CFD/RBD Coupled Simulation of Discus Flight Trajectory and Analysis of Throwing Strategy

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Abstract

Investigating the aerodynamics and flight mechanics of the discus throwing process and accurately predicting the discus flight trajectory can guide athletes in adopting better throwing strategies to improve competition performance. In this study, numerical virtual flight simulation technology is employed to couple the unsteady Reynolds-averaged N-S equations with the rigid-body dynamics equations, fully accounting for the significant unsteady aerodynamic/motion coupling effects during discus flight. The flight trajectories and motion attitudes under different discus throwing parameters are simulated and predicted, the effects of throwing parameters such as spin angular velocity and release attitude angles on the discus flight distance are analyzed, and the combination of throwing parameters that maximizes the flight distance is selected. The numerical simulation results show that significant aerodynamic hysteresis exists during the high-angle-of-attack stalled flight phase of the discus, and stall and aerodynamic hysteresis can reduce the precession speed of the discus in spinning flight, thereby exerting a significant influence on its flight trajectory. Therefore, accurately accounting for the hysteresis effect of discus aerodynamic forces is crucial for accurately predicting its flight trajectory and attitude. By increasing the spin angular velocity and configuring appropriate initial roll and initial pitch angles, the precession speed of the discus flight can be reasonably controlled, aerodynamic forces can be used to extend the airborne time, and the discus flight distance can thereby be effectively increased.

Full Text

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Abstract: Studying the aerodynamics and flight mechanics involved in discus throwing, and accurately predicting the flight trajectory of the discus, can guide athletes in adopting better throwing strategies to improve competitive performance. In this study, numerical virtual-flight simulation technology is employed. The unsteady Reynolds-averaged N–S equations are coupled with rigid-body dynamics equations, with full consideration of the significant unsteady aerodynamic/motion coupling effects during discus flight. The flight trajectories and motion attitudes of the discus under different throwing parameters are simulated and predicted; the effects of throwing parameters such as spin angular velocity and release attitude angles on discus flight distance are analyzed; and the combination of throwing parameters that maximizes the flight distance of the discus is identified. The numerical simulation results show that the discus exhibits a pronounced aerodynamic hysteresis phenomenon during the high-angle-of-attack stalled flight phase. Stall and aerodynamic hysteresis can reduce the precession speed of the discus during spinning flight, thereby exerting a significant influence on the flight trajectory of the discus. Therefore, accurately accounting for the hysteresis effect of the aerodynamic forces on the discus is critical for accurately predicting its flight trajectory and attitude. By increasing the spin angular velocity and selecting appropriate initial roll and initial pitch angles, the precession speed of the discus flight can be reasonably controlled, and aerodynamic forces can be used to prolong the airborne time of the discus, thereby effectively increasing its flight distance.

Keywords: virtual flight simulation; dynamic aerodynamics; hysteresis effect; high angle of attack; precession; discus

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CFD/RBD flight simulation and throwing strategy analysis of discus

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Abstract: Studying the aerodynamics and flight mechanics of discus throwing and accurately predicting trajectory of the discus can help athletes improve their performance in competition by using optimal throwing strategies. In this study, numerical virtual flight simulation is adopted to solve unsteady Reynolds average Navier-Stokes equations combined with rigid body dynamics equations, taking into full consideration of unsteady effects caused by coupling aerodynamics and motion. By predicting the trajectories and motion attitude of discus under different throwing parameters, such as spin rate and initial attitude angles, the influence on discus flight distance is investigated, and the optimal combination of throwing parameters that

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maximizes the flight distance is determined. The results reveal that significant aerodynamic hysteresis exists in discus stall at high angles of attack. However, stall and aerodynamic hysteresis can reduce the precession speed of the discus and significantly influence the discus trajectory. Therefore, accurately simulating aerodynamic hysteresis is crucial for predicting the trajectory and attitude motion of a discus. By increasing the spin rate and specifying appropriate initial roll and pitch angles, the precession speed of the discus can be reasonably controlled, and the aerodynamic force can extend the hang time of the discus. Thus, the flight distance of the discus can be effectively improved.

