Proceedings of the
International Conference on Mechanical Engineering and Renewable Energy 2011
(ICMERE2011) 22- 24 December 2011, Chittagong, Bangladesh

ICMERE2011-PI-174

AERODYNAMICS OF AMERICAN FOOTBALLS UNDER CROSSWINDS

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Abstract- *The flight trajectory of an American football largely depends on its aerodynamic characteristics. Despite the popularity of the game, it appears that little information on the aerodynamic force experienced by an American football especially under crosswinds is available in the open literature. The shape of an American football is similar to that of an ellipsoid. It has more pointed ends and has a rough surface. The ball used in college level teams possesses a pair of seams at each of pointed ends. All these features and crosswind make the airflow around the ball more complex. The primary purpose of this study is to experimental measure the aerodynamic forces of NFL and College Level American footballs under a range of wind speeds and yaw angles (crosswinds). The non-dimensional drag coefficient were estimated and compared. The results indicate that the American footballs possess drag coefficient close to that of other oval shaped balls such as Rugby and Australian rule footballs. It also shows that the drag coefficient can be almost four times higher under crosswinds.*

Keywords: Drag coefficient, Yaw angle, American football, Wind tunnel, Reynolds number, Crosswinds

1. INTRODUCTION

American Football is one of the most popular sports in North America. The football game is played and watched by millions of people and the ball remains the central piece of it. The shape of an American football is similar to that of an ellipsoidal projectile such as Rugby and Australian Rules football with rough surfaces and more pointed ends. The ball used in college level games administered by the National Collegiate Athletic Association (NCAA) possesses a pair of seams at the pointed upper ends. This can make the airflow around the ball even more complex and asymmetric. The ball used in professional games administered by the National Football League (NFL) has no such pair of seams at the pointed ends. The flight trajectory of an American football largely depends on its aerodynamic characteristics. Despite the popularity of the game, it appears that very limited information on the aerodynamic forces experienced by the American football is available in the open literature. Although attempts were made to construct the flight trajectory of the ball, without knowing the aerodynamic properties such as drag coefficient, it is extremely hard to build such a model. Despite several studies undertaken by Rae [1], Rae & Streit [2], Brancazio [3], Watts & Moore [4], and Horn & Fearn [13] on aerodynamics of American footballs over the last two decades, no reliable aerodynamic forces data, except those by Rae & Streit [2], has been reported. The reported drag coefficient varies from 0.05 to 0.3 when the major axis is pointed into the wind. The drag coefficient of an American football under crosswinds is not available in the open literature at all. The shape of an American football makes it more difficult to throw than a spherical ball as its two-dimensional origin to the ellipse rather than the circle, giving the pigskin its prolate spheroid shape. The aerodynamic behaviour of spherical and other oval shaped sports balls has been well studied by Alam et al. [5, 8, 9], Mehta et al. [10, 19] and Asai et al. [12]. As mentioned earlier, no in-depth aerodynamic studies have been undertaken on American footballs despite its great popularity. Due to its complex shape, the airflow around an American football is believed to be significantly complex and little understood. As a result, the accuracy of long distance kicking/punting by elite level players to the desired point/goalpost is very low. A statistical study conducted by Hopkins [16-17] reported that the accuracy of kicking of oval shape balls is close to 50% and not much has been improved over the last three decades although numerous efforts have been made. 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. The primary purpose of this study is to experimentally measure the aerodynamic forces of NFL and NCAA footballs under a range of wind speeds and yaw angles

(to simulate the effects of crosswinds). Some features of American football game that need the knowledge of aerodynamics are shown in Figure 1.

Fig. 1: Avenues for gaining advantage in the field

2. EXPERIMENTAL PROCEDURE

2.1 Description of Balls

Two new American footballs that are officially used in National Football League (NFL) and National Collegiate Athletic Association (NCAA) games are selected for this study. Their physical properties are shown in Table 1. Both balls were inflated with 13 psi (89.6 kPa) pressure. They were made of four leather segments (see Figures 2 & 3). It should be noted that the NCAA ball has 4 semi circular stitch rings on the upper side of its both conical ends as shown in Figure 3.

