[1] Kaibin Fan
[2,*] Sujie Mao

Numerical Analysis of Tennis Serve Performance based on Aerodynamic Characteristics

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Abstract: - Using the method of computational fluid dynamics, the influence of the spin axis angle of the tennis ball on the pressure distribution, lift coefficient and drag coefficient of the flow field around the tennis ball under three different serving styles, namely, flat stroke, topspin and sidespin, is investigated in depth. The results show that the lift coefficient of the tennis ball is significantly affected by the side spin serve, while the change of the lift coefficient is not obvious in the flat and top spin serves. In addition, for the drag coefficient, both topspin and sidespin serves had a significant effect on it, while the effect of the flat stroke was relatively small. It is worth noting that the changes in the spin axis angle did not lead to significant changes in the static pressure distribution on the surface of the tennis ball and the surrounding flow field under the three different serving styles. This finding is of great academic value and practical guidance for further understanding the hydrodynamic phenomena in tennis and for improving the serve technique.

Keywords: Tennis; Serve; Motion simulation; Computational fluid dynamics.

I. INTRODUCTION

Currently, tennis serve technique is one of the hotspots in tennis research. Related research and analysis often focus on the biomechanical characteristics of athletes' serving techniques [1-5]. By studying the serve motion and muscle force characteristics, the dynamics and kinematics related to serving can be revealed. In addition, the analysis of kinematic characteristics during the flight of a tennis ball is also an important research method in serve studies.

Early researchers studied the aerodynamic characteristics during the flight of a tennis ball and found that the lift and drag coefficients are related to its rotation state and surface roughness [6-9]. Further research has shown that as the spin speed and flight speed of the tennis ball increase, its surface lift coefficient and drag coefficient also increase accordingly [10-11]. In addition, with the ball height and hitting speed remaining unchanged, as the hitting angle increases, the landing point deviation of the tennis ball gradually becomes more pronounced [12]. Regarding the rotation axis of the tennis ball, studies have found that the angle between the rotation axis and the ball's trajectory is close to perpendicular [13]. However, the aerodynamic characteristics of this process are still unclear, and the complex fluid dynamics involved in serving are difficult to measure through traditional experimental methods. Moreover, the process is complicated, and testing instruments are expensive.

Computational Fluid Dynamics (CFD) is an interdisciplinary field between mathematics, fluid mechanics, and computers. Its main research content is to solve fluid dynamics control equations through computers and numerical methods, and to simulate and analyze fluid dynamics problems. Computational fluid dynamics provides an inexpensive tool for simulation, design, and optimization, and facilitates the analysis of complex three-dimensional flow fields. Under complex conditions, experimental measurements are often difficult or even impossible, while CFD can easily provide detailed information about all flow fields. Compared with experimental results, computational fluid dynamics has the characteristics of being unrestricted by parameters, low cost, and no interference to the flow field. Due to the advantages of computational fluid dynamics, we chose it to simulate the tennis serve process. In short, the role of computational fluid dynamics is to study the flow structure in detail by visually displaying the calculation results.

The analysis of tennis motion state characteristics involves the flight speed, rotation speed, and spatial position of the rotation axis of the tennis ball. Numerical simulation methods are used to conduct detailed research on the relationship between tennis motion characteristics and their influencing factors, aiming to provide some reference for constructing serving indicators for elite male tennis players.

[1] School of Sports Training; Nanjing Sport Institute, Nanjing Jiangsu, China
[2] Nanjing Sport Institute, Nanjing Jiangsu, China
*Corresponding author: Sujie Mao

II. NUMERICAL METHODS

Computational fluid dynamics is built upon the foundations of classical fluid dynamics and numerical computation methods. It utilizes computers to solve the governing equations of fluid motion, quantitatively describing the numerical solution of the flow field in both time and space. This allows for the investigation of physical problems. Among these, mesh generation plays a crucial role in the numerical computation of computational fluid dynamics. Generating a high-quality mesh set will significantly improve computational accuracy and convergence speed.

A. Computational Theory Equations

Air is a common incompressible fluid that follows the continuity equation in three-dimensional steady or unsteady numerical computations. The theoretical calculation formula [14] is as follows:

$$\frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}=0 \quad (1)$$

$$\mathrm{divu}=0 \quad (2)$$

In the formula, ux, uy, and uz represent the movement speeds in the x, y, and z directions, respectively, m/s.

