Aerodynamic drag measurements of FIFA-approved footballs

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Abstract

Increasing technological advancements and demand for performance compel the ball manufacturers to introduce new designs. Construction of spherical footballs has been significantly changed over the years since 1970 from 32-panel leather stitched ball to 8-panel synthetic thermally bonded modern football. Despite being most popular game in the world, no data is available on aerodynamic properties of recently FIFA approved balls such as Adidas Cafusa (thermally bonded 32-panel), Nike Maxim (32-panel stitched), Umbro Neo (14-panel stitched, and Mitre Ultimax (26-panel stitched) footballs. Hence, the primary objective of this study was to determine aerodynamic drag of these balls and compare the findings with other balls introduced in late 2000. The aerodynamic forces were measured experimentally for a range of wind speeds in wind tunnel environment and their non-dimensional coefficients were determined and compared. Additionally, a field test was also carried out to understand the perception of professional footballers.

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1. Introduction

The flight trajectory of a football, the centre piece of the game, is significantly influenced by its aerodynamic characteristics. Based on aerodynamic behaviour, the ball can deviate from its anticipated flight trajectory. The deflection of such flight path is called swerve and is well observed in other spherical ball games including cricket, baseball, golf, tennis and volleyball. Therefore, the aerodynamic properties of a football are considered to be the

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fundamental for understanding the flight trajectory. It is true that a football among all other spherical sports balls is more symmetrical. Since 1970s, the design of footballs has undergone a series of technological changes utilising player feedback, new designs and improvements in manufacturing processes. Adidas, the official supplier of footballs to FIFA has applied thermal bonding replacing traditional stitching to make a seamless surface design by using 8 curved panels instead of 32 panels in its 2010 FIFA World Cup ball. The surface structure (e.g., texture, grooves, ridges and seams) of the ball has also been altered in the development process. In 2013, the same company introduced Cafusa, a 32-panel ball which was thermally bonded using traditional pentagonal or hexagonal panels. Two other balls namely Umbro Neo (14-panel stitched) and Mitre Ultimax (26-panel stitched) were introduced in 2012 and 2013 respectively. Similarly, Nike introduced a 32-panel football named Nike Maxim in 2012 where the surface of the football is constructed by stitching together the traditional pentagonal and hexagonal shaped panels. However, the company introduced roughness in the form of grooves onto the external surface of Nike Maxim ball.

Although the aerodynamic behaviour of other sports balls have been studied by Alam et al. (2012), Mehta et al. (2008) and Smits et al. (2004), little information is available about the aerodynamic behaviour of recently introduced footballs except the experiential studies by Alam et al. (2011) and Asai et al. (2011). Studies by Goff and Carre (2010), and Barber et al. (2009) provided some insights about the effect of surface structure of 32-panel balls, however, no such data is available for new generation footballs introduced in 2012 and 2013. Therefore, the primary objective of this study was to experimentally measure the aerodynamic drag of 9 footballs made of different number of panels (e.g., 32, 26, 23, 14 and 8) and construction materials (e.g., leather and synthetic) to understand their aerodynamic behaviour.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| $F_D$  | Aerodynamic drag |
| $C_D$  | Aerodynamic drag coefficient |
| $Re$   | Reynolds number |
| $V$    | Wind velocity |
| $\mu$  | Absolute dynamic viscosity of wind |
| $\rho$ | Air density |
| $A$    | Projected frontal area of ball |
| $d$    | Ball diameter |

### 2. Methodology

#### 2.1. Description of soccer balls

A total of 9 balls including 4 recently introduced balls were selected for this study. The recently introduced balls are: (a) 32-panel Adidas Cafusa (2013), (b) 26-panel Mitre Ultimax (2012) (c) 14-panels Umbro Neo (2012), and (d) 32-panels Nike Maxim (2012/2013). The panels of Adidas Cafusa ball are thermally bonded whereas the panels of other 3 balls are stitched together. The panels of Adidas Cafusa are traditional pentagons and hexagons. Similarly, the panels of Mitre ball have complex shapes. The other two balls have traditional pentagon and hexagon panels. Other 5 balls are: (e) 8-panel Adidas Jabulani (2010), and (f) 32-panel Nike T90, (g) 14-panel Adidas Teamgeist III (2009), (h) 14-panel Adidas Teamgeist II (2006), and (i) 32-panels Adidas Fevernova (2002). Physical characteristics of all 9 balls are given in Table 1. A pictorial view of all these balls is shown in Fig. 1.
Table 1. Physical characteristics of 9 footballs.

