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ACOUSTICAL CFD AND AERODYNAMIC ANALYSIS OVER GOLF BALL

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ABSTRACT

The aerodynamics of golf balls is considerably more complex than that of many other spherical balls. The surface roughness in the form of dimples intensifies the level of complexity and three-dimensionality of air flow around the golf ball. Prior studies have revealed that golf ball aerodynamics is still not fully understood due to the varied dimple size, shape, depth and pattern. The current study experimentally measured drag coefficients of a range of commercially available golf balls, under a range of wind speeds. It was found that the drag coefficients of these balls varied significantly due to varied dimple geometry. Playing golf and "driving" a ball with some degree of proficiency is difficult, and almost as time-consuming to perfect as "driving" a plane. For one, the rules of golf do not permit "Artificial Devices.Unusual Equipment which might assist [the player] in making a stroke in his play," which essentially means that golfers don't get the benefit of autopilot.Second, golf requires a person to stroke an object (the ball) with another object (the club head), which is attached to the end of a 40-inch shaft (+/-5 inches). This action must be performed so precisely that the ball will fly approximately 280 yards in the air, within a horizontal window of 4 degrees from the launch pad. stay in the fairway (short grass)…only so you can find it and repeat the process with another club, resulting in a completely different trajectory.Swinging the club with some degree of consistency is enough of a challenge. Never mind making contact with the ball at precisely the right point on the clubface in order to achieve maximum distance. But these challenges are just part of what makes the game so addictive.

1. INTRODUCTION

The player's performance can significantly be enhanced if the aerodynamic behavior of the golf ball is understood and the potential benefit exploited intelligently. A wide variety of commercially manufactured golf balls are available to suit individual golfer's style of play. Of particular relevance to this work is the variation in dimple geometry. The flight trajectory is influenced by the aerodynamic forces exerted on the ball, which are significantly dependent on the physical features of the dimples. Most commercially manufactured golf balls have between 250 and 500 dimples, however these dimples vary in size, shape and depth.

Golf ball manufacturers often claim superior aerodynamic performance of their balls, however there is an absence of detailed aerodynamic data available in the public domain.

A golf ball usually moves at a speed that is sufficiently high to reduce its' drag to about half that of a smooth sphere. This favorable reduction in drag is caused by the dimples on the golf ball surface which trigger the boundary layer to transition from laminar to turbulent flow on golf ball aerodynamics under spinning and non-spinning conditions.

Despite this work the mechanisms through which the dimpled surface influence the boundary layer transition have not been fully understood to the extent that accurate force and trajectory prediction would be possible.

Studies conducted by commercial golf ball manufacturers are generally kept "in-house" as confidential information in a highly competitive market, and consequently very little information is available in the public domain on development and the current performance of golf balls.

In this context the primary objective of this research is to experimentally evaluate the aerodynamic properties, especially drag, of a series of commercially available golf balls with varied dimple characteristics, which are widely used in professional and amateur/recreational golf.

The golf is one of the popular and widely watched sports in many countries of the world. Apart from individual natural skills of the player, the performance is largely depends on the equipment used. Arguably the two most important pieces of the equipment are the golf ball and the club.

However, from the aerodynamics point of view, the main centre piece is the dimpled ball. The aerodynamic behaviour of the golf ball is primarily relies on the physical features of the complex dimples.

Most commercially manufactured golf balls have dimple numbers ranging from 250 to 500. These dimples vary in sizes, shapes and depths. At present, golf ball manufacturers claim and counter claim about the superior aerodynamic performance of their balls, however there is no independent study confirms their claims.

With so many different golf balls in the market with a wide range of prices, the question must be asked: is a more expensive golf ball generally better, Golf balls are made by many different manufacturers and are available in a wide variety of configurations to suit a golfer's style of play and choice. These include the construction of the ball, the number and the shape of the dimples.The aerodynamic behaviour of the golf ball is primarily dependent on the physical features of complex dimples. The dimples vary in sizes, shapes and depths which generate complex aerodynamic flow pattern around the ball.

Although some studies have been conducted on golf ball aerodynamics, the aerodynamic behaviour of dimple characteristics is not fully understood. The primary objective of this research is to experimentally evaluate the aerodynamic properties (drag, lift/down force) of a series of commercially available golf balls. Each of these new balls has different dimple characteristics. These balls were tested under a range of speeds.