Key words: virtual flight; dynamic aerodynamics; hysteresis; high angles of attack; precession; discus

As a traditional track-and-field event in which the competition outcome depends on throwing distance, discus throwing involves complex unsteady and nonlinear problems in aerodynamics and flight dynamics during the flight process. Studying the aerodynamics of discus flight and accurately predicting the flight trajectory can guide athletes in adopting better throwing strategies to improve competitive performance. For this reason, many researchers in China and abroad have studied the aerodynamic characteristics and flight trajectories of the discus. GALSEN[^1] measured the lift and drag coefficients of a discus at different incoming-flow velocities and angles of attack through wind-tunnel tests. The results showed that, compared with the influence of angle of attack, the effect of Reynolds-number variations caused by the incoming-flow velocity on the lift and drag coefficients of the discus can be neglected. FROHILICH[^2] used these wind-tunnel data and, neglecting the lateral displacement and attitude changes of the discus during flight, simulated the discus trajectories in the horizontal and vertical directions. The results showed that aerodynamic forces have an extremely important influence on the flight distance of a discus. SOONG[^3] combined wind-tunnel test data with classical velocity-potential theory to approximately obtain the aerodynamic forces and moments acting on a rotating discus, achieved a six-degree-of-freedom flight simulation of the discus, and studied the influence of throwing parameters on the flight distance. HUBBARD et al.[^4] made comprehensive use of wind-tunnel test data, established a six-degree-of-freedom dynamic model of the discus, and optimized the throwing parameters on this basis. The above studies only realized analyses of steady aerodynamic characteristics and flight simulations supported by steady aerodynamic-force data.

When an athlete throws a discus, although the rotational throwing method enhances the flight stability of the discus, the statically unstable aerodynamic characteristics of the discus, together with precession and nutation induced by spin, cause significant unsteady aerodynamic effects arising from attitude changes during flight. In particular, in the middle and later stages of flight, the discus often exhibits a "high-angle-of-attack" [^5-^8] flight attitude, and unsteady effects such as aerodynamic hysteresis[^9-^11] become increasingly significant. Therefore, in discus flight simulation, it is necessary to accurately predict its strongly unsteady and nonlinear dynamic aerodynamic characteristics.

The continuous development of computational fluid dynamics (CFD) and low-speed wind-tunnel testing technology has provided high-performance CFD solvers and more advanced wind-tunnel measurement techniques for studying the aerodynamic characteristics of discus flight at high angles of attack. POTTS et al.[^12] used ANSYS Fluent software in combination with wind-tunnel tests to carry out verification and validation research on the aerodynamic characteristics of the discus. Their results showed that, under high-angle-of-attack conditions, both CFD computations and wind-tunnel-test results have relatively large uncertainties. SEO et al.[^13] used PIV technology[^14] to study the flow phenomena of a discus at high angles of attack. Their study showed that aerodynamic hysteresis exists near the stall angle of attack of the discus: the stall angle of attack during increasing angle of attack is larger than that during decreasing angle of attack. During flight, a discus is often accompanied by precession involving coupled rolling and pitching, whereas SEO et al.[^13] did not consider the unsteady hysteresis problem under complex attitude motion.

Numerical virtual flight (NVF) simulations[^15-^17], which couple the solution of the unsteady flow governing equations with the rigid body dynamics (RBD) equations, can accurately account for the unsteady aerodynamic effects caused by complex attitude motion during flight. In recent years, NVF has found key applications in dynamically coupled problems with strong unsteady aerodynamic effects, such as salvo water-exit of high-speed vehicles[^18-^19], flapping-wing motion[^20], parachute recovery of unmanned aerial vehicles[^21], and the controlled motion of the "Genesis" return capsule[^22].

To fully account for the unsteady coupling effects between aerodynamics and motion during discus flight, this study uses the NVF method to simulate the flight processes of a discus under different throwing parameters. It compares and analyzes the differences between the transient aerodynamic forces during discus flight and the static aerodynamic forces at the same attitude, examines the unsteady aerodynamic effects during discus flight, studies the changes in transient aerodynamic forces during discus flight caused by different throwing parameters and the dynamic mechanisms that ultimately influence discus flight, analyzes discus throwing strategies, and screens out the combination of throwing parameters that yields the greatest flight distance.

