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On the Swing of a Cricket Ball

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The aerodynamics of the swing of a cricket ball has been investigated by experimental methods in the past, and these wind tunnel studies have indicated that a seam angle in the range 10°-20°, and a bowling speed of about 30 ms^{-1} should produce the maximum swing of a new cricket ball (Barton, 1982 and Bentley et al., 1982). However, informal observations and approximate measurements by the authors, and inquiries made from the fast bowlers, during the games in the West Indies, indicate that the critical bowling speed - for the maximum swing of a new ball - is about 36 ms^{-1}, and the optimum seam angle for the same is close to 10°. For examining this inconsistency, wind tunnel tests were recently carried out on a non-spinning new cricket ball, and the results indicate that the maximum swing of a new cricket ball should occur at a seam angle of about 10° and at a flow speed of about 35 ms^{-1}. It is believed that Barton (1982) and Bentley et al. (1982) relatively underestimated the critical speed, probably due to the inherent limitations of the indirect method used for measuring the side force on a cricket ball. It is hoped that the experimental results, presented in this paper, would narrow the gap between the laboratory-based results and the observations in the cricket field.

1. Introduction

The asymmetric boundary layer separation plays an important role in the sport of cricket by introducing an element of surprise and excitement. Specifically, the seam on a cricket ball, under certain conditions, causes asymmetric boundary layer separation. This leads to an asymmetric pressure distribution that produces the side force responsible for the swing of a cricket ball. Mehta (1985) presents a good review of a number of experimental studies, in Australia and UK, which were carried out to study the underlying aerodynamics of a cricket ball, which is hereinafter referred to as a ball. More recently, Sayers and Hill (1999), in South Africa, have presented experimental results over a wide range of bowling speeds and seam angles. However, the swing phenomenon has been studied in depth only by Barton (1982) and Bentley et al. (1982).

Barton (1982), based on experiments in a wind tunnel in Australia, found that the swing was the greatest for a new ball at a flow velocity of about 30 ms^{-1} with a seam angle of 10°-15° and a back spin of 5-8 rev s^{-1}. Concurrently, Bentley et al. (1982), in a similar experimental study in the UK, found that the maximum swing occurred at a seam angle of 20°, for a back spin of about 11 rev s^{-1} and at a flow speed of approximately 30 ms^{-1}. Informal observations and approximate measurements by the authors[2], and inquiries made from the fast bowlers, during the intermissions in the games in the West Indies, however, indicate that the critical bowling speed - for the maximum swing - is about 36 ms^{-1}, and the optimum seam angle is close to 10°.

An experimental study was, therefore, carried out on a non-spinning new ball to examine the before-mentioned inconsistency and this paper presents a brief report on the same (Da Silva and Shrivastava, 1999). The non-spinning mode was selected for the tests for enabling the direct measurement of the aerodynamic forces and thereby avoiding the limitations, if any, of an indirect method used by Barton (1982) and Bentley et al. (1982). The indirect method is explained in greater detail subsequently in this paper. It may also be noted that results for a non-spinning

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[1] Made by a stopwatch with an accuracy of up to 100th of a second, for the bowling speed, and a protractor, for the seam angle, respectively.

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ball are not yet available in the literature for the speed range of 30-42 ms^{-1} with seam angles in the range 10°-20°.

It is recognised that some back spin is inevitably imparted by bowlers, and it - apart from stabilising the seam orientation during the flight - certainly increases the magnitude of the side force. Thus, the results of Barton (1982) and Bentley et al. (1982), which relate to spinning cricket balls, simulate the field conditions more realistically than tests on a non-spinning ball. However, as far as the occurrence of critical condition is concerned, the effect of spin may be ruled out since the spin is perpendicular to the seam plane, and thus the asymmetry is maintained (Mehta, 1985). This assertion can also be deduced from the aforementioned equivalence, of the critical bowling speed, obtained by Barton (1982) and Bentley et al (1982) at two considerably different rates of back spin. Further, the effect of different meteorological conditions, e.g., in Australia, UK and the West Indies, on the swing may be considered insignificant based on the findings of Barton (1982 and Bentley et al. (1982).

2. Experimental Setup

The wind tunnel tests were carried out on a non-spinning new ball in the Fluid Mechanics Laboratory at the University of the West Indies, for measuring its lift, drag and side force coefficients in the speed range of 25-42 ms^{-1} and for the seam angles of 10°, 15° and 20°. The experimental set up and procedure is described as follows.

The balls tested had a diameter of approximately 7.2 cm and a mass of approximately 156 gm. They were new, good quality balls used in the test matches. The primary seam was machine stitched and comprised six rows of stitching, with about 70 stitches in each row, on a leather skin. The stitches were along the equator holding the two leather hemispheres together. There were no quarter or secondary seams.

