Numerical investigations on the sabots discard process of an APFSDS at different angles of attack

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Abstract: Sabot asymmetric discard after the projectile being launched from the muzzle at various angles of attack and 4Ma is investigated. This is implemented by the coupling computational fluid dynamics (CFD) and six degrees-of-freedom exterior ballistic code through the unstructured dynamic mesh and user defined function. The flow field characteristics during sabot discard process and the trajectory parameters of all three sabots have been obtained. In addition, the aerodynamic coefficients of the projectile are also obtained. The numerical results show that the asymmetric discard of sabot is more obvious along with the increasing angle of attack. Moreover, the aerodynamic forces of projectile have a larger change and the pressure distribution of projectile are also obtained. This means the aerodynamic interference at a non-zero angle of attack contributes more significantly to shooting dispersion and flight stability than that at zero angle of attack and the influence increases as the angle of attack increases.

1 Introduction

Armor piercing fin stabilised discarding sabot (APFSDS) made up of a penetrator and three sabots is an extremely important tank gun ammunition and used by various countries in the world. It can be divided into petal and saddle type according to the sabot configuration. The characteristics such as a flat trajectory and short flight time caused by high flight velocity can ensure not only the high accuracy of the projectile but also the low dispersion. Also, APFSDS has a series of good performance characteristic such as superior target penetration, anti-bounce performance and after effect etc. Therefore, it has a wide application prospect in the antitank area [1–4].

However, APFSDS is ineffective if not delivered accurately at the target. One important factor affecting the launch and flight of such projectile is the sabot discard. It has been pointed out by [5] that the sabot discard process has an extremely important influence on the total firing error. During the process of sabot discard, though a set of mechanical and aerodynamic interferences may result in alteration of the projectile trajectory but it has been investigated that aerodynamic effects can be amplified source of launch disturbances [6, 7]. Hence, numerical investigations about aerodynamic interference have important research significance during the sabot discard.

A series of steady-state computational solutions of several configurations of the symmetric discard of a three-segment sabot located some representing positions with respect to the projectile were obtained by a fully implicit, co-located, finite volume method. The region of high pressure on the projectile was revealed [8]. The steady axisymmetric flow field for a hypervelocity free-stream flows over an APFSDS with different fixed locations of sabot was calculated by the explicit multi-stage high-resolution upwind flux-difference split scheme on the basis of the multi-block mesh generation technology [1, 9]. The aerodynamic characteristics of the projectile and sabots were obtained by fluid mechanics simulation software in different Mach numbers [10]. On the basis of the coupling of Euler equations and six degrees-of-freedom (6DOF) exterior ballistic equations by means of the user defined function (UDF) of FLUENT, the sabot symmetric dynamic discard process has been simulated numerically at 4Ma and zero angle of attack [11].

However, the positions and attitudes of the projectile and sabot cannot be completely symmetric during the whole process of sabot discard. The aerodynamic interference is amplified by the asymmetry of the sabot discard and vice versa. The influence of the asymmetry also increases on the shooting dispersion and flight stability of the projectile. The conclusion has been verified by relevant experiment [12–14]. Until recently, only a few numerical results exist concerning the sabot asymmetric dynamic discard by the coupling between the three-dimensional unsteady aerodynamics and 6DOF exterior ballistic code of a sabot. This paper was initiated to get a better understanding of the aerodynamic interference during the sabot asymmetric discard at non-zero angle of attack and 4Ma. The flow fields and the discard trajectories of the sabot during the discard process are computed and compared with those at zero angle of attack.

2 Numerical methodology and model

The numerical results obtained in this paper are through the coupling of the flow field solver and the 6DOF exterior ballistic code via UDF. The flow field is distinctly revealed by solving the fluid dynamics governing equations in the flow field solver. The aerodynamic forces and moments of sabots and projectile are calculated by integrating the surface pressure over the wall at each time interval. Other forces (e.g. gravity etc.) and corresponding moments are embedded in 6DOF exterior ballistic code via UDF. The location and attitude of sabot are achieved by simulating 6DOF exterior ballistic equations on basis of the forces and moments above mentioned. After the sabot moves a certain distance, the unstructured dynamic mesh method composed of spring-based smoothing and local remeshing is adopted to move the nodes or remesh the volume mesh for improving the volume mesh quality. The detail theory about the dynamic mesh approach can be referenced in [11, 15–17].