1 Computational Method

1.1 Flow Governing Equations

The numerical simulation of the unsteady flow field around the discus uses the unstructured hybrid-grid N-S equation solver independently developed by our research group.

is carried out in HUNS3D [23]. To simulate a flow field containing a six-degree-of-freedom moving boundary, it is necessary to solve the flow governing equations described by an arbitrary Lagrange–Euler (ALE) method. Here, the integral form of the unsteady Reynolds-averaged Navier–Stokes (URANS) equations described by the ALE method is given as

$$\frac{\partial}{\partial t}\iiint_{\Omega} Q\, d\Omega + \iint_{\partial\Omega} F\left(Q, V_{\text{grid}}\right)\cdot n\, ds = \iint_{\partial\Omega} G\left(Q\right)\cdot n\, ds \tag{1}$$

where
$Q = [\rho \quad \rho u \quad \rho v \quad \rho w \quad \rho E]^{\mathrm{T}}$; ρ denotes the fluid density; u, v, and w denote the fluid velocities in the x, y, and z directions, respectively; E denotes the total internal energy of the control volume; Ω denotes the control-volume volume; V_{grid} denotes the grid-motion velocity; $\partial\Omega$ denotes the control-volume boundary; n denotes the outward unit normal vector on the control-volume surface; and $F(Q, V_{\text{grid}})$ and $G(Q)$ denote the inviscid flux and viscous flux, respectively. Their specific forms may be found in Ref. [23].

The HUNS3D code spatially discretizes $F(Q, V_{\text{grid}})$ and $G(Q)$ in Eq. (1) by means of a cell-centered finite-volume method, and uses a fully implicit dual-time-step scheme [24] to advance and solve the spatially discretized form of Eq. (1) in time.

1.2 CFD/RBD Coupled Solution Procedure

During the flight of the discus, its shape does not change; therefore, rigid-body dynamics can be used to study its flight motion. The position and attitude changes of a rigid body in space can be described by six dynamic equations [25–26].

In an inertial system, the equations of motion for translation of the rigid-body centroid are

$$\begin{cases} m\dfrac{dV_x}{dt} = F_x \\ m\dfrac{dV_y}{dt} = F_y \\ m\dfrac{dV_z}{dt} = F_z \end{cases} \tag{2}$$

In the body-axis system, the equations of motion for rotation of the rigid body about its centroid are

$$\begin{cases} I_x \dfrac{d\omega_{bx}}{dt} + \left(I_z - I_y\right)\omega_{by}\omega_{bz} = M_{bx} \\ I_y \dfrac{d\omega_{by}}{dt} + \left(I_x - I_z\right)\omega_{bz}\omega_{bx} = M_{by} \\ I_z \dfrac{d\omega_{bz}}{dt} + \left(I_y - I_x\right)\omega_{bx}\omega_{by} = M_{bz} \end{cases} \tag{3}$$

where m denotes the rigid-body mass; V_x, V_y, and V_z denote the velocity components of the rigid body along the x, y, and z directions; F_x, F_y, and F_z denote the forces acting on the rigid body in the three coordinate directions; M_{bx}, M_{by}, and M_{bz} denote the moments acting on the rigid body in the three coordinate directions in the body-axis system; I_x, I_y, and I_z denote the rotational inertias of the rigid body in the three coordinate directions in the body-axis system; and ω_{bx}, ω_{by}, and ω_{bz} denote the angular velocities of the rigid body in the three coordinate directions in the body-axis system.

The system of equations composed of Eqs. (2)-(3) is a system of ordinary differential equations, and solving this system is an initial-value problem for ordinary differential equations. In this study, an improved Adams predictor-corrector method [27] is used to solve it.

