Research on flight stability of non rotating fin arrow shaft

Yachao Guo¹,a, Guanglin He¹,b and Jiashuo Zhang¹,c

¹School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China.
²xingchencho110@163.com, ³heguanglin@bit.edu.cn, ⁴644699667@qq.com

Abstract. To research the influence of the variable density fin arrow shaft warhead on flight stability, three different structures of non rotating fin arrow shaft warhead of the individual small caliber cluster arrow projectile is put forward and designed. The aerodynamic characteristics, static stability reserve and the change of the attack angle in the fin arrow shaft warhead are calculated and analyzed through using the static stability reserve theory and the rigid body trajectory equations. The results show that the static stability reserve of the variable density steel-aluminum composite fin arrow shaft warhead is about 21% ~ 27%, which is obviously higher than 13% ~ 17% of the single density steel material. When the initial velocity is 280 m/s and range is 100 m, the attack angle of the fin arrow shaft warhead of variable density and single density are reduced from ± 5 degree to within ± 1 degree. It is indicated that dynamic stability is guaranteed; however, dynamic stability of the former is better than that of the latter according to the decay rate of the attack angle.

1. Introduction
The flight stability of the projectile has rotation stability and fin stability. The stability of the fin can be divided into the fin stability of the non rotating and that of the low rotating[1]. The flight stability of the projectile is calculated and analyzed for the stability of the projectile, such as the stability of the gyroscope, the dynamic stability and the follow up stability. The flight stability of the rod type projectile is improved based on the simplified force model and the improved flight attitude in reference [2]. The flight stability of the bullet is improved by studying the stability of the length, width, material and shape of the stabilizer in reference [3]. The flight stability of the projectile is analyzed through analyzing influence of the angle of shooting, wind and trajectory initial angular velocity in reference [4]. The flight stability of the fin arrow shaft damage element is the fin stability of the non rotating in this paper. Three kinds of structures is designed, and the influence rule of variable density fin arrow shaft on the stability of flight is studied emphatically. The aerodynamic parameters of the fin arrow shaft are calculated based on the finite element analysis software. The static stability reserve and the change of the attack angle during the flight are calculated and analyzed with the theory of static stability reserve of the fin projectile and the rigid body trajectory equations. This provides a strong theoretical support for the design of the fin arrow shaft warhead in the individual small caliber cluster arrow projectile.

2. The structure scheme of the fin arrow shaft warhead
The fin arrow shaft has a smaller diameter, and its combat mission is to combat the soldier wearing bulletproof helmet and bulletproof clothe and the target within the hidden weak obstacle. The distance between the center of mass and the center of pressure is directly related to the flight stability of the fin arrow shaft warhead.
arrow shaft warhead. In view of this, the design idea of the variable density fin arrow shaft warhead is put forward. In order to study the effect of variable density on the flight stability of the warhead, three kinds of the fin arrow shaft warhead are designed as shown in fig. 1. The arrow shaft diameter of variable density structure of the scheme 1 and scheme 2 are 2.5mm. The front part of the arrow shaft is a high density of rigid material, and the latter part is a small density of aluminum material. The scheme 3 is the single density structure scheme of homogeneous steel with 2.5mm diameter. The fins of the scheme 2 and scheme 3 are equally scaled down in contrast to scheme 1.

![Scheme 1](image1.png)  
**Scheme 1:** aluminum steel  

![Scheme 2](image2.png)  
**Scheme 2:** aluminum steel  

![Scheme 3](image3.png)  
**Scheme 3:** steel  

Fig. 1 The structure of the fin arrow shaft warhead

3. The theoretical model of flight stability of the fin arrow shaft warhead

3.1. The static stability reserve theory

The relationship of the static moment $M_z$, the lift force $R_y$, the drag force $R_x$, and the distance $h$ between the center of pressure $P$ and the center of mass $O$ as follows:

$$M_z = R_x h \sin \delta + R_y h \cos \delta$$  \hspace{1cm} (1)

$$m_z = (c_y \cos \delta + c_x \sin \delta) h / l$$  \hspace{1cm} (2)

Where $\delta$ is the attack angle; $l$ is the projectile length; $c_y$ is the lift coefficient; $c_x$ is the drag coefficient and $m_z$ is the pitch moment coefficient.