The aerodynamic properties were analysed. Due to varied dimple geometry, the magnitudes of drag coefficients of these balls were varied significantly. The non-dimensional drag coefficient for each ball was compared. The effects of spin on drag and lift have also been evaluated. However, spin data was not included in this paper.

1.1 DRAG AND LIFT

Instead of decomposing the air resistance force vec-tor into its horizontal and vertical components, it is more convenient to make a different choice of coordi-nate directions: namely, the direction opposite to the motion of the ball, and the direction orthogonal to that and directed skyward . The correspond-ing components of the force of air resistance are then called the *drag* and the *lift*, respectively.

Drag is the same force you feel pushing on your arm if you stick it out of the window of a moving car. Golfers want to min-imize it, so their ball will travel farther. Lift is largely a consequence of the back spin of the ball, which speeds the air passing over the top of the ball and slows the air passing under it. By Bernoulli's principle, the result is lower pressure above and therefore an upward force on the ball.

Lift is advantageous to golfers, since it keeps the ball aloft far longer than would otherwise be the case, allowing it to achieve more distance.

Drag and lift are very much affected by how the air interacts with the surface of the ball. In the middle of the nineteenth century.

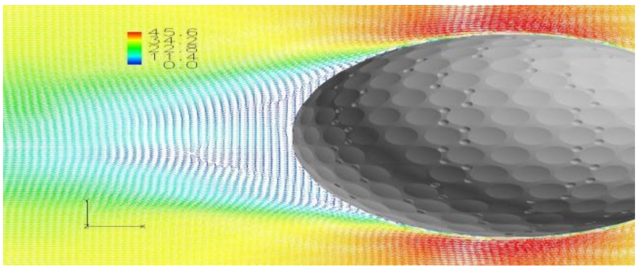

FIGURE 1.1 PRESSURE CONTOUR

when rubber golf balls were introduced, golfers noticed that old scuffed golf balls traveled farther than new smooth balls, although no one could explain this unintuitive behavior. This even-tually gave rise to the modern dimpled golf ball. Along the way a great deal was learned about aerodynam-ics and its mathematical modeling. Hundreds of dif-ferent dimple patterns have been devised, marketed, and patented.

1.2 FLOW MODELING IN SPORT

By 1976 the "Overall Distance Standard" (ODS) was adopted. The standards were based on launching a ball using a mechanical golfer to simulate real field conditions and setting a limit on the distance under specified test conditions. Individual properties of the ball, which contributed to the overall distance, were not isolated or limited for two reasons: first, they were not understood; nor were they able to be measured at the time.

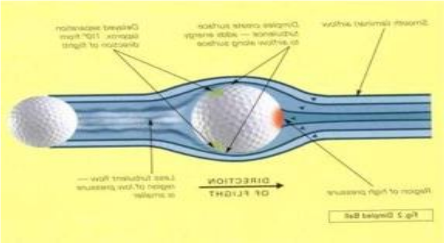

Figure 1.2 SMOOTH BALL

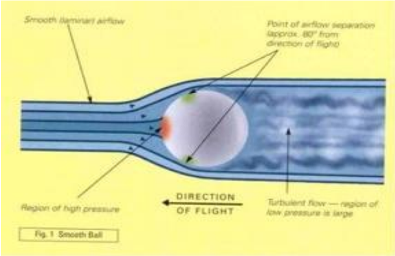

Figure 1.3 DIMPLED BALL

Things have changed since, and the USGA has perfected the “Indoor Test Range” (ITR) which supersedes a wind tunnel and force-balance system to measure the aerodynamic properties of a ball. The ITR is a 70-foot-long open area with a series of stations along its length. At each station, the exact ball position and speed are measured as it passed by. This method of firing a spinning ball through a still body of air has proven to produce far more accurate and reliable data than trying to support a spinning ball in a laminar stream of air in a wind tunnel.

From the information collected in the ITR, the coefficients of lift and drag for a number of different speeds and spin rates are calculated and combined for use in a simulation to describe the complete trajectory of any golf ball tested**.**

1.3 REYNOLDS NUMBER

Drag and lift—which are also essential to the design of aircraft and ships, the swimming of fish and the flight of birds, the circulation of blood cells, and many other systems—are not easy to model mathematically. The friction between the ball’s sur-face and the air, and the difference in pressure ahead of and behind the ball. The size and relative impor-tance of these contributions depends greatly on the flow regime. In the second half of the nineteenth cen-tury, George Stokes and Osborne Reynolds realized that a single number could be assigned to a flow that cap-tured a great deal about its qualitative behavior.