The free flight of an object is an aerodynamics/motion coupling process, and CFD/RBD coupled simulation can reflect this process. In the CFD/RBD coupled simulation, the CFD module computes and outputs the aerodynamic forces and aerodynamic moments; the RBD system takes the aerodynamic forces and aerodynamic moments as input parameters and computes the displacement, flight velocity, attitude-angle variations, and other parameters at the next time step. These parameters are used to perform rigid transformations of the computational mesh, thereby obtaining the grid-motion velocity required by the ALE-form URANS equations. Thus, CFD and RBD are coupled iteratively. When the termination criterion is satisfied, the calculation is stopped. Figure 1 shows the flowchart of the above coupled computational method.

Text in the flowchart:

- Start
- Initial steady calculation
- Unsteady calculation of fixed-axis rotation using the initial angular velocity
- Non-coupled module
- Solve six-degree-of-freedom rigid-body dynamics equations
- Unsteady aerodynamic force
- Whether the termination condition is satisfied
    - Yes → End

  - No
- Displacement and attitude angle
- Rigid-body mesh motion
- Solve unsteady N-S equations
- Coupling module

Figure 1. Flowchart of the CFD/RBD coupled solution process
Fig. 1 Flowchart of the CFD/RBD coupling simulation flowchart

A series of previously conducted numerical examples, such as multibody separation simulations [28] and flight-trajectory simulations of supersonic spinning projectiles [29], have verified that the above algorithm can effectively simulate the flight trajectory and motion attitude of an aircraft, can accurately capture unsteady effects in the flow field, and has relatively high computational accuracy.

2 Computational Model

The simulation in this study adopts a men' s standard discus [30], with diameter $d = 0.22$ m, thickness $h = 0.045$ m, mass $m = 2$ kg, and center of gravity located at its geometric center. The moments of inertia are $I_x = I_y = 0.007\,72\ \mathrm{kg \cdot m^2}$ and $I_z = 0.015\,446\ \mathrm{kg \cdot m^2}$. The discus diameter d is taken as the reference length, and the area of the horizontal symmetry plane of the discus (hereinafter referred to as the "discus plane") is taken as $S =$

$0.038\,01\ \mathrm{m^2}$ was taken as the reference area [3]. The geometric dimensions of the discus are shown in Fig. 2.

Fig. 2 Schematic of discus dimensions
Visible annotations: 85 mm, 25 mm, 45 mm, $R = 6$ mm, X_b, Z_b.

The throwing parameters of the discus are defined as shown in Fig. 3. Here, ω denotes the spin angular velocity of the discus, whose direction is perpendicular to the discus plane; V denotes the initial velocity of the discus; and β denotes the angle between V and the ground-axis X_g, i.e., the release angle. In the body-axis system $OX_bY_bZ_b$ of the discus, the X_b-axis is defined as the line of intersection between the vertical plane containing V and the discus plane; the Z_b-axis is perpendicular to the discus plane and points downward; and the Y_b-axis is determined according to the right-hand rule. Once the body-axis system of the discus is defined, the initial attitude angles are also defined: θ denotes the initial pitch angle of the discus, i.e., the angle between the X_b-axis and the horizontal plane X_gOY_g, with nose-up taken as positive. φ denotes the initial roll angle of the discus, i.e., the angle between the Z_b-axis and the vertical plane X_gOZ_g; viewed along the X_b-axis, clockwise rotation is taken as positive. The discus is assumed to be released at sea level under standard atmospheric conditions, with air density $\rho = 1.225\ \mathrm{kg/m^3}$.

Fig. 3 Initial parameters of discus throw

The definitions of the principal aerodynamic forces acting on the discus and of the angle of attack are shown in Fig. 4.

Fig. 4 Definition of AoA and aerodynamic force

The angle of attack α is defined as the angle between the direction of motion of the discus and the discus plane; because the discus is rotationally symmetric, sideslip is not considered. The pitching moment M is perpendicular to V and to the discus body-axis Z_b, with the moment that raises the discus nose taken as positive. The lift L is perpendicular to V and points upward relative to the pitching moment M, while the drag D is opposite to V.

