, low calculation cost and low hardware requirements. It is mostly used for the demonstration and screening of the initial design of the aerodynamic shape design of the projectile. In this paper, a type 155 D2BCP is taken as the research object. The aerodynamic parameters are calculated by Datcom. Compared with the wind tunnel test data, the accuracy and error characteristics of the aerodynamic parameters are analyzed.

2. Datcom software introduction
Datcom's full name is Missile Data Compendium. Datcom uses a combination of empirical or semi-empirical formulas and theory to perform aerodynamic calculations, and uses the wind tunnel test data integrated in the software to interpolate the calculation results. When the software is running, firstly calculate the aerodynamic parameters of the aircraft body and rudder of the projectile, and then combine them with different combination coefficients and methods to finally obtain the aerodynamic parameters of the full bomb [9].

2.1. Aerodynamic calculation method
At subsonic speed and they $\alpha$ are less than $5^\circ$~$10^\circ$, the $C_N$ is calculated as:

$$C_N = -\frac{1}{S_{ref}} \int_{0}^{1} \int_{0}^{2\pi} C_p R \cos \theta d\theta dx$$

(1)

$C_p$ is the pressure coefficient.

$$C_p = -\frac{2}{U} \frac{\partial \phi}{\partial x} \left( \frac{\partial R}{\partial x} \right)^2 + \left( 1 - 4 \sin^2 \theta \right) \alpha^2$$

(2)

$$\phi = U \alpha \frac{R(x)^2}{r} \cos \theta$$

(3)

The pitching moment coefficient ($C_m$) is calculated as

$$C_m = -\frac{4\pi}{S_{ref} l_{ref}} \left[ \int_{0}^{1} (x_{ref} - x) (\alpha_0 + \varepsilon) R \frac{dR}{dx} dx + \int_{0}^{1} (x_{ref} - x) R^2 \frac{d^2 \varepsilon}{dx^2} dx \right]$$

(4)
When the $\alpha$ is large, the viscous flow theory of Allen and Perkins is used to divide the normal force and the pitching moment into a bit stream term and a viscous term, and then the calculation results are linearly superimposed. The calculation formula is:

$$C_N = -\frac{C_{Na}}{2}\sin 2\alpha \cos \frac{\alpha}{2} + \eta C_{De} \sin \alpha | \sin \alpha | \frac{S_p}{S}$$  \hspace{1cm} (5)

$$C_m = \frac{C_{Na}}{2}(\frac{x_{sp} - x_{cg}}{l}) \sin 2\alpha' \cos \frac{\alpha'}{2} + \eta C_{De} \sin \alpha | \sin \alpha | \frac{S_p}{S} \left(\frac{x_c - x_{cg}}{l}\right)$$  \hspace{1cm} (6)

$$\alpha' = \begin{cases} 
\alpha & -90^\circ < \alpha < 90^\circ \\
\alpha - 180 & 90^\circ < \alpha < 180^\circ 
\end{cases}$$  \hspace{1cm} (7)

$C_{Na}$ is the derivative of the $C_N$ to the $\alpha$, $C_{De}$ is the cross flow resistance coefficient.

In calculating the axial force coefficient, when $30^\circ \leq \alpha < 90^\circ$, the modified version of Allen and Perkins theory is used. When $\alpha > 90^\circ$, Jorgensen’s slender body theory is adopted, by reducing the dynamic pressure along the body. The axial force is corrected. The calculation formula is:

$$C_A = C_{A0} + C_{A\alpha} \begin{cases} 
\alpha & 0^\circ < \alpha \leq 30^\circ \\
\cos^2 \alpha & 30^\circ < \alpha < 90^\circ 
\end{cases}$$  \hspace{1cm} (8)

$C_{A0}$ is zero liter axial force coefficient, $C_{A\alpha}$ is the axial force coefficient when there is an $\alpha$.