Table 1: Physical parameters of balls

	NFL Ball	NCAA Ball
Length, mm	280	280
Circumference (Longitudinal), mm	700	690
Circumference (Lateral), mm	530	530
Mass, gm	410	395
Air Pressure, psi	13	13
Panel Numbers	4	4
Panel Type	Leather	Leather
Surface Finish	Rough with Pimples	Rough with Pimples
Lace Exposed	Yes	Yes
Shape	Oval with Conical Ends No stitch ring	Oval with Conical Ends Two semi-circle stitch rings on upper side at both conical ends

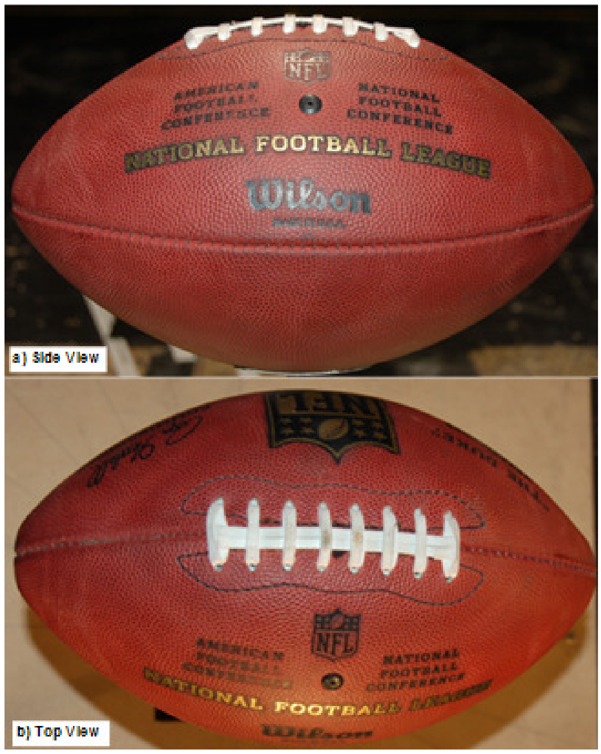

Fig. 2: Wilson made American Football used in NFL game

Fig. 3: Wilson made American Football used in NCAA game

2.2 RMIT Industrial Wind Tunnel

In order to measure the aerodynamic properties of both balls experimentally, the RMIT Industrial Wind Tunnel was used. The tunnel is a closed return circuit with a maximum speed of approximately 150 km/h. All three forces (drag, lift and side force) and their corresponding moments were measured. Experimental set ups for both balls are shown in Figures 4, 5 & 6.

More details about the tunnel can be found in Alam et al. [1]. Tests were conducted at a range of wind speeds under ±90° yaw angles to simulate the crosswind effects. Yaw angle can be defined as the angle between the ball centreline (longitudinal axis) and the mean direction of airflow experienced by the ball.

A sting mount was designed to hold each ball, see Figure 4. The distance between the bottom edge of the ball and the tunnel floor was 235 mm, which is well above the tunnel's boundary layer and the ground effect is considered to be insignificant.

The aerodynamic forces and moments were measured under a range of wind speeds (40 km/h to 130 km/h with an increment of 20 km/h) and yaw angles (±90° with an increment of 15°). The non-dimensional parameters such as drag coefficient (C_D) and side force coefficient (C_S) were estimated from

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

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

where D, ρ, V, S, A are the drag, air density, wind velocity, side force, projected frontal area of the ball respectively. The projected frontal area was determined by

$$A = \frac{\pi d^2}{4} \tag{3}$$

where d is the diameter of the ball 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. The repeatability of the measured forces was within ±0.01 N and the wind velocity was less than 0.5 km/h.

