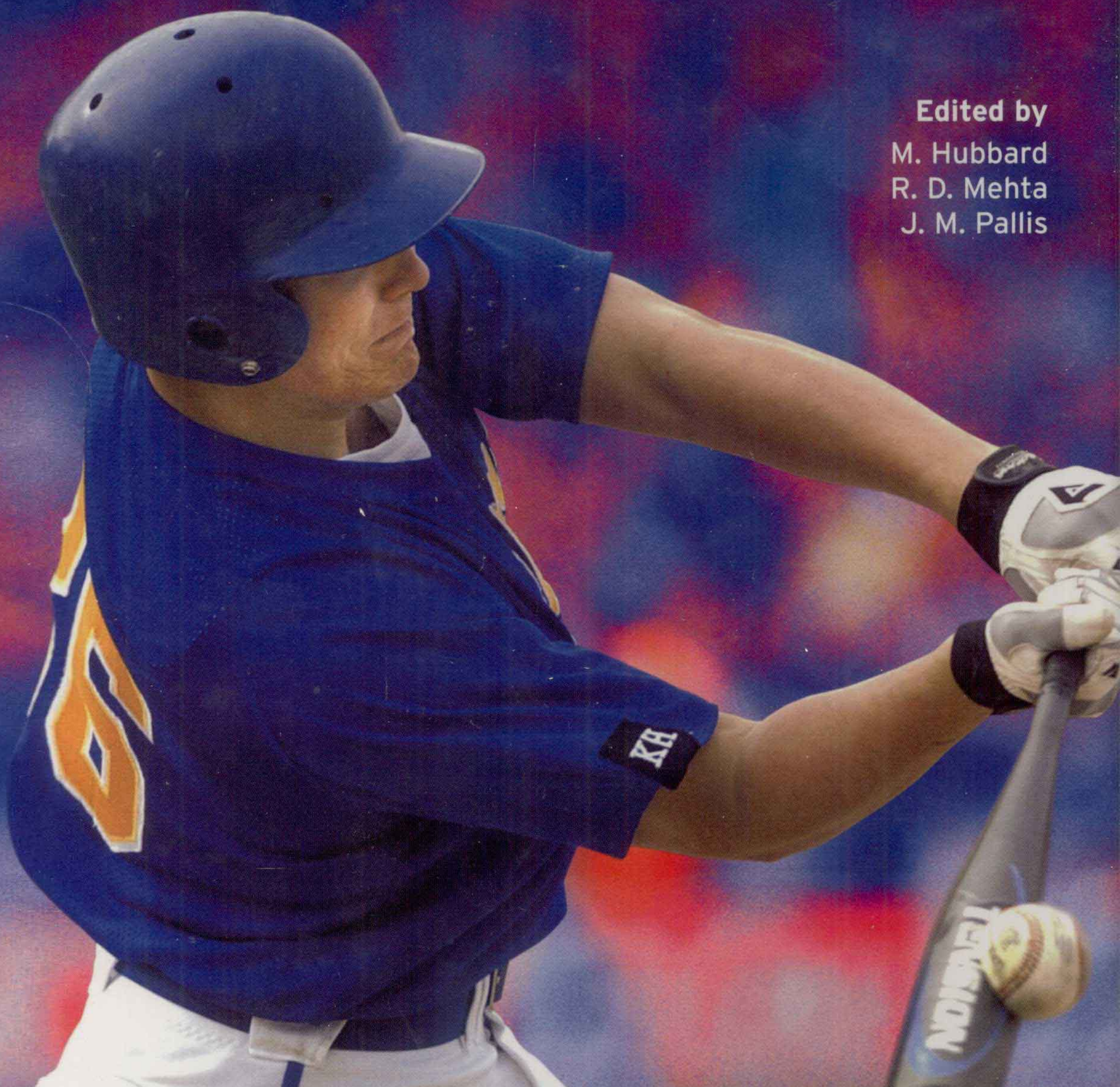
The Engineering of Sport 5

Volume 1

Edited by
M. Hubbard
R. D. Mehta
J. M. Pallis



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Editorial Office:
Department of Mechanical Engineering
The University of Sheffield
Mappin Street
Sheffield
S1 3JD
Tel. +44 114 222 7891

