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学　位　論　文　内　容　の　要　旨
DISSERTATION ABSTRACT

博士の専攻分野の名称　　博士（工学）　　氏名　李 景

学　位　論　文　題　名
Title of dissertation submitted for the degree

Numerical Investigation of the Aerodynamics of a Golf Ball
(ゴルフボール周り流れの数値解析)

As one of the most appealing topics relating to both the fundamental fluid dynamics and science behind sports ball games, the aerodynamics of a golf ball has been progressively receiving attention in the past decades. Two important factors that strongly affect the golf ball aerodynamics are the surface roughness introduced by the dimples and the golf ball's self-spinning motion. The former is usually discussed in terms of the enhancement of the drag crisis, which remarkably reduces the drag force and increases the flying distance in the direction against the incoming flow, whereas the latter is considered to directly affect the flying trajectory through the additional lift force generated as a result of the Magnus effect. However, there are still some open questions regarding the golf ball aerodynamics which remain not fully understood, such as the mechanism of drag reduction by dimples, the ordinary/negative Magnus effect on golf balls, the lateral force variation on both stationary and self-spinning golf balls, and the transient features of golf ball aerodynamics. Accordingly, the aims of the present research are to numerically study the above unresolved questions, and achieve a more comprehensive understanding of the aerodynamics of a golf ball.

The geometry models used in the present research are a real golf ball product, and a smooth sphere for the sake of comparison. For both models, triangular meshes are generated on the geometry surface while prism layers are allocated along the normal-wall direction of the surface. The numerical method adopted for the flow simulation in the present study is the Large-eddy simulation (LES) method. The dynamic subgrid-scale eddy viscosity model is used for properly resolving the boundary layer flow. Particularly, the arbitrary Lagrangian-Eulerian (ALE) method was applied to impose the self-spinning motion on the golf ball, whereas for the smooth sphere, the rotating motion was imposed by directly adding an angular velocity on the geometry surface as a boundary condition.

The simulation results obtained in the present study successfully reproduced the drag crisis of the stationary golf ball at a visibly lower critical Reynolds number than the smooth sphere, which agrees very well with the experimental data. The detailed analysis on the local flow behaviors inside individual dimples reveals the mechanism responsible for the drag reduction of the golf ball occurring at a lower Reynolds number when compared to the smooth sphere. It is observed that the flow locally separates on the leading edges of some dimples when it passes over the golf ball surface in the supercritical regime. The locally detached shear layer quickly becomes unstable and oscillates considerably as it travels further downstream. Meanwhile, small-scale vortices are generated inside the individual dimples. As a result of the shear layer instability, the momentum in the near-wall flow increases, and

with the increased momentum, the flow that reattaches on the trailing edges of the dimples is able to overcome the adverse pressure gradient more and travel further downstream, which consequently delays the full flow separation.

The investigation of the lateral force variation and wake flow structure for the stationary cases shows that for both the golf ball and smooth sphere, the lateral forces change irregularly with time in both the magnitude and direction in the subcritical regime, and a large-scale wave motion is pronounced in the wake areas of both models with a wavelength similar to each other. In the critical regime, the lateral forces acting on both models exhibit a larger magnitude of oscillation when compared to the subcritical cases, and the directions of the lateral forces differ irregularly with time. In the supercritical regime, both models are subjected to a nonzero lateral force during a long time interval, and the lateral force direction exhibits a rotation trend with time. However, the magnitude of the lateral force acting on the golf ball is visibly smaller when compared to the smooth sphere, indicating a suppression of the lateral force in the supercritical golf ball case.

The ordinary Magnus effect and negative Magnus effect were successfully reproduced for both the self-spinning golf ball and smooth sphere. In the subcritical and supercritical regimes, the boundary layers on the top side, where the geometry surface rotates with the approaching flow, and the bottom side, where the geometry surface rotates against the approaching flow, exist in the same state. As a result of the self-spinning motion, the near-wall flow gains momentum on the top side while it loses momentum on the bottom side. This further leads to the flow separating at a position further downstream on the top side than on the bottom side, which consequently gives rise to a positive Magnus force acting on both of the models. In contrast, in the critical regime, the boundary layer on the top side stays laminar whereas on the bottom side it becomes turbulent. This is attributed to the locally higher relative Reynolds number on the bottom side which makes the flow on this side more sensitive to perturbations and consequently promotes the laminar-turbulent boundary layer transition. As a result, the flow separates at a position further downstream on the bottom side than on the top side, which consequently produces a negative Magnus force acting on both models.

The investigation of the lateral force variation and wake flow structure for the self-spinning cases shows that for both models in the subcritical regime, the variation of the lateral force is more regular when compared to the stationary cases, and the lateral force oscillation is more dominant in the lift force direction than in the side force direction. In the critical regime, the lateral force acting on the rotating golf ball experiences a visibly smaller oscillation when compared to the stationary case, whereas the lateral force acting on the rotating smooth sphere exhibits a considerable oscillation in the lift force direction. In the supercritical regime, the variation of the lateral force is more regular for both rotating models when compared to the stationary cases. Interestingly, the lift force acting on the golf ball is around 40% smaller when compared to the smooth sphere, while the drag force acting on these two models remains comparable.