For modelling the ball, a steel mould (**Figure 1**) was constructed to make a wax mould of a hollow hemisphere of a diameter equal to the internal diameter of the ball. Two such hollow hemispheres were then joined with glue to form a hollow sphere. A new ball was cut into half along the seam equator and the cork ball inside was removed. The skin of the ball was placed on the hollow wax sphere. Grid lines were then drawn, with reference to the equator, at 30° spacing of the latitudinal and longitudinal angles (**Photograph 1**). Fine holes were then drilled at each of the 72 grid areas (**Figure 2**) through the leather skin and wax mould to serve as pressure tappings (**Photograph 2**). A 1 cm diameter hole was then cut, in the hemisphere with the trailing seam, through the leather skin and the wax mould. A hollow steel tube was inserted into the hollow wax mould through this hole. The ball was mounted on a 90° angle (**Photograph 3**) in the wind tunnel. This procedure was repeated for each of the three seam angles of 10°, 15° and 20°. Thin plastic tubes, connected to the pressure tappings on the leather skin, were brought out through this steel tube and were connected to a water manometer bank (**Photograph 4**).

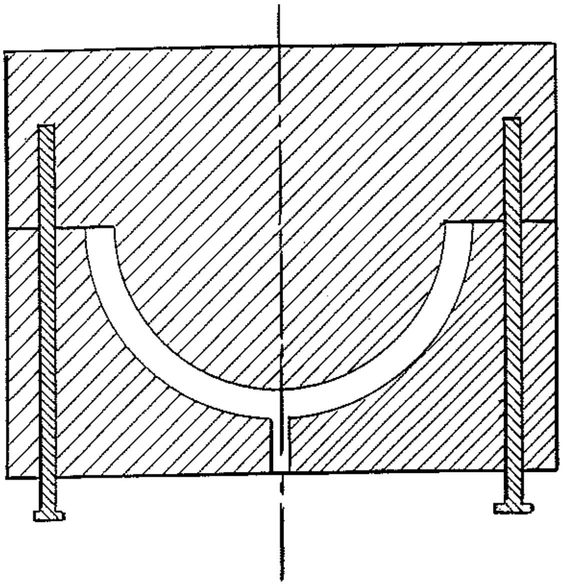


FIGURE 1: *The Cross Section through the Steel Mould*

The wind tunnel was of the open circuit type. The 220 cm long perspex working section had a square cross section of 30 cm x 30 cm, and the inlet section had a square cross section of 91.5 cm x 91.5 cm. The air flow was generated by two contra-rotating fans mounted downstream of the working section, and the air speed was controlled by means of a throttle valve downstream of the fans. The maximum wind tunnel speed was 44 ms^{-1} and the flow velocity in the wind tunnel was measured by means of a Prandtl Tube. The area blockage caused by the ball was about 4.5%, and this effect was accounted for in the measurement of the flow velocities in the wind tunnel. The flow in the working section was uniform across the cross section except for turbulent fluctuations whose r.m.s speed was less than 2% of the indicated air speed of the tunnel. This property held within 2 cm of the wall (Da Silva and Shrivastava, 1999). The tests were carried out at a temperature of about 25°C.

3. Results

Eighteen (18) tests, i.e. six wind speeds for each of the three seam angles, were conducted. **Table 1** shows the gauge pressure measurements at the 72 nodes for one such test, and the complete set of test data can be found elsewhere (Da Silva and Shrivastava, 1999). The drag, lift and side