Low *Reynolds number* flows are slow, orderly, and laminar. Flows with high Reynolds number are fast, turbulent, and mixing.

The Reynolds number has a simple formula in terms of four fundamental characteristics of the flow: (1) the diameter of the key features (e.g., of the golf ball),(2) the flow speed, (3) the fluid density, and (4) the fluid viscosity. The formula is simple: the Reynolds number is simply the product of the first three of these divided by the fourth.

This results in a dimensionless quantity: it does not matter what units you use to compute the four fundamental characteristics as long they are used consistently.

The *viscosity*, which enters the Reynolds number, measures how thick the fluid is: water, for example, is a moderately thin fluid and has viscosity 5×10^{-4} lb/ft s, while honey, which is much thicker, has a viscosity of 5 in the same units, and pitch, which is practically solid, has a viscosity of about 200 000 000. Using the diameter of a golf ball (0.14 feet), its speed (257 feet per second), and the density (0.74 pounds per cubic foot) and viscosity (0.000012 lb/ft s) of air, we compute the Reynolds number for a professionally hit golf ball in flight as about 220 000, much more than a butterfly flying (4000) or a minnow swimming (1), but much less than a Boeing 747 (2 000 000 000).

1.4 CHARACTERISTICS OF GEOMETRY,GRIDS AND FLOW FIELD

The objectives of this investigation are to determine the shape of golf ball which produces different aerodynamics characteristics and then to use those shape parameters for the simulation of golf ball flying trajectory.

In addition to, discuss thorough of flow field character and physical property, included the relationship between sound frequency with sphere shape ball.

Its surface consists of hundreds of dimples of different sizes and depths. The combination of these dimples has made the process of grid generation greatly complicated and therefore very time consuming.

It is possible in some cases that two dimples may interlock with each other and eventually lead to lethal grid generation errors. Hence, this step requires extreme carefulness and the experience gained from numerous trials. 3-D grid systems contain structured grid and non-structured grid. Figs. 3 and 4 show these kinds of grid near the sphere.

In those cases used non-uniform distribute grid system which could increase more mesh in key-position, this way would simulation more complete flow field near the sphere.

The 3-D golf ball simulation in this paper uses structured and unstructured grid for comparison. Table 1 lists the parameters of every case. The golf ball diameter is 42.6 mm while the domain size is 600 mm × 400 mm × 400 mm in the x, y, and z-directions.

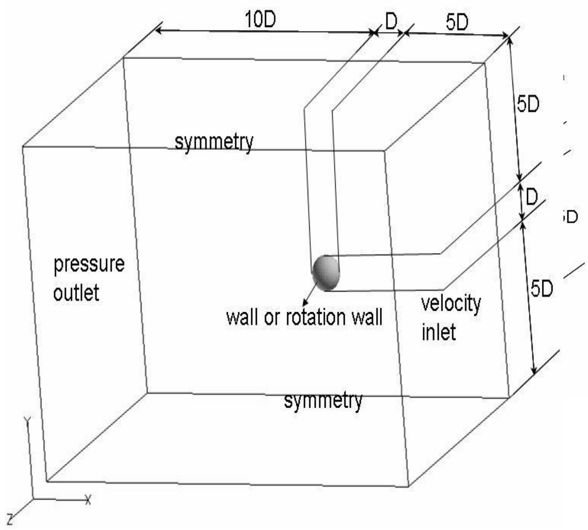

FIGURE 1.4 GOEMETRY OF GOLF BALL

2 .LITERATURE REVIEW

2.1 REVIEWS ON ACOUSTICAL CFD AND AERODYNAMIC ANALYSIS OVER GOLF BALL

Aerodynamic evaluation of larger systems, from bicycles to airplanes, is an important topic and requires significant effort and financial investment in today's efficiency-driven world. Whether the application of the product is racing, where speed is key, or it is commercial transportation, where efficiency of moving goods around the country may be the highest priority, wind tunnel experiments and CFD simulations must be an area of serious consideration. This work addresses the need for development of a virtual wind tunnel, to be used as a design instrument for large-scale systems. The specific objectives of this research are:

1. Developing 3-D scanning methodology for the digitization of large systems.

2. Developing CFD methodology for aerodynamic analysis of large systems.

3. Applying developed methodologies to investigation of drag characteristics of various time-trial bicycle riding position.

