CFD Simulation of a Finned Smart Bullet with Micro-actuator

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Abstract. The geometric configuration of the micro-actuators is known to have a large impact on control authority. This study describes a finned smart bullet (FSB) to support the requirements of various missions. The flow control system consists of micro-actuator located at the rear body of FSB, alter the flow field in the rear region of FSB to create asymmetric pressure distributions and thus produce aerodynamic control forces and moments. This work seeks to derive an optimal mass centre (MC) for FSB and explore the FSB configuration with rear micro-actuator. Computational fluid dynamics simulations are performed to study the MC position for FSB stable flight and review the aerodynamic characteristics FSB configuration with actuator. For control trajectory of the FSB, the further work will explore the FSB best configuration to finish the projectile dynamic model for standard 6DOF projectile flight dynamic model in order achieve flight control.

1. Introduction

Direct-fire projectile are fired by line-of-sight aiming from ground-based platforms, helicopters, and fixed-wing aircraft, especially individual soldier. A number of conditions can cause projectiles to miss an intended target. These conditions include manufacturing inaccuracies of the gun tube, propellant, and projectile, along with variable atmospheric conditions, firing platform motion, and aiming errors. With rapid development of modern high-tech ammunition, it tends to have high-efficiency and high-reliability of combat capability. The digital age has brought about profound changes in long established areas of weapons technology, and the artillery is no exception with digital technology penetrating into guided artillery rounds and navigation systems. Precision guidance technology has been mature in big artillery and missile application, but it is still in the stage of research in small caliber projectile or bullet, such as 0.50-inch caliber EXACTO round and DARPA’s self-guided bullet [1-5].

The FSB additionally relates to non-spinning small caliber having forward viewing optical sensor, fixed strakes and electrically actuated control fins for steering a bullet toward the target [6]. Therefore, a variety of novel control effector concepts designed specifically for gun-launched precision munitions have been proposed. These include three main classifications control mechanisms, such as aerodynamic load mechanisms, jet thrust mechanisms, and internal load mechanisms. Example of aerodynamic control mechanisms gives canards, ram air deflectors, and moveable noses, which count on aerodynamic
effect on control force and moment. Others, such as gas jet thrusters and explosive thrusters, rely on on-board thrust mechanisms. While the third class of actuator devise, examples of inertial control mechanisms include internal translation of a control mass and internal rotation of an unbalanced part [6-12].

In general, the theoretical calculation method of projectile flight stability is to calculate the stable margin in several positions at different work situation. There are different methods to modify its position of projectile or bullet [13], one way is to employ applicable material, and others is to change bullet mass distribution or nose structure. It is required 12%-20% stability margin to achieve a better flight stability for the fin-stabilized projectile or missile. Here, if static margin is too large, not only lead to wind disturbance, but also increase vibration frequency. In order to flexibly operate the guided projectile or missile, it requires static margin ranging from 2% to 5% and even static instability design [14].

Therefore, the aerodynamic characteristic of FSB is investigated in this work. The rest of the paper is organized as follows: A detailed description about static margin analysis on FSB is discussed in Section 2. The geometries model and computational girds of FSB is provided in Section 3. The experimental of range flight is shown in Section 4. The numerical study for MC position optimization and this FSB configuration is analyzed in Section 5. The conclusions are summarized in Section 6.

2. Static margin analysis

The aerodynamic force and moment diagram acting on a rigid FSB is shown in Fig 1. To describe projectile or bullet aerodynamic force and moment, a ground-based frame OXYZ is used as the absolute coordinate frame fixed on the earth ground and body fixed reference frame O1ABC. Vector of O1A is direction of bullet velocity and total angle of attack (AOA) $\alpha$. OA is axis of the projectile or bullet, bullet velocity is measured vertically upward and is simplified to MC, O1 is the position of MC and P is the pressure center (PC) position. This rigid-body model is similar to use in next [15]:

![Fig. 1 Schematics of aerodynamic force and moment acting on FSB](image)

There is a need to state that $\alpha$ is equivalent to total AOA in the numerical calculation. The aerodynamic force and moment coefficient are related to bullet shape, Mach number and attack angle [16]. The static aerodynamic relationship can be achieved from Fig.1 $M_{\alpha}, L_{\alpha}$ and $D_{\alpha}$ have a certain steady-state relationship for a symmetric bullet, that is:

$$M_{\alpha} = D_{\alpha} l_d \sin \alpha + L_{\alpha} l_d \cos \alpha$$

(1)

Where $M_{\alpha}, L_{\alpha}, D_{\alpha}$ are the drag force, lift force and pitching moment at AOA, the $l_d$ is the distance between MC and PC.

