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Aerodynamics of Oval Shaped Sports Balls

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Abstract

Oval shaped sports balls are used in American, Australian and rugby football codes. The flight trajectory of oval shaped balls largely depends on their aerodynamic characteristics which are significantly different from spherical balls. Despite the popularity of the game, it appears that there is scant information on the aerodynamic forces experienced by oval shaped balls especially the American and Australian Rules football is available in the open literature. Attempts were made to construct the flight trajectory of oval shaped balls, however without knowing the aerodynamic properties; it is difficult to build such a model. The primary purpose of this study is to experimental measure the aerodynamic forces of several oval shaped balls (American football, rugby ball and Australian Rules football) under a range of wind speeds and yaw angles. The non-dimensional drag coefficient were estimated and compared. The results indicate that the drag coefficients of these balls are close to each other. The results also illustrate that the drag coefficient is nearly four times lower when the longitudinal axis is pointed to the wind.

Introduction

Oval shaped sports balls such as Rugby ball, Australian Rules football and American football have aerodynamic properties that lead to interesting and sometimes highly unexpected flight trajectories [1-2, 4, 12]. Our present understanding of these aerodynamic properties is rather limited [4]. Even when the ball is round, as in the case of golf balls and tennis balls, the aerodynamic parameters such as the coefficients of lift and drag, and their dependence on spin rate, are not known a priori, and must be found empirically [2, 4, 7-8]. The oval shapes of Rugby, Australian Rules and American footballs present additional challenges to the understanding of their aerodynamics, such as the action of two separate spin axes and the possibility of tumbling [6-10, 12].

The Rugby, Australian football and American football - all are oval in shapes. The Rugby ball is larger than the Australian and American footballs and its surface is roughened with pimples. The pimples are intended to increase hand traction and minimise the slip during passing. However, they also influence the lift and drag forces and thus affect the trajectory and flight distance [2-3, 5, 11]. The American and Australian footballs have distinctive features such as laces in contrast to the Rugby ball. The Rugby ball had also laces which were eliminated in the new design since 2004. The American football has also pimples to increase hand traction. However, the Australian football does not have any pimples. Both Australian and American footballs are made of leather panels. Physical properties of rugby ball, Australian Rules football and American football are shown in table 1.

The external shapes of Rugby, Australian and American balls appear similar but they are actually significantly different in terms of geometrical properties. As All 3 balls are made of 4 panels, with leather being used for the panels of Australian and American footballs, and synthetic rubber panels for the Rugby ball [1, 4]. The seams created by joining the panels can also play an important role in the aerodynamic performance of the ball, as is well known from studies of cricket balls and baseballs. The two ends of a Rugby and Australian balls are similar and appear to be bullet head shape in contrast the American football's two ends are conical in shape.

Table 1. Physical parameters of balls, adapted from [1, 4, 12]

	Rugby Ball	Australian Football	American Football
Length, mm	280 - 300	270 - 280	280 - 292
Circumference (Longitudinal) mm	740 - 770	720 - 735	711 - 724
Circumference (Lateral) mm	580 - 620	545 - 555	527 - 530
Mass, gm	410 - 460	450 - 500	400 - 430
Air pressure, kPa	66 - 69	62 - 76	86 - 93
Panel Numbers	4	4	4
Panel Type	Synthetic	Leather	Leather
Surface Finish	Rough with Pimples	Smooth	Rough with Pimples
Lace Exposed	No	Yes	Yes
Shape	Oval with Bullet Ends	Oval with Bullet Ends	Oval with Conical Ends

Prior aerodynamic studies on spherical sport balls include Alam et al. [3], Mehta et al. [11], and Asai et al. [5]. However, no knowledge about the aerodynamic forces of more “ellipsoidal” balls is available in the public domain except limited studies conducted by Alam et al. [1-2, 4], Brancazio [6], Rae [7] and Rae and Streit [8]. The airflow around a Rugby ball, Australian foot ball and American football is believed to be very complex and three dimensional, especially because these balls can experience both lateral and longitudinal rotational motion during flight. Due to complex behaviour, the accuracy of long distance kicking/punting by the elite level players to the desired point/goalpost is very low. A statistical study conducted by Hopkins [13] reported that the accuracy of kicking of oval shape balls is close to 50% and not much improved over the last three decades despite undertaking numerous efforts. A comprehensive aerodynamics study therefore is paramount to understand the balls' behaviours in flight and subsequently build flight trajectory models of the ball for players and coaches so that they can develop better game strategy. However, the work is challenging, time consuming and costly. In this paper, we will present some aerodynamic data mainly under non spinning condition. The steady-state aerodynamic properties, such as drag and side force (or lift) acting on a Rugby ball, Australian football and American football will be investigated and compared. The steady aerodynamic properties were measured experimentally for a range of wind speeds and yaw angles. It may be noted that the American and Rugby footballs tested were taken from the 2011 NFL and 2011 Rugby World Cup, both have significantly altered surface design when compared to older balls tested by Alam et al. [1,2].