The governing equations in this work are the Euler equations, the same as [11]. The finite volume method is used to discrete space. The convective term is approximated by a second-order advection upstream splitting method (AUSM) scheme. The second-order Runge–Kutta method was employed to the time integration. The 6DOF exterior ballistic equations are the Newton–Euler equations of motion which can be calculated by numerically
integrating to obtain the trajectory of the sabot discard using a fourth-order multi-point time integration scheme. The relevant equations can be referenced in [11, 15, 16].

The basic model and global coordinate system used in the numerical calculations are shown in Fig. 1. Its geometry is the same as the previous numerical simulations of the sabot symmetric discard and the detailed information is listed in [11]. There are 8 million tetrahedral meshes which are flexible to handle complex geometries such as the APFSDS in the computational domain. The wall boundary of all three sabots and projectile is a slip. An adiabatic wall has been taken into account, the specification is no heat flux from the wall to the fluid. According to the pressure far-field condition, a characteristic analysis grounded on Riemann invariant is applied to compute the flow variable on the outer boundary of the computational domain. The air density is obtained based on the perfect gas assumption since the vibration energy of the flow is not significant at this velocity. The value of initial pressure is equal to standard atmospheric pressure and the acceleration of gravitation ($g$) is $9.8 \text{ m/s}^2$ with 300 K ambient temperature.

3 Results

3.1 Flow fields of the sabot discard at different angles of attack

The contours of the pressure distribution of the $xoz$-plane (symmetric plane of the angle of attack) in time of the process sabot discard are shown in Figs. 2–5 at 0, 2, 4, 6 angles of attack and 4Ma. The detailed flow field analysis is not thoroughly discussed any more during the process of sabot discard. The variation of the flow field at a non-zero angle of attack can also be divided into three phases which are similar to that at zero angle of attack and it can reference [11]. The main objective of this section is to investigate the variations of the flow field structures and
pressure distributions with angles of attack and discuss the aerodynamic interference during the sabot asymmetric discard process.

In the ultrashort time after the sabots begin to move ($t \leq 0.1$ ms), the flow field structures and pressure distributions are almost similar and the asymmetry of them cannot be observed obviously, as shown in Figs. 2a–5a. With the continued discard of the sabot, the asymmetry of the flow fields begins to arise. For example, the pressure in the back of the saddle part of sabot 1 enlarges as the angle of attack increases, whereas the one in the sabot 2 and sabot 3 keeps unchanged with the angle of attack variation. The above phenomenon is also applied to the intensity of the oblique shock wave induced by the collision of the flow with the back of the saddle part of the sabot. This result in the inequality and asymmetry of the aerodynamic force induced by the pressure on the sabots' wall and the shock wave for the three sabots during this discard time period. Since the aerodynamic force not only affords the help for the axial and radial separation of the sabot discard but also produces the moments maintaining the pitch motion of the sabot; the sabot discard will be in asymmetry.

From the flow field figure at $t = 0.6$ ms, the difference of the pressure value and the asymmetry of shock wave located at the back of the saddle part of sabot reduce. On the contrary, due to the difference of the pitch angle of the sabots relative to the projectile and the existence of angle of attack, the high-pressure region caused by the collision of the shock wave on the projectile is no longer symmetric. The asymmetry also increases as the attack angle increases. The asymmetry of the high-pressure region causes a larger fluctuation of the lateral force than the one at zero angle of attack. Such a lateral force fluctuation will affect the flight stability of the projectile.

By comparing Figs. 2f–5f, it is known that the location of the impinging of the oblique shock wave induced by the sabot 1 on the projectile moves upstream with the increase of angle of attack at the same time. However, the ones relevant to the other sabots move downstream as the angle of attack increases. Therefore, it can be concluded that the duration of aerodynamic interference between the sabot 1 and projectile is longer than the ones between other sabots and projectile at a non-zero angle of attack. It also means that the aerodynamic interference acting on the projectile increases with the increasing angle of attack.

Fig. 6 shows the Schlieren photograph of the experiment results in [18]. It shows that the numerical flow structures around the projectile and sabots agree fairly well with those in the picture at zero angle of attack, see Fig. 2e. In particular, the shock wave located before the front of the sabot is clearly revealed. It is demonstrated that the numerical method in this paper is feasible for this asymmetric sabot discard problem.