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Preface

Sports engineering is the glue that holds together all of sports. It has a broad base, encompassing all the fields of engineering that have to do with design of equipment, enhancement of performance in sporting events through modeling and simulation, design of experimental systems and experiments to measure techniques and performances of competitors, and all other technical aspects of sports. It also deals with the development of educational programs to perpetuate the science and art of sports. One of the main roles of sports engineering is to focus on using improvements in science and technology to better understand and enhance equipment efficacy and individual performance in all sports. Engineers in sports, recreation and fitness have the same goals as other sports professionals: enhance performance; prevent injury; assure safety; increase enjoyment and health benefits; support longevity, accessibility and diversity (to participate throughout the human life cycle regardless of physical challenge).

Sports engineering naturally includes materials, dynamics, design, manufacturing and experimental techniques. It is the intellectual fabric that allows for the design and evolution of equipment with the potential to revolutionize specific sports. As an example, the introduction of fiberglass pole vaulting poles in the early 1960's dramatically changed the rate of improvement of the world record. Similar instances of remarkable changes in the evolution of specific sports as a result of improvements in equipment have occurred in the javelin throw, tennis and golf, to name only a few.

Sports typically involve motion. This allows mathematical models based on Newton's Laws to be developed of the dynamics of the human competitors and their implements and/or vehicles. The models assist in improving our basic understanding of the events. In addition, such models can assist in the design of implements and equipment to withstand the loads of continual use, providing safety and durability for the user.

These two volumes of the proceedings contain 172 papers presented at the 5th Conference on Engineering of Sport held on the campus of the University of California, Davis, during September 13-16, 2004. The conference was jointly sponsored by the International Sports Engineering Association and the Bioengineering Division of the American Society of Mechanical Engineers. Although papers were contributed from more than 15 countries, the meeting and proceedings had a particularly American flavor.

Numerous special sessions addressed many aspects of the sports of baseball, golf, swimming, gymnastics, track and field, cycling, soccer, skiing, tennis, fly fishing, rock climbing, and winter sports. In addition many papers touched on more general topics such as shoes/surfaces, design, applied aerodynamics and hydrodynamics, experimental techniques, education, entrepreneurship and industrial concerns.

The 5th Conference on Engineering of Sport continues a series of meetings held since 1996 in Sheffield (2), Sydney and Kyoto. The 5th Conference witnessed a 50% growth in the number of papers and a broadening of participation to include more industrially affiliated engineers and scientists. The next conference is scheduled to be held in Munich, Germany in the summer of 2006.

The two volumes are organized along fields rather than categorized into specific sports, in order to better show the relations between and the interdisciplinary flavor of the fields. The quality of the papers herein is due to the hard work and diligence of both the authors and the reviewers who contributed to this volume. We also gratefully acknowledge the editorial assistance of Amanda Staley from ISEA headquarters at Sheffield University, whose help has been invaluable.

Mont Hubbard
Rabindra Mehta
Jani Macari Pallis

Editors
September 2004

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Golf ball aerodynamics

A. J. Smits
Department of Mechanical & Aerospace Engineering, Princeton University, Princeton, NJ, USA
S. Ogg
Callaway Golf, Inc., Carlsbad, CA, USA

ABSTRACT: We discuss the nature of the flow over a spinning golf ball, with particular attention to the effect of the dimples and their arrangement on the surface. We also describe the design methods used by the golf ball companies in their search for better performance, and the testing procedures used in studying golf ball aerodynamics.

INTRODUCTION

For a typical tee shot by a low-handicap golfer (Fig. 1), there exist three distinct phases in the motion of the ball (Smits and Ogg, 2004). First, there is the impact phase. The contact time between the club and the ball is typically about 400 to 500 μs, during which the ball accelerates from rest to a velocity of about 230 ft/s, and acquires a spin rate between 2000 and 3000 rpm. The ball deforms extensively during contact with the club, compressing to about 80% of its diameter, but regains its original shape within a couple of diameters along its trajectory. Second, there is the flight phase, which is about 250 to 300 yards long (the "carry" distance), about 35 yards high at its maximum point, and takes about 6 seconds. The third and final phase of the motion begins when the ball impacts the ground. It may bounce a number of times before rolling some distance and then coming to rest.