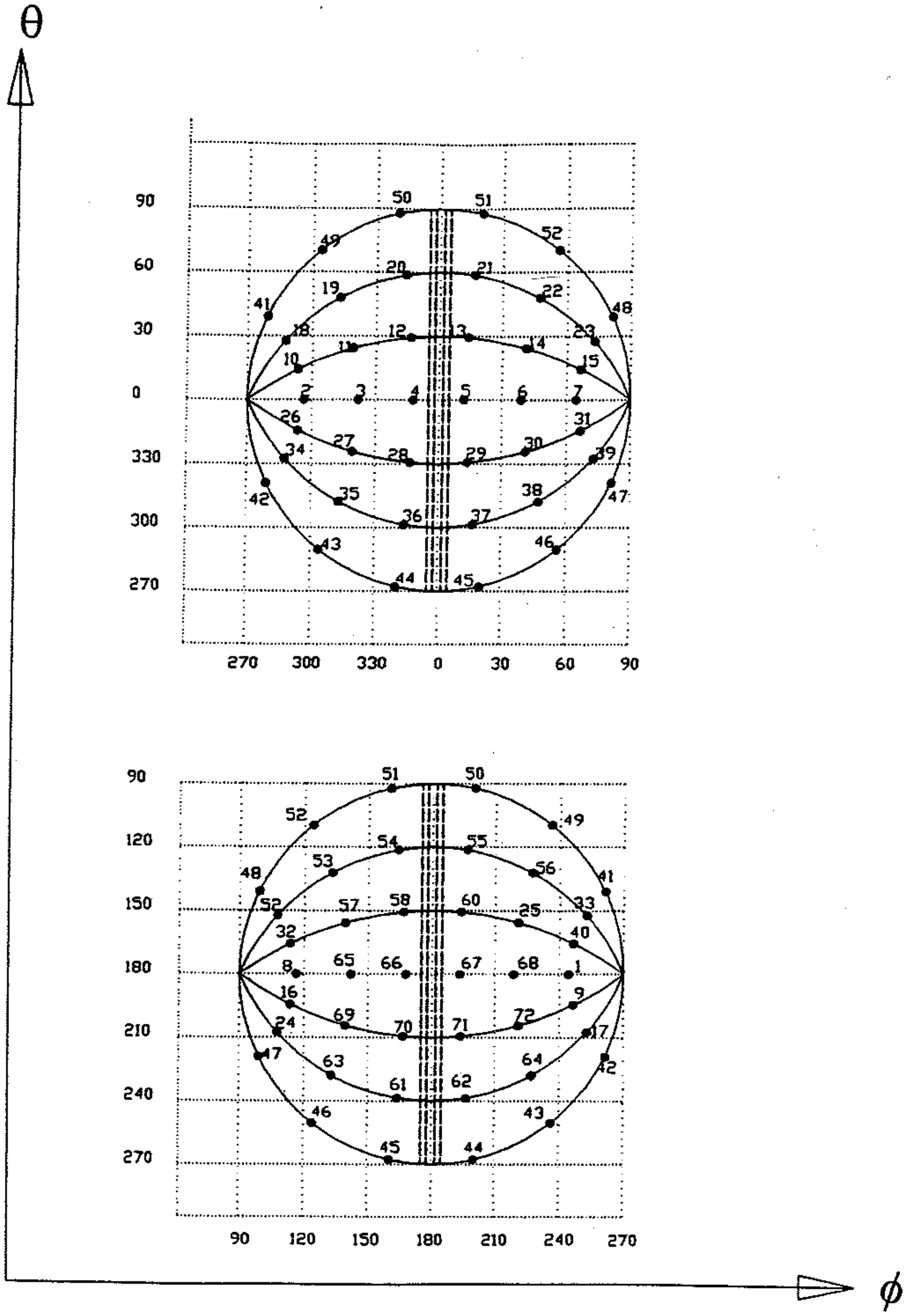
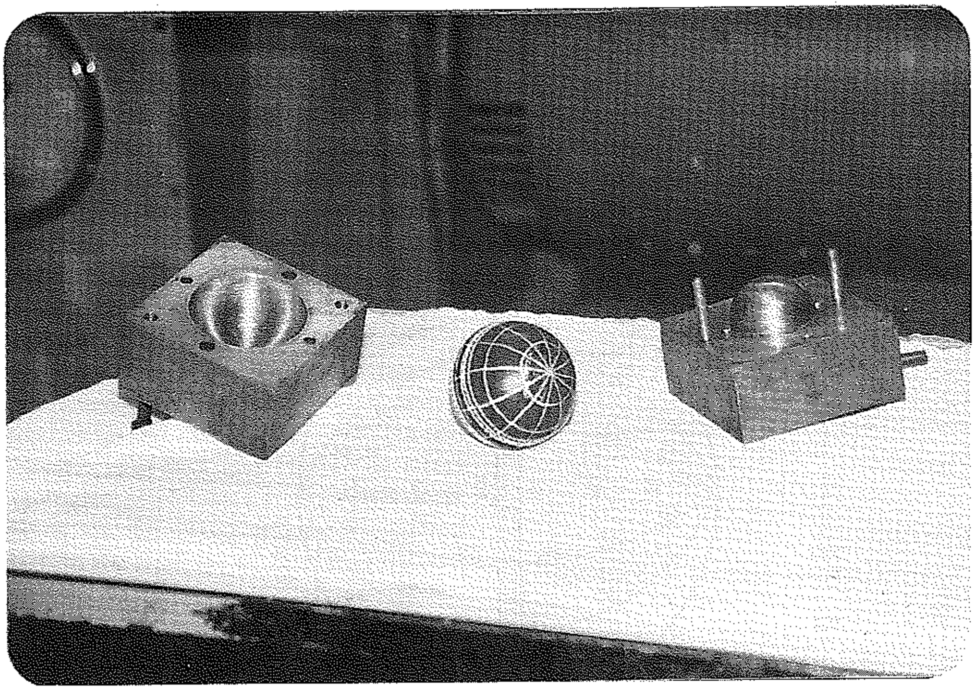
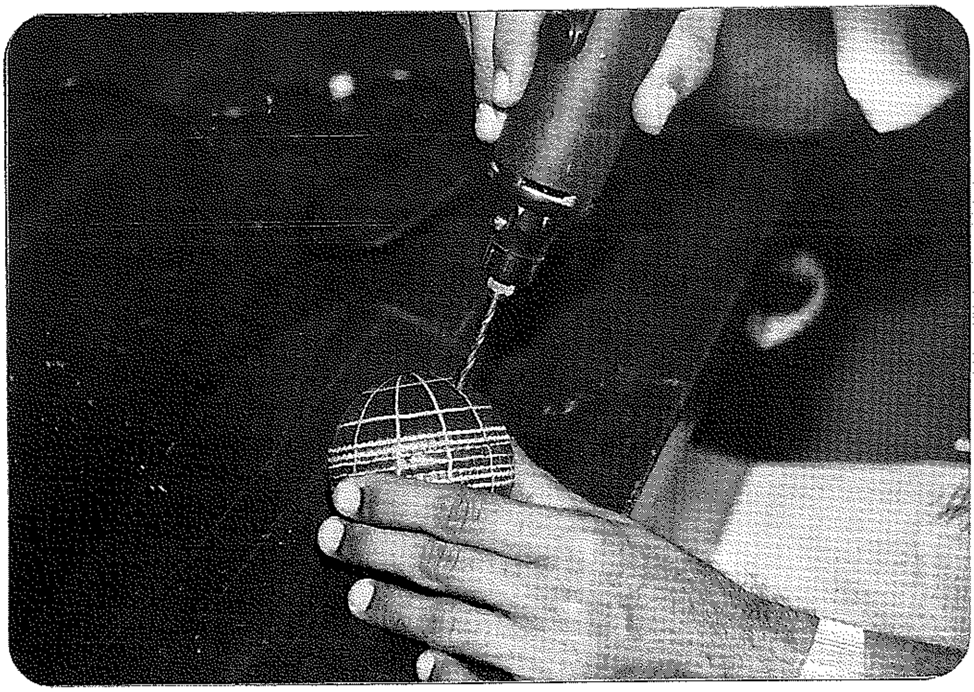


