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Aerodynamic and Flying Characteristics of Knuckle Ball in Soccer

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ABSTRACT

Background: The purpose of this study is to analyze high-speed video images of the flight trajectory of a ball in three dimensions by considering the knuckle effect as a fundamental aerodynamic property. Two high-speed video cameras were used to analyze the three-dimensional flight trajectory of a ball in flight, where one of the cameras was set behind the goal to record the trajectory of the oncoming ball and the other was placed to the side to record the lateral view. A multi-purpose kick robot was manufactured and is now under performance test. This machine was designed for the purposes of ball performance test of soccer and volley balls for ball design, and detail studies of the mechanism of ball kicking and of aerodynamic flight of a ball. Highly reproducible shot of a ball is expected by using this machine. It is planned to conduct experiments on the knuckling effect of a non-or low-spinning soccer ball. It was determined that the peak of the irregular force in this experiment was about 2.0 N (s.d.=0.4 N). It can be concluded that the emergence of irregular forces is one of the characteristics of knuckle balls in soccer. This irregular force acts in both up-down direction and left-right direction within a range of ± 0.3 for both the lateral force coefficient and the lift coefficient.

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INTRODUCTION

Aerodynamics plays a prominent role in defining the flight of a ball that is struck or thrown in the air in almost all ball sports. The main interest lies in the fact that the ball can often deviate from its initial straight path, resulting in a curved, or sometimes an unpredictable, flight path. It is particularly fascinating that not all the parameters that affect the flight of a ball are always under human influence. Lateral deflection in flight, for example, commonly known as swing, swerve or curve, is well recognized in cricket, tennis, golf, soccer, volleyball, and baseball. The study of sports ball aerodynamics requires consideration of a number of fundamental fluid mechanics phenomena including boundary layer flow and transition, boundary layer separation, turbulence, flow over rough surfaces, the Magnus effect, and both the steady and the unsteady wake behavior.

Soccer is widely regarded as the most popular sport in the world, and the exact velocity, swerve or dip of a soccer ball can be match-deciding. Recent developments in soccer ball manufacturing technology have led to the possibility of radical changes in surface geometry and seam configurations. The consequences of such radical changes to the ball flight can only be fully realized if a detailed understanding of the aerodynamics is gained.

In the studies on the aerodynamics of soccer balls, Griffiths *et al*. (2005) investigated the trajectory and rotation of a ball as a three dimensional manner using a motion capture system. The measured ball speed was ranged by 15-18 m/s where the values of *CL* showed slightly larger than the previous measurement (Carré *et al*., 2002). Also, although the values of *CL* increased according to the increase in the value of *Sp*, the values of *CL* showed a limit as the value of *Sp* was about 1.3. Cook & Goff (2006) theoretically investigated the trajectory of free kicks and corner kicks at a point in front of a goalpost. Also, they considered the speed and rotation of a ball, foot angle for kicking, and time to reach the goalpost for each parameter.

In a spinning ball, although the term of *CL* showed a tendency that it is increased with the value of *Sp* and is to stay for the same line with the condition of $Re > Recrit$, it represented a decrease in the value of *CL* as it approaches to the transition. Also, it showed a negative value as it is below the transition. It was regarded that although the boundary layer maintained a laminar at the side of regression, the side of progress formed

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turbulence and that moves the separation point in the laminar to the upper stream. Therefore, the wake was curved to its reverse direction as the positive side represents a turbulence boundary layer. It is called as a reverse Magnus effect. The reverse value of *CL* at *Sp* = 0.26 for *Re* = 8.5 × 104 was agreed with the transition point of *CD*. As the rotational velocity was assumed as a constant level, the trajectory was drawn using the measured *CD* and actual kicks in which the term of *Sp* was decreased according to the decrease in the speed of the ball and that increases the value of *CL*.

Spaminato *et al*. (2004) performed an experiment that a soccer ball produced as an actual scale was tested with a wind speed and rotational velocity of 47 rad/s similar to an actual game in a wind tunnel. In the case of the test without movements, the term of *Recrit* was determined as 4.0 × 105 for a smooth ball at around 2.0 × 105 and that agrees with the results of the conventional studies. The term of *CD* was decreased from about 0.55 to 0.33 and increased as about 0.35 in a trans-critical region. Such high values revealed that there were lots of interferences in this configuration. In the case of the ball without rotation, a partial lateral force was measured. It showed that there were some asymmetric wakes even though it was small because of slight asymmetry in the ball. In the case of the ball with rotation, there was transition instantaneously in which the range of *CD* was 0.75 - 0.61 at *Re* = 5.0 × 104 and decreased as about 0.38 at *Re* = 5.0 × 105. As the value of *Re* was increased as more than 1.5 × 105, the term of *CS* was maintained as a constant level relatively and determined as 0.42 - 0.62 and 0.31 - 0.39 at *Re* = 5.0 × 104 and *Re* = 5.0 × 105, respectively. Also, the value of *CS* in a smooth ball was -0.22.