The unstructured hybrid mesh adopted is shown in Fig. 5. The y^+ value of the first near-wall mesh layer on the body surface is set to 0.8, the growth rate of the boundary-layer mesh height is 1.15, and the total number of mesh cells is approximately 3.9 million.

Fig. 5 Aerodynamic mesh for discus

3 Analysis of Computational Results

3.1 Unsteady aerodynamic effects during discus flight

To investigate the unsteady aerodynamic effects during discus flight, this section uses the NVF method to perform a flight simulation of the discus, obtains the transient aerodynamic forces during flight, and compares them with the static aerodynamic forces at the same attitudes and with the wind-tunnel test data of SEO et al. [13]. It should be noted that SEO et al. [13] only provided the commercial name of the discus used in the wind-tunnel test, namely Super HM, and did not give its specific dimensions. However, it is likewise a discus compliant with the standard [30], so its shape differs little from that of the discus used in the simulations of the present study.

The "optimal" throwing parameters of the discus identified in the study by SOONG [3] are selected: initial velocity $V = 25.5$ m/s, release spin rate $\omega = 12\pi$ rad/s, release height 1.8 m, release angle $\beta = 35°$, initial pitch angle $\theta = 26°$, and initial roll angle $\varphi = 0°$.

Under the above throwing parameters, the discus flight trajectory and motion attitude obtained by the NVF simulation are shown in Fig. 6.

Fig. 6 Trajectories and motion attitude of discus

As can be seen in Fig. 6, the rotating discus exhibits precession during flight[2]: after release, the discus is acted upon by a pitching moment perpendicular to its spin angular momentum; the direction of the spin angular momentum continuously shifts, causing the discus to roll over to one side.

Figure 7 shows the variation curves of the discus angle of attack α and the instantaneous aerodynamic coefficients with flight distance. Locally, α and the lift and drag coefficients exhibit slight oscillations, which are caused by the nutation of the discus[2,31]. In terms of the overall trend, α increases after release of the discus, until precession-induced side roll causes α to decrease. In the first half of the flight, the lift and drag coefficients increase as α increases, until the discus stalls and the lift coefficient drops abruptly.

Fig. 7 Variation curve of AoA and aerodynamic coefficients with flight distance

Figure 8 presents the dynamic aerodynamic-characteristic curves obtained by simulation with the NVF method, the aerodynamic-characteristic curves obtained from static CFD calculations, and the wind-tunnel experimental data of SEO et al.[13].

Fig. 8 Variation curve of aerodynamic coefficients with AoA

(a) Lift-coefficient curve

(b) Drag-coefficient curve

It can be seen from the figure that the stall angle of attack obtained by the NVF method and by the wind-tunnel experiments of SEO et al.[13] is larger than that obtained by the static CFD calculation. The comparison of the Y-direction vorticity distributions at an angle of attack of 30°, obtained by the NVF method and by static CFD calculation, is shown in Fig. 9. Compared with the result obtained by static CFD calculation, the leading-edge separation vortex obtained by the NVF method is closer to the wall. In simulating the flight process of the discus, the NVF method accounts for the unsteady aerodynamic hysteresis effect that affects discus flight; therefore, the stall angle of attack is larger than that obtained by static CFD calculation.

Fig. 9 The component of vorticity in Y direction at AoA = 30°, which are obtained by NVF and static CFD

(a) NVF

(b) Static CFD

Color scale: Y-direction vorticity /s^{-1}, from -3 to 3. Coordinate axes: X, Y, Z, O.

Using the angle of attack α of the discus at each position obtained by NVF in Fig. 7, together with the lift and drag coefficients from the static CFD calculation at each angle of attack α given in Fig. 8, the static aerodynamic forces corresponding to the flight attitude at each flight position in the discus flight trajectory obtained by NVF can be derived. The comparison between the instantaneous aerodynamic forces during discus flight and the static aerodynamic forces under the same flight attitude is shown in Fig. 10. The results show that, in the later stage of flight at large angles of attack ($X_g > 36$ m), the instantaneous aerodynamic forces on the discus differ significantly from the static aerodynamic forces under the same flight attitude. This indicates that it is necessary to use the NVF method, which incorporates nonlinear and unsteady aerodynamic effects.

