Sabot Discard Characteristics under Different Spin Rates of the Rifled Barrel Launching APFSDS

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Received 1 April 2021; Accepted 29 April 2021; Published 10 May 2021

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The sabot discard asymmetry caused by spinning affects the exterior ballistic characteristics and shooting accuracy of a gun with the rifled barrel. To gain a deeper understanding of the complex sabot discard performance for the armor-piercing, fin-stabilized discarding sabot (APFSDS), a numerical investigation is performed to assess the effects of the spin rate on the sabot discard characteristics. We obtain the calculation boundary by the interior ballistics and the firing conditions and carry out a numerical simulation under different spin rates using computational fluid dynamics (CFD) and a dynamic mesh technique. We analyze four aspects of sabot discard characteristics, namely, sabot separation, rod surface pressure, rod aerodynamic parameters, and discarding quantization parameters. Computational results show that the sabot separation nearly presents perfect symmetry at 0 rad/s, and when the initial rate of the sabot increases, there is more obvious separation asymmetry, and it contributes to the relative position variation among the sabots and the rod. The distinction of rod surface pressure indicates that the choked flow is the strongest flow source, and the spin rate has almost no effect on the pressure of the rod front part. When the monitoring point moves towards the fins, the pressure distribution and intensity change more dramatically. The initial spin rate and separation asymmetry produce a variation in the surface pressure, which further influences the rod aerodynamic characteristics. The discarding quantization parameters exhibit a certain variation rule with its spin rate. 2,000 rad/s has a significant influence on the rod aerodynamic coefficients during the weak coupling phase. When the spin rate is in the range of 0–900 rad/s, the discarding characteristics remain the same. However, when the spin rate exceeds 900 rad/s, the separation time and aerodynamic impulse have a quadratic polynomial relationship with the rate. Additionally, a spin rate of 1,000 rad/s is the optimal value for a rifled barrel gun.

1. Introduction

The ultimate challenge of conventional weapons is the achievement of a longer firing range, higher muzzle velocity, and higher firing accuracy; therefore, the armor-piercing projectile comes into being and has a broad array of applications in tube-launched weapons [1]. An APFSDS is a kinetic energy projectile with high velocity, excellent ballistic performance, high energy density, and other advantages. Generally, APFSDS comprises several sabots, a slim long rod, an obturator, and other parts. The function of sabots is to transfer the axial load and support the projectile. As a kind of low-density and high-strength metal material, aluminum alloy is widely used in automobile, aerospace, machinery manufacturing, shipbuilding, and other industries [2, 3]. Thus, aluminum alloy is the preferred material for sabots to meet the high overload requirements of launching. A slipping obturator is essential to provide the rifled barrel of Gatling gun, and it can seal gunpowder gas and give the rod a low spin rate [4]. When the APFSDS is ejected from the gun tube, the separation of sabots from the rod is called as the sabot discarding process (SDP), and it is accompanied by mechanical and aerodynamic interference [5]. In particular, the sabot spin rate and tangential velocity of the APFSDS affect the aerodynamic interference of the SDP, which results in the loss of stability and a sacrifice of accuracy [6, 7].
We use high-speed photography to capture the APFSDS projectile attitude and provide a photo of the launching phenomenon in Figure 1, which is a millisecond-level process. The schematics in Figures 2(a) and 2(b) illustrate the aerodynamic interaction of the SDP. When the APFSDS is out of the barrel constraint, the gunpowder gas quickly coats the projectile. Then, it escapes from the muzzle flow field, and the high-velocity airstream impinges on the front scoop of the sabots, and the back of the sabot is hardly affected by the gunpowder gas. Aerodynamic forces and moments cut a nylon ring into small pieces, and the APFSDS begins to separate dynamically without the obturator restriction. Generally, as shown in Figure 2(a), the incoming flow is divided into three parts: one flows from the surface of the rod and sabots, another passes through the gaps among the sabots or between the sabots and the rod, and the rest mostly hit the sabot scoop. A series of shocks, including attached waves, detached shock waves, choked flows, reflected waves, and expansion waves, as shown in Figure 2(b), accompany the SDP. Therefore, this separation is a complex process that involves various shock wave interactions [6].