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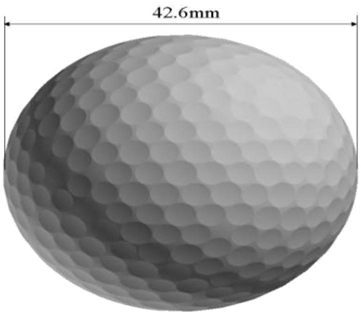

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3. BASICS OF COMPUTATIONAL FLUID DYNAMICS

3.1 CONCEPT OF CFD

Computational Fluid Dynamics (CFD) is the simulation of fluids engineering systems using modeling (mathematical physical problem formulation) and numerical methods (discretization methods, solvers, numerical parameters, and grid generations, etc.). The process is as figure 3.1.

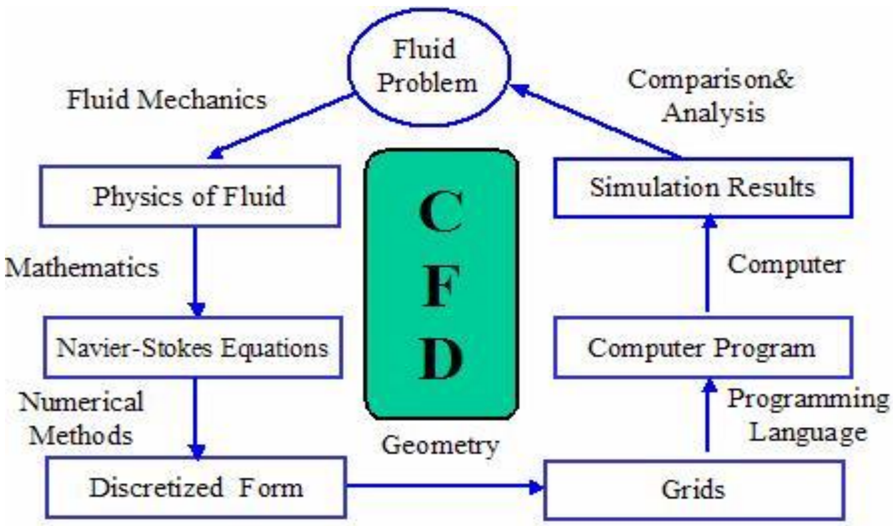

FIGURE 3.1 Process of Computational Fluid Dynamics

Firstly, we have a fluid problem. To solve this problem, we should know the physical properties of fluid by using Fluid Mechanics. Then we can use mathematical equations to describe these physical properties. This is Navier-Stokes Equation and it is the governing equation of CFD. As the Navier-Stokes Equation is analytical, human can understand it and solve them on a piece of paper. But if we want to solve this equation by computer, we have to translate it to the discretized form.

3.2. IMPORTANTS OF CFD

There are three methods in study of Fluid: theory analysis, experiment and simulation (CFD). As a new method, CFD has many advantages compared to experiments. Please refer table 1.

	Simulation (CFD)	Experiment
Cost	Cheap	Expensive
Time	Short	Long
Scale	Any	Small/Middle
Information	All	Measured Point
Repeatable	Yes	Some
Safety	Yes	Some Dangerous

TABLE 4.1 Comparison of Simulation and Experiment

3.3. APPLICATION OF CFD

As CFD has so many advantages, it is already generally used in industry such as aerospace, automotive, biomedicine, chemical processing, heat ventilation air condition, hydraulics, power generation, sports and marine etc.

3.4. PHYSICS OF FLUIDS

Fluid is liquid and gas. For example, water and air. Fluid has many important properties, such as velocity, pressure, temperature, density and viscosity. The density (1) of a fluid is its mass per unit volume. If the density of fluid is constant (or the change is very small), we call the fluid is incompressible fluid. If the density of fluid is not constant, we call the fluid is compressible fluid. Normally, we can treat water and air as incompressible fluid. If the fluid is incompressible, we can simplify the equations for this type of fluid.

$$\frac{M}{V}\ \frac{kg}{m^3} \qquad (1)$$

The viscosity (2) is an internal property of a fluid that offers resistance to flow. For example, to stir water is much easier than to stir honey because the viscosity of water is much smaller than honey.

$$\mu = \frac{Ns}{m^3} = [Posie] \qquad (2)$$

TABLE 3.2 shows the densities and viscosities of air, water and honey.

