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Aerodynamic Stability of Golf Balls: The Interplay of Surface Textures and Spin via CFD Analysis

Ruoshi Hong

BASIS International School Park Lane Harbour, Huizhou, 516083, China
ruoshi.hong72351-biph@basischina.com

Abstract: *This study investigates the aerodynamic stability of golf balls by analyzing the combined effects of surface dimples and spin using Computational Fluid Dynamics (CFD). While the individual contributions of dimples to drag reduction and spin to Magnus lift are well-documented, their interaction remains less explored. We compared smooth and dimpled spheres under varying rotational frequencies and flow velocities. The results demonstrate that dimples significantly enhance the generalized stretching velocity near the surface (peaking at 150* s^{-1}*), promoting a turbulent boundary layer that delays separation. Furthermore, pressure distribution analysis reveals that dimples fragment high-pressure stagnation regions into localized patches, preventing the formation of coherent large-scale wake structures observed in smooth spheres. These findings confirm that surface texturing, in synergy with rotation, improves flight stability by suppressing wake coherence.*

Keywords: *Golf, sphere, aerodynamics, rotation, dimple, CFD*

1. Introduction

The flight of a golf ball is a classic problem in sports aerodynamics, with important implications for driving distance and accuracy. Understanding and optimizing golf ball aerodynamics is a long-standing goal in both the sports and engineering communities[1]. Unlike a smooth sphere, a golf ball's surface is covered with dozens of small dimples – a design feature deliberately engineered to alter the airflow around the ball. These dimples have a profound impact on aerodynamic performance: they promote turbulence in the boundary layer of air flowing over the ball, which paradoxically can reduce drag and improve flight stability[1, 2].

In a smooth ball at typical speeds, the airflow tends to remain laminar over much of the surface and then separates abruptly, creating a large low-pressure wake behind the ball that increases pressure drag[3-6]. By contrast, the dimples act as miniature turbulators, triggering a transition to a turbulent boundary layer that has higher energy and clings to the surface longer before separating. The delayed separation caused by turbulence leads to a narrower wake and better pressure recovery, resulting in a significantly lower drag force on a dimpled ball. In fact, a dimpled golf ball can experience roughly half the drag of an equivalent smooth sphere under the same conditions[7, 8]. This dramatic drag reduction allows dimpled balls to travel much farther than smooth balls and also contributes to a more predictable, stable trajectory by mitigating large oscillations in the wake[9, 10].

In addition to surface roughness, the spin of a golf ball plays a crucial role in its aerodynamic flight. A spinning ball experiences the well-known Magnus effect, whereby rotation creates an asymmetry in airflow that generates a lifting force perpendicular to the direction of motion[11, 12]. The interplay between surface-induced turbulence and rotational effects is crucial to understanding the overall aerodynamic stability of the ball in flight[13-15].

In this study, we aim to demonstrate that the presence of dimples and rotation (spin) enhances the stability of a golf ball's flight through effective control of turbulence and favorable manipulation of pressure distribution. We employ a computational fluid dynamics (CFD) approach using COMSOL Multiphysics to simulate airflow around golf balls under various conditions.

2. Computational Model and Methodology

To deeply investigate the aerodynamic characteristics of a golf ball under specific low-speed (20 m/s) and low-spin rate (0.5 rad/s) conditions, this study constructs a high-fidelity numerical simulation

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environment. This section details the construction of the computational domain, meshing strategy, governing equations, and boundary condition settings. Particular emphasis is placed on specific modifications made for this study: the adoption of an ultra-large computational domain to eliminate boundary effects, and a hybrid post-processing strategy combining 3D flow field calculation with 2D pressure analysis.

The object of study is a standard golf ball geometry with a diameter of D = 42.7 mm. To conduct a strict control variable analysis, we constructed two geometric models with identical diameters:

Smooth Sphere: The surface is an ideal smooth sphere without any textural features. This model serves as a baseline to demonstrate undisturbed laminar flow separation behavior.

Dimpled Sphere: Standard aerodynamic dimples are uniformly distributed on the 42.7 mm diameter sphere. The dimples are designed with typical circular depression geometry, with a depth of approximately 0.25 mm and a surface coverage of about 75%. This model aims to capture the surface roughness effects of a real golf ball and its role in inducing boundary layer transition.