Previous investigations have demonstrated that multiplex interference factors can result in a ballistic disturbance during the SDP [7], and the aerodynamic interference remains a major disturbance that affects the projectile flight stability, and it ultimately influences the exterior ballistic and shooting accuracy [7, 8]. Hence, some scholars have achieved initial results with the APFSDS SDP. Original studies involved shooting tests and engineering practices to study the basic phenomena [7–9]. Scholars have analyzed several sticking points of the SDP at different periods. In the 1980s, Schmidt and Shear [6, 7] conducted several important and fundamental investigations in shooting tests and measurement. Consequently, Schmidt and Shear [6] showed that aerodynamic interference affected the rod characteristics, and Schmidt [7] revealed the effects of multiple shock and boundary layer interactions. In the 1990s, Dick and Dolling [9] conducted tests at 5 Ma for two fixed SDP stages, and the results showed that the interference of splitter plates mainly affected the bow shock generated by the projectile. However, shooting tests and wind tunnels have disadvantages, including time consumption, high risk, motion uncertainty, and testing difficulty. Nonetheless, the above critical results provide a foundation for sabot design.

Advances in computer technology and numerical algorithms have promoted the rapid development of CFD, which can be used to solve complex flow problems with supersonic characteristics [10]. The implantation of multi-body dynamics, dynamic mesh, and even turbulence models has led to many improvements to aerodynamic calculations [11] and dynamic separation results [12–14]. Lee and Wu [12, 13] used CFD to research the SDP in a fixed attitude case, concluding that the pressure distribution of the spring was more consistent with the test results [14, 15]. Snyder et al. [16] adopted unstructured dynamic grids to settle store separation simulations, which are built upon a foundation for unsteady SDP. Cayzac et al. [17, 18] applied the two-dimensional Euler algorithm to predict the sabot trajectory, and the computational result was in good agreement with experimental data. Huang et al. [19] claimed a combination of the unstructured dynamic mesh technology to solve the unsteady SDP problem, revealing the basic phenomenon of the SDP and the symmetrical separation. Li et al. [20] established a coupled model to explore the SDP under different angles of attack (AOA) and induced that the greater the AOA, the more intense the disturbance for the SDP. Reck et al. [21] confirmed the conclusion that the asymmetric disturbance, acting by an angular rate of the armature, affects the sabot separation process to a minor extent using the wind tunnel and numerical calculations. Additionally, Li [5] proposed a basic standard that the weaker aerodynamic interference and shorter separation time of the SDP would be more logical for sabot design.

Numerous scholars have conducted detailed studies on the SDP, but the impact of the sabot spin rate is a factor that cannot be ignored. The spin rate can affect the variation in sabot motion and rod aerodynamic, which further result in the difference of sabot discard characteristics. Against this background, a small-caliber APFSDS was chosen as a sub-caliber representative configuration with three sabots in the simulation of a rifled barrel gun. We consider the Gatling gun launching peculiarity and the interior ballistic model to establish a simulation model under different spin rate cases. We then adopt the dynamic unstructured grid technology to solve the APFSDS separation and flow field. Subsequently, these analyses of sabot discard characteristics are conducted by sabot separation, rod surface pressure, rod aerodynamic forces, and discarding quantization parameters.

### 2. Simulation Model

#### 2.1. Model Assumption

For the spin rate effect on the SDP, we make the following assumptions:

1. The influence of the propellant gas on the projectile is so small that the propellant gas action is not considered [19].
2. The total separation time of the SDP is in the millisecond scale; thus, we can neglect the velocity attenuation of the APFSDS.
3. The rod spin rate is very low; thus, its rotational motion is not considered.
4. There are several positioning grooves between the sabots and the rod, and the relative displacement between them is extremely small during cutting an obturator. Thus, we set the initial axial clearance as 1 mm between the rod and sabots.
5. We assumed that the inlet flow is a perfect gas.

#### 2.2. Interior Ballistic Model

The propellant type of the APFSDS is a single charge used to solve the simulation initial boundary, and the interior ballistic model can be written as follows [22].

State equation of the propellant gas:
Equation of energy conservation:
\[ m_g \text{ART} = f m_g A - 0.5 (k - 1) B m_p v_p^2. \]  

Kinetic equation of the projectile:
\[ B m_p \frac{d v_p}{dt} = S_p p_p, \]
\[ v_p = \frac{df}{dt}, \]
\[ a_p = \frac{dv_p}{dt}, \]
\[ v_\tau = \omega p r_p. \]

The numerical parameters (i.e., distance, time, velocity, and average pressure) are processed as dimensionless, and the fourth-order Runge–Kutta scheme is adopted to solve the internal ballistic equations.

2.3. Solution Method. For dynamic grids of cases, the general form of the control equation is obtained as follows:
\[ \frac{\partial (\rho \phi)}{\partial t} + \text{div} (\rho \phi (u - u_{ij})) = \text{div} (\Gamma \text{grad} \phi) + S. \]  

Regarding equation (4), the first item on the left side is the transient term, and the second is the convection term. Moreover, the first on the right is the diffusion term, and the second is the source term.