When a spinning tennis ball flies in the air, in addition to gravity, it experiences additional lift and drag forces. The drag force (FD) acts in the opposite direction of the ball's trajectory, and its theoretical calculation formula [14] is shown in equation:

$$F_D=\frac{1}{8}\pi\rho C_D d^2 V^2 \quad (3)$$

Where C_D is the drag coefficient, V is the absolute velocity, and d is the diameter of the oncoming spherical ball.

Furthermore, lift can be described as a force perpendicular to the trajectory of motion, and its theoretical calculation formula [14] is shown in equation (4):

$$F_L=\frac{1}{2}\rho A C_L V^2 \quad (4)$$

Where C_L is the lift coefficient, ρ is the density of air, A is the cross-sectional area of the sphere, and V is the velocity of the ball.

B. Numerical Model

The physical model of the entire computational domain is shown in Figure 1, where the tennis ball has a diameter of 6.5 cm, and the geometric dimensions of the fluid domain are 300 mm × 1000 mm × 300 mm. The spatial position of the tennis ball's axis of rotation is depicted in Figure 2, where the angle represents the angle between the axis of rotation and the horizontal plane, and the angle represents the angle between the projection of the axis of rotation on the horizontal plane and the direction directly opposite the court.

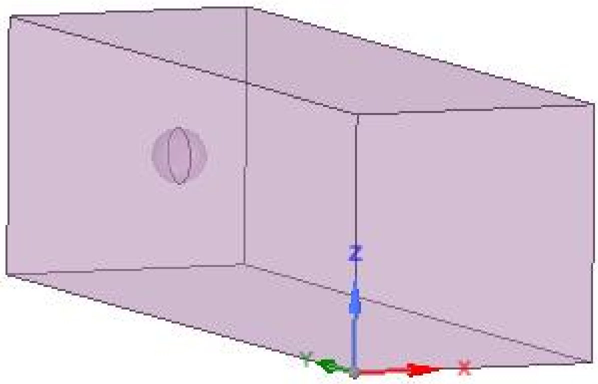


Figure 1. Physical Model of the Tennis Ball Computational Domain

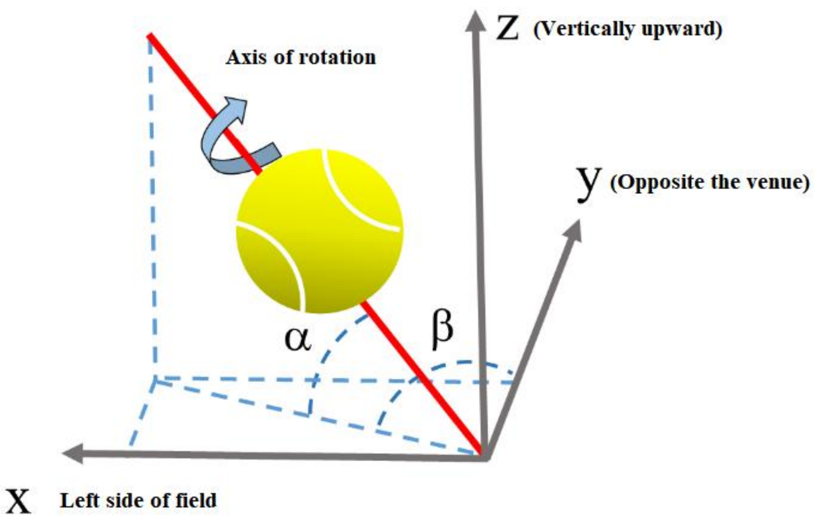


Figure 2. Spatial Position of the Tennis Ball's Axis of Rotation During Serve

Regarding mesh construction and generation, the entire computational domain is divided into a global mesh using fully hexahedral elements. The computational domain is further divided into the tennis ball rotation domain and the fluid static domain. The height of the first layer of the mesh near the tennis ball wall is set to 0.5 mm, with a mesh growth rate of 1.1, as shown in Figure 3.