Fig. 10 Variation of aerodynamic coefficients with flight distance obtained by the NVF method and static CFD.

3.2 Simulation Analysis of the Discus Flight Trajectory

3.2.1 Effect of Spin Angular Velocity

To examine the influence of spin angular velocity on the flight trajectory and motion attitude of the discus, flight simulations were carried out for discuses released with different spin angular velocities. According to observational data, the limiting spin rate that male discus throwers can impart is approximately 14π rad/s [2, 31]. The spin angular velocities of the discus were set to $\omega = 0,\ 4\pi$ rad/s, 8π rad/s, 12π rad/s. The other throwing parameters were set as follows: the initial speed V was 25.5 m/s, the release height was 1.8 m, the release angle was $\beta = 35°$, the initial pitch angle was $\theta = 26°$, and the initial roll angle was $\varphi = 0°$.

The flight trajectories and motion attitudes of the discus at different spin angular velocities are shown in Fig. 11. It can be seen that, in terms of the flight trajectory, the greater the spin angular velocity, the higher the discus flies and the farther it travels. In terms of motion attitude, the discus with $\omega = 0$ flips after release under the action of the pitching moment, whereas a discus with initial spin undergoes precessional side-flipping motion; the greater the spin angular velocity, the slower the precession.

Fig. 11 Trajectories and motion attitudes of discuses with different spin rates.

The variation of the forward velocity V_{X_g} of the discus with flight time T at different spin angular velocities is shown in Fig. 12. It can be seen from the figure that the decreasing trend of the forward velocity of the discus is relatively small, indicating that the lateral aerodynamic drag has little influence on the flight distance of the discus. By contrast, the flight duration largely determines the flight distance of the discus; that is, the aerodynamic lift in the vertical direction is the key factor affecting the flight distance of the discus.

Fig. 12 Variation of forward velocity with time.

Figures 13 and 14 respectively show the variations of the vertical aerodynamic force F_{Z_g} and the angle of attack α of the discus with flight distance. It can be seen that, after release, the increase in α causes F_{Z_g} to increase. However, precessional side flipping also reduces the vertical component of the aerodynamic force acting on the discus; therefore, F_{Z_g} first increases and then decreases as the flight distance increases. For the discus with $\omega = 4\pi$ rad/s, after it flies to $X_g = 45$ m, it has completely side-flipped (Fig. 11), and the vertical component of the aerodynamic force on the discus is directed downward; consequently, the decrease in α causes F_{Z_g} to rise again. Comparing the variation patterns of F_{Z_g}

and α for discuses with different spin angular velocities, it can be seen that a discus with a larger spin angular velocity undergoes side flipping later. Thus, during the flight, a discus with a larger spin angular velocity can obtain a larger maximum angle of attack and a larger maximum vertical aerodynamic force; consequently, its flight duration is longer and its flight distance is farther.

Fig. 13 Variation of vertical aerodynamic force with flight distance.

It is worth noting that, in Fig. 13, after the discuses with $\omega = 8\pi$ rad/s and 12π rad/s fly to $X_g = 48$ m, the decreasing trend of F_{Z_g} suddenly slows.

This makes the upward impulse supplied by F_{Zg} to the discus during the subsequent flight increase, thereby prolonging the discus' s time aloft. As described above, the precessional rollover of the discus causes F_{Zg} to decrease, while the rate of precession is determined by the spin angular momentum and the magnitude of the pitching moment. During the flight of the discus, the attenuation of the spin angular velocity can basically be neglected; the dominant factor is the change in the aerodynamic pitching moment acting on the discus.