Finite volume method [15, 16] implicit time integration scheme [18–20], and advection upstream splitting method (AUSM) form were adopted to discretize the governing equation. The implicit time scheme has an absolute advantage in terms of simulation stability and time consumption reduction. The discretization in the convective fluxes can be written by the three-point scheme in the conservation form as in [23]:
\[ (\rho \phi_j)^{n+1} = (\rho \phi_j)^n - \left( \frac{\Delta t}{\Delta x} \right) \cdot \left( f^p_{(j+1/2)} - f^p_{(j-1/2)} \right). \]

For the interface \( j + 1/2 \) straddling the \( j \)th and \( (j + 1) \)th cells, the numerical flux is the sum of the numerical convective flux and numerical pressure flux and the subscripts, and “L” and “R” are the left-side and right-side states of the cell interface.

The turbulence model plays a key role in supersonic behavior, especially in dynamic separation with complex shock interactions. Chen et al. [24] concluded that the two-equation turbulence model performed much better than the one-equation version with up to 20% discrepancy, and the \( k-\omega \) model had approximately 5% accuracy relative to the \( k-\epsilon \) model for the wind tunnel [25]. Not only is the influence of turbulent fluctuations in the projectile boundary layer considered but the effect of the far field is also not ignored. The SST \( k-\omega \) model can effectively ameliorate the reverse pressure gradient flow compared with the standard \( k-\epsilon \) model. Therefore, the SST \( k-\omega \) model is an ideal turbulence model for SDP simulation.
The dynamic equations and kinematics can describe the sabot separation motion and are derived using a Newtonian approach with inertial and flat earth assumptions. Therefore, the center of gravity (CG) translational motion and the rotational motion of CG are associated with the resulting forces and moments as follows:
\[
\begin{align*}
\dot{X}_i &= (u, v, w), \\
\dot{\omega}_i &= (p, q, r), \\
F &= (F_x, F_y, F_z), \\
M &= (M_x, M_y, M_z), \\
I &= (I_{xx}, I_{yy}, I_{zz}),
\end{align*}
\]
where \( V = (u, v, w) \), \( \omega = (p, q, r) \), \( F = (F_x, F_y, F_z) \), \( M = (M_x, M_y, M_z) \), and \( I = (I_{xx}, I_{yy}, I_{zz}) \).

The inertial position kinematics and Euler angle kinematics are then determined:
\[
\begin{align*}
\dot{\psi} &= CV_i, \\
\dot{S}_i &= E\omega_i,
\end{align*}
\]
where \( \psi \), \( \theta \), and \( \chi \) are the roll, yaw, and pitch Euler angles representing rotation on \( X \), \( Y \), and \( Z \), respectively. For the shorthand notation, \( S_i = \sin (\chi) \) and \( C_i = \cos (\chi) \) were used in the transformation matrices of \( C \) and \( E \).

Figure 3 presents the numerical process of the unsteady APFSDS SDP using ANSYS Corp.’s FLUENT system. Based on the interior ballistics, firing conditions, and projectile structure, we obtained the initial conditions and established a numerical grid to implement discretization in space. User-defined functions (UDFs) were used to endow these sabot parameters and the APFSDS initial state, and the diameter and length of the rod were set to initial reference parameters. After initializing the simulation condition, we adopted the AUSM scheme and the SST k-\( \omega \) turbulence model to solve the fluid parameters and to check their convergence. Then, by combining the initial state of the APFSDS, the rigid body equations were used to account for every sabot motion and to update the mesh. The following step repeats this process until it reaches the set of calculation steps. Then, we monitored the specific point pressures, the APFSDS aerodynamic dynamic, and the sabot motion history. Finally, we processed the flow field characteristics using post-processing software.

3. Numerical Verification

The Army-Navy Basic Finned Missile (ANF) model discussed in Army Ballistic Research Lab Report 539 is usually utilized to verify the projectile aerodynamic, and we created its physical model with a 20 mm diameter [26]. As shown in Figure 4(a), the ANF model is configured with a cylinder body, a cone, and four fins, and we provided these values as 200 mm full length, 20° cone angle, 1.6 mm maximum thickness, 20 mm length, and the width of the fins. Additionally, the refined zone had a nine-caliber diameter and length, and the boundary layer had a prism mesh of \( H_{max} = 0.001 \text{mm} \) and \( N_L = 10 \text{ boundary layers} \). The computed grid is shown in Figure 4(b). Free-stream conditions and properties from [26] were used to obtain the aerodynamic parameters, and Figure 5 presents a comparison of the ANF drag coefficient (DC) between the calculated (Cal.) and experimental (Exp.) conditions. The Cal. results are very close to the measured data in [26], and the maximum error is 3.4% for the 1.5 Ma case, and the average error is 1.39% at others. The fitted curve of the simulation is in good agreement with [27].