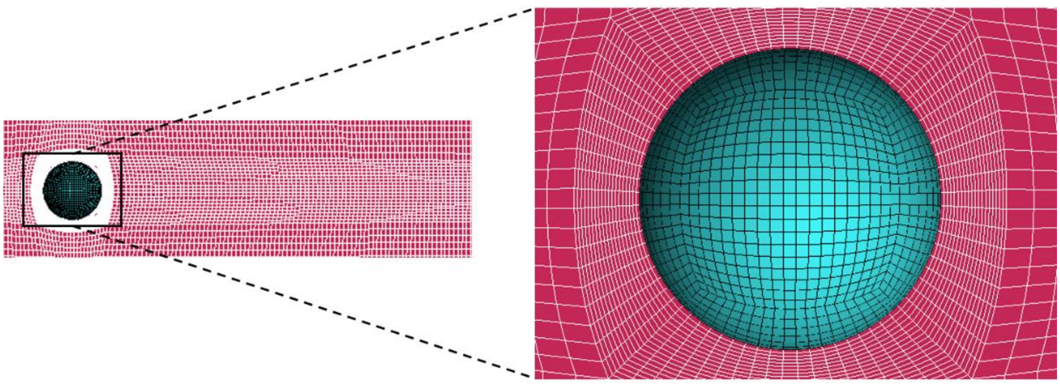


Figure 3. Cross-sectional View of the Computational Domain Mesh

C. Boundary Conditions for Computational Fluid Dynamics

The density of air used in the numerical calculations is 1.225 kg/m3, and the viscosity is 1.7894×10-5 kg/(m·s). To investigate the characteristics of tennis ball motion for different types of serves, average parameter values for three different serves by seven elite male athletes, measured by Sakurai et al. [13], are referenced, as shown in Table 1.

Table 1. Average Parameters for Three Different Serves by Seven Elite Male Athletes

Serve Type	Ball Speed (m/s)	Rotation Speed (rad/s)	β（°）
Flat Serve	52	127	10
Slice Serve	46	232	64
Topspin Serve	40	336	80

During its flight, a tennis ball undergoes both translational and rotational motion. The tennis ball is selected as the relative reference frame, and the incoming flow direction and surrounding boundaries are set as velocity inlets to calculate the translational effect of the tennis ball. The remaining boundaries are set as pressure outlets. Additionally, the Multiple Reference Frame (MRF) model is adopted to calculate the rotational motion of the tennis ball. Considering the calculation of lift and drag coefficients on the surface of the tennis ball, the SST k-ω turbulence model is chosen to handle the near-wall boundary layer flow.