When attack angle $\alpha$ is small, lift force coefficient and pitching moment coefficient can be expressed with its differential coefficient to AOA, just as shown in the next:

$$C_{L_{\alpha}} = C_{\alpha}' \alpha$$

(2)
\[ C_{Ma} = C'_{Ma} \alpha \]  
(3)

\[ \sin \alpha = \alpha \]  
(4)

\[ \cos \alpha = 1 \]  
(5)

Where \( C_{La}, C_{Ma} \) are the coefficients of derivative for lift force and pitching moment. If equations are substituted in, the following of equations can be provided:

\[ C'_{Ma} = \frac{l_d}{l} \left( C'_{La} + C_{Da} \right) \]  
(6)

As usual for fin stabilized projectile or bullet as expressed below: \( C'_{Ma} \gg C_{La} \),

\[ R = \frac{l_d}{l} \approx \frac{C'_{Ma}}{C'_{La}} = \frac{C_{Ma}}{C_{La}} \]  
(7)

The non-dimensional ratio \( R \) called static margin mainly reflects the static stability of the bullet, and it is important that \( R \) be efficient to keep the bullet flight performance. Formula (7) shows that the distance between PC and MC is a decisive factor for its static margin when the bullet reference length is a given parameter [17].

3. FSB Geometries model and Computational Girds

3.1. FSB Geometries model Setup

This paper is part of a larger research effort to characterize the aerodynamic performance of FSB and design them in order to achieve the best performance to support the requirements of various missions. The FSB structure adapted is to be fired from smooth bore gun barrels, when light weapon is desired to increase the accuracy of placing the bullet on a target from long range (e.g. 2000 meters and beyond) [6]. It is self-guided to a target illuminated by a laser target designator. To compute the control effects of micro-actuators, a series of CFD simulations was performed in order to finish the study of the pre-program feasibility for the FSB aerodynamic configuration which can provides the control authority. The rare micro-actuator for FSB is chosen as the main subject used for all aerodynamic prediction and simulation studies throughout this paper. The bullet modeled in this study is triangle fins of main body, a cone-cylinder-finned configuration. A schematic diagram of this FSB provides basic geometry normalized by the bullet reference caliber is shown in Fig.2 and two micro-actuators mechanism which is composed of two set of orthogonal and same size of micro-actuator located at the rear body. The length of the bullet is 11 cal and the diameter is 12.7mm, and the nose is 3 cal, the connecting piece is 1.1 cal and is followed by 5.8 cal fixed fins, the rear body length is 0.78 cal. For the case in this paper, the micro-actuator width is set to 6mm and the depth is 1.5mm. Unless otherwise noted, the spoiler full extension from the surface of the projectile is assumed to be 0.2mm.
Fig. 2 Schematics of the finned smart bullet

Fig. 3 Micro-actuator geometry parameterization

Fig. 4 Finned body geometry (a) without and (b) with rear micro-actuator mechanisms

Fig. 4 shows the 3D computational models of FSB both with and without micro-actuator. Fig 4.(b) and presents single micro-actuator control mechanisms at the rear body, and they are intended to create asymmetric pressure distributions and flow field in the rear of FSB and provide control force and moments needed for bullet control maneuver.

Different nose material and various nose structure meets the electronic components, optical system and other parts in assembly, and there are MC position range located at between 86mm and 100mm from the rear body. Five types of MC location are accomplished in order to explore the logical position for bullet static-stability. As shown in Fig.4 (a), the different kinds of MC location the bullet without micro-actuator are 86mm, 88.5mm, 93mm, 96.5mm and 100mm for initial study of bullet. Steady-state computation have been performed for FSB without of different MC position at Mach number from 0.3 to 3Ma and at AOA from 0° to 8°. For the body without micro-actuator, the different kinds of MC location produce essentially aerodynamic force and moment.