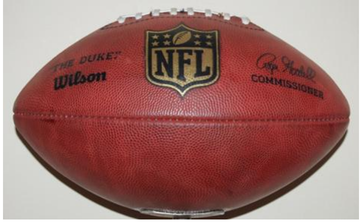
Methodology

Description of Balls

Three new balls: Rugby, Australian football and American foot ball were selected for this study. The Summit Rugby ball was manufactured by Heritage Sports Australia. The Sherrin Australian football was made by Sherrin and Spalding (a subsidiary of Russell Corporation). The American football was manufactured by Wilson. The selected American football is used at professional (NFL) level games. The dimensions of the Rugby ball used for this work are 280 mm in length and 184 mm in diameter. The dimensions of the Australian football are approximately 276 mm in length and 172 mm in diameter. The dimensions of the American football are approximately 280 mm length and 175 mm diameter. Diameters for all 3 balls were measured at their midpoints. The yaw angle The Australian and American footballs are closely circular in cross-section and the Rugby ball departed from a circular section by around 10 mm. Side views of all three balls are shown in Figure 1. A sting mount was used to hold each ball, and the experimental set up in the wind tunnel test section is shown in Figure 2. The aerodynamic effect of sting on the ball was measured and found to be negligible. The distance between the bottom edge of the ball and the tunnel floor was 420 mm, which is well above the tunnel boundary layer and considered to be out of the ground effect.

(a) Summit Rugby Ball

(b) Sherrin Australian Football



(c) Wilson American Football (NFL)

Figure 1. Balls used for experimental study

Experimental Procedure

In order to determine the aerodynamic properties of oval shaped - balls experimentally, the RMIT Industrial Wind Tunnel was used. It is a closed return circuit wind tunnel with a maximum speed of approximately 150 km/h. The rectangular test section's dimension is 3 m (wide), 2 m (height), 9 m (long), and is equipped with a turntable to yaw the model. The balls were mounted on a six component force sensor (type JR-3) and a purpose made computer software was used to digitize and record all 3 forces (drag, side and lift forces) and 3 moments (yaw, pitch and roll moments) simultaneously. Two support systems for vertical and horizontal setups were developed. A notable variation in results was noted using these two experimental setups. The yaw angle is defined as the angle between the major axis (length of ball parallel to flow at 0 degree) and the minor axis (when ball is offset to either end). The aerodynamic effect of the support device was subtracted from the support with the ball. The aerodynamic drag coefficient (C_D) is defined as "equation (1)".

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 A} \tag{1}$$

where D, ρ, V and A are drag, air density, wind velocity and projected frontal area of the ball respectively. The Reynolds number (Re) is defined as "equation (2)".

$$R_e = \frac{\rho V d}{\mu} \tag{2}$$

where ρ, V, d and μ are the air density, wind velocity, ball diameter and the air absolute dynamic viscosity respectively.

The side force coefficient (C_S) was determined using equation 3.

$$C_s = \frac{S}{\frac{1}{2}\rho V^2 A} \tag{3}$$

where D, ρ, V, S and A are the drag, air density, wind velocity, side force, and projected frontal area at zero yaw angle of the ball respectively. The projected frontal area used to normalise the drag force was the frontal projected area at zero yaw angle and was determined using equation 4.

$$A = \frac{\pi d^2}{4} \tag{4}$$

The diameter of the ball is measured at the midpoint of the ball. The tare forces were removed by measuring the forces on the sting in isolation and removing them from the force of the ball and sting.