III. RESULTS AND ANALYSIS

A. Variation Patterns of Lift and Drag Coefficients on the Tennis Ball Surface

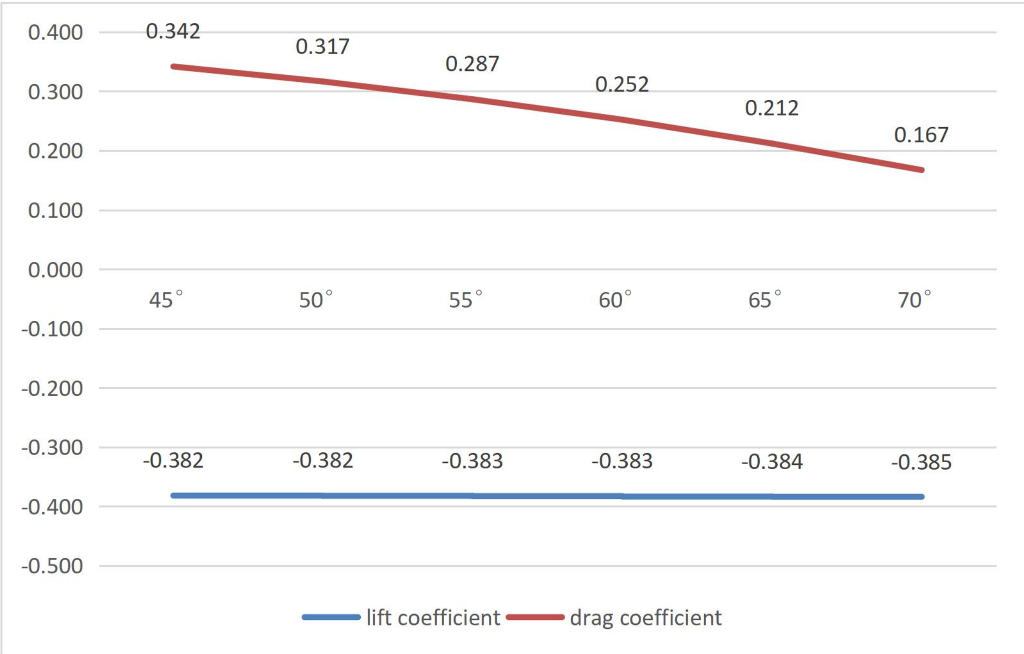


Figure 4. Patterns of Lift and Drag Coefficients on the Tennis Ball Surface for Flat Serves

The patterns of lift and drag coefficients on the tennis ball surface for flat serves are shown in Figure 4. The lift coefficient values on the tennis ball surface remain largely unchanged, while the drag coefficient exhibits a characteristic trend of decreasing and then increasing in value. Notably, the drag coefficient becomes negative at an angle of 70°, and the overall drag coefficient values fluctuate around 0. This suggests that for flat serves with relatively low rotational speeds, changes in the angle of the axis of rotation have minimal impact on drag. Additionally, the lift coefficient values are smaller compared to the other two types of serves.

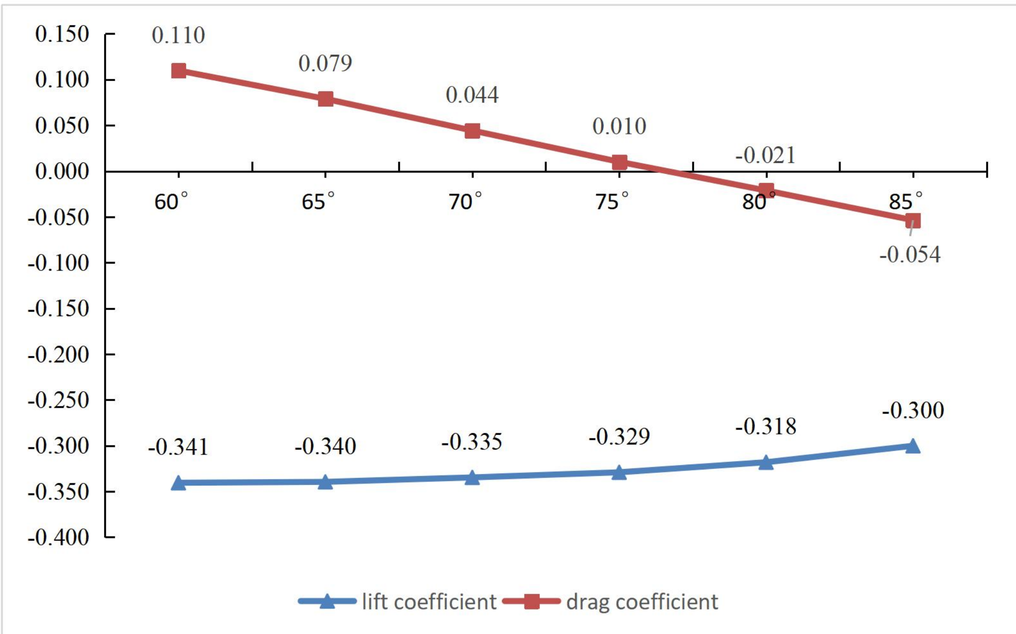


Figure 5. Patterns of Lift and Drag Coefficients on the Tennis Ball Surface for Slice Serves

The patterns of lift and drag coefficients for slice serves are illustrated in Figure 5. As the angle of the axis of rotation increases, the lift coefficient values on the tennis ball surface show a decreasing trend. This decrease becomes more pronounced when the angle exceeds 70°. In terms of the drag coefficient, there are noticeable changes in its value, exhibiting a similar trend to that of the flat serve, where it first decreases and then increases. It's worth noting that when the angle of the axis of rotation ranges from 70° to 80°, the lift coefficient is relatively high, while the drag coefficient remains at a low level. Specifically, the drag coefficient reaches its lowest point at an angle of 75°.