Aerodynamics is important only in the second phase, and the aerodynamic performance of a golf ball in flight is completely determined by its size and inertial characteristics, and the shape and distribution of the dimples on its surface. Very small changes in dimple design can have important consequences for the ball trajectory, particularly its carry distance, the maximum trajectory height, and the angle of incidence at the point where it hits the ground (Hale *et al.* 1994; Veilleux and Simonds, 2004; Beasley and Camp, 2002). These parameters are important to a golfer, and there is continuous innovation pressure on the manufacturers to satisfy the demand from golfers for a better, longer, more accurate ball.

Golfers discovered, some time in the middle of the nineteenth century, that the ball flew further and better when scored or marked. This discovery initiated a wave of innovation in cover design, eventually leading to the invention of dimples, first patented by William Taylor in 1901 (Martin, 1968). By 1930, the round dimple had become accepted as the standard design for golf balls, with 330 or 336 dimples arranged in regular rows and a typical depth of about 0.010 in. (Bearman and Harvey, 1976; Veilleux and Simonds, 2004). More recently, the number of dimples has ranged from as low as 252 up to a high of 812, and their shape has gone from circular to hexagonal, with many variations in between. Their arrangement on the surface has also seen many changes with those based on the icosahedral design, where the ball surface is divided into segments defined by 20 equilateral triangular patches, becoming very popular (see, for example, the 1932 British patent by Pugh, and the 1984 US patent by Ayoma, #4,560,168). Today's ball is likely to have about 384 dimples, of 5 to 6 different sizes, covering about 80% of the ball surface.

Here, we discuss the nature of the flow over a spinning golf ball, with particular attention to the effect of the dimples and their arrangement on the surface. We also describe the design methods used by the golf ball companies in their search for better performance, and the various kinds of test procedures used to study the aerodynamics of golf balls.

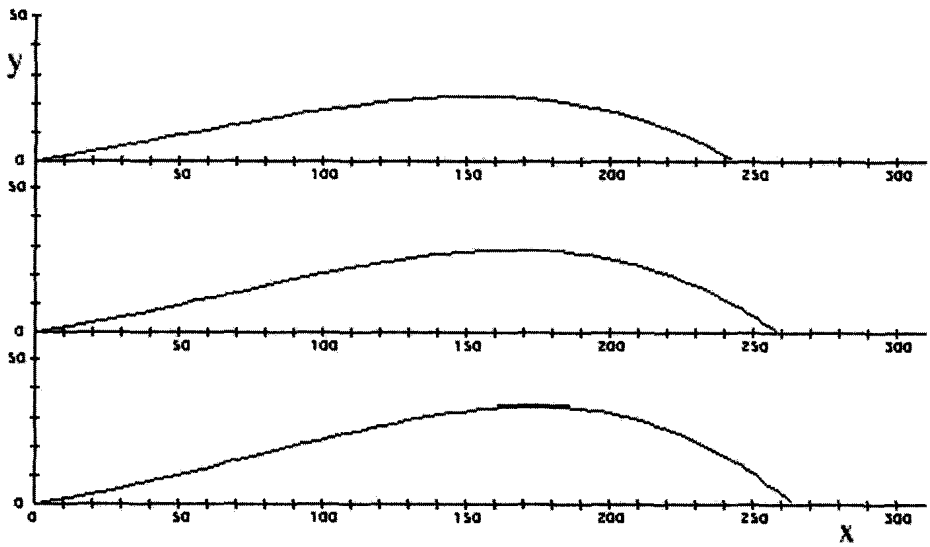

Fig. 1 Typical trajectories of a driver shot, initial velocity 240 ft/s, launch angle 10°. Top: 1800 rpm; Middle: 3000 rpm; Bottom: 4200 rpm.

BASIC AERODYNAMIC PRINCIPLES

Consider the free body diagrams shown in Fig. 2. F_L and F_D are the lift and drag force, respectively, defined as the components of the total force taken in the direction normal to and along the direction of motion of the ball. Note that during the ascent there is a component of the lift vector, Lh, that acts in a horizontal direction opposing the travel of the ball. There is a component lift force opposing the gravitational force, Lv, but there is also a horizontal component, Lh, that is resisting the down-range travel of the ball. Furthermore, the drag force has a component that acts in a vertical direction opposing the vertical component of lift. The drag force is not only causing the ball to decelerate, but is pulling the ball down. Given that with the creation of additional lift comes increased drag, it becomes clear that for ascending flight minimization of lift is critical.