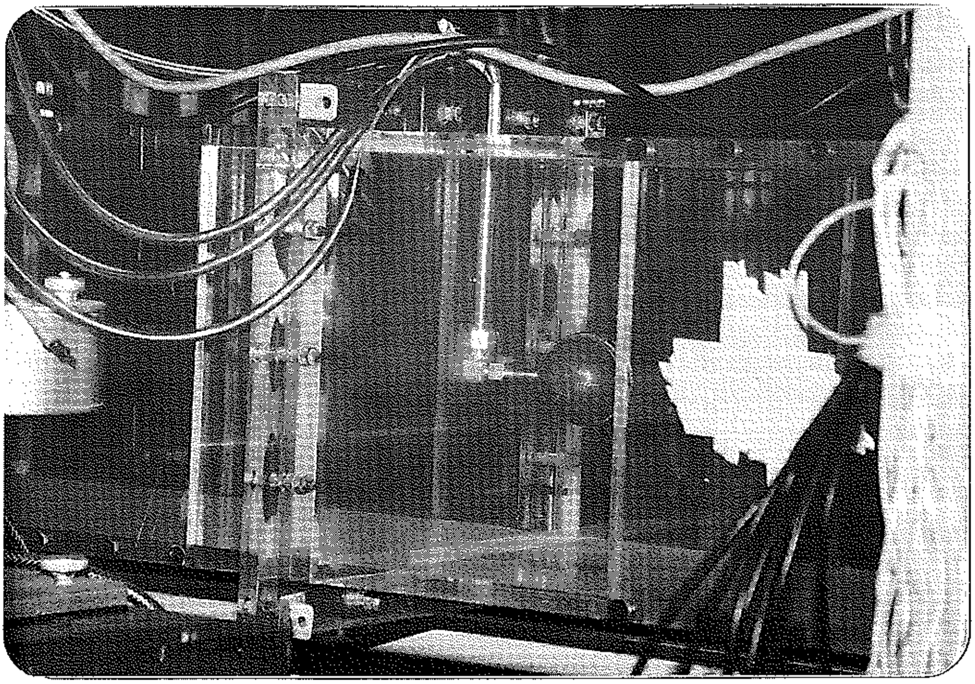
FIGURE 2: *Schematic of Location of the Pressure Tappings and the Grids for the Numerical Integration of the Aerodynamic Forces*