### 2.2. Aerodynamic calculation of individual rudder

The calculation of the $C_N$ and the $C_M$ is divided into linear and nonlinear parts, which are respectively calculated and then added. The calculation formula is:

$$C_N = \frac{C_{Na}}{2}\sin 2\alpha + C_{Na\alpha} \sin \alpha | \sin \alpha |$$  \hspace{1cm} (9)

$C_{Na\alpha}$ is the rate of change of the $C_N$ with the $\alpha$ in the nonlinear part, which is related to the $\alpha$ and the airfoil.

$$C_m = \left(\frac{x_{ac} - x_{cg}}{l}\right) C_{NP} + \left(\frac{x_c - x_{cg}}{l}\right) C_{NV}$$  \hspace{1cm} (10)

$C_{NP}$ is the potential force coefficient of the potential, $C_{NV}$ is the viscous normal force coefficient. The calculation of the $C_A$ of the rudder is the same as the body and will not be described again.

### 2.3. Combination calculation of individual components

When combining components for calculations, Datcom considers the effects of interference between components. For angles of attack in the linear range (less than $10^\circ$), the transfer loads of the projectile and rudder are calculated by the method proposed by Nielsen, Pitt and Katali. When the $\alpha$ exceeds $10^\circ$, the “equal $\alpha$” is used (assuming that the influence of the normal force of the rudder can be expressed as
the $\alpha$ increment and added to the original $\alpha$ to form an equivalent $\alpha$). It has higher accuracy when the $\alpha$ is less than 30°.

3. Accuracy analysis of calculating aerodynamic parameters
The D2BCP selected in this paper is shown in Figure 1. The four rudders are located at the head of the projectile fuze. Figure 2(a) shows the correction component model of the fuze head including the rudder. Figure 2(b) is a schematic diagram of the rudder deflection. No. 1 and No. 3 rudders provide reverse rolling aerodynamic force for the fuze head, and No. 2 and No. 4 rudders provide ballistic correction force for the projectile, and four rudders are in a “+” configuration.

Figure 1. D2BCP model

![D2BCP model](image1)

Figure 2. Correction component model.

3.1. Wind tunnel test
In this paper, the wind tunnel test data of the D2BCP is taken as the standard. The test conditions are set as shown in Table 1, including the aerodynamic parameters corresponding to different Mach numbers and different angles of attack conditions. The test process is shown in Figure 3, Figure 3 (a) shows the arrangement of the projectile in the wind tunnel, and 3 (b) shows the test pattern. In this paper, the $C_A$, $C_N$ and $Mza$ are selected to analyze.

Table 1. Wind tunnel test condition setting.

| Serial number | 1    | 2    | 3    | 4    | 5    | 6    | 7    |
|---------------|------|------|------|------|------|------|------|
| MACH          | 0.8  | 1.05 | 1.2  | 1.52 | 2.01 | 2.51 | 3.02 |
| $\alpha$ °    | -6   | -4   | -2   | 0    | 2    | 4    | 6    |
| T K           | 280.2~293.2 |

Figure 3. Wind tunnel test

![Wind tunnel test](image2)
3.2. Datcom calculation
The wind tunnel test using the is a 1:2 reduction model with the actual D2BCP. Therefore, this paper selects the model with the proportional size of the wind tunnel test for calculation. The selected test conditions are the same as the wind tunnel test conditions. Minimize systematic errors caused by test objects and inconsistent conditions.

The $C_A$ and $C_N$ with different Mach numbers change with the $\alpha$ as shown in Figure 4 and Figure 5 (partial data). It can be seen from Figure 4 that the $C_A$ increases with the increase of the absolute value of the $\alpha$. When the $\alpha$ is the same as the absolute value, the $C_A$ of the positive $\alpha$ is slightly larger than the $C_A$ of the negative $\alpha$. This is due to the fact that the No. 2 rudder and the No. 4 rudder of the projectile correction assembly have opposite angles of 4°, which provide the upward normal force to the projectile. It can be seen from Figure 5 that the lift coefficient has a very linear relationship with the change of the $\alpha$.

The variation of the different coefficients with the Mach number is shown in Figure 6 to Figure 8 (partial data). It can be seen from Figure 6 that the larger the absolute value of the $\alpha$, the larger the value of the $C_A$, and the larger the overall $C_A$ when the projectile has a $4^\circ \alpha$. It can be seen from Figure 7 that due to the correction of the No. 2 rudder and the No. 4 rudder angle, there is also a positive $C_N$ when the $\alpha$ is 0, when the $\alpha$ of the projectile is $+4^\circ$, the value of the overall normal force coefficient is the largest. It can be seen from Figure 8 that the variation law of $C_{Ma}$ is similar to the $C_A$. As the Mach number increases, $C_{Ma}$ increases first and then decreases.
The wind tunnel test results of the axial force coefficient and the Datcom calculation results are shown in Table 2.