With the micro-actuator installed in the rear body of FSB, the drag force perturbation $\delta_D$ and the lift moment perturbation $\delta_M$ actually generate control in opposite directions. However, the moment perturbation typically dominates the effects of the drag force $\delta_D$ because it directly generates the AOA [19]. Furthermore, although the micro-actuator increases the resulting perturbation moment, it also increases drag. When evaluating the performance of the rear micro-actuator configuration, it is important to settle terminal error correction for a notional FSB equipped with micro-actuator. The FSB mission for the correction only and the trajectory error is not known until the bullet-target distance is small and thus control is only exerted over a short period of time near the end of the trajectory. The following reward function may be defined for comparing geometric configuration for the correction scenario:
\[ K = \frac{\delta_m}{D \delta_D} \] (8)

Note that, in Eq. (8) the reference diameter \( D \) is included so that \( K \) is non-dimensional. In order to fulfill the mission, it is important that the micro-actuator be efficient in producing control authority by generating as large a control moment as possible for the smallest sacrifice in drag force. Additionally, the drag is of less importance, and the overall magnitude of the control moment \( \delta_m \) may be used directly to compare the effectiveness of various configurations.

3.2. Computational Girds
In order to analyze external flow field of FSB, it can be considered cylindrical slender body approximately, so the 400mm × 800mm computational region around of FSB was created by modeling software with Boolean. It was a full three-dimensional unstructured hexahedral mesh for the simulation of FSB. Fig 5 reveals the computational mesh for the bullet configuration without micro-actuator. The domain to be solved is divided into two parts, the inner domain was the bullet surface in purple, and out domain was in green. Bullet surface of mesh is shown in Fig 5.b). The boundary conditions in out domain were set as pressure far-field, the bullet surface was set to no-slip adiabatic and stationary wall condition. Because gun of firing bullet is a direct fire weapon, the firing gun is similar to a flat-fire ballistic trajectory, and the firing process of the bullet is analogous to the weather feature [19-23]. Let us suppose that the flow is ideal, the flight simulation condition is shown in Table 1.

![a). Computational and bullet surface of mesh](image1)

![b). Bullet surface of mesh](image2)

**Fig. 5 Schematics of computational and bullet surface of mesh**

| Table 1. Flight simulation condition |
|-------------------------------------|
| Parameter                           | Symbol, unit | Value   |
|-------------------------------------|--------------|---------|
| Pressure                            | P [Pa]       | 101325  |
| Temperature                         | Ta [K]       | 288.13  |
| Far field velocity                  | v [Ma]       | 0.3-3   |
| AOA                                 | \( \alpha \) [degree] | 0-8     |
4. Experimental of Range Flight

Bullet range flight without micro-actuators was obtained experimentally at Chongqing Jialing special equipment Co., Ltd. During such tests, a set of prototype ammunition were fired along a flat trajectory through an enclosed building and high-speed photography at 2m from gun muzzle was used to catch the flight attitude of FSB. Because of flight stabilization of FSB, a 12.7mm smooth bore gun tube was selected for this experimental in order to eliminate rotation effects. For ease of manufacturing, as shown in Fig 6, the entire test bullets were combination of different components and nose body and main body were connected by M 0.5 screw. The final test FSB can be seen in Fig 6, (a) exhibited the FSB with sabot and there was no sabot for FSB in (b). In total, 15 shots were recorded on film, and it was without micro actuator to finish new aerodynamic configuration verification. The final design parameters for range test FSB are listed in Table 2. Total FSB weight was about 38.2g, with its MC located at about 86mm of the overall FSB length measured from the rear base.

![Prototype bullet and FSB ammunition](image1)

**Fig. 6 Prototype bullet and FSB ammunition**

| Number | 1#-a | 1#-b | 2#-a | 2#-b | 3#-a | 3#-b |
|--------|------|------|------|------|------|------|
| Powder(g) | 12.5 | 13 | 12.5 | 13 | 12.5 | 13 |
| Bullet weight(g) | 38.5 | 38.1 | 38.2 | 38.2 | 38.15 | 38.05 |
| $X_{MC}$(mm) | 84.88 | 86.78 | 85.95 | 86.54 | 86.84 | 87.05 |

![High-speed photography frames of the gun muzzle](image2)