| Name               | Number of panels | Panel shape               | Surface finish | Panel joint type | Year     |
|--------------------|------------------|---------------------------|----------------|------------------|----------|
| (a) Adidas Cafusa  | 23               | Complex                   | Grooved        | Bonded           | 2013     |
| (b) Mitre Ultimax  | 2                | Complex                   | Smooth         | Stitched         | 2012     |
| (c) Nike Maxim     | 32               | Pentagon & hexagon        | Grooved        | Stitched         | 2012/2013|
| (d) Umbro Neo      | 14               | Pentagon & hexagon        | Smooth         | Stitched         | 2012     |
| (e) Adidas Jabilani| 8                | Complex                   | Grooved        | Bonded           | 2010     |
| (f) Nike T90       | 32               | Pentagon & hexagon        | Grooved        | Stitched         | 2010     |
| (g) Adidas Teamgeist III | 14    | Complex                   | Grooved        | Bonded           | 2009/2008|
| (h) Adidas Teamgeist II | 14  | Complex                   | Smooth         | Bonded           | 2006     |
| (i) Adidas Fevernova| 32              | Pentagon & hexagon        | Smooth         | Stitched         | 2002     |

Fig. 1. Footballs with various panel and surface configurations used in this study.

2.2. Experimental setup

The experimental study was undertaken using RMIT Industrial Wind Tunnel. The tunnel 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 (high) and 9 m (long), and it is equipped with a turntable to yaw the model. Each ball was mounted on a six component force sensor (type JR-3) as shown in Fig. 2, and 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. More details about the tunnel and its flow conditions can be found in Alam et al. (2003). A strut support was developed to hold the ball on a force sensor in the wind tunnel, and the schematic of experimental setup with a strut support is shown in Fig. 2. The aerodynamic effect of the strut support was subtracted from the
mount with the ball. The distance between the bottom edge of the ball and the tunnel floor was 300 mm, which is well above the tunnel boundary layer and considered to be out of significant ground effect.

The aerodynamic drag coefficient \( C_D \) and Reynolds number \( Re \) are defined as:

\[
C_D = \frac{F_D}{\frac{1}{2} \rho V^2 A}
\]

\[
Re = \frac{\rho V d}{\mu}
\]

The lift and side forces and their coefficients were not determined and presented in this paper. Only drag data is presented here.

3. Results and discussion

Each of 9 balls as well as a smooth sphere was tested at 20 km/h to 120 km/h with an increment of 10 km/h. The aerodynamic drag was converted to non-dimensional drag coefficient, \( C_D \) as defined in equation 1. The wind speed was converted to non-dimensional parameter Reynolds number \( Re \) using equation 2. The smooth sphere was made of stainless steel. The influence of the support on the ball was checked and found to be negligible. The repeatability of the measured forces was within ±0.01 N and the wind velocity was less than 0.027 m/s (e.g. 0.1 km/h). The \( C_D \) variations with Reynolds numbers for all balls and the smooth sphere are shown in Fig 3. The flow transition for the sphere was noted at approximately \( Re = 1.00 \times 10^5 \) which agreed well with the published data (Achenbach, 1972). The airflow reached supercritical Reynolds number at approximately \( 3.50 \times 10^5 \). The critical Reynolds number for the Mitre (complex shaped 18-panel & stitched) ball occurs at \( 2.03 \times 10^5 \) at which the drag coefficient is around 0.12. The flow transition from laminar to fully turbulent occurs between 5 and 20 m/s (~ 20-70 km/h). The critical Reynolds number for Nike Maxim ball (32 pentagon and hexagon panels and are stitched together) occurs at \( 2.03 \times 10^5 \) at a drag coefficient of 0.12. The drag coefficient is around 0.18 in the fully turbulent flow regime. The Umbro ball with 32 pentagon and hexagon panels and stitches undergoes flow transition between \( Re = 1.15 \times 10^5 \) and \( Re = 1.40 \times 10^5 \). The flow transition for occurs much later due to its relatively smooth surface compared to all other balls and the foam-made sphere. The critical Reynolds number occurs at \( Re = 1.30 \times 10^5 \) and the flow is fully turbulent after \( Re = 3.40 \times 10^5 \). The drag coefficient at the beginning of transition is 0.40, 0.14 at the supercritical transition and 0.16 at the end of transition.
It is worthwhile to mention that the $C_D$ value for the foam-made sphere with rough surface is 0.40 at the beginning of the flow transition, 0.09 at super critical transition and 0.2 at transcritical transition. The flow transitional behaviour of Adidas Cafusa, Nike Maxim and the foam-made sphere is very similar. The Mitre ball constitutes the roughest surface due its complex panel design and stitches and experiences the flow transition earlier than all other balls and the sphere tested. The surface with Umbro Neo ball is the smoothest with its 32 pentagon and hexagon panels that are stitched together allows the flow transition much later than all other balls and the foam-made sphere as shown in Fig. 3.