Figure 2. Experimental set up in the test section of RMIT Industrial Wind Tunnel

Results and Discussion

Only drag force coefficient (C_D) for all three balls are presented in this paper and they are plotted against yaw angles. The repeatability of the measured forces was within ±0.01 N and the wind velocity was less than 0.5 km/h. Alignment errors have been minimised by using electronic sensors to accurately measure the yaw angle relative to flow. The turbulence intensity of the flow was measured and integrated with the results. The variation of drag coefficients (C_D) with yaw angles and speeds for the Rugby ball, Australian football and American foot ball is shown in Figures 3 to 5.

The C_D values for the Rugby ball, Australian football and American football at zero yaw angles are 0.18, 0.10 and 0.20 respectively. At zero yaw angle, the American football displayed higher drag coefficient compared to other two balls: Rugby and Australian football. The drag coefficient for all three balls increases with an increase of yaw angles due to a larger and very complex flow separation. The C_D values at +90° (windward side) yaw angle for the Rugby, Australian and American footballs are approximately 0.65, 0.55 and 0.78 respectively. The C_D values at -90° vary significantly among all three balls (e.g., 0.45, 0.56 and 0.77 respectively). The minimum asymmetry in C_D values was found for the American football compared to the Rugby ball and Australian football. No significant Reynolds number (varied by wind speeds in this study) dependency was found at zero yaw angle for all three balls except at the lowest speed tested for the Rugby ball and Australian football. However, the Reynolds number (*Re*) variation is significant between 60 km/h and all other speeds for the Rugby ball at all yaw angles. In contrast, small variation was noted for the Australian football at ±25° and a significant Reynolds number dependency was observed between +70° and +90° yaw angles. Minor variation of Reynolds number between 60 km/h and all other speeds was noted for the American football at ±40° yaw angles and significant variation between lower speeds (e.g. 60 and 80 km/h) and other speeds (100, 120 and 140 km/h) at high yaw angles (over 60°) irrespective of windward or leeward side yaw angles.

A comparison of drag coefficients at all speeds and yaw angles for the Rugby ball and Australian football indicates that there is a slight lack of symmetry in the results (Figures 3 and 4). Whilst some errors are associated with airflow and force sensor asymmetry (due to small misalignment of sensor axis and ball axis) and some minor deflections of the ball under wind loading (mainly from the bending of the support strut), the errors are primarily due to asymmetries in the ball themselves. A close visual inspection of the balls also supports this observation. In contrast, there was no major asymmetry noted for the American football.

The American football possesses higher drag coefficient compared to other two balls. The American football has conical ends compared to nearly bullet ends of other two balls (Rugby and Australian foot ball). The lowest C_D value is found for the Australian football. The surface of the ball is much smoother compared to the Rugby and American football. Both American and Rugby balls have noticeable surface roughness that might be the reason for the higher drag of these two balls.

The C_D variation with yaw angles at 100 km/h for all 3 balls is shown separately in Figure 5. The American football and Rugby ball possess similar C_D value at yaw angles 0 to +60° and differ significantly above +60° yaw angle. However, a notable difference is observed with an increase of yaw angles in the leeward side (negative yaw angles). On the other hand, the C_D value is significantly lower at all yaw angles for the Australian football compared to other two balls. The differences in C_D values among the balls at different yaw angles are primarily due to shapes, presence of laces, surface roughness and the balls' geometric asymmetry. The aerodynamic behaviour (drag, lift and side forces) will significantly be complex and variable when multi-axes spin and angle of attacks are involved.

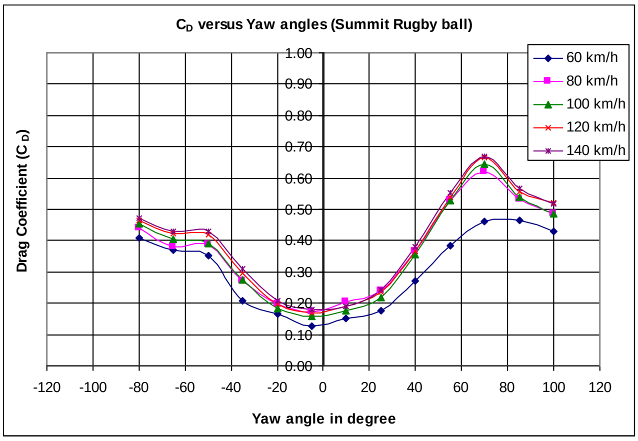


Figure 3. Drag coefficient (C_D) as a function of yaw angles and speeds (Rugby ball)