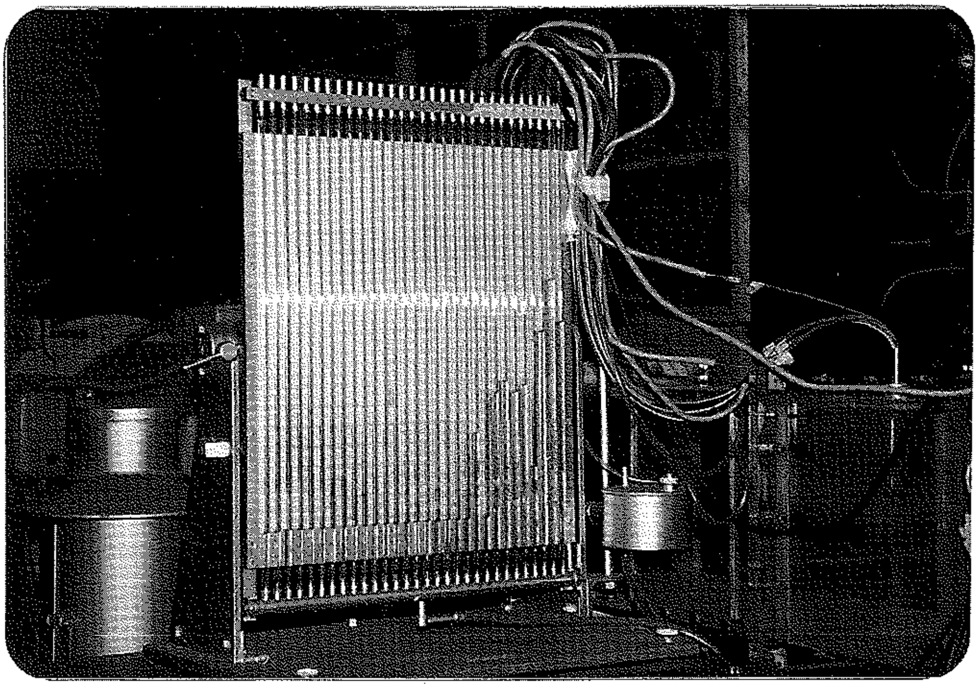
PHOTOGRAPH # 1: *The Steel Mould and the Hollow Cricket Ball with the Grid Lines*



PHOTOGRAPH #2: *The Drilling of Fine Holes for the Pressure Tappings*



PHOTOGRAPH # 3: *An Overview of the Experimental Set Up in the Wind Tunnel*



PHOTOGRAPH # 4: *The Manometer Bank*

TABLE 1: *A Sample of Results (Seam Angle 10^0, Air Velocity - 41.98 m s^{-1})*

Grid Number	θ Degree	φ Degree	P (Pa x 10^4)	Grid Number	θ Degree	φ Degree	P (Pa x 10^4)
1	265	180	0.283	37	25	300	0.264
2	295	0	0.201	38	55	300	0.371
3	325	0	0.064	39	85	300	0.401
4	355	0	0.003	40	115	120	0.352
5	25	0	0.114	41	295	90	0.276
6	55	0	0.249	42	265	270	0.320
7	85	0	0.269	43	235	270	0.292
8	115	180	0.203	44	205	270	0.254
9	265	210	0.395	45	175	270	0.248
10	295	30	0.274	46	145	270	0.324
11	325	30	0.102	47	115	270	0.347
12	355	30	0.036	48	85	90	0.343
13	25	30	0.144	49	325	90	0.345
14	55	30	0.258	50	355	90	0.306
15	85	30	0.236	51	25	90	0.273
16	115	210	0.154	52	55	90	0.309
17	265	240	0.114	53	145	120	0.152
18	295	60	0.175	54	175	120	0.151
19	325	60	0.300	55	205	120	0.159
20	355	60	0.291	56	235	120	0.218
21	25	60	0.202	57	145	150	0.155
22	55	60	0.312	58	175	150	0.160
23	85	60	0.273	59	205	150	0.154
24	115	240	0.182	60	235	150	0.171
25	265	150	0.150	61	175	240	0.160
26	295	330	0.179	62	205	240	0.165
27	325	330	0.251	63	145	240	0.199
28	355	330	0.281	64	235	240	0.318
29	25	330	0.216	65	145	180	0.168
30	55	330	0.335	66	175	180	0.164
31	85	330	0.312	67	205	180	0.164
32	115	150	0.159	68	235	180	0.180
33	265	120	0.241	69	145	210	0.170
34	295	300	0.267	70	175	210	0.170
35	325	300	0.236	71	205	210	0.193
36	355	300	0.250	72	235	210	0.189

forces were computed by numerical integration as shown below.