4. Physical Model

Based on the SDP mechanism, APFSDS structure, and assumptions (1)–(4), we simplified the projectile as a model having a five-fin rod and three sabots [19], and we describe its parameters using \( D \) in Figure 6(a). As shown in Figure 6(b), these sabots are marked as S1, S2, and S3 in the counterclockwise rotation. The nose points forward on the \( X \)-axis to coincide with the rod axis, the \( Y \)-axis extends in the negative direction of gravity, and the \( Z \)-axis is determined by the right-hand rule. The coordinates of the sabots are set as \( 0 \text{mm} \) on the \( X \)-axis so that the origin of the coordinates is the intersection of the plane created by the sabot CG point and the rod axis.

Based on the APFSDS parameters and the estimated sabot motions, we established the outer flow zone with a hemisphere in the front and a cylinder in the back, and we optimized the outer field with \( D_0 = 46.3D \) and \( L_0 = 88.7D \). The origin point of the zone is the hemisphere center. Subsequently, we performed a subtraction operation between the outer flow zone and the APFSDS to produce the simulation model, and we adopted the T-grid method to generate the unstructured tetrahedral mesh with ANSYS Corp.’s ICEM-CFD software. First, the shell grid was generated on the APFSDS surface and far field. Then, the prism grid was generated on the shell grid of sabots and rod, and the volume mesh finally grew from the prism grid to the shell grid as shown in Figure 7(a). The refined zone with \( L_R = 39D \) and \( D_R = 22D \) covers the APFSDS in Figure 7(b). To ensure simulation accuracy, we created the \( H_{max} = 0.015 \text{mm} \) and \( N_L = 10 \text{ boundary layers} \) as shown in Figure 7(c).

After fulfilling the model discretization in space, we set the far field as the inlet pressure. Moreover, the wall of the APFSDS is assumed to be an adiabatic boundary. Considering the gravity effect and assumption (5), the incoming
flow was a perfect gas with its parameter from state equations. Thus, the ambient conditions were 101325 Pa and 300 K. Combining assumptions (2) and (3) and the results from Section 2.2, the incoming Mach number was 3.6035 Ma, the attack angle was 0.64°, and the rod spin rate was 0 rad/s. For the given firing parameters of the rifled gun, this maximum value can reach approximately 2,000 rad/s. Hence, we determined the sabot spin rate for different cases as shown in Table 1. Next, we utilized the UDF code to endure the physical characteristics of all sabots’ internal statuses, as shown in Table 2. We also performed the optimization operation in the grid number and step time to content simulation requirements [28, 29]. Thus, the optimized parameters were 20.53 million and $2.5 \times 10^{-4}$ ms, respectively. For the initialization of parameters to solve aerodynamic coefficient, the reference in area and length was 91.61 mm$^2$ and 170 mm, respectively. After solution initialization using the above model and various parameters for different spin rate cases, we monitored the pressure variation with separation time at the rod surface points and obtained the aerodynamic parameters of the rod and sabots and the motion history of the three-sabots system.
Figure 6: Model definition. (a) Model configuration and dimension (D) and $D = 10.8$ mm. (b) Sabot number.

Figure 7: Continued.
5. Result Analysis

As described in [5], SDP is a complex interaction process between sabots and rods, namely, aerodynamic interference and mechanical interference. For the case of 0 rad/s, the APFSDS separation of the Gatling gun is consistent with that of a tank gun [19]. However, the intensity and interaction position of the rod change with an increase in the spin rate, and the shift in the aerodynamic characteristics is affected by the rod surface pressure. Therefore, we conducted an analysis in four aspects of discarding characteristics described below.

5.1. Sabot Asymmetry Separation. The dynamic characteristics of sabots are affected by the interaction of their initial states, the aerodynamic parameters, and gravity. Therefore, we investigated the boundary condition, aerodynamic characteristics, and kinematic parameters of the SDP under different spin rates. First, the initial state of the sabots is shown in Figure 6(b), and the three sabots are evenly distributed on the YOZ-plane. S2 and S3 are symmetrical about the XOY-plane. Each sabot has a gravity effect in the negative direction of the Y-axis. Concerning lift, the direction of S1 is positive, whereas that of S2 and S3 is negative. The lateral forces of S2 and S3 are in opposite directions. Furthermore, the 14 m/s inflow simulates the APFSDS tangential velocity in the positive direction of the Z-axis. The incoming flow in the Z-axis and the external force in the Y-axis express asymmetry.