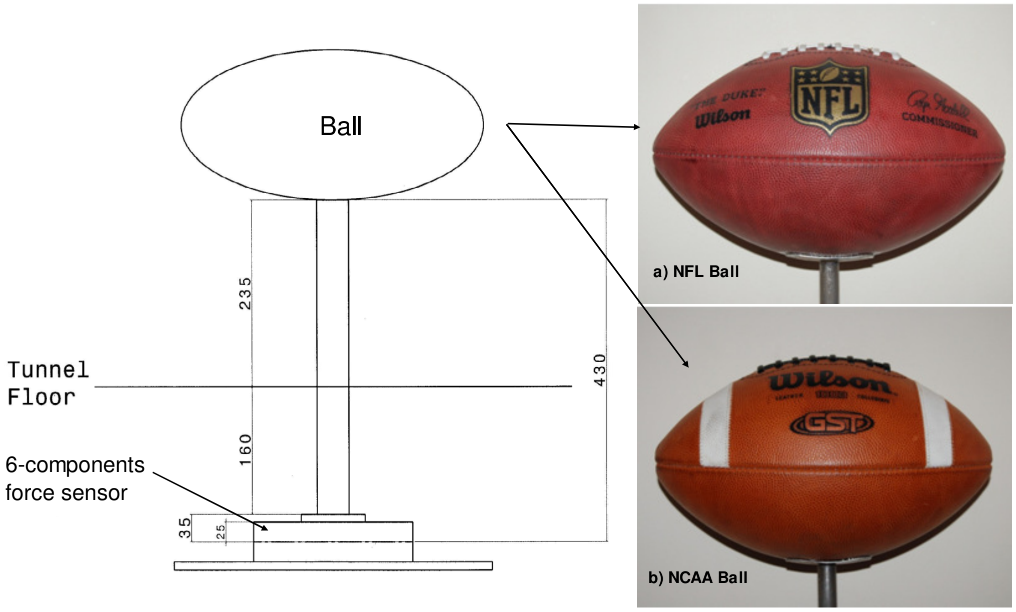

Fig. 4: Schematic of Experimental Setup

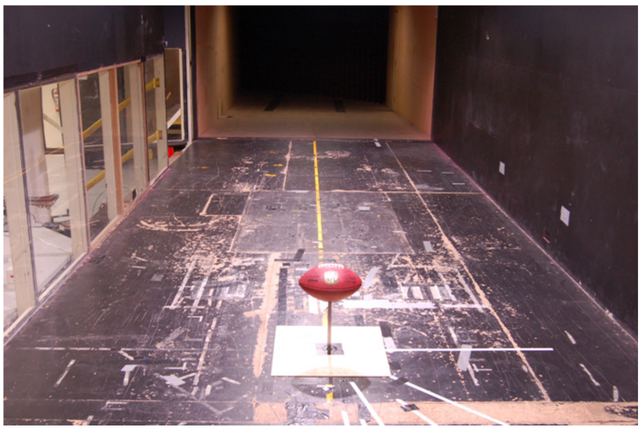

Fig. 5: Experimental setup of NFL ball in the test section of RMIT Industrial Wind Tunnel at 90° yaw

Fig. 6: Experimental setup of NCAA ball in the test section of RMIT Industrial Wind Tunnel at 0° yaw