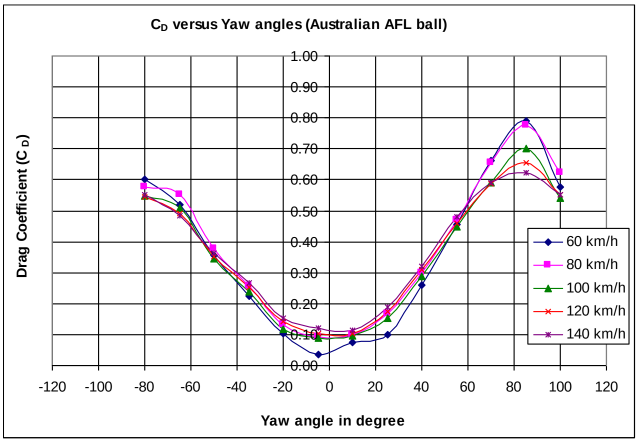


Figure 4. Drag coefficient (C_D) as a function of yaw angles and speeds (Australian football)

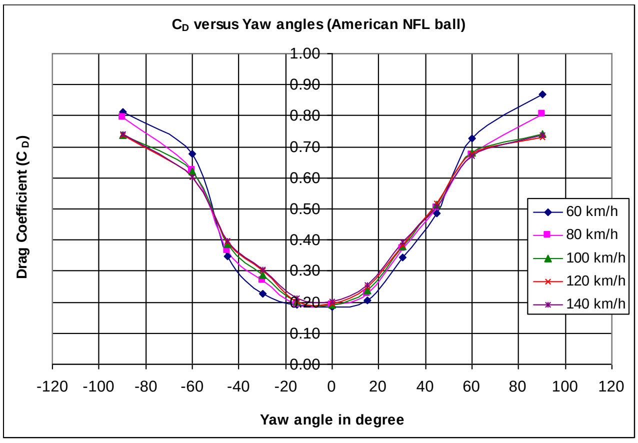


Figure 5. Drag coefficient (C_D) as a function of yaw angles and speeds (American NFL football)

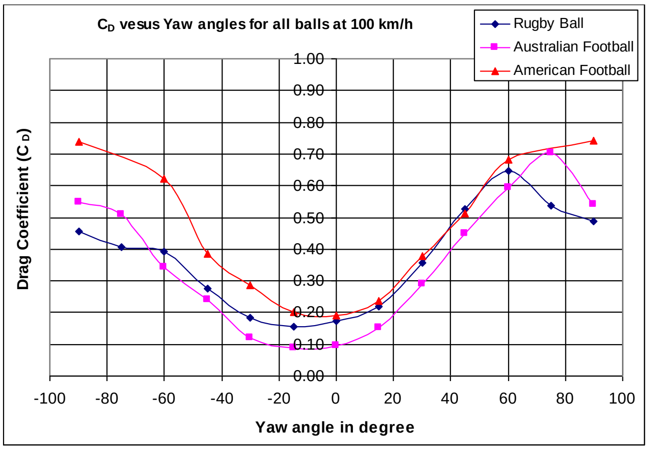


Figure 6. Drag coefficient (C_D) as function of yaw angles and speeds (for 3 balls at 100 km/h speed)

Conclusions

The following conclusions have been drawn from the work presented here:

The aerodynamic behaviour of oval shape balls is extremely complex even when the ball is not spinning. The airflow around the ball is 3 dimensional and axisymmetric for the case of zero yaw angle.

The average drag coefficients for the Rugby ball, Australian football and American football at zero yaw angle are 0.10, 0.18, 0.20 respectively.

The crosswinds have significant effects on drag coefficient and vary with the ball's yaw angles, external shape, surface roughness and other extrusions.

The Rugby ball and the Australian football generate more asymmetric drag forces under leeward and windward yaw angles compared to the American football.

The Reynolds number dependency in drag coefficient was noted at lower speeds at all yaw angles. However, the variation is minimal at high speeds (e.g. high Reynolds numbers).

The coefficients of drag, side and lift forces are important as they are essential for the development of 3D flight trajectory models under a range of conditions including multi axes spin, angles of attack, crosswinds and varied atmospheric turbulence.

Future Work

Investigation on spin effect is important as spin can have paramount impact on oval shaped ball's flight trajectory. Development of oval shaped ball's flight trajectory is desirable as it will assist players and coaches to muster the skills and enhance the participation in oval shaped ball games.

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