**Fig. 7 High-speed photography frames of the gun muzzle**
Target sheet 35m Target sheet at 70m

a) Target sheet holes of 1#-a FSB

Target sheet 35m Target sheet at 70m

b) Target sheet holes of 2#-a FSB

Target sheet 35m Target sheet at 70m

b) Target sheet holes of 3#-a FSB

Fig 8 Two target sheet holes of different FSB

Fig 7 provides a series of picture of FSB in supersonic flight when FSB 1#-a, 2#-a, 3#-a FSB left the gun muzzle and Fig 8 shows target sheet holes of different FSB, the mark of 35m target sheet had slightly deformed round hole and 70m distance sheet gave circular hole for FSB 1#-a. The experimental results consist of Fig 8 a), b), c) indicate that test FSBs play an important role in critical stability flight performance and that the MC position needs to be further optimized to meet the FSB without micro-actuator flight performance firstly. In next section, the influence of MC location on FSB flight performance is simulated and analyzed concretely.

5. Numerical Study

5.1. MC position optimization

The Fig 13 and Table 3 present that static margin can be achieved by the parameters of aerodynamic characteristics and 86mm MC position, and the static margin range of 86mm MC position is from 1.05% to 9.52%, maximum R is 9.25% at 1Ma and 2 AOA and there is approximate 1.5% static margin at higher than 1.5Ma supersonic flight, and Fig 9 shows the velocity contours of numerical calculation for different Mach number. However, the flight experiment happened to critical flight performance of FSB and was not deemed acceptable.
Table 3. Static margin with 86mm MC position

| Ma | 2   | 4   | 6   | 8   |
|----|-----|-----|-----|-----|
| 0.3| 0.01658 | 0.01059 | 0.01286 | 0.03092 |
| 0.5| 0.02068 | 0.01708 | 0.02883 | 0.03721 |
| 1  | 0.19522 | 0.1469 | 0.11286 | 0.10647 |
| 1.3| 0.07701 | 0.03063 | 0.04961 | 0.04967 |
| 1.5| 0.0467 | 0.0159 | 0.03106 | 0.03798 |
| 2  | 0.01979 | 0.01394 | 0.02138 | 0.02279 |
| 2.5| 0.01594 | 0.01422 | 0.02753 | 0.02543 |
| 3  | 0.01268 | 0.01559 | 0.01122 | 0.02647 |

Fig. 9 Static margin vs. Mach number with 86mm MC position

Fig. 10 Velocity contours of numerical calculation for different Mach number

How to judge the static margin is reasonable in this case, it is important that the different MC position be efficient in variety of static margin by interfering sizable aerodynamic characteristics. The following reward function may be defined for comparing geometric MC position for the flight performance:

\[ J = \frac{R_{\alpha}}{C_{\alpha}} \]  

(9)
Note that, in the aerodynamic coefficients Eq. (9) are included so that \( J \) is non-dimensional, and value \( J \) can be a symbolic date for the flight performance of different MC position FSB. Especially, as shown in Table 4, which reveals FSB configuration static margin, drag coefficient and value \( J \) of 2° AOA at different MC position.

| Table 4. FSB configuration of 2° AOA at different MC position |
|-----------------|-------|-------|-------|-------|-------|
| MC              | 86    | 88.5  | 93    | 96.5  | 100   |
| \( R \)         | 0.0925| 0.1645| 0.1883| 0.2321| 0.2401|
| \( C_D \)       | 0.7891| 0.7425| 0.7215| 0.7712| 0.8834|
| \( J \)         | 0.1172| 0.2215| 0.2276| 0.3048| 0.2717|

Fig. 11 Drag coefficients vs. Mach number of 0 AOA at different MC location

Fig. 12 Drag coefficient vs. MC location of 0 AOA at different Mach number

Fig. 13 Static margin vs. Mach number at AOA 0°

With the premise of ensuring FSB flight performance, a reasonable location with lower drag is chosen to determine the optimal MC location. Increase of static margin is the important value for MC position, but the value of drag coefficient is the main parameter determining the FSB effective firing range. The geometrical parameters defining each of different MC position cases and the results of reward value \( J \) are shown in Table 4. Starting with the based MC 86mm used in the previous simulation and range test, this MC position is not the ideal configuration for the flight performance. As expected, this is noted that by comparing the position minimum and maximum, although the percentage increase in static margin
was greater when the MC max position 100mm than the previous prototype position 86mm, and also clearly produced the highest value 0.88 in drag coefficient. Overall, examining the specific value function shown in Table 4, 93mm position configuration yields an impressive 100% increase in static margin with a better 8.6% decrease in drag. The 96.5mm position configuration had a value $k$ of 0.3048 and an outstanding value in static margin and still the value only 2.2% decrease in drag. There is drag coefficient variation trend of different MC position in Fig 11 and Fig 12, and the maximum drag is as high as 0.88 at the 100mm MC and these coefficients are also bigger than another MC position at various AOA. The cave of different MC shown in Fig 13, there are something noted that the maximum margin always appeared at 1Ma at different MC position and the $R$ almost changed rarely when the relative airflow velocity of FSB is exceeding 1.5Ma range. The percentage increase in the flight static margin is greater four times at the supersonic flight when the MC position moves from the 86mm to 100mm. Considering the three factors of stability margin, drag coefficient and ratio $J$, the 93mm MC position is the relatively superior result. This 93mm MC location is used in further investigations throughout this study.