Analysis of Experimental Results

With reference to the wind axis:

$$F_{xx} = \sum_{\theta=0}^{360} \sum_{\phi=0}^{360} p r^2 \cos^2 \phi \sin \Theta \, d\phi \, d\Theta \qquad (1)$$

$$F_{yy} = \sum_{\theta=0}^{360} \sum_{\phi=0}^{360} p r^2 \cos \phi \sin \phi \, d\Theta \, d\phi \qquad (2)$$

$$F_{zz} = \sum_{\theta=0}^{360} \sum_{\phi=0}^{360} p r^2 \cos^2 \phi \cos \Theta \, d\phi \, d\Theta \qquad (3)$$

Where: F_{xx}, F_{yy} and F_{zz} are the drag, lift and side force respectively.

p = mean gauge pressure at any given node
r = radius of the cricket ball
ϕ and Θ are latitudinal and longitudinal angles respectively.

$$C_d = \frac{F_{xx}}{\frac{1}{2}\rho V^2 A} \qquad (4)$$

$$C_l = \frac{F_{yy}}{\frac{1}{2}\rho V^2 A} \qquad (5)$$

$$C_s = \frac{F_{zz}}{\frac{1}{2}\rho V^2 A} \qquad (6)$$

Where: C_d, C_l and C_s are coefficient of drag, lift and side force respectively.

p = Density of air at 1 atmosphere and 25°C
V = Mean velocity of the air in the working section of the wind tunnel
A = Projected area of the cricket ball

The Reynolds number, R_e, is defined as:

$$R_e = \frac{V D}{v} \qquad (7)$$

Where: D = Diameter of the cricket ball and
v = Kinematic viscosity of air at 1 atmosphere and 25°C

Table 2 and **Figures 3, 4** and **5** show the summary of the results obtained. Although, the present work only relates to the side force, results are also given for the lift and drag forces for the sake of aerodynamic completeness. The fluctuations in the gauge pressure measurements were perhaps caused by the turbulence in the wind tunnel, and therefore a mean value of the gauge pressure measurements was used. Finally, the 72 pressure tappings on the surface of the ball made it slightly rougher than actual. Thus, it is believed that the experiments mildly underestimated the critical speed.

4. Discussion

The results showed that the critical Reynolds number, at which the transition from the laminar to turbulent boundary layer occurs, lies in the range of $1.8 \times 10^5 - 2.1 \times 10^5$, i.e. in the speed range of 35-42 ms^{-1}. Further, the maximum swing was found to occur at a seam angle of 10° and at a speed of approximately 35 ms^{-1}. It may be noted that fast bowlers are known to achieve speeds of up to 40 ms^{-1} (Mehta, 1985). The results of this study, as far as the side force is concerned, are consistent with the results of Barton (1982) and Bentley et al. (1982); albeit with a speed lag of about 5 ms^{-1}.

A plausible explanation for the before-mentioned speed lag, of the results of Barton (1982) and Bentley et al. (1982), may possibly lie in the limitations of the indirect method used in these two studies for measuring the side force. In the indirect method, the ball was rolled along its seam down a ramp located on the working section roof and into the flow through a slot. The side force was calculated by measuring the conditions at the landing point and its subsequent transverse displacement (Barton, 1982). It was not possible for the authors to comment on any possible limitation of the indirect method, except to say that it does not seem possible to devise a better method for measuring the side force on a spinning ball.

Now a few words about the illusive phenomenon of the late swing, which is a particularly interesting feature of the fast bowling and which intensifies the element of surprise. Late swing occurs when a bowler delivers the ball at a velocity close to or greater than the critical velocity such that the boundary layers on both hemispheres are turbulent. Later in flight, as the ball slows by friction, the boundary layer on the hemisphere, with the lagging seam, becomes laminar and the resulting asymmetry of the boundary layers cause the late swing (Barton, 1982). The spread of the Reynolds number in the trans-critical range (**Figure 5**) should explain why the late swing is quite an unpredictable phenomenon, and it confirms the observation

TABLE 2: *Summary of the Wind Tunnel Test Results*

Seam Angle (Degrees)	Air Speed, (m s^{-1})	Coefficient of Drag, C_d	Coefficient of Lift, C_l	Coefficient of Side Force, C_s	Reynolds Number, R_e
10	25.06	0.28	-0.18	0.11	1.30×10^5
10	29.98	0.28	-0.18	0.12	1.56×10^5
10	35.15	0.22	-0.14	0.13	1.83×10^5
10	37.12	0.12	-0.14	0.06	1.93×10^5
10	39.24	0.21	-0.19	0.07	2.04×10^5
10	41.98	0.20	-0.19	0.04	2.18×10^5
15	25.06	0.29	-0.19	0.00	1.30×10^5
15	29.98	0.25	-0.19	0.02	1.56×10^5
15	35.15	0.25	-0.16	0.07	1.83×10^5
15	37.12	0.21	-0.13	0.07	1.93×10^5
15	39.24	0.22	-0.13	0.02	2.04×10^5
15	41.98	0.23	-0.18	0.03	2.18×10^5
20	25.06	0.31	-0.12	-0.03	1.30×10^5
20	29.98	0.30	-0.19	0.03	1.56×10^5
20	35.15	0.33	-0.17	0.05	1.83×10^5
20	37.12	0.20	-0.03	-0.05	1.93×10^5
20	39.24	0.26	-0.11	-0.02	2.04×10^5
20	41.98	0.23	-0.13	-0.04	2.18×10^5

of Barton (1982) that, as far as the late swing is concerned, the best a bowler can do is to bowl at about the critical speed and hope that the phenomenon will occur.