Substance	Air (18ºC)	Water (20ºC)	Honey (20ºC)
Density (kg/m^3)	1.275	1000	1446
Viscosity (P)	1.82e-4	1.002e-2	190

3.5. FINITE VOLUME METHOD

The Navier-Stokes equations are analytical equations. Human can understand and solve them, but if we want to solve them by computer, we have to transfer them into discretized form. This process is discretization. The typical discretization methods are finite difference, finite element and finite volume methods. Here we introduce finite volume method.

3.5.1. THE APPROACH OF FINITE VOLUME METHOD

Integrate the general form of Navier-Stokes equation over a control volume and apply Gauss Theory

$$\int_V \frac{\partial}{\partial x_i} \Phi dV = \int_S \Phi \cdot n_i \, dS$$

We can get the integral form of Navier-Stoke equation

$$\int_V \frac{\partial(\rho\Phi)}{\partial t} dV + \int_S \left(\rho U_i \Phi - \Gamma \frac{\partial \Phi}{\partial x_i}\right) \cdot n_i \, dS = \int_V q_\Phi dV$$

To approximate the the volume integral, we can multiply the volume and the value at the center of the control volume. For example, we have a 2D domain as fig 2. To approximate the mass and momentum of control volume P, we have

$$m = \int_{V_i} \rho \, dV \approx \rho_p V , \qquad mu = \int_{V_i} \rho_i u_i \, dV \approx \rho_P u_P V$$

To approximate the surface integral, for example pressure force, we have

$$\int_{S_i} P \, dS \approx \sum_k P_k S_k \qquad k = n, s, e, w$$

Normally we store our variables at the center of control volume, so we need to interpolate them to

get P_k, which are located at the surface of control volume.

Typically, we have two types of interpolations, one is upwind interpolation, and the other one is central interpolation.

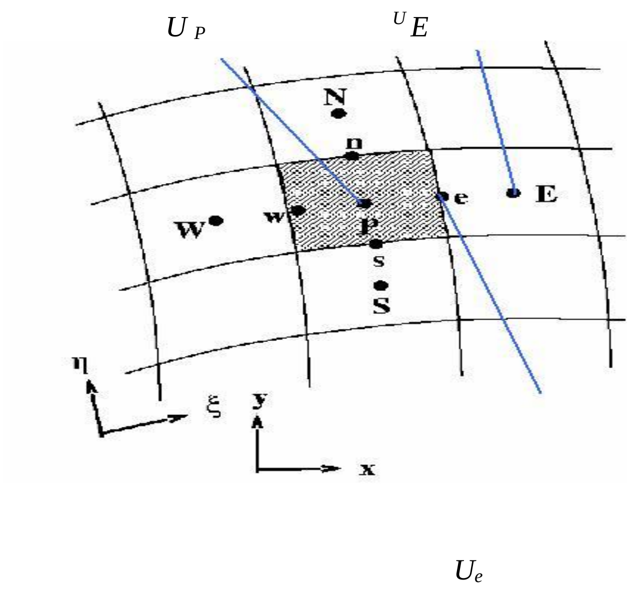

FIGURE 4.2 2D Structured Grid Domain

3.6. CONSERVATION OF FINITE VOLUME METHOD

If we use finite difference and finite element approach to discretized Navier-Stokes equation, we have to manually control the conservation of mass, momentum and energy. But with finite volume method, we can easily find out that, if the Navier-Stokes equation is satisfied in every control volume, it will automatically be satisfied for the whole domain. In another words, if the conservation is satisfied in every control volume

4. EXPERIMENTAL PROCEDURE

4.1 DESCRIPTION OF GOLF BALL

Eight brand new commercially available. golf balls that are widely used in major tournaments around the world were selected for this study.

A Squash ball was also used in this study. The external surface of the Squash ball is relatively smooth and its diameter is close to the average diameter of the golf ball . The commercial brand name and their physical characteristics diameter, mass, price, dimple shapes, etc. The pictorial dimple shapes of these balls.

