Impact Factor (SJIF): 5.301

International Journal of Advance Research in Engineering, Science & Technology

e-ISSN: 2393-9877, p-ISSN: 2394-2444

Volume 5, Issue 8, August-2018

Investigation of the Cricket Ball Swing using CFD Modelling: Effect of Rotation and Surface Roughness

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Abstract ***—For many years, lateral flight of the cricket ball has been equally fascinating the players and the spectators. The cricket ball, whose outer shell is a two piece stitched-up leather, follows certain aerodynamics principles which have been explored in the past few decades, particularly for the 'reverse swing'. The factors which contribute to the side-ways swing of the ball are ball speed, seam position, rotation speed and roughness proportion on both sides of the ball. Several CFD studies have been conducted to investigate aerodynamics of the cricket ball, but due to over-simplified ball geometry, bluff seam shape and adoption of non-rotating models while neglecting Magnus effect, those models were not able to capture the actual phenomenon of lateral swing. In this study, CFD model is created which takes into account exact 3D geometry of the ball in accordance with standard IS 10800 which can help to visualize the effect of actual seam, ball rotation, ball speed and ball roughness on conventional and reverse swing. It was found that ball tends to swing towards smooth side irrespective of rotation however lift force is affected mostly by the ball speed.***

Keywords- Cricket Ball, Swing, Rotation, Roughness, CFD Model

I. INTRODUCTION

A Cricket is an amazing sport which is capable to fascinate millions of spectators around the globe. Cricket, a game played with a ball and bat, was first introduced by British and called 'Gentleman Game'. The sight worth watching in this sport is the contest between skills of bowler and the batsman where each of them tries to subdue other by epitomizing their abilities. Although it is great to watch the batsman hitting the ball out of the ground, yet bowlers have continued to attract the onlookers by trying to dominating the batsman with clever use of shape and condition of the ball.

Bowling is considered as an art in cricket. The bowler throws the ball towards the batsman which normally hits the ground before reaching the batsman. While delivering the ball, it is entirely up to the bowler to control speed, spin and direction of the ball before it hits the ground. Once the ball leaves the bowler's hand, it comes under the influence of aerodynamic forces which comes into play according to the condition, orientation, speed and spin of the ball at which it is delivered. A skillful bowler exploits all these parameters to throw the ball at a certain distance and direction to dominate the batsman. For example, in order to dismiss the batsman through a ball called 'yorker', it is considered important for a bowler to bowl as fast as possible in such a way that it lands between the legs and bat of the batsman.

During last few decades, bowlers have continued to mesmerize the spectators by inventing the new bowling techniques. Swing ball, for example, moves sideways during the flight and exploits aerodynamic forces acting on the fast moving ball. It is regarded as weaponry of fast bowlers. A type of lateral ball swing called 'reverse' swing, which was first demonstrated by Pakistani bowlers in 1970s, have continued to intrigue the batsman as the fast moving old ball moves in the other direction where it is supposed to swing conventionally during the flight. The advent of reverse swing led some researchers to study the aerodynamics of the cricket ball more rigorously.

Even before reverse swing was introduced, Cooke [1] studied the aerodynamic effects on conventional swing on scientific grounds and investigated why it becomes difficult for the fast bowlers to swing the old ball. Later, Lyttleton [2] , and then Horlock et al. [3] presented theories on the cricket ball swing. Subsequent publications followed on focusing the factors affecting the ball swing. It is interesting that most of the cricketers believe that humidity plays a vital role in swinging the cricket ball. However, experiments have always been unable to support this popular myth [4, 5]. Binnie et al. [6] studied the effects of humidity on the ball swing and proposed that the violent condensation on the low pressure side of the ball upsets the laminar boundary layer leads to abnormal effect on swing of the cricket ball. Barton[4] argued that humidity does not affect ball swing and late swing is uncontrollable effect. He studied the effects of seam position in wind tunnel experiments and found that backward rotation of the ball during lateral swing helps the ball in maintaining its orientation. Also. Mehta et al. [7] conducted detailed experimental studies on the cricket ball and compared aerodynamics of the cricket ball with other sports balls. In order to determine the flow field around the rotating ball, measurements of the aerodynamics forces were made by Sayers et al. [8]. They measured the side forces of spinning ball with different orientation and speed, and determined the effects of surface roughness on the side forces. More recently, Lock et al. [9] demonstrated conventional and reverse swing using flow visualization and pressure measurements. Later, Scobie et al. [10] et al. used thermal imaging technique to conclude that separation with turbulent reattachment leads to the reverse swing.