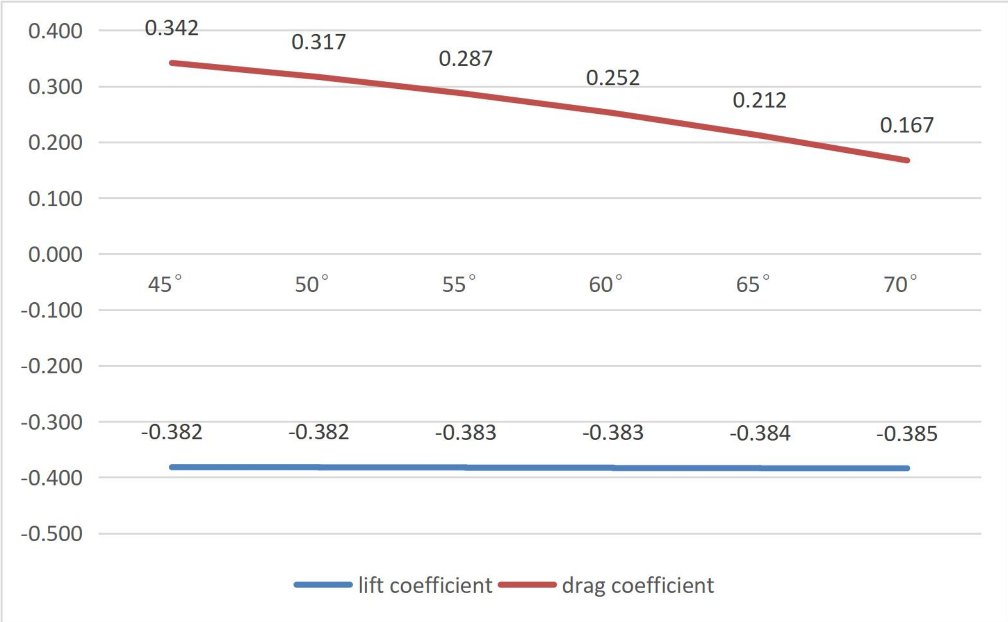
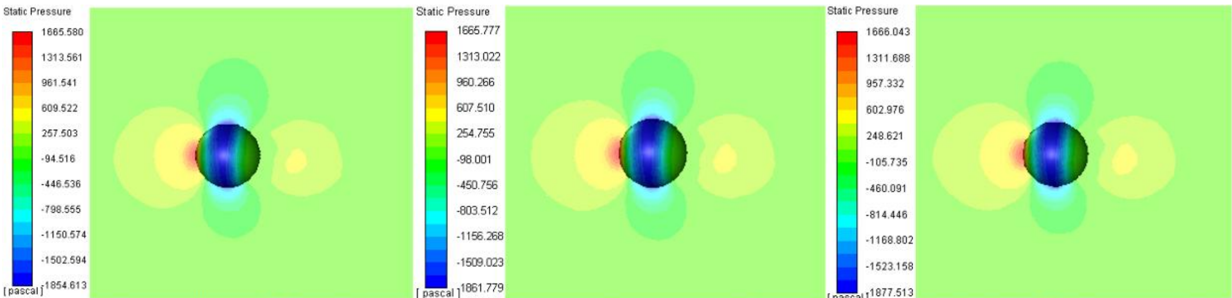


Figure 6. Patterns of Lift and Drag Coefficients on the Tennis Ball Surface for Topspin Serves

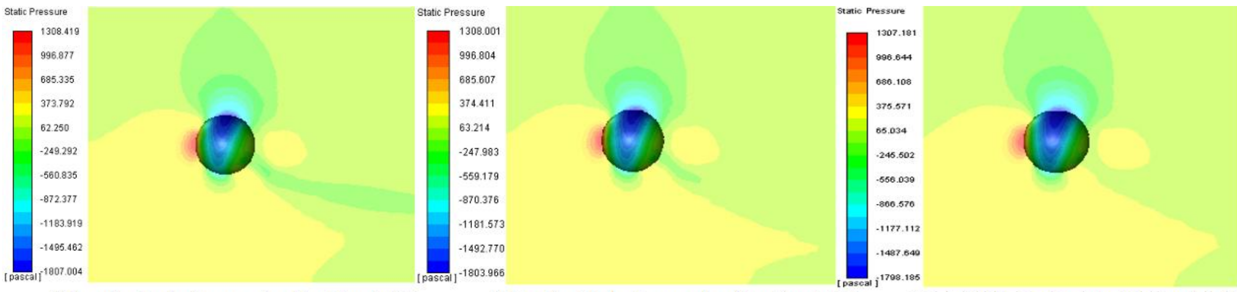
The patterns of lift and drag coefficients for topspin serves are presented in Figure 6. Similar to flat serves, the lift coefficient values on the tennis ball surface remain relatively constant. However, as the angle of the axis of rotation increases, the drag coefficient shows a significant decreasing trend, decreasing by 0.175.