5. Conclusions

The results of this study should reflect, more closely, the aerodynamics of swing bowling at the cricket field. It is believed that the inconsistency, with the previously reported studies of Barton (1982) and Bentley et al. (1982), is probably due to the inherent limitations of the indirect method used by these researchers for the measurement of the side force. However, the precise reasons for the inconsistency between the results, of Barton (1982) and Bentley et al. (1982) on one hand, and the field observations in the game on the other hand, remain unknown.

Notation

A = Projected area of the cricket ball
C_d = Coefficient of drag force
C_l = Coefficient of lift force
C_s = Coefficient of side force
D = Diameter of the cricket ball
F_{xx} = Drag force
F_{yy} = Lift force
F_{zz} = Side force
p = Pressure at any given node
r = Radius of the cricket ball

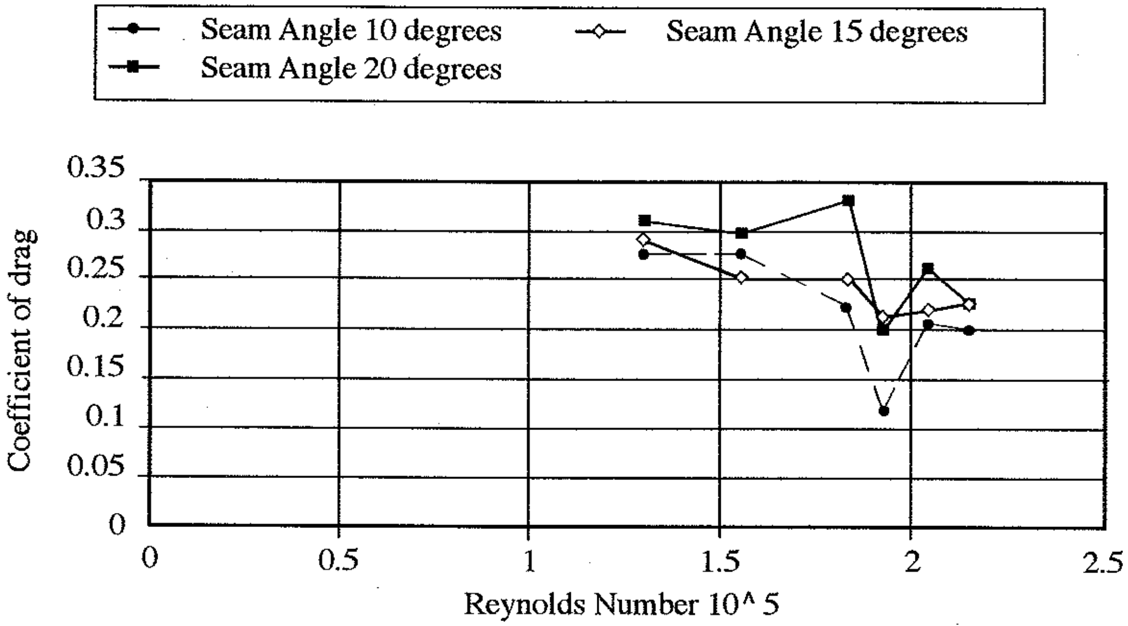


FIGURE 3: *The Variation of the Coefficient of Drag with the Reynolds Number*

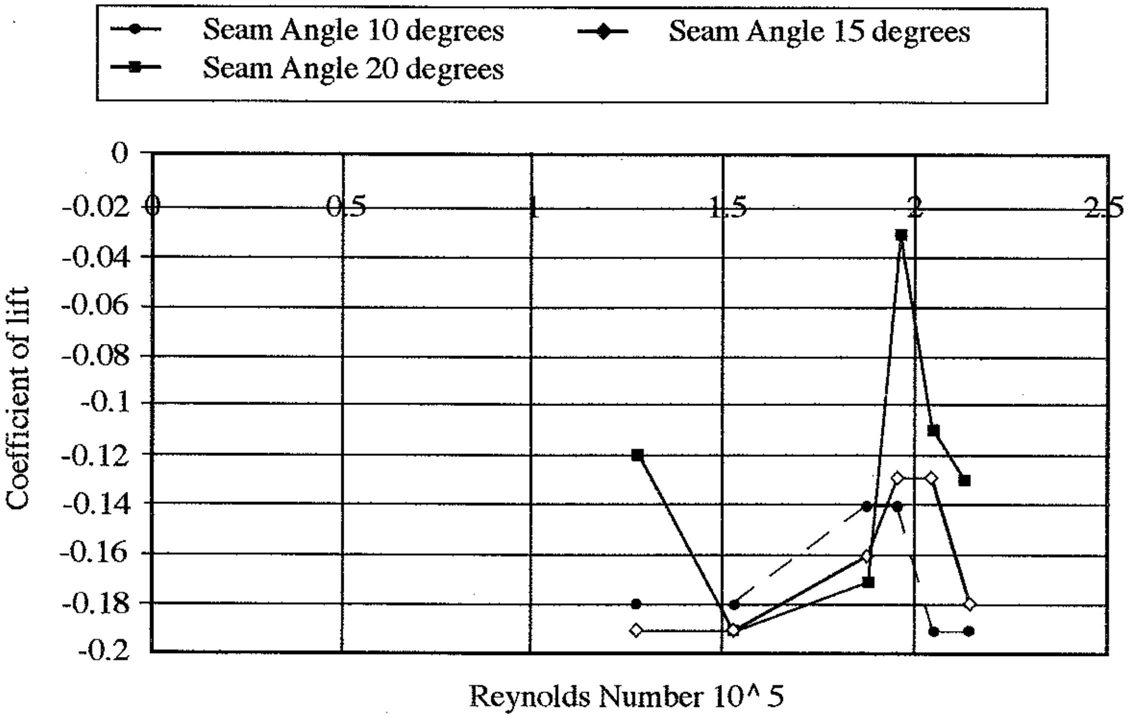


FIGURE 4: *The Variation the Coefficient of Lift with the Reynolds Number*

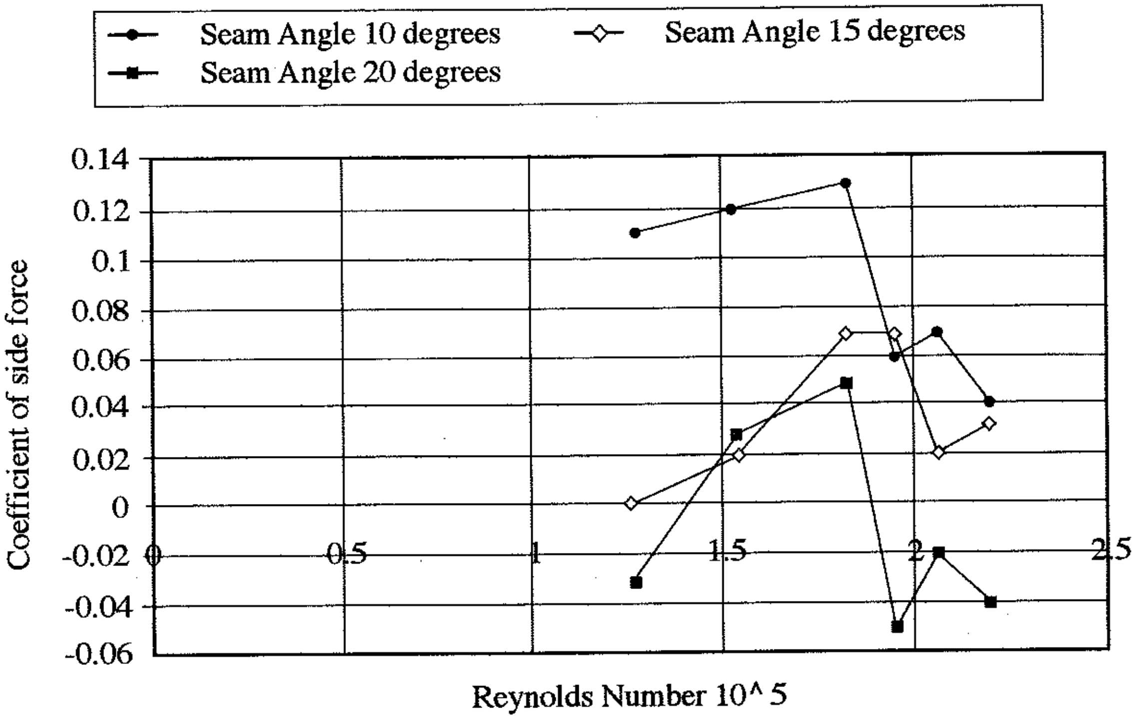


FIGURE 5: *The Variation the Coefficient of Side Force with the Reynolds Number*

V = Mean velocity of the air in the working section of the wind tunnel
R_e = Reynolds Number
ν = Kinematic viscosity of air at 1 atmosphere and 25°C
ϕ = Latitudinal angle
θ = Longitudinal angle
ρ = Density of air at 1 atmosphere and 25°C

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