The first use of Computational Fluid Dynamics (CFD) to investigate the aerodynamic effects on the cricket ball was made by Penrose et al. in 1996 [11]. Later Pahinkar et al. made numerical simulations of reverse swing [12]. More recently analysis of the cricket ball swing using CFD was conducted by different researchers [13-15] but none of these studies considered the effect of rotation of the ball in third dimension and hence cannot be relied for the purpose of thorough analysis on the cricket balls on the field. In present study we developed a 3D numerical model of spinning the cricket ball using high fidelity Navier-Stokes turbulent flow. This model takes into account the effect of rotation and surface roughness on the cricket ball swing. The geometry is developed within the framework of Solidworks, and discretized using ICEM grid generator, and was simulated and analyzed within the framework of Ansys Fluent.

II. CRICKET BALL SWING

Cricket ball swing depends on flow asymmetry within the boundary layer on each side of the ball. The ball is thrown with high speed in such a fashion that the central halving seam of the ball tips boundary layer on one side while flow on the other side remains laminar. This asymmetrical flow changes pressure distribution on the ball, which in result forces the ball to deviate sideways. The orientation of the seam position, speed and surface roughness governs the direction of ball swing[16]. With relatively new ball (i.e. a ball not used much in the ground), when the ball deviates in the direction of the seam position, the flight is said to be conventional swing. In reverse swing, the ball is relatively old and instead of swinging in the direction pointed by the ball seam, it deviates in reverse direction. Contrast seam occurs when both halves of the ball have different roughness magnitude and seam position is pointed in the same direction of direction of ball trajectory. As can be seen from Fig.1, direction of contrast seam is governed by the speed of the ball.

III. NUMERICAL MODELING

3.1. Methodology and Approach

With advent of high speed computers, it has become easier to analyze the complex flows around any possible geometry. Computer Aided Design (CAD) modeling was used to make 3d geometry of the ball and suitable size flow domain was created around the ball. Current model considers the wind-tunnel experiment model where the ball does not move in linear direction and air hits the surface of backward rotating ball surface from right hand side. To consider flow around the ball, Multiple Reference Frame (MRF) approach was used in Ansys Fluent to rotate the flow around the spinning ball surface. In order to implement MRF, a rotation zone was created around the ball surface while the remaining part of thee geometrical zone was considered as simple flow zone. The system was solved for different cases of inlet velocity, surface roughness and ball rotation.

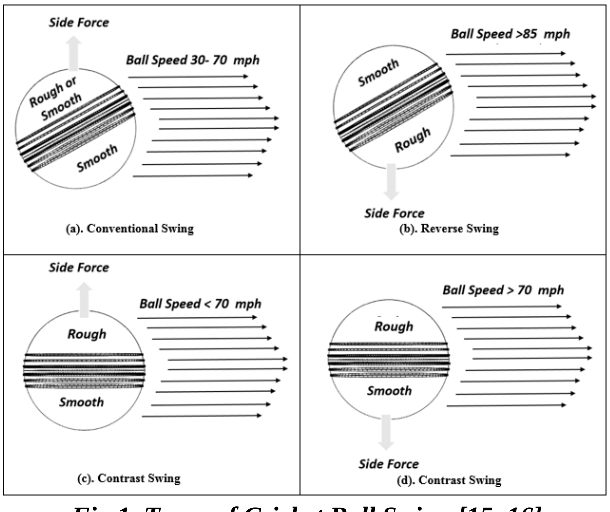

Fig.1. Types of Cricket Ball Swing [15, 16]

3.2. Governing Equations

W After leaving the bowler's hand, similar to a spherical shaped body, there are three aerodynamic forces which act on the cricket ball. These three forces are drag, lift and side forces. Magnitude and direction of these forces depend on the ball speed, rotation, surface roughness and seam position. These forces are given as:

Drag Force:

$$F_d = \frac{1}{2} C_d \left(\frac{\rho \pi d^2 V^2}{4} \right) \tag{1}$$

Lift Force:

$$F_l = \frac{1}{2} C_l \left(\frac{\rho \pi d^2 V^2}{4} \right) \tag{2}$$

Side Force:

$$F_s = \frac{1}{2} C_s \left(\frac{\rho \pi d^2 V^2}{4} \right) \tag{3}$$

Continuity for flow is governed by the equation:

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial u}{\partial x} + \rho \frac{\partial v}{\partial y} + \rho \frac{\partial w}{\partial z} = 0 \tag{4}$$

Momentum of the flow is governed by unsteady Navier Stokes equations.