Different spin rates can produce a difference in the movement and attitudes of sabots. Hence, we provide the sabots’ separation on the YOZ-plane at different rates. As shown in Figure 8 (a1–d1), the initial rate of the sabots has little effect on the movement state at 0.025 ms, and the pressure distribution at the sabot front scoop is the same. Moreover, as shown in Figure 8 (a2–d2), regarding the separation time of 0.1 ms, the pressure distribution of S1 and S2 is obviously different on the sabots’ front scoop, and the rate existence causes the sabots’ sides to remain close to the rod. Still, the movement position slightly changes. Then, Figure 8 (a3–d3) shows the sabots’ movement at 1.5 ms. For the 1,500 rad/s case, the sabots’ rolling motion is on the Z-axis, and there is a different pressure distribution simultaneously at the outer surface. A similar phenomenon occurs at 2,000 rad/s. As shown in Figure 8 (a4–d4), when the separation time arrives at 1.95 ms, the sabot status has completely changed with the pressure distribution and strength. Overall, the 1,500 rad/s rate is the demarcation point, resulting in the interaction of the aerodynamic forces and CG motion.

We plotted the aerodynamic coefficient curve for different spin rates. Figures 9(a)–9(f) show the time history of the aerodynamic coefficients of the sabots in cases 1–6. When a sabot’s windward side reaches the largest area in the YOZ-plane, the DC presents its maximum value. Like the DC, the lift coefficient (LIC) and lateral force coefficient (LAC) conform to this trend along the responding plane.
The increase in the initial spin rate and the sabot rolling movement can be observed by comparing LIC and LAC in Figures 9(b)–9(d), which exhibit wave variations at the same amplitude. Comparing the sabot coefficients of a tank gun, the coefficients in Figure 9(a) are in good agreement with those of [19]. The DC of the sabots and the S2 and S3 LICs are symmetrical, and the S2 and S3 LACs show approximate symmetry. However, the S1 LAC nearly preserves zero. In summary, when the rate is equal to 0 rad/s, the sabot coefficients are nearly symmetrical.

As the spin rate increases, the aerodynamic coefficients exhibit asymmetry. When the rate reaches 750 rad/s as compared with all forces in Figure 9(b), the DC shows a slight asymmetry, but the LIC of S2 and S3 exhibits obvious asymmetry. As shown in Figure 9(e), the DCs of sabots are only slightly convex at around 1.5 ms, which leads to insufficient drag. This is the main reason for the increase in separation time. As seen from Figure 9(f), when the spin rate reaches 2,000 rad/s, the LIC and LAC change periodically while maintaining asymmetry, but the DC reappears at near symmetry and produces a platform effect in 0.5–1.4 ms. Therefore, when the rate is in the range of 750–1,050 rad/s, all aerodynamic forces are asymmetrical. There is an initial spin rate of sabots, and the asymmetry of LIC and LAC becomes more obvious in contrast to the DC.

The following presents the CG motion in Figure 10, and Schmidt and Shear [6] found that the aerodynamic force was a primary source of external forces for sabot separation, which determines the relative movement between the sabots and the rod. As shown in Figure 10(a) at 0 rad/s, considering

Figure 8: Sabots’ motion of the YOZ-plane. Letters a, b, c, and d, respectively, stand for case 1, case 3, case 5, and case 6. Numbers 1, 2, 3, and 4 are the time of 0.025, 0.1, 1.5, and 1.95 ms, respectively.
Figure 9: Continued.
Figure 9: Aerodynamic force coefficients. Letters a–f stand for cases 1–6, respectively. DC is the drag coefficient, LIC is the lift coefficient, and LAC is the lateral force coefficient.

Figure 10: CG velocity of all sabots. Letters a, b, and c, respectively, stand for cases 1, 4, and 6. ~S2 is the opposite value of S2.
the 1,250 m/s muzzle velocity, we can calculate the sabot velocity difference to be less than 1%, and the motion in the X-axis is nearly symmetrical. Those of the other axes present certain symmetry. Regarding the CG velocity of the Y- and Z-axes, Figures 10(a)–10(c) show that the higher the rate of the sabot, the more obvious the asymmetry. However, owing to the presence of the muzzle velocity, the impact of the spin rate can be negligible for symmetry along the X-axis. In summary, the initial sabot spin rate can result in a certain asymmetry in the YOZ-plane movement.