Figure 15 gives the variation curve of the aerodynamic pitching-moment coefficient C_M with the angle of attack α during the flight of the discus. It can be seen from the figure that, for the discus with $\omega = 4\pi$ rad/s, the maximum angle of attack does not exceed the stall angle of attack, and the pitching-moment coefficient varies linearly with the angle of attack. For the discus with $\omega = 8\pi$ rad/s and $\omega = 12\pi$ rad/s, the maximum angle of attack exceeds the stall angle of attack, and the pitching-moment coefficient drops sharply after the discus stalls. For the discus with $\omega = 8\pi$ rad/s, aerodynamic hysteresis occurs during flight: when α begins to decrease, the unsteady aerodynamic hysteresis causes the pitching moment acting on the discus to remain relatively small. Stall and aerodynamic hysteresis cause the pitching moment acting on the discus to drop abruptly and remain at a low level, slowing the precession of the discus and thereby helping to increase the flight distance.

Fig. 14 Variation curve of AoA with flight distance

Visible labels: x_g/m, $\alpha/(^\circ)$; $\omega = 4\pi$ rad/s, $\omega = 8\pi$ rad/s, $\omega = 12\pi$ rad/s.

Fig. 15 Variation curve of pitching moment coefficient with AoA

Visible labels: C_M, $\alpha/(^\circ)$; $\omega = 4\pi$ rad/s, $\omega = 8\pi$ rad/s, $\omega = 12\pi$ rad/s; points A, B, C, D.

Figure 16 gives, for the discus with $\omega = 8\pi$ rad/s, the distribution of the Y-direction vorticity in the flow around the surface at points A, B, C, and D in Fig. 15, that is, during the processes in which the angle of attack α increases and decreases. It can be seen that as α increases, the leading-edge vortices first separate on both sides of the discus. After the discus stalls, the leading-edge vortices are completely separated. When α decreases to 25°, because of aerodynamic hysteresis, the leading-edge vortices still have not returned to the attached state before stall.

Fig. 16 Distribution of the Y-direction vorticity near the surface during the increase and decrease of the discus AoA

Visible panel labels: point A, $\alpha = 25°$; point B, $\alpha = 29°$; point C, $\alpha = 29°$; point D, $\alpha = 25°$. Color scale label: Y-direction vorticity /s^{-1}, from -3 to 3. Coordinate labels: X, Y, Z, O.

3.2.2 Effect of the Initial Attitude Angle

Considering that, when an athlete releases the discus, it is difficult to ensure both the release linear velocity and the spin angular velocity at the same time, this section selects the moderate rotational speed 8π rad/s as the spin angular velocity of the discus, and investigates the influence of the initial roll angle φ on the flight distance of the discus. The initial roll angle φ is set to 0°, 15°, 30°, 45°, 60°, and 75°, respectively, for simulation calculations. The other initial parameters are as follows: initial velocity $V = 25.5$ m/s, release height 1.8 m, release angle $\beta = 35°$, and initial pitch angle $\theta = 35°$.

Figure 17 shows the flight trajectories and motion attitudes of the discus for different initial roll angles φ. It can be seen from the figure that as φ increases from 0° to 60°, the flight distance of the discus increases; when φ increases to 75°, the flight distance decreases. The variation curves of the vertical-direction aerodynamic force F_{Zg} of the discus for different initial roll angles φ are shown in Fig. 18. It can be seen from Fig. 18 that increasing the initial roll angle φ causes the vertical component of the aerodynamic force after release to decrease. However, increasing φ also increases the angle through which the discus must roll in order to overturn completely; during flight, the maximum value of F_{Zg} increases, and the time for which F_{Zg} remains upward is prolonged. Therefore, when the other throwing parameters are given, there [[unclear: text continues beyond the visible page]].

the optimal initial roll angle that gives the maximum discus flight distance.

Fig. 17 Trajectories and motion attitudes of the discus with different initial roll angles

Fig. 18 Variation curve of the vertical aerodynamic force on the discus with flight distance

As with increasing the spin angular velocity, setting an initial roll angle φ is conducive to causing the discus to stall in the later stage of flight. Fig. 19 gives the curves of the pitching moment coefficient of the discus versus angle of attack for different initial roll angles φ.