X-direction:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{dP}{dx} + \upsilon\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \tag{5}$$

Y- direction:

$$\frac{\partial v}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{dP}{dy} + \upsilon\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \tag{6}$$

Z-direction:

$$\frac{\partial w}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{dP}{dz} + \upsilon\left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right] \tag{7}$$

Turbulence of the flow was modeled by the eddy viscosity k-ε model. The two transport equations for this model are:

$$\frac{\partial(\rho k)}{\partial t} + \nabla.(\rho k V) = \nabla.\left(\frac{\mu_t}{\sigma_k}\nabla k\right) + 2\mu_t E_{ij}.E_{ij} - \rho\varepsilon \tag{8}$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \nabla.(\rho \varepsilon V) = \nabla.\left(\frac{\mu_t}{\sigma_\varepsilon}\nabla \varepsilon\right) + 2C_{1\varepsilon}\frac{\varepsilon}{k}\mu_t E_{ij}.E_{ij} - \rho C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{9}$$

3.3. Geometry

In order to perform simulation of the cricket ball which are practically applicable on the cricket field, it was made sure that shape and dimensions of the ball are exactly the same as prescribed by the standards. For this purpose, 3D model was generated in accordance with the IS10800 UDC 685-635-82 [17]. According to this standard, outer shell of the cricket ball comprises of two halves of leather. These halves are joined together around the core by three dual rows of double stitching. The number of stitches should be in range of 80-85. 3D model of the ball geometry in Solidworks environment as shown in Fig. 2. Dimensions of the ball are given in Table 1.

Ball Radius	36.45 mm
No. of Seams	6 Nos.
Distance between farthest seams	20 mm
Number of stitches in each seam	85 Nos.
Height of each seam	0.80 mm

Table 1. Geometrical parameters of the Cricket Ball used for Numerical Simulation

Fig 2. 3D Geometry of Cricket Ball

For analysis, the domain of air flow was considered as 1,200 x 1,200 x 2,600 mm cuboid where outlet and side walls are at distance of 27.43 and 16.46 times of the ball diameter from center of the ball. The air inlet is on the right hand side and at a distance of 600 mm from the center of the ball center.

3.4. Mesh

High quality mesh was created using Ansys ICEM. where two flow zones were created to implement MRF: the rotating zone which is starts immediately after ball surface, and the normal flow zone which is the remaining part of the overall flow domain. As shown in Fig 3, due to very small size and shape of numerous seams around the ball, very small size of mesh was required to capture the accurate flow field on and around the seam and surface of the ball. Moreover, in order to consider roughness of 0.4 mm on the ball surface, the used mesh size on and near the surface was below 0.4 mm. Minimum size of mesh on the ball and seam surface was 0.35 mm and total mesh size was of order 4 million elements.

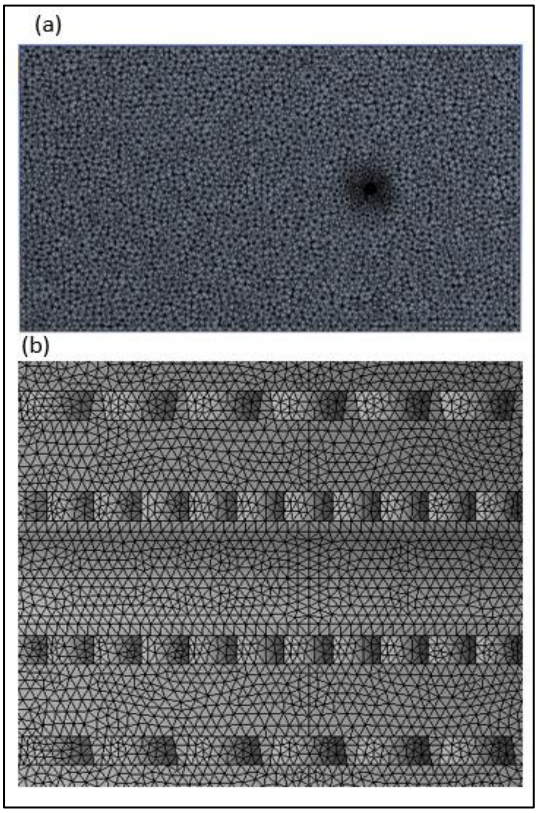

Fig. 4.Mesh used for Numerical Modeling (a). Flow domain. (b) Fine mesh over and near the seam on the ball