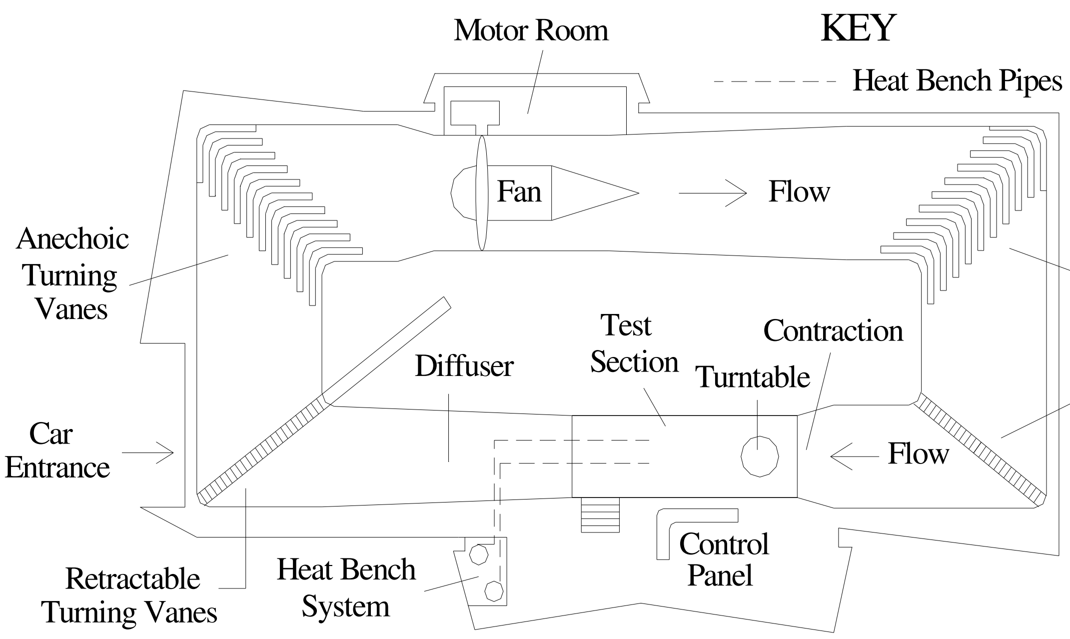

Fig. 7: A plan view of RMIT Industrial Wind Tunnel

3. RESULTS AND DISCUSSION

The drag force coefficient (C_D) and side force coefficient (C_S) for both balls were plotted against yaw angles and presented in Figures 8 to 9. The C_D values for the NFL and NCAA balls at zero yaw angles are 0.19 and 0.20 respectively. At zero yaw angle, the NCAA ball displayed slightly higher drag coefficient than the NFL ball. This slight increase is believed to be due to the surface profile of the NCAA ball. The drag coefficient for both balls increases with an increase of yaw angles due to a larger and very complex flow separation. The average C_D values at +90° (windward side) yaw angle for the NCAA and NFL balls are approximately 0.75 and 0.78 respectively. The C_D values at -90° (leeward side) for the NFL & NCAA balls are 0.75 and 0.77 respectively. The negligible asymmetry in C_D values was found for the NCAA ball. However, slight asymmetry in C_D values was noted for the NFL ball (0.78 & 0.77). No significant Reynolds number ($\mathrm{Re} = \frac{\rho V d}{\mu}$ varied by wind speeds in this study) dependency was found at zero yaw angle for both balls. However, significant Reynolds number (Re) variations are noted at speeds below 100 km/h under yaw angles over 50°. With the increase of speeds (Reynolds numbers), the variation becomes almost zero (e.g., at 100 km/h and over) due to either elimination or minimisation of local flow separation. The asymmetry in C_D values is minimal for the NCAA ball whereas slight asymmetry was noted for the NFL ball. Moreover, the NFL ball also shows a slight Reynolds number variation between -20° to -50° yaw angles (leeward side). Such variation was not observed for the NCAA ball. It is difficult to compare C_D values at 0° yaw angle with the published data as most of these data are unreliable and often contradictory [4, 13]. The only reliable C_D data reported to the public is due to Rae and Streit [2]. Their measured C_D value at 0° yaw angle is around 0.16 which is very close to the findings of this work (0.19 & 0.20). However, there are no C_D values for the NFL and NCAA ball reported in the public domain till to-date except the values reported here. Similarly, no C_D values have been reported for NFL and NCAA balls when the minor axis is pointed into the wind (e.g., ±90° yaw angles). The graphs for C_D values for both balls show that the NFL ball displays the C_D values in relatively narrow band compared to the NCAA ball (see Figures 8 & 9). It was still not quite clear why this discrepancy occurred. It may be due to the slight variation in dimensions and the presence of two semi circular stitches on two upper cone sides of the NCAA ball. A comparison of CD values found by various researchers is shown in Table 2.

The side force coefficients (C_S) for both balls displayed a similar pattern (data not shown here for brevity). The side force coefficients have minor off-set from 0° yaw angle for the NCAA ball which is believed to be from a small mounting error. Reynolds number variations for both balls are clearly evident over 40° yaw angles at both leeward and windward sides (angles). Nevertheless, the variation is more dominant for the NFL ball.

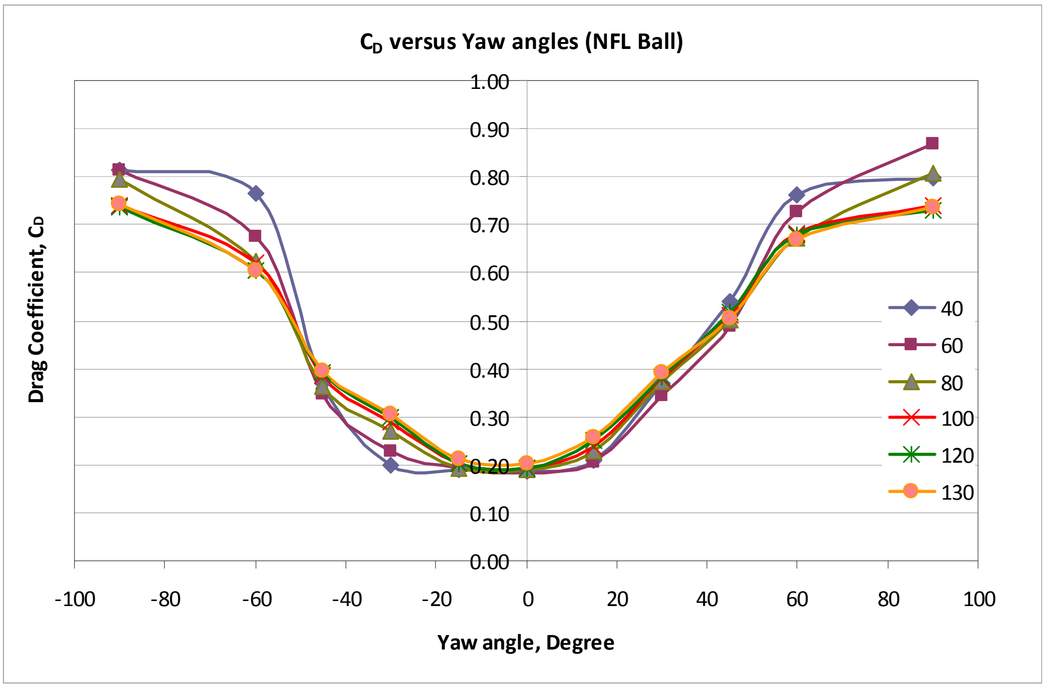

Fig. 8: Drag coefficient (C_D) as a function of yaw angles and wind speeds (NFL ball)