In descending flight the lift force is not only opposing the force of gravity, via the component Lv, but as indicated by the horizontal component, Lh, is pulling the ball

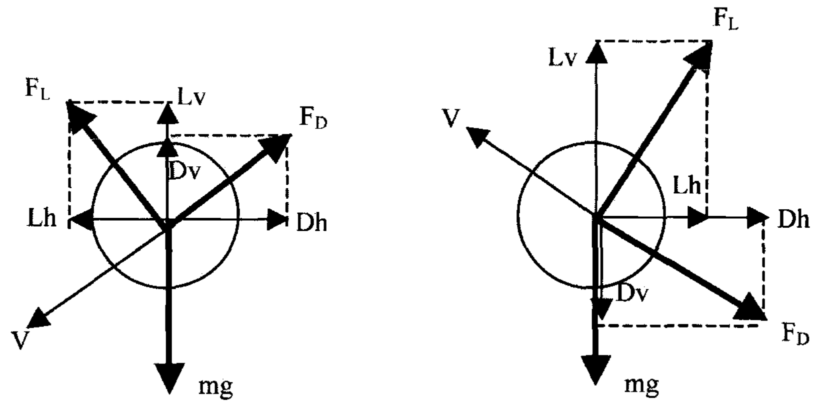

Fig. 2 Free body diagrams showing the forces acting on a golf ball in flight: (a) Descending ball; (b) Ascending ball.

forward. The lift force is therefore contributing to increased carry distance and, by reducing the incoming angle to the ground, increased roll distance. But what about the increase in drag associated with maximizing lift at this low speed condition? While the drag force certainly acts to decelerate the ball, observe that it now has a vertical component, Dv, that is opposing the force of gravity and hence helping to keep the golf ball in the air.

In a general sense, the resultant aerodynamic force F acting on the ball depends on its velocity V, its size, the spin rate ω, the fluid density ρ and viscosity μ, and the nature of the surface. In turn, the spin rate at any point in the trajectory depends on the initial spin imparted to the ball by the club and the rate of spin decay, which depends on the moment of inertia among other parameters. The size of the ball is characterized by its diameter, D, radius, R, or its cross-sectional area, $A = \pi R^2$. The nature of the surface is determined by the dimple pattern, and each particular dimple pattern will have its unique influence on the ball performance. In this section, we will assume that the effects of the dimple pattern can be described by a single length scale, such as, for example, the rms amplitude of the dimple depth, k. Hence:

$$F = f\left(V, D, \omega, \rho, \mu, k\right) \qquad (1)$$

where f indicates a functional relationship. By dimensional analysis (Smits and Ogg, 2004):

$$\frac{F}{\frac{1}{2}\rho V^2 A} = g\left(\frac{\rho V D}{\mu}, \frac{\omega R}{V}, \frac{k}{D}\right) \qquad (2)$$

In terms of the lift and drag coefficients C_L and C_D we have:

$$C_L = g_1(\mathrm{Re}, W, \varepsilon) \qquad (3)$$

and

$$C_D = g_2(\mathrm{Re}, W, \varepsilon) \tag{4}$$

where

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} \quad \text{and} \quad C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A}. \tag{5}$$

The other non-dimensional groups are the Reynolds number Re, the spin rate parameter W, and the relative roughness, ε, given by:

$$\mathrm{Re} = \frac{\rho V D}{\mu}, \qquad W = \frac{\omega R}{V}, \qquad \varepsilon = \frac{k}{D}. \tag{6}$$

The Reynolds numbers for a golf ball during a typical driver shot varies between approximately 50,000 to 200,000, corresponding to balls traveling at 60 to 240 ft/s in air at 70°F and atmospheric pressure. The spin rate parameter varies from about 0.05 to 0.12 (for spin rates between 200 and 4000 rpm).

LAMINAR AND TURBULENT FLOW

Consider first the case of a non-spinning ball. Here, there is no lift, only drag (we shall see why later), and Eq. 4 reduces to

$$C_D = g_3(\mathrm{Re}, \varepsilon) \tag{7}$$

That is, the drag coefficient is only a function of Reynolds number and relative roughness (that is, dimple shape and distribution). Figure 3 shows that the function depends on the relative roughness, but all curves show a similar behavior: at low Reynolds numbers the drag coefficient is approximately constant at a value of about 0.5, while at higher Reynolds numbers the drag coefficient drops to a much lower value of about 0.1 or 0.25, before increasing with further increases in Reynolds number.