B. Pressure Contours for Different Types of Serves



(a) The motion state when the space angle a of the rotation axis is 60° (b) The motion state when the space angle a of the rotation axis is 70° (c) The motion state when the rotation axis space angle a is 80°

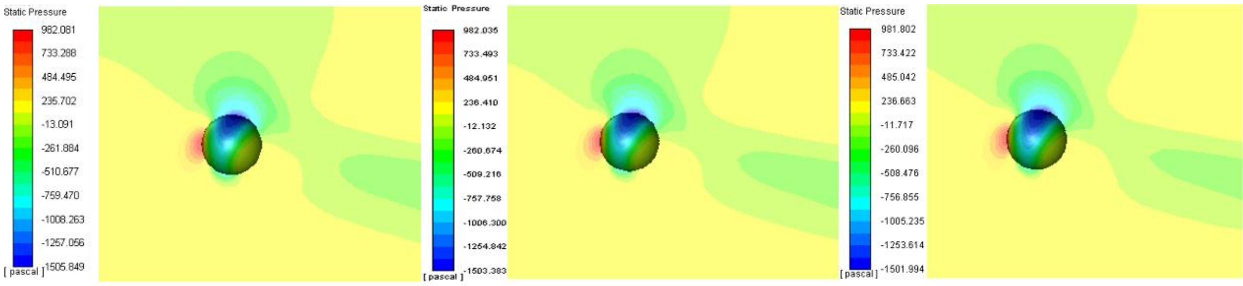
Figure 7. Static Pressure Distribution Contours on and around the Tennis Ball Surface for Flat Serves



(a) The motion state when the space angle a of the rotation axis is 60° (b) The motion state when the space angle a of the rotation axis is 70° (c) The motion state when the rotation axis space angle a is 80°

Figure 8. Static Pressure Distribution Contours on and around the Tennis Ball Surface for Slice Serves

(b) The motion state when the space angle a of the rotation axis is 70°



(a) The motion state when the space angle a of the rotation axis is 60° (b) The motion state when the space angle a of the rotation axis is 70° (c) The motion state when the rotation axis space angle a is 80°

Figure 9. Static Pressure Distribution Contours on and around the Tennis Ball Surface for Topspin Serves

Regarding the distribution characteristics of static pressure on the surface of the tennis ball and the surrounding flow field for three different types of serves, the captured plane is parallel to the direction of the tennis ball's flight (cross-section x=0.15 m).For flat serves, as shown in Figure 7, the static pressure distribution on and around the tennis ball surface is largely symmetrical, indicating a more stable flight trajectory in the air. Moreover, as the angle of the axis of rotation increases, there are no significant differences in the distribution of the flow field around the tennis ball surface.In the case of slice serves, illustrated in Figure 8, the upper half of the tennis ball surface and the surrounding area exhibit lower static pressure. This reflects the influence of lift on the tennis ball during flight, resulting in a certain offset in the flight trajectory. Additionally, as the angle of the axis of rotation increases, a noticeable difference in the deflected wake appears in the opposite direction of the tennis ball's flight.For topspin serves, depicted in Figure 9, similar to slice serves, the upper half of the tennis ball surface and the surrounding area show lower static pressure, with a noticeably asymmetrical distribution. As the fastest spinning serve, a distinct low-pressure wake is observed around the tail of the tennis ball. However, unlike slice serves, there are no significant visible differences in the deflected wake behind the tennis ball as the angle of the axis of rotation increases.