In the case of small the attack angle, $c_y = c_y' \cdot \delta \cdot \sin \delta \approx \delta$, $\cos \delta \approx 1$, The formula can be expressed as:

$$m_z = m_z' \delta, m_z' = (c_y' + c_x) h / l$$  \hspace{1cm} (3)

Usually, $c_y' >> c_x$, $m_z' < 0$:

$$m_z' \approx c_y' h / l$$  \hspace{1cm} (4)

$$m_z' = \frac{x_i - x_p}{l} (c_y' + c_x) \approx \frac{x_i - x_p}{l} c_y', |x_i - x_p| = h$$  \hspace{1cm} (5)

$$m_z' = \frac{m_z}{\frac{c_y' \cos \delta + c_x' \sin \delta}{l}} = \frac{m_z}{c_y'}$$  \hspace{1cm} (6)

Where $c_y'$ is the derivative of $c_y$; $m_z'$ is the the derivative of $m_z$; $x_i$ is the position of the center of mass and $x_p$ is the position of the pressure.

3.2. The rigid body trajectory equations

The 6-DOF rigid body ballistic equations of the projectile[5] as follows:
After the fin arrow shaft warhead is scattered, the flight is non rotating in the case of wind. The mass is symmetrical along the longitudinal axis. The gyro effect, magnus force and its torque, glove inertia force are ignored. The variables in the equation and formula derivation refer to the literature [5].

4. The analysis of aerodynamic characteristic of the fin arrow shaft warhead

The FLUENT fluid mechanics analysis software [6] is used in order to study the aerodynamic characteristic of the fin arrow shaft warhead. The Spalart-Allmaras turbulence model and second order upwind scheme are chosen to use. Mach number of the numerical simulation is 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.2 and 1.4 in unit of ma, and the attack angle is 0, 2, 4, 6 and 8 in unit of degree. The drag coefficient ($c_x$), the lift coefficient ($c_y$) and the pitch moment coefficients (Where $m_z$ is the absolute value) of the three structural schemes are shown in fig. 2 to fig. 4 at different the attack angle.

![Fig. 2 The change of the drag coefficient $c_x$ with the mach number from left to right followed by the scheme 1, 2, 3](image-url)
Fig. 3 The change of the lift coefficient $c_y$ with the mach number from left to right followed by the scheme 1, 2, 3

Fig. 4 The change of the pitch moment coefficient $m_z$ with the mach number from left to right followed by the scheme 1, 2, 3

The results (Fig. 2 ~Fig. 4) indicate the following:

1) When the mach number is (0.4~0.9) ma or (1.2~1.4) ma, the drag coefficient of the three schemes at the same attack angle is small proportion linearly decreasing with the increase of mach number. When the mach numbers is (0.9~1.0) ma, the drag coefficient of the three schemes at the same attack angle increases exponentially with the increase of mach number. When the mach number is (1.0~1.2) ma and the same attack angle, the drag coefficient of scheme 1 or 2 increases of decreasing form with the increasing of mach number. However, the drag coefficient of the scheme 3 is reduced.

2) When the mach numbers is (0.4~0.9) ma or (1.0~1.4) ma, the lift coefficient and the pitch moment coefficient increase slightly with the increase of mach number at the same attack angle (except 0 degree). At (0.9~1.0) ma, the lift coefficient and the pitch moment coefficient also increase with the increase of the mach number at the same attack angle (except 0 degree) ; however, the proportion of increasing was significantly higher than that of (0.4~0.9) ma and (1.0~1.4) ma.

5. The analysis on the static stability reserve of the fin arrow shaft warhead

The static stability reserves is calculated through using the static stability reserve theory with the aerodynamic parameters of the fin arrow shaft warhead are shown in table 1.
Table 1 The static stability reserves (%)  

| Scheme | Ma Angle (degree) | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1.0 | 1.2 | 1.4 |
|--------|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Scheme 1 | 2 | 25.24 | 25.16 | 25.35 | 25.30 | 25.17 | 24.95 | 25.57 | 26.10 | 26.77 |
|         | 4 | 24.41 | 24.51 | 24.64 | 24.70 | 24.75 | 24.83 | 25.74 | 26.04 | 26.54 |
|         | 6 | 24.18 | 24.62 | 24.47 | 24.73 | 24.68 | 24.65 | 25.82 | 26.06 | 26.29 |
|         | 8 | 24.21 | 24.51 | 24.60 | 24.99 | 25.02 | 25.14 | 25.99 | 26.18 | 26.39 |
| Scheme 2 | 2 | 21.66 | 22.09 | 22.75 | 23.12 | 23.43 | 22.83 | 25.06 | 25.66 | 26.82 |
|         | 4 | 22.61 | 23.11 | 23.43 | 23.65 | 23.75 | 23.48 | 25.31 | 25.76 | 26.58 |
|         | 6 | 22.48 | 24.01 | 23.47 | 23.87 | 24.19 | 23.84 | 25.36 | 25.64 | 26.21 |
|         | 8 | 23.25 | 23.89 | 23.72 | 23.66 | 24.14 | 24.56 | 25.57 | 25.63 | 25.93 |
| Scheme 3 | 2 | 13.03 | 13.26 | 13.36 | 13.44 | 13.47 | 13.40 | 14.17 | 15.28 | 16.01 |
|         | 4 | 13.18 | 13.28 | 13.52 | 13.59 | 13.69 | 13.72 | 15.06 | 15.55 | 16.05 |
|         | 6 | 14.04 | 13.58 | 13.71 | 13.85 | 13.92 | 14.17 | 15.38 | 15.78 | 16.18 |
|         | 8 | 13.43 | 13.50 | 14.10 | 14.25 | 14.43 | 14.63 | 15.79 | 16.10 | 16.40 |