The Reynolds number where the drag coefficient takes a sudden dip is called the "critical" Reynolds number. For a golf ball its value lies somewhere between 40,000 and 60,000, whereas for a smooth ball it lies between about 350,000 and 400,000 (Fig. 3). For a Reynolds number above the critical value, a golf ball has about half the drag of a smooth ball. That is, for velocities greater than about 70 ft/s, a golf ball experiences less than half the air resistance experienced by a smooth ball of the same size.

To understand the physical mechanisms that cause this sudden change in drag coefficient, consider the state of flow inside the boundary layer, the region of flow next to the surface of the ball where strong velocity gradients lead to significant viscous forces. Below the critical Reynolds number, the flow in the boundary layer over the entire front face of the ball is laminar. As the flow passes over the "crest," the freestream velocity changes from an accelerating flow to a decelerating one, so that the force due to pressure differences acts in the upstream direction. This force causes the low-momentum fluid in the boundary layer to start to move in the upstream

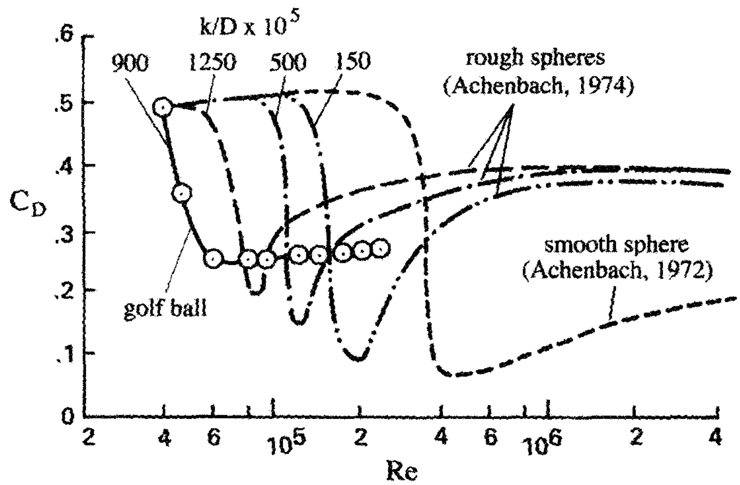

Fig. 3 Drag coefficients as a function of Reynolds number for spheres with different degrees of roughness. Adapted from Bearman and Harvey (1976). With permission of the Royal Aeronautical Society.

direction, so that the flow separates (Fig. 4). Instead of following the surface of the ball, a large region of low velocity and low pressure forms over the rear of the ball, and a simple momentum balance shows that a large drag force acts on the ball.

Above the critical Reynolds number, the boundary layer over the front face of the ball becomes turbulent while the flow just outside the boundary layer is still very much the same as that seen at lower Reynolds numbers: That is, a pressure difference is generated that leads to a force on the fluid in the boundary layer that acts in the upstream direction. However, a turbulent boundary layer resists separation more effectively than a laminar boundary layer because (1) it has a "fuller" velocity profile and the flow enters the region of adverse pressure gradient with relatively high momentum near the wall, and (2) even as the boundary layer enters the adverse pressure gradient region, turbulent mixing continues to take place, helping to replenish the momentum loss near the wall by bringing higher momentum fluid from the outer part of the boundary layer closer to the wall. As a result, the width of the wake is smaller (Fig. 4), the total momentum deficit in the wake is reduced, and the total drag force is smaller.

EFFECT OF DIMPLES

Figure 3 showed how the critical Reynolds number decreases with increasing surface roughness. When the ball is made rough, as by scoring or marking it in some way, the roughness elements introduce disturbances in the boundary layer, and this causes the boundary layer to become turbulent at a Reynolds number lower than in the smooth case. By this means, the critical Reynolds number is lowered, and if the roughness is of the right type and amplitude the entire flight envelope will occur above the critical Reynolds number. Consequently, the drag force acting on the ball will be lower and the ball will fly further.

Dimples are a particularly effective form of roughness. To compare the difference