Common features of the static pressure distribution on and around the tennis ball surface for all three types of serves include: Firstly, the windward side of the tennis ball's front end displays a red area indicating high pressure, which means the static pressure (and thus the resistance) is greatest at the front. Secondly, for all three types of serves, the static pressure, whether at its highest or lowest values, changes minimally (within 30 Pa) as the angle of the axis of rotation increases.

IV. Discussion

This study found that the lift coefficient of flat serves remains largely unchanged at different spin axis angles, while the drag coefficient becomes negative at an angle of 70°, showing an overall trend of first decreasing and then increasing. This indicates that due to the low rotation speed of flat serves, changes in the spin axis angle have minimal impact on the drag. The lift coefficient of side spin serves decreases as the spin axis angle increases, especially between 70° and 80°, where the lift significantly reduces, while the drag coefficient first decreases and then increases, reaching its lowest point at 75°. This finding reveals that side spin serves have an aerodynamic advantage at specific angles, reducing drag while maintaining ball speed and rotation. For topspin serves, the drag coefficient significantly decreases as the spin axis angle increases, while the lift coefficient changes little. This indicates that with high rotation speed, the aerodynamic drag is significantly reduced as the spin axis angle increases, allowing the ball to maintain higher speed and stability in the air. This result suggests that when executing topspin serves, attention should be paid to adjusting the spin axis angle to reduce drag and optimize the serve's effectiveness. Athletes should focus on practicing the rotational control and angle adjustment of topspin serves to enhance serve quality in competitions.

This study used numerical simulations to analyze in detail the aerodynamic characteristics of different serving methods at various spin axis angles, revealing the changes in lift and drag for flat, side, and topspin serves. These findings provide scientific evidence for athletes in practical training, helping them optimize their serving techniques and improve their competitive level. Athletes should adjust the spin axis angle according to the characteristics of different serving methods to maximize the aerodynamic advantages and improve serve quality and performance in matches.

Compared to earlier related studies, this research reveals the specific impact of the spin axis angle on lift and drag during tennis serves. Previous studies mainly focused on the effects of surface roughness and rotational state on lift and drag. Achenbach (1974) found that the lift and drag coefficients of tennis balls are closely related to surface roughness[15]. This study further explores the role of spin axis angle in different serving methods. Cross and Lindsey (2014) measured the drag and lift of tennis balls in flight and found that rotation speed significantly affects lift and drag[16]. The results of this study are consistent with these findings but provide a more detailed description of the specific impact of the spin axis angle on lift and drag, especially in the performance differences among various serve types.

From an aerodynamic perspective, the low rotation speed of flat serves means that changes in the spin axis angle have minimal impact on drag. This is because, at low rotation speeds, the fluid flow around the ball is relatively stable, resulting in a consistent lift coefficient and minor changes in drag coefficient. Changes in the spin axis angle mainly affect the separation point of the flow on the windward side of the ball, but due to the low rotation speed, these changes have little impact on drag. This indicates that during a flat serve, the ball is primarily influenced by gravity and minor air resistance, resulting in a more linear and stable trajectory.

As the spin axis angle increases during side spin serves, the lift significantly decreases while the drag initially decreases and then increases. This may be due to the high rotation speed during side spin serves, which causes significant changes in the fluid flow around the ball. As the spin axis angle increases, the angle between the windward side and the direction of the ball's movement increases, leading to a decrease in lift. Regarding drag, the initial increase in angle reduces the windward area, decreasing drag; however, as the angle continues to increase, the separation point moves forward, increasing vortices, and thus drag begins to rise again. This complex aerodynamic characteristic results in different trajectories at various angles for side spin serves, requiring athletes to adjust the spin axis angle in training to find the optimal serving angle, reduce drag, and optimize serve performance.

For topspin serves, the drag coefficient significantly decreases as the spin axis angle increases, while the lift coefficient changes little. High rotation speeds lead to asymmetric pressure distribution on the ball's surface, creating significant vortices in the low-pressure area behind the ball, thereby reducing drag. As the angle increases, the pressure difference between the windward and leeward sides increases, further reducing drag. This phenomenon, known in aerodynamics as the "Magnus effect," results in the ball maintaining a more stable flight trajectory and reduced air resistance at high rotation speeds. In sports training, athletes should focus on adjusting the spin axis angle during topspin serves to fully utilize the Magnus effect for optimal serving performance.