5.2. Geometric with micro-actuator study

This purpose of study is focused on the investigation of aerodynamic characteristics and control authority problem caused by the given structure of FSB with 6mm × 0.2mm micro-actuator. This micro-actuator in this configuration is 6mm width and approximately 0.2mm extension, the deflection angle between the micro-actuator and the bullet body is 90. For this case with rear micro-actuator, computations were performed to quickly provide the extent of control force that could be generated using the micro-actuator. The results of in the previous section were restricted to Mach 1 only for FSB configurations. Additional CFD simulations were performed for configuration F at the range of Mach number between 0.3 and 3, again at a zero AOA. Fig 14 shows the results of these studies for Mach number-dependent, there are no any significant change for control force and moments at below 1 Mach number and all these are linearly variation in the case of supersonic flight. Note the general trend that control forces and moments, as well as drag, increase as a function of Mach number as expected due to the higher dynamic pressure on the upwind side of the micro-actuator surface.

Fig.14 Forces and moments vs. Mach number (AOA=0°)

All the results present here for different AOA are again at the same Mach number 1Ma. Again the effect of AOA is studied use the effective candidate configuration with 6mm × 0.3mm micro-actuator. Computed results have been obtained for this configuration at diverse AOA from 0 to 8. In this paper, because the rear micro-actuator special structure of FSB can up-down and left-right retractable
movement, so the small range positive AOA indicate the control force and moment variation tendency. The results aerodynamic delta parameters for AOA-dependent are shown in Table 5. These results seem to indicate that control force and moment, and even $J$ value are generated across the range of AOA is not as significant for AOA, and the AOA $4^\circ$ has better $J$ value which is no qualitative change.

**Table 5. Variation of delta force and moments due to micro-actuator with AOA at 1Ma.**

| $\alpha$ (°) | $\delta_x$, N | $\delta_y$, N | $\delta_z$, N·m |
|-------------|--------------|--------------|------------------|
| 0           | -1.98        | 0.93         | 0.024            |
| 2           | -1.75        | 0.89         | 0.022            |
| 4           | -1.63        | 0.94         | 0.021            |
| 6           | -1.85        | 0.99         | 0.023            |
| 8           | -1.67        | 0.91         | 0.021            |

6. Conclusion
The study reported here details the FSB overall configuration and the aerodynamic characterization with and without micro-actuator for FSB. Through a serious of steady computational fluid simulations, the main two research aspects concentrate on the MC position and the given micro-actuator aerodynamic study. A combination of steady computational fluid simulations and range test of flight can be adopted to analyze the FSB without rear micro-actuator aerodynamic characteristics for the MC position optimization, steady simulation for five different kinds of MC position give the conclusion that 93mm MC location can be called the optimal results relative to four others, when comprehensive study of stability margin, drag force and ratio value $K$ is conducted to comparatively analyze at 1 Mach number and $0^\circ$ AOA. In this case, 93mm position configuration yielded an impressive 100% increase in static margin with a better 8.6% decrease in drag. When MC position moved forward to the nose from 86mm to 93mm, the static margin maintains 6.5% increases three times at the supersonic flight exceed 1.5Ma range. In the previous study, steady-state solutions were firstly gained for FSB without rear micro-actuator at a 1Ma. This configuration of FSB with $6\text{mm} \times 0.3\text{mm}$ rear show that some control authority of micro-actuator exists even at flight trajectory. For control trajectory of the FSB, the further work will explore the FSB best configuration to finish the projectile dynamic model for standard 6DOF projectile flight dynamic model in order achieve flight control.

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