Analysis of Cristiano Ronaldo's Free Kick using Computational Fluid Dynamics (CFD)

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1 OBJECTIVES

The aerodynamics of footballs has come into prominence in the last decade with the advent of new ball designs, particularly for the world cup. In this study, the free kick goal from Cristiano Ronaldo against Spain in the group stages of the 2018 world cup is studied (FIFATV, 2018). Detached Eddy Simulation (DES) method in the CFD code, Simcenter™ STAR-CCM+™ is used. Simulations of a spinning football are performed on the Telstar 18 ball from 2018 and the Jabulani ball from 2010. This study aims to uncover the influence of football design and the resulting aerodynamics on curving free kicks in match situations, in addition to detailed flow features. Full, transient CFD simulations of ball behaviour will help ball designers and players in understanding curving free kicks. The amount of curvature resulting from Magnus force (side force) for different balls calculated from simulations will also impact the choice and success of free kicks in match situations.

2 METHODS

2.1 CFD Setup

To perform CFD simulations, a 3-dimensional (3D) model of the Telstar 18 (geometrically constructed) and Jabulani (laser-scanned) balls are used (Figure 1). Ball diameter (d) is 0.22 m and weight (m) is 0.436 kg (Goff et al., 2018). Ronaldo kicked the ball 22 meters away from the goal traveling at 60 mph (26.8 m/s) and spinning at approximately 5 revolutions per second. The speed corresponds to a Reynolds Number (Re) of 3.828 x 10^5. The ball took 0.82 seconds to hit the goal. Surface roughness is unknown and assumed to be 5 microns from literature.

Boundary conditions are based on the kick characteristics detailed earlier. Flow turbulence is modelled using the DES principle, a combination of Reynolds Averaged Navier Stokes (RANS) method closer to surfaces and Large Eddy Simulations (LES) in regions of high vorticity.

The balls are meshed in Simcenter STAR-CCM+ with trimmed hexahedral cells (between 20 and 30 million cells). Proper wake refinement is added in the wake of the ball to capture the oscillating wake region due to spin. 15 prismatic cells are used near the surface to capture the boundary layer flow accurately.

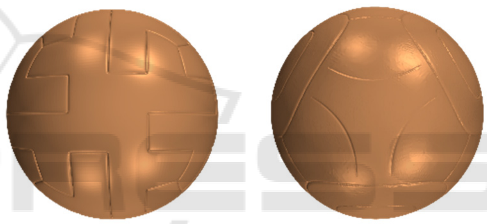

Figure 1: Telstar 18 (left) and Jabulani (right).

The DES runs have a time step of 5e-4 seconds running for a total of 0.82 seconds, the time of flight of Ronaldo's kick. This ensures a 1 degree rotation of the ball per time step to accurately capture flow fluctuations in time and space. Ball is rotated using Rigid Body Motion (RBM) method in Simcenter STAR-CCM+. Simulations are run on 96 cores. Lift (Fl), drag (Fd) and side (Magnus) force (Fs) and the force coefficients are computed with time, using ground conditions on match day.

2.2 Validation of Methodology

To confirm the validity of the Telstar geometry and simulation methodology, comparisons are made with wind tunnel data (Goff et al., 2018) at 69 mph and 76 mph on a non-spinning Telstar. Re at these speeds corresponds to 4.426 x 10^5 and 4.858 x 10^5 respectively. In these conditions, lift and side forces are negligible and hence only drag coefficient (CD) is compared (Table 1).

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Table 1: Comparison with wind tunnel data.

Speed (mph)	CD (test)	CD (CFD)
69	0.201	0.220
76	0.196	0.222

Wind tunnel blockage effects are unaccounted for and the laser scanned geometry from test is different from the simulation model. With these assumptions and investigation of flow physics, the result is deemed satisfactory for the purpose of the study. Flow features around the seams, wake behind the ball and flow separation are investigated and confirmed.

2.3 Calculating Ball Deviation

As a soccer ball rotates, the boundary layer closer to surface is ‘pulled’ in the rotation direction leading to late flow separation compared to the other side. This force imbalance generates a side force, called the Magnus force (Kiratidis et al., 2017). This force causes the ‘deviation’ or ‘curve’, a phenomenon referred to as the Magnus effect.

Total deviation (curve) of a spinning ball from a straight line path over 0.82 seconds is calculated from the aerodynamic side force (Fs) data using “bending” calculations from NASA (Hall N., 2015). Radius of curvature (V^2/a) is calculated from kick speed (V) and acceleration due to gravity, a (Fs/m). Ball deviation (Yd) is then derived from the formula:

$$Yd = R - \text{sqrt}(R^2 - D^2) \qquad (1)$$

where D is the distance from the goal (22 m).

The deviation of the ball for Ronaldo’s kick executed with the Telstar and Jabulani are compared. A knuckle ball simulation is also performed on the Telstar at 60 mph with no spin to compare Ronaldo’s trademark kick with the free kick studied here.

Deviation of the actual kick is calculated using match footage (FIFATV, 2018) from various angles. Standard goal post measurements (7.32 m wide) are used. The ball curves away from the goal initially before curving back towards the goal. From final ball location, diameter and goal width, actual ball deflection is calculated to be approximately 3.5 m.