A. Applications and Recommendations

Athletes can choose the most suitable serving method in different situations to enhance the quality and competitiveness of their serves using aerodynamic principles. Through scientific training and technical adjustments, athletes can achieve higher levels of serving performance in competitions.

1). Athletes should focus on practicing the power and accuracy of their serves while maintaining an appropriate spin axis angle to ensure stability and accuracy. For athletes with lower height or hitting point, flat serves are effective as they maintain ball speed while reducing the risk of going out of bounds.

2). During side spin serve training, athletes should focus on precise control of the spin axis angle. By repeated practice to find the optimal angle, athletes can leverage the lift and drag advantages of side spin serves to increase serve variation and difficulty, making it harder for opponents to predict and return. Coaches are advised to use video analysis and technical monitoring in training to help athletes adjust and optimize the spin axis angle.

3). When training for topspin serves, athletes should adjust the spin axis angle to minimize drag and utilize aerodynamic advantages to improve serve performance. Especially as the angle increases, the ball can better maintain a stable flight trajectory. Athletes should conduct repeated trials and scientific measurements during training to find the most suitable spin axis angle, ensuring both speed and stability in serves. Coaches should also strengthen guidance on topspin serve techniques to enhance consistency and accuracy in serves.

B. Study Limitations

1). The Computational Fluid Dynamics (CFD) model and assumptions used in this study have certain limitations. They ignore the impact of atmospheric condition changes and simplify the tennis ball model without considering surface roughness and wear, which may lead to discrepancies between the calculated results and actual conditions.

2). The experimental parameters used in the study (such as ball speed and rotation speed) are based on average values under specific conditions, which may not fully represent all actual match scenarios.

3). Numerical simulations, despite providing detailed flow field information, may have certain deviations when compared to actual experimental results. The results of numerical simulations need to be validated through actual experiments to ensure their accuracy and repeatability. Therefore, future studies should incorporate more experimental data to validate and supplement the conclusions of numerical simulations, enhancing the scientific validity and practical value of the research.

V. CONCLUSION

Detailed research on the relationship between the characteristics of tennis motion and its influencing factors has been conducted using numerical simulation methods, leading to the following conclusions:

1)Under flat serve conditions, as the spatial angle of the axis of rotation increases, the changes in lift and drag coefficient values are minimal among the three different types of serves. Moreover, the static pressure on the surface of the tennis ball and the surrounding flow field exhibits a generally symmetrical distribution. This aerodynamic characteristic suggests that for athletes with a lower height and hitting point, choosing a flat serve carries a higher risk of serving out of bounds when attempting to hit a faster ball while ensuring it clears the net.

2)Under slice serve conditions, both the lift and drag coefficient values change as the spatial angle of the axis of rotation increases. Specifically, when the angle α is 75°, the lift coefficient on the tennis ball surface is relatively high, while the drag coefficient is near its lowest value. This is beneficial for the flight of the tennis ball, as it maintains a certain height over the net while minimizing speed and spin loss.

3)For topspin serves, as the spatial angle of the axis of rotation increases, the lift coefficient value on the tennis ball surface remains largely unchanged, while the drag coefficient gradually decreases. Based on this aerodynamic characteristic, when executing a topspin serve in practice, players should avoid throwing the ball too far forward, which would result in a smaller axis of rotation angle and greater resistance, while ensuring a certain level of force and distance with a spiral upward motion of the torso.

4)Examining the pressure contours for the three different types of serves, it is evident that for slice and topspin serves, the upper half of the tennis ball surface and the surrounding area exhibit lower static pressure. This indicates the presence of lift during the flight of these two types of serves.

5)As the angle of the axis of rotation increases, there are no significant changes in the pressure contours. Additionally, although the drag coefficient for slice and topspin serves varies by more than 0.1, the minimum and maximum values of static pressure on and around the tennis ball surface show minimal changes. In summary, variations in the angle of the axis of rotation have a limited impact on the lift and drag forces during a tennis serve.

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CONFLICTS OF INTEREST

All the authors declare have no conflicts of interest to report regarding the present study.

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