Therefore, the separation process shows near symmetry under 0 rad/s, which is the same conclusion about the tank gun in [19]. However, the asymmetry of the boundary condition has an almost negligible effect on separation. Owing to the presence of spin rate, LC, LAC, and the YOZ-plane movement still show a certain asymmetry.

5.2. Rod Surface Pressure. The separation asymmetry changes the relative position between the sabots and the rod, further affecting the intensity and action position of the shock wave. Therefore, the direct result is a variation in rod pressure and distribution. We established a series of monitoring points on the rod surface to explore the pressure intensity located at the rod axis section. As shown in Figure 11, these sectional planes are named A, B, C, and D, and the X-axis coordinates of the corresponding planes are described in Table 3. Arabic numerals mark these points, and their direction is counterclockwise along the section plane. The A-, B-, and C-planes are evenly arranged with six points, and the D-plane is evenly configured with five points on the fin surface.

As mentioned in [5], the main types of shock waves in the rod/sabot interaction are attached shock, detached shock, reflected shock wave, expansion waves, and others. Furthermore, when the flow rate of the incoming flow is much greater than that of the outgoing flow, the choked flow creates a high-pressure zone that emerges from multiple reflected shock waves. For a rate of 0 rad/s, we obtained the maximum pressure of the monitoring points in Table 4 and plotted their pressure changes over time, as shown in Figure 12(a). Regarding the pressure intensity, we can see that there are two pressure peaks in the A- and B-planes, and the C-plane has a wave peak. However, the D-plane is relatively gentle. During the initial phase [19], these sabots are located at the rod body, and the gap between all sabots and the rod is extremely narrow so that a choked flow is generated in the front part. However, the flow gradually stabilizes from the nose to the fins, and the pressure gradually decreases. In other words, the pressure intensity of the front part is significantly higher than that at the back. During the coupling phase [19], these sabots flip backward, and the reflected shock wave hits the front or middle of the rod body to form a high-pressure zone on the body. Then, the sabots continue to flip back and generate a narrow gap between their tail and the rod. Hence, a choked flow emerges at the back body. Subsequently, it is relative to the rearward movement of the rod. Only the detached shock acts on the fins to form a high pressure on the fin. Generally, the pressure strength of the fins is weaker than that of the rod body. The above detailed separation description produces the pressure change tendency at 0 rad/s.

Figures 12(a)–12(d) show the pressure change at different rates. During the time range of 0-0.1 ms, the relative positions of the sabots/rod are the same, and the A- and B-planes are located in the front part of the rod so that their pressure intensities and distributions exhibit the same trend. Thus, the rate has almost no effect on the pressure. Moreover, owing to the C-plane location of the back part and the gap difference from various rates, the pressure intensity will be significantly reduced. However, the pressure on the D-plane of the fins remains nearly the same. The pressure intensity and the action time increase only at 2,000 rad/s.

For the pressure intensity at 0 rad/s in Table 4, the A-plane peaks are front-body choked flow and reflected shock, and the corresponding average values are 2.805 and 1.302 MPa. However, compared with the A-plane, the peak values of B are much weaker. As the gap increases and the relative motion varies between sabots and the rod, the C-plane peak, resulting from the choked flow action, still reaches 1.437 MPa. However, it is only half that of the A-plane. For the D-plane intensity, the pressure at D4 is approximately four times that of the others, and it results from the detached shock of the sabots and the increased gap between the sabots and the rod. Therefore, choked flow is the most intensive source during separation.
To further explore the pressure intensity at various rates, as shown in Figure 12, we see that A6, B6, C3, and D4 are the maximum intensities for their corresponding planes. Thus, we analyze the pressure at these points in Figures 13(a)–13(d). The spin rate has little effect on A6, followed by B6. However, C3 and D4 have the maximum impact. With an increase in the spin...
rate, the second peaks of A6 and B6 and the C3 peak decrease obviously, as does the acting time of the C3 pressure. At the D4 point, the maximum pressure decreases gradually in the range of 0–1,050 rad/s, but the peak and the acting time remain the same. However, when the spin rate exceeds 1,500 rad/s, the peak value and acting time increase. This trend is caused by the relative position diversification of the sabots and the rod. In short, the pressure distribution and variation show similar liability. However, the spin rate has an influence on the pressure intensity. Hence, the uneven pressure distribution is the reason for the variation in the aerodynamic characteristics.