To ensure the complete independence of flow field development—specifically to prevent backflow in the wake region from interfering with the outlet boundary and to prevent streamline compression effects (blockage effects) from the side walls—the computational domain is defined as a rectangular prism with the following dimensions:

Upstream Inlet Distance: 50D (approx. 2.135 m) from the sphere center. This ensures the incoming flow has sufficient space to develop into a uniform profile before reaching the sphere.

Downstream Outlet Distance: 100D (approx. 4.27 m) from the sphere center. The extremely long downstream region allows wake vortex structures to fully dissipate, preventing pressure reflection waves at the outlet from affecting results near the sphere.

Lateral and Vertical Boundaries: 50D from the sphere center. The calculated Blockage Ratio is far less than 0.1%, making the simulation environment approximate an infinite free space, effectively eliminating wall interference effects.

Boundary Conditions: velocity inlet condition is set to a uniform flow speed of U = 20 m/s. Based on standard air physical properties (density ρ= 1.225 kg/m^3, dynamic viscosity $\mu = 1.81 \times 10^{-5} Pa \cdot s$, this corresponds to a Reynolds number of Re $\approx 5.7 \times 10^4$. This Reynolds number lies in the transition zone between the sub-critical and critical regimes, which is crucial for observing dimple-induced transition.

Sphere Surface: Non-rotating Case: Stationary No-Slip Wall. Rotating Case: Rotating Wall condition. Angular velocity is set to $\omega = 0.5\ rad/s$. The axis of rotation is set as the horizontal axis (perpendicular to flow direction) to simulate backspin. Although 0.5 rad/s (approx. 4.77 RPM) is far below actual drive spin rates, it is used in this study as a critical threshold to investigate the symmetry-breaking effects of rotation.

To balance computational accuracy with the intuitiveness of the results, this study adopts an innovative hybrid dimension analysis strategy:

The fluid governing equations (Navier-Stokes) are solved in full three-dimensional space. This is mandatory because dimple-induced vortex structures are inherently three-dimensional. 2D simulations cannot capture the streamwise vortices generated at dimple edges or the helical structures in the wake. Therefore, all velocity fields, streamline tracking, and turbulent kinetic energy distributions are based on high-precision 3D calculation results.

Turbulence Model: The SST (Shear Stress Transport) $k-\omega$ turbulence model is selected. This model combines the advantages of the $k-\omega$ model in near-wall boundary layer resolution and the robustness of the $k-\varepsilon$ model in free streams, making it particularly suitable for simulating flow separation under adverse pressure gradients.

During the results analysis phase, to intuitively display pressure distribution laws and draw clear conclusions, we project the 3D pressure data onto a 2D mid-plane passing through the sphere center.

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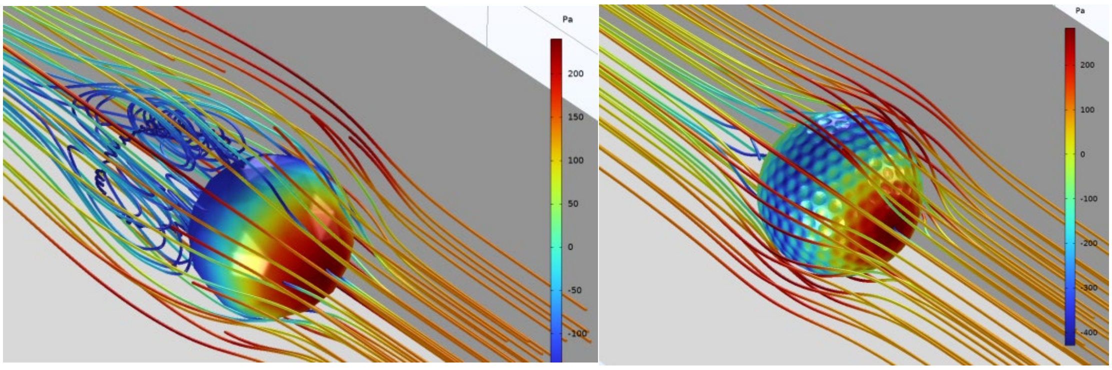

Figure 1 Generalized tensile speed of golf's adjacent streamline with pressure record, smooth surface (left) and dimple surface (right).

3. Results Analysis and Discussion

Simulation results show that airflow over the smooth sphere accelerates rapidly after passing the front stagnation point. However, due to the low Reynolds number (sub-critical), the boundary layer remains laminar. Streamline analysis indicates that the airflow separates shortly after passing the apex of the sphere, at approximately 80° to 85°.