FIGURE 5.1 GOLF BALL TYPES

The aerodynamic properties (drag, lift and side force and their corresponding moments) were measured at wind speeds of 40 km/h to 140 km/h. The aerodynamic forces acting on the balls were determined by testing balls with the supporting gear (mounting stud) and then subtracted from the forces acting on the supporting gear only. An alternative mounting support to the one used in this study is currently being under construction to minimise the interference of the mounting device on aerodynamic properties.

4.2 EXPERIMENTAL FACILITIES

The study was conducted in RMIT Industrial Wind Tunnel. It is a closed return circuit wind tunnel with a turntable to simulate the cross wind effects. The maximum speed of the tunnel is approximately 150 km/h. The dimension of the tunnel’s test section is 3 m wide, 2 m high and 9 m long and the tunnel’s cross sectional area is 6 square meter. A plan view of the tunnel . More details about the tunnel can be found . The tunnel was calibrated before conducting the experiments and tunnel’s air speeds were measured via a modified NPL ellipsoidal head Pitot-static tube (located at the entry of the test section) connected to a MKS Baratron pressure sensor through flexible tubing.

A mounting stud was manufactured to hold the ball and was mounted on a six component force sensor (type JR-3) . Purpose made computer software was used to compute all 6 forces and moments (drag, side, lift forces, and yaw, pitch and roll moments) and their non-dimensional coefficients. The experimental set up in the test section of RMIT Industrial Wind Tunnel .

FIGURE 5.2 MOUNTING BALL ON FORCE

4.3 FUTURE WORK

- The work is underway to characterise the dimples and relate them to aerodynamic properties.
- The effects of spin on aerodynamic properties especially on drag and lift will be analysed.
- A thorough flow visualisation around the golf ball will be made.
- A comparative study of CFD and EFD of golf ball aerodynamic properties is currently being undertaken.

5 . RESULT AND DISCUSSION

This study used structured and non-structured grids for numerical simulation. Figure 7 showed the drag coefficients of two types of grid. Since the benchmark values for drag coefficient are between 0.25 ~ 0.27 [13], the drag coefficient obtained is closer to the benchmark values via structured grid simulation than non-structured grid. On the other hand, according to the performance test by the manufacturer of this golf ball, the actual flying distance of this ball was 240 m. Figure 8 showed the flying distance which was 268.1 m obtained from the simulation using non-structured grids. It had an error of 11.7% compared with the actual distance.The distance predicted by the structured grid simulation was 225.2 m, which had an error of 6.2%. Judging based on flying distance, a simulation based on a structured grid system produces a higher accuracy.

However, both the structured and non-structured grid systems are qualitatively reliable for the trends of drag coefficient obtained through both these systems produce are the same. The speed of the golf ball considered in this study ranges from 0.345 m/s to 83.82 m/s. This corresponds to Reynolds numbers ranging from 1×10^3 to 2.43×10^5. Figure 9 shows the flow field. Around a typical golf ball (Case 1). In Case 2, additional dimples are added onto the original golf ball surface considered in Case 1. The orientation of these additional dimples is depicted. It is found, based on Figure 10, that the flow field associated to Case 2 is no longer symmetrical because of the presence of the additional dimples. Figure 11 demonstrates the distribution of lift and drag coefficients of Cases 1 and 2.

Clearly, the addition of small dimples increases the drag. However, for lower Reynolds numbers, their estimated sound pressures were 10 dB greater than the theoretical ones.

6. CONCLUSION

This study has examined various conditions for the problem considered. The flying distance of the golf ball is used as the criterion to quantify the success of a simulation. Based on this study, several conclusions can be drawn as follows:

(1) As far as the selection of grid distribution is concerned, structured grid will produce more accurate results. Unfortunately, simulations with structured grid normally take longer time to accomplish. Nowadays, this can be overcome by using parallel computation technique. As a matter of fact, the results obtained from non-structured grid qualitatively resemble those from structured grid. Therefore, simulations based on non-structured grid are very useful in providing preliminary understanding of a problem.

(2) Adding small dimples to the original golf ball surface increases both the drag and lift as evidently shown in Cases 1 and 2. Between these two cases, the amount of lift force increased was 2.86 greater than drag causing lift effect to be greater than drag effect and making the sphere of Case 2 fly farther.

(3) With the same coverage area, it is found that the golf ball with deeper dimples is associated to greater drag and lift. Hence, the flying distance of a specific golf ball design

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