It can be seen from Table 2 that Datcom calculates the $C_A$ value to be too small at subsonic speed, and Datcom calculates the $C_A$ value to be too large at transonic and supersonic speeds. For $C_A$ at different Mach numbers, Datcom calculation results have larger systematic errors with wind tunnel test data. For the calculation results of different $\alpha$ of the same Mach number, there is a relatively consistent systematic error.

| $\alpha$ $^\circ$ | Wind tunnel | Datcom | error % | Wind test | Datcom | error % | Wind test | Datcom | error % | Wind test | Datcom | error % | Wind test | Datcom | error % | Wind test | Datcom | error % | Wind test | Datcom | error % |
|-----------------|-------------|--------|---------|-----------|--------|---------|-----------|--------|---------|-----------|--------|---------|-----------|--------|---------|-----------|--------|---------|-----------|--------|---------|
| 0.8             | 0.161       | 0.190  | 17.727  | 0.150     | 0.175  | 16.380  | 0.144     | 0.176  | 16.971  | 0.148     | 0.176  | 14.127  | 0.150     | 0.190  | 17.537  | 0.156     | 0.212  |
| 1.05            | 0.346       | 0.230  | -33.449 | 0.325     | 0.212  | -44.090 | 0.321     | 0.205  | -47.563 | 0.318     | 0.215  | -47.981 | 0.305     | 0.219  | -46.602 | -23.690    | 0.246  |
| 1.2             | 0.392       | 0.219  | -44.090 | 0.381     | 0.200  | -37.588 | 0.371     | 0.193  | -47.563 | 0.371     | 0.202  | -47.981 | 0.378     | 0.219  | -46.602 | -23.690    | 0.246  |
| 1.52            | 0.327       | 0.204  | -37.588 | 0.310     | 0.188  | -36.308 | 0.303     | 0.181  | -48.274 | 0.303     | 0.187  | -48.274 | 0.310     | 0.200  | -47.981 | -23.690    | 0.222  |
| 2.01            | 0.316       | 0.201  | -36.308 | 0.298     | 0.182  | -37.588 | 0.288     | 0.172  | -48.274 | 0.287     | 0.177  | -48.274 | 0.294     | 0.191  | -47.981 | -23.690    | 0.214  |
| 2.51            | 0.266       | 0.192  | -27.944 | 0.251     | 0.172  | -37.588 | 0.239     | 0.162  | -50.076 | 0.238     | 0.166  | -50.076 | 0.248     | 0.179  | -49.381 | -23.690    | 0.202  |
| 3.02            | 0.231       | 0.187  | -19.125 | 0.220     | 0.168  | -37.588 | 0.214     | 0.158  | -52.076 | 0.218     | 0.156  | -52.076 | 0.218     | 0.173  | -51.381 | -23.690    | 0.196  |

It can be seen from Table 3 that Datcom calculates $C_N$ accuracy higher when the Mach number.
is greater than 2.01, and Datcom calculates $C_N$ accuracy is lower at subsonic and transonic speeds. For $C_N$ with different Mach numbers, Datcom calculation results have larger systematic errors with wind tunnel test data. At the small angle of attack, Datcom calculated that the projectile lift coefficient error is large and unacceptable.