\[ \text{(transcritical)} \]

The Adidas Fevernova begins transition shortly before at $Re = 1.00 \times 10^5$ and becomes fully turbulent at $2.00 \times 10^5$. The drag coefficient at the beginning of the transition is about 0.44 while in the turbulent region it is initially 0.23 before rising to 0.25. Transition occurs between 6.7 and 13.5 m/s (24.1 - 48.6 km/h). The critical Reynolds number for Adidas Teamgeist II occurs at about $1.37 \times 10^5$ at a drag coefficient of 0.5. The flow is observed to be fully turbulent at $3.52 \times 10^5$ and the drag coefficient is around 0.22. The Teamgeist III ball which was introduced by Adidas in late 2008 undergoes flow transition between $Re = 1.04 \times 10^5$ and $Re = 3.5 \times 10^5$. The flow transition for Teamgeist III occurs much due to its relatively rough surface compared to Teamgeist II. For Jabulani ball, the critical Reynolds number occurs at $Re = 1.37 \times 10^5$ and the flow is fully turbulent at $3.91 \times 10^5$. The drag coefficient at the beginning of transition is 0.44 and is 0.23 at the completion of transition. The drag coefficient in the turbulent regions continues to increase to a value of about 0.25 at about $Re = 8.00 \times 10^5$. Transition occurs between 9.5 and 14 m/s (33- 50.4 km/h). The transition for Nike T90 ball occurs shortly before $Re = 8.00 \times 10^4$ and the flow becomes fully turbulent at $Re = 2.76 \times 10^5$. The drag coefficient at the beginning of transition is observed at 0.54 and begins the turbulent range at $C_D = 0.24$ before rising steadily. This profile is more synonymous with the drag coefficient profile of a golf ball. Transition is seen to occur at 5.5 m/s and finish just before 21 m/s (54 km/h).
The field trial of recently introduced footballs (i.e., Adidas Cafusa, Mitre Ultimax, Nike Maxim and Umbro Neo) was conducted to understand the player’s perception about these balls. The field tests were conducted over two days, at ideal day and night conditions. Five elite level (State premium divisional professional) players were selected for this study. Tests were undertaken with following characteristics: each ball was tested after each other with the same player so that they can express their opinions on each ball accordingly. The first test was a penalty kick. The test was done by each player, and they were instructed to kick each ball the same way. The players then rated each ball out of 5. The second test was a free kick from the edge of the 18 yards box. The players were advised to kick each ball consistently, either to place the ball or to go for power, then rate each ball out of 5. The third test was a corner. The players were told to aim for the penalty spot, and they had to kick each ball consistently. Each player then rated the behaviour of the ball at a scale of 1 to 5. The fourth test was a kick from the halfway line. The findings of the field measurements showed that the Umbro Neo was the most consistent ball to play with; each player rated it in the top two, with either Adidas Cafusa or Nike Maxim in other slot. The reason for the Umbro Neo being preferred to instead of other balls is due to its 14-panel structure and under layer foam design. Weight tests carried out on the balls also concluded that Umbro Neo was the lightest ball with Adidas being the heaviest. The tests incorporated every phase of the game.

4. Conclusions

At higher speeds, the Adidas Cafusa maintains a lower drag coefficient than all other balls and it possesses less surface disturbances due to thermal bonding instead of stitches. Although transitional flow occurred at same velocity for Adidas Cafusa and Nike Maxim, the Cafusa experienced a lower drag coefficient at transcritical stage of the turbulent flow. The Mitre Ultimax due to its complex surface roughness has the lowest drag coefficient prior to the super critical transition. However, it also displays the similar behaviour to that of the Cafusa ball after supercritical and transcritical regions. The Umbro Neo undergoes flow transition at higher Reynolds number compared to all other ball which is believed to due to its relatively smooth surface compared to other balls. Among other balls, the Teamgeist II maintains a lower drag coefficient than the Jabulani at high speed as it possesses less surface disturbances. The Fevernova experienced a much lower drag coefficient at transition and throughout the early stages of turbulent flow. The aerodynamic behaviour of Teamgeist III ball is in between Fevernova and Jabulani ball. The addition of surface roughness to the Nike T90 has caused transition to occur earlier.

The limited field trial indicates that Umbro Neo ball is relatively consistent in terms of player’s anticipated target. However, most players prefer Adidas Cafusa and Nike Maxim as match balls due to relatively easier control and better stability. Further aerodynamic study is required to determine the aerodynamic stability of these balls.

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