The results (Table 1) indicate the following:
1) The static stability reserves of three kinds of the fin arrow shaft warhead are more than 13%, this three schemes have sufficient static stability.
2) The static stability of the scheme 1 is the best, and its range of static stability reserve is about (24 ~ 27)%. Although the range of the static stability reserve of scheme 2 is about (21 ~ 27)%, its range of change is wider than that of the scheme 1. The static stability of the scheme 3 is the worst, and its range is about (13 ~ 17)%.
3) The static stability of variable density steel-aluminum composite fin arrow shaft warhead is better than that of single density steel material.
4) The static stability reserves of the three schemes increase with the increase of mach number at the same attack angle.

6. The analysis on the change of attack angle of the fin arrow shaft warhead
The fin arrow shaft warhead should not only have sufficient static stability reserve, but also make sure the dynamic stability in the flight process. That is to say, the amplitude of the attack angle is decreasing or always within the permissible range in the flight process. The change of the attack angle in the flight process is calculated and analyzed by making use of the rigid body trajectory equations. The initial disturbance attack angle is 5 degree, and the initial velocity is 280 m/s, and the range is 100m distance. When the angle of shooting is 0 degree, 10 degree, and 20 degree, the change of attack angle is shown in fig. 5 to fig. 7.
The change of the attack angle at 0 degree angle of shooting

![Graph showing the change of attack angle at 0 degree](image1)

Fig. 5 The change of the attack angle at 0 degree angle of shooting

The change of the attack angle at 10 degree angle of shooting

![Graph showing the change of attack angle at 10 degree](image2)

Fig. 6 The change of the attack angle at 10 degree angle of shooting
The results (Fig. 5 ~ Fig. 7) indicate the following:

1) When the angle of shooting is same and the initial disturbance attack angle is 5 degree, the attack angle of the three schemes in the range of 100m is decreasing with the flight time. In terms of decay rate, decay rate of scheme 1 is the fastest, and following the scheme 2, and the worst is the scheme 3. However, the ranges of the attack angle of three scheme are within ± 1 degree.

2) The flying time of the fin arrow shaft warhead increases as the angle of shooting increases.

3) The three schemes can guarantee the dynamic stability during the flight process. In terms of decay rate, the dynamic stability of the scheme 1 is the best, and the second is the scheme 2, and the worst is the scheme 3.

4) The dynamic stability of variable density steel-aluminum composite fin arrow shaft warhead is better than that of single density steel material.

7. Conclusions

The structural schemes of three kinds of the fin arrow shaft warhead are designed, calculated and analyzed to study the flight stability of the fin arrow shaft warhead in the individual small caliber cluster arrow projectile.

1) The drag coefficient \(c_x\), the lift coefficient \(c_y\) and the pitch moment coefficient \(m_z\) of the three kinds of structural schemes at different attack angles are calculated by numerical simulation with the help of the fluid mechanics analysis software.

2) The static stability of variable density steel-aluminum composite fin arrow shaft warhead is better than that of single density steel material through analyzing the static stability reserve. In terms of the static stability reserve of the three kinds of structural schemes, the static stability of the scheme 1 is the best and its range of static stability reserve is about \((24 \sim 27)\%\). The second is the scheme 2 and its range of static stability reserve is about \((21 \sim 27)\%\). The worst is the scheme 3 and its range of static stability reserve is about \((13 \sim 17)\%\).

3) By studying the change of the attack angle of the three structural schemes, it shows that the attack angles of the three schemes are declining. When the initial velocity is 280 m/s and range is 100 m, the attack angle of the fin arrow shaft warhead of variable density and single density are reduced from ± 5 degree to within ± 1 degree. It is indicated that dynamic stability is guaranteed; however, dynamic stability of the former is better than that of the latter according to the decay rate of the attack angle.
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