IV. RESULTS

CFD simulations were performed for the ball with different configurations. Total of four cases were studied while modifying the speed, roughness on both sides of the ball and ball spin. Configuration of four cases have been given in Table 2.

	Rotation (rpm)	Roughness on upper surface (mm)	Roughness on lower surface (mm)	Velocity (ms^{-1})
Case 1	750	0.40	0	30
Case 2	750	0.40	0.35	30
Case 3	0	0.40	0	30
Case 4	0	0.40	0	25

Table 2. Configuration for different cases

4.1. Effect of Rotation

It can be seen from Fig. 5, for case 1 and case 3, although the roughness on both sides, speed and seam position of the ball remains the same, yet the shape of high wall fluxes at the upper surface change due to ball rotation in case 1.However no change in lift force was observed as lift force in both cases were measured to be -0.16 N (downward). These results are qualitatively in agreement with the experimental results by Sayers et al. [8]. Also, there was no significant change in total pressure on the ball surface (Fig. 6). The only change observed in total pressure change was that the pressure between the seam becomes more symmetric for flow with zero rotation (case 3 and case 4). It can also be observed from figure 7 that in case of rotating ball (1 and 2), the swirls formed by low velocity vectors on the trailing side of the ball stretches towards the lower surface of the ball while for the cases without rotation (3 and 4), swirling mainly occurs on the upper surface of the ball.

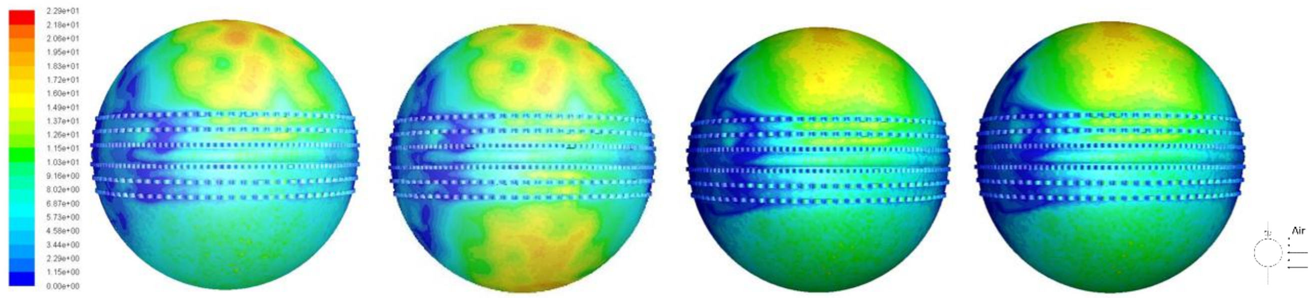

Fig. 5.Top view of the ball for Wall fluxes (Pa) on ball surface for (from left) Case 1, Case 2, Case 3 and Case 4

4.2. Effect of Ball Speed

Two ball speeds of 25 and 30 m/s were studied in this work. Swing in terms of lift force was observed to be highly effected by velocity. For ball speed of 30 m/s in case 3, lift force was found to be 0.16 N, but in case 4 where ball speed was decreased to 25 m/s and all other parameters were considered constant, lift force was decreased to 0.04 N.

4.3. Effect of Surface Roughness

A constant value of 0.4 mm for roughness was used for upper surface for all the four cases. For case 1, where lower surface was kept constant, the ball tends to swing on the smooth surface side with lift force of 0.16 N. However, for case 2 when lower surface was not smooth anymore and its roughness was changed to 0.35 mm, the lift force decreased to a very low magnitude of 0.03662 N. This is similar to case of old ball where swing becomes difficult with both rough surfaces. Moreover, the wall fluxes also increase on the lower surface of the ball as shown in Fig. 5.