3 RESULTS

The Telstar 18 curves less compared to the Jabulani while the knuckleball has minimal curvature (Table 2). Transient animations of the velocity and vorticity fluctuations behind the ball at center plane are compared with video footage. These show larger vortices behind the Jabulani in comparison to the Telstar 18 (Figure 2) leading to a larger deviation.

Table 2: Comparison of side force and deviation.

Scenario	Fs (N)	Fl (N)	Yd (m)
Telstar 18	4.9	0.277	3.95
Jabulani	5.65	0.366	4.57
Telstar 18 knuckleball	0.41	0.58	0.59

The net side force is a result of the vortex pairs in the wake and the size of the vortices, measured by vorticity. Skewing of the wake to one side and the side force direction from Simcenter STAR-CCM+ confirm deviation in the correct direction.

Figure 2: Vorticity behind Telstar 18 (left) and Jabulani (right) with video footage at 0.62 s (Footage courtesy: FIFATV).

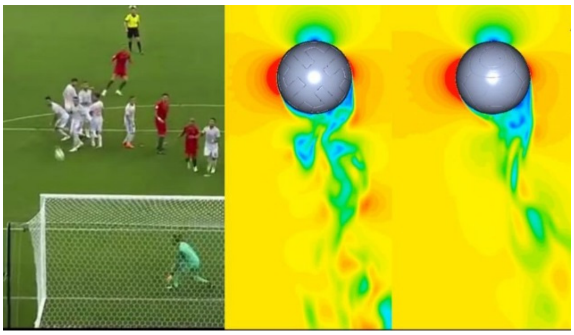

Figure 3: Velocity behind Telstar 18 (left) and Jabulani (right) compared with video footage at 0.6 s (Footage courtesy: FIFATV).

Knuckleball simulations show a deviation of just 0.59 N but the side force changes direction throughout the time of flight. This causes the knuckling effect, causing the ball to oscillate unpredictably. In this scenario, animations show that counter rotating vortex pairs behind the ball are unstable. This coupled with vortex breakdown causes the unstable knuckling behaviour.

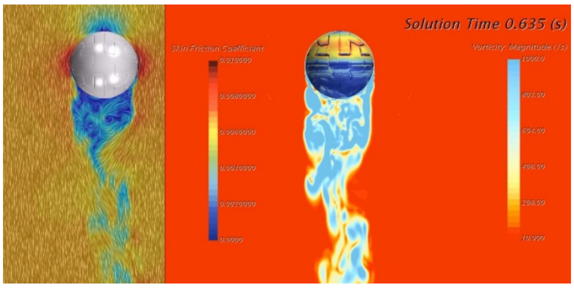

Figure 4: Line Integral Convolution (LIC) and vorticity in knuckleball scenario at 0.63 s.

4 DISCUSSION

Spanish goalkeeper, David De Gea is 6 ft 3 in (1.9 m) tall with an overall reach of 2.2 m when diving. Before the kick, he is around 2.75 m from the left post (Figure 5) and the ball hits the net around 5.9 m from the left post. The gap of 3.15 m is too far considering his diving range, hence he doesn't even attempt to stop the kick. Simulations show that the Jabulani would deviate a further 0.7 m towards De Gea compared to the Telstar, leaving a gap of only 2.45 m between De Gea and the ball. Goalkeepers rely on instinct and with the ball just 0.25 m outside his range and accounting for trigger motion, De Gea could have stopped the Jabulani kick.

The seam depth of the Jabulani is 0.5 mm while that of Telstar 18 is 1.1 m. The balls have different panel shapes and numbers as well. Flow visualizations with skin friction coefficient suggest that flow separation occurs at different points for both balls, precisely due to the depth and geometry of the seams. This leads to differences in wake size and vorticity behaviour, contributing to different aerodynamics of the balls.

Even though Ronaldo's signature kick is the knuckleball, simulations show that lift force changes direction during flight and the side force is small. The small distance to the goal means that getting the elevation and dip to go over the defenders wall with precision is risky considering there was no curve to the ball. The longer the ball is in flight, the more fluctuations occur in the wake causing more knuckling and making the kick harder to stop.

Assumptions in the study due to lack of information included initial seam orientation, surface roughness and spin rate. The arc of the ball from the ground to its position above the defenders wall and the dip is not accounted for.

Figure 5: Initial position of David De Gea (FOX Soccer, 2018).

5 CONCLUSION

The simulations show detailed deviation differences between the Telstar 18 and Jabulani due to seam depth and panel shapes, meaning that ball trajectory is reliant on ball design. Predictable ball behaviour, a smoother curve during free kicks and deviation distance all factor into game results and success of a ball design. DES analysis of spinning soccer balls will provide additional information on ball behaviour to ball designers, players and teams, influencing ball design, style of play and game outcome.

An important subject for future analysis is repeating the simulations with more game and ball information. Dynamic Fluid-Body Interaction (DFBI) technique in conjunction with RBM and overset meshing will allow for modelling the exact position and path of the ball at each time step by moving the ball based on instantaneous deviation.

ACKNOWLEDGEMENTS

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