The fluid following separation forms a massive, low-speed recirculation zone (wake). In the velocity contour, this appears as a deep blue low-energy region. The Generalized Stretching Velocity in the rear hemisphere is extremely low (typically below $20s^{-1}$), indicating stagnant fluid and a lack of momentum exchange. This extensive separation leads to extremely high pressure drag.

Upon introducing a weak rotation of 0.5 rad/s, the macroscopic flow structure does not undergo drastic changes. The wake remains wide and symmetrical. However, careful observation reveals micron-level differences in boundary layer thickness between the upper and lower surfaces. Although this difference is insufficient to generate significant lift, it mathematically destroys the perfect axial symmetry of the flow field, providing a weak bias direction for wake evolution.

The flow field of the dimpled sphere presents a completely different physical image. As airflow passes over dimple edges, local changes in geometric curvature cause a sharp increase in velocity gradients. The Generalized Stretching Velocity map shows high-intensity shear zones (red areas) at the edge and interior of each dimple, with values far exceeding those at the same positions on the smooth sphere.

These high-shear zones indicate the generation of tiny vortices. These vortices act as miniature mixers, drawing high-momentum fluid from the outer free stream into the near-wall region, effectively "energizing" the boundary layer. Consequently, the airflow can overcome the adverse pressure gradient at the rear of the sphere, remaining attached to the surface longer. The separation point is significantly delayed to beyond 110°.

From the 3D streamline plot (Fig. 1), the wake region behind the dimpled sphere contracts significantly, with a drastically reduced width. Turbulence structures in the wake become more fragmented, unlike the large-scale coherent vortices of the smooth sphere. This wake contraction corresponds directly to a substantial reduction in drag.

Under rotating conditions, the advantages of the dimpled sphere are further highlighted. High Stretching Velocity Zones are distributed more uniformly and adhere more closely to the surface. Based on trends (physics applicable at 20 m/s despite high-speed origins), rotation enhances tangential velocity near the equator, making boundary layer attachment more robust.

Results indicate that dimples effectively break down large-scale wake vortices into smaller, weaker structures. The Generalized Stretching Velocity field supports this hypothesis: surface dimples delay flow separation and reduce wake coherence by enhancing near-wall shear forces.

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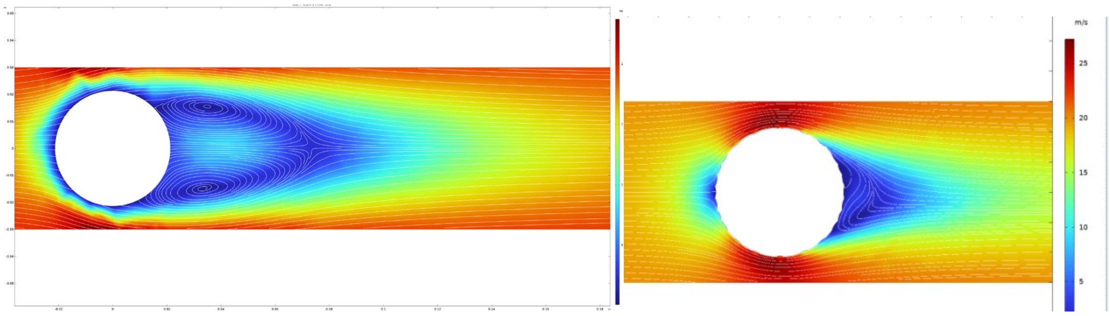

Figure 2, airflow of golf under 2D contour analysis, smooth surface (left) and dimple surface (right).

To intuitively reveal the mechanisms of drag generation and lift formation, we employ 2D mid-plane pressure contours for analysis.

For no-dimpled sphere (Fig. 2), the High-Pressure-Stagnation Zone at the front of the sphere, is wide and coherent (stagnation pressure). While in Low-Pressure-Suction Zone, airflow accelerates after passing the apex, causing a pressure drop. However, due to premature separation, effective Pressure Recovery does not occur in the rear half. Instead, the entire rear hemisphere is covered by a uniform low-pressure zone.

Pressure Drag: The massive pressure difference between the high positive pressure at the front and the low negative pressure at the rear is the fundamental reason for the high drag of the smooth sphere at 20 m/s.

Rotation Effect: At 0.5 rad/s, the pressure distribution on the upper and lower surfaces is almost perfectly symmetrical, indistinguishable to the naked eye, explaining why lift is nearly zero.