5.3. Rod Aerodynamic Characteristics. The uneven pressure distribution mentioned in Section 5.2 causes the aerodynamic alteration in force and moment. Figures 14 and 15 present the aerodynamic force coefficients and moment coefficients under different cases.
During the time of 0-0.1 ms in Figure 14(a), the spin rate has almost no effect on the DC. Subsequently, the maximum value first increases, then decreases, and finally increases with the increase in the spin rate. Regarding the variation tendency and peak numbers, the important spin rate is 900 rad/s. Thus, two values, namely, that one is between 750 and 900 rad/s and the other is 1,500 rad/s, are the decomposition points. As shown in Figures 14(b) and 14(c), LIC and LAC fluctuate violently during the SDP. For the LIC, the maximum value changes more obviously, but the minimum value is basically the same. Moreover, there are two peaks at 2,000 rad/s. Toward the LAC, the changes in cases 1 and 2 are similar, which also applies to groups of cases 3-4 and 5-6. Generally, the rate has a greater influence on the LIC, and the rate of 1,500 rad/s is the demarcation point of the aerodynamic force.

Figures 15(a)–15(c) display the RMC, YMC, and PMC. The minimum value of RMC increases gradually with the
increase in rotating speed, but the maximum value is the same. Additionally, that of the 2,000 rad/s case decreases significantly. The variation process of YMC is similar in the time range of 0–0.5 ms; subsequently, with the increase in the rate, the maximum value first increases and then decreases. However, the minimum value first remains unchanged, then it decreases, and finally increases. The maximum PMC gradually increases with the rate at a time of 0–0.5 ms; after that, the maximum value first increases, then decreases, and finally increases. Then, the minimum value remains unchanged. Finally, in the 2,000 rad/s case, there is an extreme value at 1.9 ms caused by the detached shock hitting the fin surface. The pressure distribution of the fin surface is the reason for the aerodynamic change at that time.

Therefore, the 1,500 rad/s rate is the dividing point of the SDP. However, 2,000 rad/s has a significant influence on the
rod aerodynamic coefficients during the weak coupling phase, which may result in the loss of flight stability.

5.4. Discarding Quantization Parameters. The fundamental requirement for the SDP is rapid separation and interference reduction [5], which can be evaluated using the discarding time and aerodynamic impulse. When a sabot’s detached shock completely leaves the fins, there is no aerodynamic interference between the sabots and rod. Therefore, we defined the corresponding moment as the discarding time. The aerodynamic impulse is a physical quantity of the aerodynamic force accumulation effect during separation time, which results in impulse changes and muzzle disturbances of the rod. Aerodynamic interference generates the disturbance characteristics in the impulse form. The drag force can cause velocity attenuation, and lift and lateral forces produce velocity disturbances, which can directly affect external ballistic characteristics and shooting accuracy. According to the impulse definition, the aerodynamic impulse of the SDP is the integral of the aerodynamic force with respect to the discarding time, and it can be written as follows:

$$P_A = \frac{1}{2} \rho v^2 S \int_{t_D}^{0} C dt,$$

where $C$ is the resultant aerodynamic coefficient.

Combining the aerodynamic parameters with the surface pressure to analyze the separation time, we calculate the aerodynamic impulse from the separation time and aerodynamic forces. Table 5 gives the separation times and aerodynamic impulses under different spin rates, and we plot the discarding characteristic curve against the spin rate.

As seen in Figures 16(a) and 16(b), the discarding characteristics show a definite trend with the spin rate. When the rate is no greater than 900 rad/s, the separation time and aerodynamic impulse basically maintain a constant value, and their average is 1.78 ms and 0.075 N·s, respectively. However, if it is over 900 rad/s, both time and aerodynamic impulse increase significantly, and these values have a quadratic function law with the spin rate. When the rate is equal to 2,000 rad/s, compared with the average values at below 900 rad/s, the time and impulse are increased by 26 and 39%, respectively. Hence, in case that the rate exceeds a certain value, the higher the spin rate of the sabot, the worse the discarding characteristic.