| $\alpha^{\circ}$ | Wind tunnel | Datcom | error % |
|------------------|-------------|--------|---------|
| 0.8              | -0.232      | -0.281 | 20.943  |
|                  | -0.146      | -0.159 | 9.173   |
|                  | -0.067      | -0.046 | -30.941 |
|                  | 0.008       | 0.056  | 645.672 |
|                  | 0.082       | 0.16   | 95.265  |
|                  | 0.168       | 0.274  | 62.621  |
|                  | 0.398       | 54.258 |
| 1.05             | -0.254      | -0.344 | 35.300  |
|                  | -0.159      | -0.191 | 20.209  |
|                  | -0.072      | -0.051 | -28.900 |
|                  | 0.011       | 0.074  | 554.288 |
|                  | 0.089       | 0.2    | 124.391 |
|                  | 0.178       | 0.34   | 91.398  |
|                  | 0.275       | 0.492  | 78.942  |
| 1.2              | -0.259      | -0.338 | 30.573  |
|                  | -0.167      | -0.191 | 14.207  |
|                  | -0.077      | -0.057 | -25.887 |
|                  | 0.009       | 0.061  | 590.827 |
|                  | 0.094       | 0.179  | 89.558  |
|                  | 0.188       | 0.312  | 65.719  |
|                  | 0.287       | 0.459  | 59.669  |
| 1.52             | -0.265      | -0.352 | 32.915  |
|                  | -0.161      | -0.206 | 27.855  |
|                  | -0.068      | -0.074 | 9.193   |
|                  | 0.024       | 0.041  | 69.492  |
|                  | 0.113       | 0.157  | 39.432  |
|                  | 0.210       | 0.288  | 36.843  |
|                  | 0.314       | 0.432  | 37.602  |
| 2.01             | -0.303      | -0.333 | 13.922  |
|                  | -0.187      | -0.199 | 9.772   |
|                  | -0.084      | -0.081 | -4.739  |
|                  | 0.013       | 0.022  | 121.543 |
|                  | 0.109       | 0.125  | 26.513  |
|                  | 0.211       | 0.244  | 24.852  |
|                  | 0.321       | 0.379  | 26.066  |
| 2.51             | -0.303      | -0.333 | 10.010  |
|                  | -0.180      | -0.199 | 10.531  |
|                  | -0.072      | -0.081 | 12.080  |
|                  | 0.029       | 0.022  | -23.744 |
|                  | 0.125       | 0.126  | -83.374 |
|                  | 0.236       | 0.244  | 3.548   |
|                  | 0.356       | 0.379  | 6.527   |
| 3.02             | -0.303      | -0.316 | 4.373   |
|                  | -0.177      | -0.189 | 6.713   |
|                  | -0.070      | -0.077 | 9.702   |
|                  | 0.033       | 0.018  | -44.785 |
|                  | 0.131       | 0.113  | -13.970 |
|                  | 0.242       | 0.226  | -6.577  |
|                  | 0.364       | 0.354  | -2.769  |

The wind tunnel test results of the $M_{2a}$ and the Datcom calculation results are shown in Table 4. It can be seen from Table 4 that the error of Datcom calculation results varies irregularly with the Mach number. Except for the individual Mach number, the error of $M_{2a}$ value is unacceptable, the overall error is not large, and the data is basically available.

| MACH | Wind tunnel | Datcom | error % |
|------|-------------|--------|---------|
| 0.8  | -0.00899    | -0.0084| -6.56   |
| 0.95 | -0.00788    | -0.0143| 81.47   |
| 1.05 | -0.01129    | -0.013 | 15.15   |
| 1.15 | -0.013      | -0.0096| -26.15  |
| 1.2  | -0.01316    | -0.0077| -41.49  |
| 1.52 | -0.01356    | -0.0162| 19.47   |
| 2.01 | -0.01676    | -0.0167| -0.36   |
| 2.51 | -0.01911    | -0.0162| -15.23  |
| 3.02 | -0.02077    | -0.0152| -26.82  |

4. Conclusion
In this paper, a two-dimensional ballistic correction projectile is taken as the research object. The wind tunnel test data of the project is used to analyse the accuracy of the aerodynamic parameters calculated
by Datcom. The analysis results show that Datcom calculates the $C_A$ of the projectile with large system deviation, but the deviation can be obtained by a certain compensation to obtain the accuracy $C_A$ under different $\alpha$ of different Mach numbers of the projectile. Under the high Mach number, Datcom calculates the $C_N$ with high precision, and calculates the lift coefficient of the projectile at small $\alpha$ with large deviation, and the deviation is unacceptable. Datcom calculates the $M_{za}$ with higher accuracy, but the error is larger under the individual Mach number, and the overall calculation result error is acceptable.

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