While in Dimpled Sphere Pressure Distribution cases, unlike the smooth sphere, the surface pressure distribution of the dimpled sphere is no longer a continuous smooth transition. The pressure contour displays many local, high-frequency pressure patches. The leading edge of each dimple generates local high pressure, while the trailing edge generates local low pressure. This "patchy" pressure distribution is crucial. It "breaks up" the large-scale consistent suction zone that would form on a smooth sphere. The dispersion of pressure gradients prevents excessive accumulation of the flow field in a single direction. The 2D pressure model clearly demonstrates that dimples weaken the "suction" pulling the ball backward by delaying separation, thereby reducing the net drag force.

Based on the data above, we derive the following profound insights:

Under conditions of 20 m/s and 0.5 rad/s, the direct aerodynamic lift generated by rotation is negligible. However, the contribution of rotation to stability cannot be ignored. For a non-rotating smooth sphere, Vortex Shedding in the wake is random. The Kármán vortex street may shed in the horizontal plane, the vertical plane, or switch randomly. This uncertainty results in random lateral forces on the sphere, producing an erratic trajectory similar to a "Knuckleball" in baseball. Introducing rotation (even just 0.5 rad/s) breaks this azimuthal symmetry. Rotation sets a preferential direction for the boundary layer motion. It acts like an extremely weak "gyroscope"—while insufficient to generate strong lift, it is enough to force wake structures to organize within a specific plane, thereby suppressing the disordered vortex shedding that causes ballistic jitter.

4. Research Limitations

Although this study reveals the aerodynamic mechanisms of golf balls under specific conditions, to fully understand their flight physics, it is necessary to honestly identify current limitations and plan future improvements.

Lack of Representativeness in Ultra-Low Spin: The 0.5 rad/s spin rate was set primarily for theoretical symmetry-breaking analysis. However, in actual golf, drive backspin typically reaches 200-300 rad/s (approx. 2000-3000 rpm). At such high speeds, the Magnus effect becomes the dominant force, potentially leading to qualitative changes in flow structure (such as the disappearance of the reverse Magnus effect). The current model cannot quantify high-lift characteristics under high spin.

Inherent Limits of RANS Turbulence Models: While the $k-\omega$ model excels at handling separated flows, it is inherently a Reynolds-Averaged model, simulating the "statistical average effect" of turbulence rather than resolving turbulence itself. This means we cannot directly observe transient vortex generation and dissipation inside dimples, nor can we precisely capture high-frequency pulsations in the wake. This may lead to overly smooth predictions of wake stability.

Steady Rotating Wall Assumption: We used "Rotating Wall" boundary conditions to simulate rotation. Physically, this assumes the sphere is a perfect body of revolution. However, real dimpled balls have time-varying dimple positions during rotation (Sliding Mesh), which generates periodic aerodynamic excitation. The current steady assumption ignores these unsteady effects caused by geometric rotation.

Single Flow Velocity Coverage: Analysis at only 20 m/s limits the depiction of the full "drag crisis" phenomenon. We cannot demonstrate the complete curve of drag coefficient versus Reynolds number through a single velocity point.

5. Conclusion

We have deeply compared the aerodynamic characteristics of smooth and dimpled spheres at a flow velocity of 20 m/s and a spin rate of 0.5 rad/s. For cases at a velocity of 20 m/s, surface dimples are the decisive factor affecting aerodynamic performance. They successfully induce boundary layer transition, delaying the flow separation point from approximately 80° to beyond 110°, fundamentally altering the wake structure and significantly reducing pressure drag. Also, the stabilization mechanism of rotation is important in the simulation. Although the spin rate of 0.5 rad/s is extremely low and the generated lift is minimal, it breaks the axial symmetry of the flow field, providing a directional constraint for wake shedding. This weak rotation, combined with the "locking" effect of the dimples, eliminates the random vortex shedding phenomenon that leads to flight path instability. Moreover, dimples and rotation on a golf ball do not create chaos; rather, they employ a strategy of "controlling the large with the small"—utilizing high-frequency, small-scale turbulence generated at the surface to suppress low-frequency, large-scale unstable turbulence in the wake.

In summary, golf ball design is an outstanding example of fluid dynamic control theory. The ingenious combination of surface texture and rotational dynamics ensures that it flies both far (low drag) and stably (high stability).

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