According to the interior ballistic parameters and launch conditions, the range of spin rate is approximately 1,000–2,000 rad/s, and the blue blocks of Figure 16 represent the spin rate range of sabots. Combined with the discarding characteristic parameters, it is concluded that a spin rate of 1,000 rad/s is the optimal value for the APFSDS launched from the rifled barrel.

| Spin rate (rad/s) | 0   | 500 | 750 | 900 | 1000 | 1050 | 1500 | 1750 | 2000 |
|------------------|-----|-----|-----|-----|------|------|------|------|------|
| Discarding time (ms) | 1.780 | 1.781 | 1.785 | 1.786 | 1.85 | 1.865 | 2.000 | 2.091 | 2.251 |
| Aerodynamic impulse (N·s) | 0.0743 | 0.0746 | 0.0751 | 0.0762 | 0.0794 | 0.0796 | 0.0855 | 0.0938 | 0.1049 |

**Table 5: Discarding characteristic under different spin rates.**

![Figure 16: Discarding characteristic. (a) Discarding time. (b) Aerodynamic impulse.](image)
6. Conclusions

In this paper, we investigated the effect of the initial spin rate on the dynamic separation of the APFSDS using CFD and dynamic mesh approaches. This study explored the separation process at various spin rates. We also quantitatively analyzed the discarding characteristics against separation time and aerodynamic impulse. Special attention was given to understanding the separation of sabots, rod surface pressure, rod aerodynamic parameters, and quantization parameters of complex discarding characteristics. The following conclusions were drawn:

(1) When the spin rate was 0 rad/s, the SDP exhibited near symmetry. As the initial spin rate of the sabot increased, there was more obvious separation asymmetry, and it contributed to the relative position variation among the sabots and the rod.

(2) The distinction of the rod surface pressure indicates that the choked flow was the strongest flow source of the SDP. The spin rate had almost no effect on the pressure distribution of the front part of the rod. When the monitoring point moved towards the fins, the pressure distribution and intensity changed more dramatically. The initial spin rate and separation asymmetry produced a variation in surface pressure, which further influenced the rod aerodynamic characteristics.

(3) For the aerodynamic coefficients, the 1,500 rad/s rate is the dividing point. However, 2,000 rad/s has a significant influence on the rod aerodynamic coefficients during the weak coupling phase, which may result in the loss of flight stability.

(4) When the spin rate is in the range of 0–900 rad/s, the discarding characteristics remain the same. However, when the spin rate exceeds 900 rad/s, the discarding time and aerodynamic impulse have a quadratic polynomial relationship with the rate. Furthermore, a spin rate of 1,000 rad/s was found to be the optimal value for the APFSDS of the rifled barrel.

(5) The results give a design reference for the APFSDS from a rifled barrel. Our future work is to calculate the dynamic separation process of the APFSDS considering the influence of gunpowder gas, making the APFSDS initial boundary agree with the firing condition.

Abbreviations

| Symbol | Description |
|--------|-------------|
| ω | Angular velocity |
| S | Euler angles |
| C | Transformation matrix from inertial to body coordinates |
| p₀ | Projectile base pressure |
| lₐ | Equivalent length of the chamber |
| A | Burned ratio of the propellant |
| R | Gas constant |
| f | Energy capacity of the propellant |
| v₀ | Muzzle velocity |
| vₙ | Tangential velocity |
| D₀₀ | Diameter of the projectile |
| H₁₀ | Height of the first layer |
| D₀ₙ | Diameter of outer flow |
| Dₖₙ | Diameter of the refined zone |
| P₀ | Aerodynamic impulse |
| S | Rod reference area |
| ρ | Fluid density |
| Δx | Space step |
| f | Pressure flux |
| m | Sabot mass |
| F | External forces |
| V | Translational velocity |
| P | Absolute coordinates |
| S₀ | Projectile base area |
| E | Transformation matrix from sabot Euler to attitude angles |
| l | Projectile displacement |
| mₜ | Propellant mass |
| B | Coefficient of secondary work |
| T | Burning temperature of the propellant |
| m₀ | Projectile mass |
| k | Specific heat |
| ω₀ | Rotational velocity of the barrel group |
| r₀ | Rotation radius of the barrel group |
| N₁ | Number of layers |
| L₀ | Length of outer flow |
| Lₖ | Length of the refined zone |
| v | Incoming flow velocity |
| t₀ | Discarding time |
| APFSDS | Armor-piercing fin-stabilized discarding sabot |
| AOA | Angle of attack |
| AUSM | Advection upstream splitting method |
| UDFs | User-defined functions |
| DC | Drag coefficient |
| LAC | Lateral coefficient |
| YMC | Yaw moment coefficient |
| Cal. | Calculated |
| SDP | Sabot discarding process |
| CFD | Computational fluid dynamics |
| CG | Center of gravity |
| ANF | Army-navy basic finned missile |
| LIC | Lift coefficient |
| RMG | Roll moment coefficient |
| PMC | Pitch moment coefficient |
| Exp. | Experimental |
Data Availability

The data used to support the findings of this study are included within this paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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