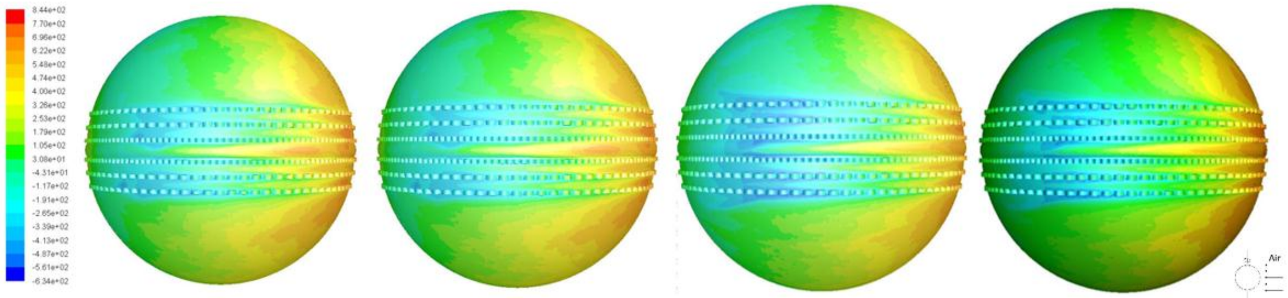

Fig. 6.Top view of the ball for Total Pressure (Pa) on ball surface for (from left) Case 1, Case 2, Case 3 and Case 4

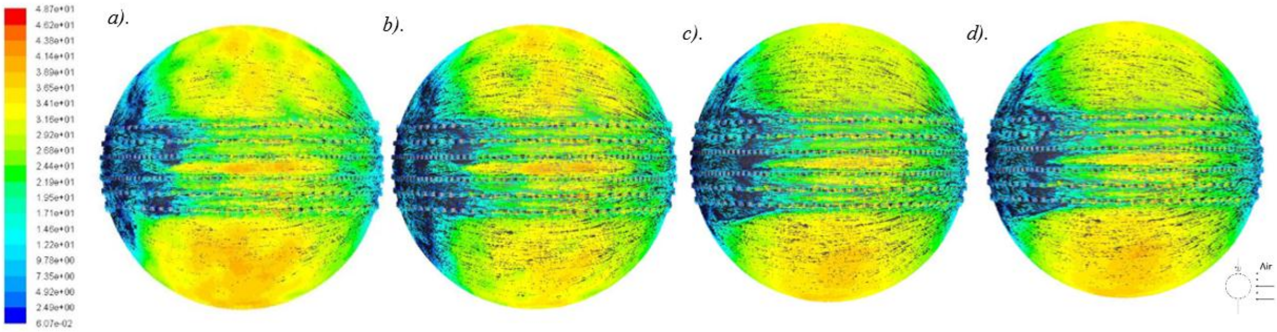

Fig. 7.Top view of the ball for Velocity vectors colored by velocity magnitude (ms^{-1}) on ball surface (from left) for Case 1, Case 2, Case 3 and Case 4

V. CONCLUSION

In this work, it was for the first time the rotation of the ball was taken into account to consider aerodynamic effects on the cricket ball. Swing of the ball was studied in terms of lift force and results of rotation asymmetric surface roughness were qualitatively validated with experiments. Roughness was found to effect direction of the side force while magnitude of the ball speed effected was found to govern the magnitude of the side force. Swing of the ball was found to be more effected by the ball speed as an increase of speed 5 m/s increased the lift force to four times. It was found that rotation of the ball helps in formation of swirls on the trailing edge of the relatively smoother side of the ball. Total pressure on the ball surface did not seem to be affected by roughness and rotation of the ball. With straight seam position, ball with asymmetric roughness tends to swing towards relatively smooth side of the ball, and more importantly, quick balls with asymmetric roughness have tendency to swing more than the slow balls with same configurations.

VI. NOMENCLATURE

d	Diameter of the ball , m
F	Force , N
u,v,w	Velocity in x , y and z direction , m/s
k	Turbulent kinetic energy , m^2/s^2
P	Pressure, Pa
V	Speed of ball , m/s

Greek Symbols

ε	Turbulent dissipation rate, m^2/s^3
ρ	Mass density, kg/m^3
μ	Dynamic viscosity, Pa.s

Subscripts

d	Drag
l	Lift
t	Turbulent

Dimensionless Number

σ	Prandtl number

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