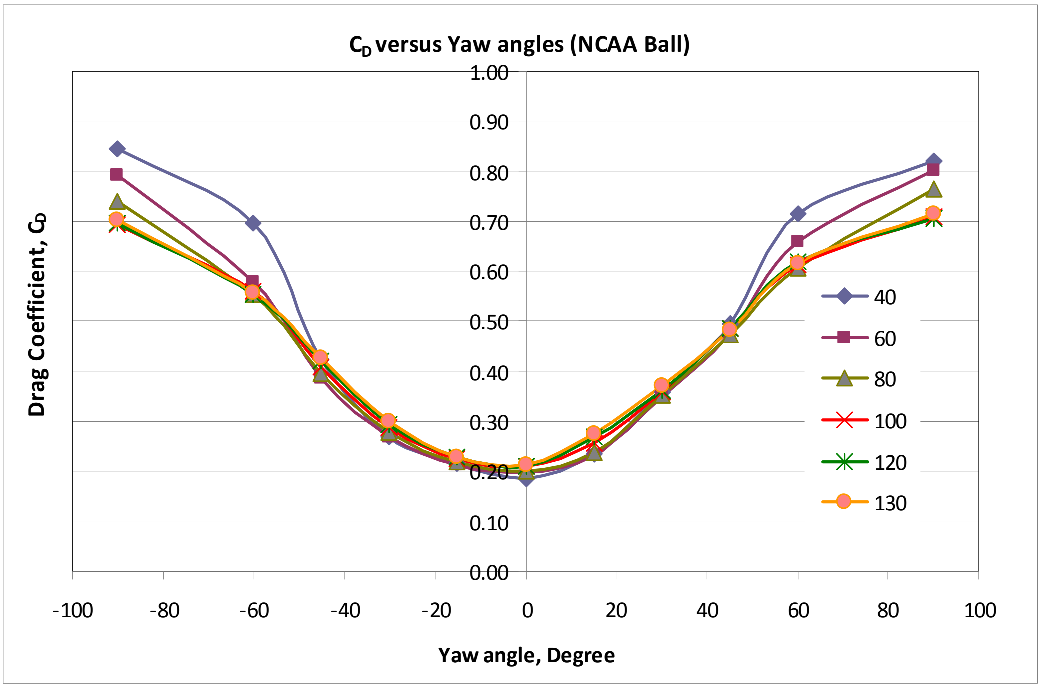

Fig. 9: Drag coefficient (C_D) as a function of yaw angles and wind speeds (NCAA ball)

Table 2: Comparison of published data

Football Type	Ellipsoidal Assumption	NFL Official match ball	Foam rubber	NFL Official match ball	NCAA Official match ball
Published data	Brancazio [3]	Rae & Streit [2]	Watts & Moore [4]	Alam et al. [9]	
Min C_D at 0° yaw angle	0.10	0.16	0.05 – 0.06	0.19	0.20
Max C_D at 90° yaw angle	0.60	0.85	N/A	0.75	0.78

4. CONCLUSIONS

The following conclusions were made based on the study presented here:

The following conclusions were made based on the experimental study undertaken in this work:

- The average drag coefficient for American footballs is in the range of 0.18 to 0.20 when the major axis of the ball pointed to the wind direction.
- The NCAA ball possesses slightly higher value of drag coefficient compared to the NFL ball.
- The average drag coefficient for American footballs is in the range of 0.75 to 0.78 when the minor axis of the ball pointed to the wind direction.
- The effect of crosswind on aerodynamic drag is significant as the drag coefficient can be four times higher under ±90° yaw angles.
- The NFL ball possesses slightly higher value of drag coefficient compared to the NFL ball drag coefficient when the minor axis of the ball pointed to the wind direction.
- The Reynolds number dependency is noted for both balls at yaw angles over ±50º.

5. ACKNOWLEDGMENTS

The authors are expressing their sincere thanks to Mr Patrick Wilkins, School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, Australia for his assistance with the experimental set up.

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7. NOMENCLATURE

Symbol	Meaning	Unit
D	Drag Force	(N)
L	Lift Force	(N)
S	Side Force	(N)
C_D	Drag Coefficient	-
C_L	Lift Coefficient	-
C_S	Lateral-Force Coefficient	-
Re	Reynolds Number	-
V	Velocity of Air	m/s
ρ	Density of Air	kg/m^3
A	Projected Area	m^2