### 3.2 Influence of angle of attack on the trajectory parameters of the sabot asymmetric discard

Fig. 7 shows the centre of gravity trajectories of the three sabots in the global inertial coordinate system as a function of time at various angles of attacks. It is clear that all of the three sabots flight rearward with respect to the projectile along the negative $x$-direction due to the aerodynamic drag. The trajectories of sabots 2 and 3 in the $y$-direction are almost the same at the same non-zero angle of attack. However, they are asymmetric to that of sabot 1. For the $z$-direction, the trajectory of sabot 1 is stationary, and the move of sabot 2 is almost symmetric with sabot 3. It can be found that the location in the $y$-direction is more sensitive to the angle of attack than others in other directions. Therefore, it has a larger variation with the increase of the angle of
attack. The angle of attack makes the speed of sabot 1 away from the projectile slow down.

Fig. 8 illustrates the radial displacements of the three sabots with respect to the projectile at various angles of attacks. It can be observed that the radial displacements of different sabot petals have different variation tendencies. The radial displacement of sabot 1 decreases as the angle of attack increases. The dominant reason is that the incoming flow has a downward component and can prevent the sabot 1 pitch. The discard of sabot 1 slows down as the angle of attack increases such that the existence time of aerodynamic interference between the sabot 1 and projectile is longer and it can be demonstrated by the flow field structure.

Since the incoming flow and the initial locations of sabot 2 and sabot 3 are symmetric about the symmetric plane of the angle of attack or the longitudinal symmetry plane, the variation tendencies of the radial displacements of sabot 2 and sabot 3 with the time are identical at the same attack angle. This means the discards of the sabot 2 and sabot 3 are symmetric about the symmetric plane of the angle of attack. Therefore, the radial displacement of sabot 2 is discussed and represents the one of sabot 3 in this section. The
of the projectile suffer from the distraction of sabots. Its accuracy and flight stability coefficients of the projectile fluctuate under the influence of shock waves induced by the sabots. The \( t_e \) is different and larger with the increase of the angle of attack. This also means the aerodynamic interference acting on the projectile is larger and longer as the angle of attack increases.

From the three figures, the fluctuating amplitude of the three aerodynamic force coefficients increases with the increase of the angle of attack. In addition, the fluctuating amplitudes of drag (\( C_d \)) and lift (\( C_l \)) force coefficients are larger compared with the lateral force coefficient (\( C_y \)). This is caused due to the symmetry of sabots 2 and 3, the induced shock waves impact on the projectile mainly cause the lift and lateral forces; however, the directions of their lateral forces are opposite and counteract with each other, which makes the total lateral force smaller.

The drag coefficient of projectile becomes the largest almost at the same time for the four cases. This is caused by the oblique shock wave impacting on the back of projectile where it has a small step. However, the largest absolute value of the lift coefficient appears at the end of the sabot discard process and increases as the angle of attack increases. However, it must be pointed out that its orientation has changed at a non-zero angle of attack compared with the one at zero angle of attack. At this time, the shock wave induced by the sabot 1 impact with the tail and fins of projectile almost perpendicularly. Meanwhile, the shock waves induced by the sabot 2 and sabot 3 are leaving from the tail and fins of the projectile and rarely works for the lift coefficient, the sum of lift generated by sabots 2 and 3 is far smaller than that of sabot 1; therefore, a negative jump and the largest absolute value appear. It can be seen that the frequency of the lateral force coefficient is more often than others from Fig. 9. It fluctuates around the value of zero and become zero lastly for a free flight of the projectile.

### 4 Conclusion

On the basis of the coupling of computational fluid dynamics technique and 6DOF exterior ballistic code through UDF and unstructured dynamic mesh approach, the sabot asymmetric dynamic discard process has been successfully simulated numerically at various angles of attacks and 4Ma. The computational results distinctly illustrate the detailed flow field structure during the sabot asymmetric discard process and coincide with the corresponding experimental investigations. In addition, the aerodynamic coefficients of the projectile are also obtained and discussed.

The existence of the initial angle of attack causes the asymmetry of the flow field during the sabot discard, which can result in the asymmetric distribution of the pressure acting on the sabot and projectile surfaces. The aerodynamic coefficients of the projectile have larger perturbations comparing with those at zero angle of attack. The sabot discard is not symmetric anymore and it aggravates the asymmetry of the flow field. Above of these are interacted on each other. As the angle of attack increases, the sabot asymmetric discard is more obvious. It can be seen that the aerodynamic effect and the sabot discard are mutual influence with each other and the natural result enlarges the shooting dispersion.

### 5 Acknowledgments

This work was sponsored by the Natural Science Foundation of Shanghai (Grant no. 17ZR1430100), the Foundation of Key Laboratory (Grant no. 6142604030162604004) and the Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant no. 30917012101) China.

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