Fig. 19 Variation curve of the pitching moment coefficient with AoA

It can be seen from Fig. 19 that, as φ increases from 0° to 45°, the maximum angle of attack during the discus flight increases; when φ increases from 45° to 60°, the maximum angle of attack decreases. For discus cases with a smaller initial roll angle ($\varphi = 0°$ and $\varphi = 15°$), the maximum angle of attack is less than or equal to the stall angle of attack of the discus, so the discus does not stall during flight, or it recovers after stalling for a period of time. For discus cases with a larger initial roll angle, however, the maximum angle of attack is greater than the stall angle of attack, and after stalling the discus remains in the stalled state until the end of the flight.

It is worth noting that, in Fig. 19, because the trends of the angle of attack during stall are different, the aerodynamic hysteresis curves are also different. This is a manifestation of nonlinear and unsteady aerodynamic effects.

In addition to adjusting the initial roll angle φ, the hang-time capability of the discus can also be enhanced by adjusting the initial pitch angle θ. If θ is smaller than the release angle β of the discus, then the angle of attack at the release instant is negative, and the discus will precess in the opposite direction for a short time after release. When the angle of attack changes from negative to positive, the discus will precess in its original direction. This process prolongs the time during which the vertical aerodynamic force remains upward. However, the drawback of releasing the discus with a negative angle of attack is obvious: the negative angle of attack at release causes the discus to experience a downward aerodynamic force for a period of time, which has a certain adverse effect on the discus' s hang time. To obtain the optimal combination of attitude angles for the thrown discus, flight simulations were carried out for a discus with $\omega = 8\pi$ rad/s (with the other initial parameters unchanged), setting different values of φ and θ, respectively. The cloud map of the discus flight distance obtained from the simulation as φ and θ vary is shown in Fig. 20. It can be seen from the figure that flight distances above 72 m appear in the diagonal region of the plot. That is, when the other initial parameters of the thrown discus are specified, there is likewise an optimal value of θ that maximizes the flight distance. Moreover, as φ increases, the value of θ that gives the maximum flight distance also increases.

Fig. 20 Cloud map of the discus flight distance varying with initial roll angle and initial pitch angle

The finally obtained combination of φ and θ that gives the optimal flight distance is $\varphi = 60^{\circ}$, $\theta = 30^{\circ}$; its flight trajectory is shown in Fig. 21. With this

The flight distance of the discus thrown with this combination of initial attitude angles is 73.03 m, very close to the current world record of 74.08 m. It can be seen that the discus thrown with this combination of initial attitude angles still does not undergo complete rollover after completing the entire flight. Figure 22 gives the variation curves of the angle of attack α and the aerodynamic force in the vertical direction F_{Z_g} with flight distance for this discus. As can be seen from Figure 22, throughout the entire flight process α consistently maintains an increasing trend. Benefiting from α, F_{Z_g} remains upward for essentially the whole flight. Even when the precessional rollover of the discus causes F_{Z_g} to begin to decrease, the reduced precession rate after stall also keeps F_{Z_g} at a relatively high level, effectively prolonging the discus's time aloft and ultimately making its flight distance the greatest.

Figure 21 Flight trajectory and motion attitude of a discus with a flight distance near optimal
Fig. 21 Trajectory and attitude of discus with flight distance near optimal

4 Conclusions

In this study, virtual flight simulation using coupled CFD/RBD solution was employed to simulate and investigate the flight process of the discus. The conclusions obtained are as follows.

1) Through numerical virtual flight simulation, it is verified that significant unsteady aerodynamic hysteresis exists in the high-angle-of-attack flight segment of the discus during the middle and later stages of flight.

2) Increasing the spin angular velocity of the discus can enhance its gyroscopic stability and thereby reduce the precession rate. It is also conducive to the occurrence of stall in the discus; stall and aerodynamic hysteresis can reduce the precession rate, ultimately increasing the flight distance of the discus.

3) Assigning appropriate initial roll and pitch angles can effectively adjust the precession of the discus in flight and extend its flight distance. The computational results of this study show that, for a standard men' s discus with a given release angle of 35° and a release spin rate of 8π rad/s, when the initial roll angle φ is about 60° and the initial pitch angle θ is about 30°, the discus can achieve a flight distance close to the maximum.

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Note: Figure translations are in progress. See original paper for figures.