However, these studies have implemented based on the measurement and estimation of aerodynamic parameter as a time mean way at a stable stationary state. There are very few studies on the aerodynamic characteristics at an instability state. Moreover, it is easy to find the non-spinning or low-spinning footballs in recent football games in which the trajectory of balls represents a characteristic of swing that is called as a knuckling effect (Fig. 1) or knuckle ball as an unsteady phenomenon (Asai *et al*., 2007).

Fig. 1: An example of the “knuckling effect ball” in soccer. (From Asai *et al*., 2007).

Also, it is necessary to explain an aerodynamic mechanism related to the effect. Regarding the characteristics of the knuckle ball, the ball speed increased rapidly from 0 m/s to 20 - 30 m/s at 1/100 s and will be irregularly changed while it decreased due to air resistance. It is a temporal situation and that is to be analyzed through an instability analysis (Hong *et al*., 2010).

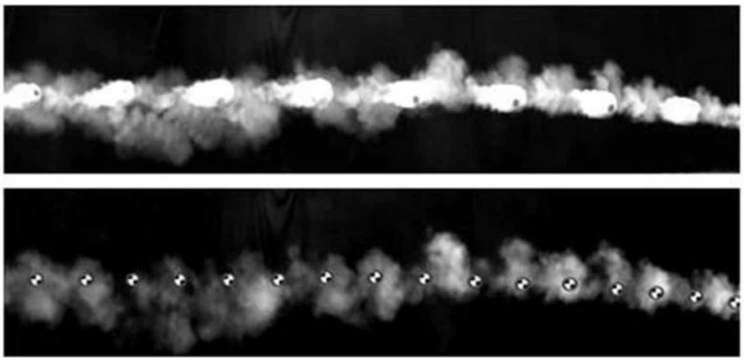

Fig. 2: Flow visualization of vortex undulation behind the real flight of the knuckling effect soccer ball (Flow is from right to left). (From Hong *et al*., 2010).

Hong *et al*. (2010) investigated visualization tests (Fig. 2) for verifying the basic dynamic characteristics of non-spinning or low-spinning actual soccer balls at an unsteady state. The knuckle ball was observed to have an average vortex lift force frequency of approximately 3.5 Hz. In the comparison of this frequency with the frequency of the vortex undulation, these two frequencies were linked, and the relationship between these frequencies represented a high correlation statistically. Also, the trajectory of the ball can be changed by the force of the air and due to the rotation and rpm of the ball.

However, the aerodynamic properties and the boundary layer dynamics of a non-spinning or slowly spinning soccer ball (knuckle ball) are not well understood. The purpose of this study is to analyze high-speed video images of the flight trajectory of a ball in three dimensions by considering the knuckling effect as a fundamental aerodynamic property. Two high speed video cameras were used to analyze the three dimensional flight trajectory of a ball in flight, where one of the cameras was set behind the goal to record the trajectory of the oncoming ball and the other was placed to the side to record the lateral view.

Experimental Method:

Fig. 3: A multi-purpose kick robot used in this study.

A kick robot was set at the experiment field at the University of Tsukuba (Fig. 3). Two high-speed video cameras (Fastcam, Photron Inc., Tokyo, Japan) were set to the side and in front of the ball trajectory between the location of the kick robot and the soccer goal (No. 1 & No. 2), and video images were taken at 1,000 fps with a resolution of 1024 × 512 pixels (Fig. 4). The kick robot delivered a non-spinning or slowly spinning soccer ball at almost the same velocity (~ 25 m/s), as would occur in a real game. Camera No. 1 (head on view camera with a focal length of 50 mm) and camera No. 2 (side view with a wide angle lens with a focal length of 12 mm) were operated, and eight separate cases were analyzed in these experiments. It is natural, in general, every ball does not rotate in the same manner as in wind tunnel experiments, and it is virtually impossible for a ball to be in a state of complete absence of rotation in a realistic free-kick situation. A FIFA approved size 5 soccer ball (Jabulani, 8 Panels, Adidas Inc., mass=0.430 kg; diameter=0.220 m) was shot 25 m towards a full size goal (7.32×2.44 m).

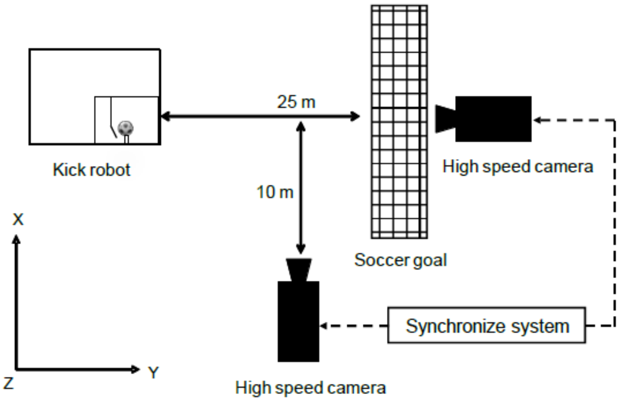

Fig. 4: Experimental setup in this study.

To calibrate the performance area, a calibration frame (12.0×4.0×3.0 m) with 76 control points was videotaped before the trials. A digitizing system (Frame DIAS 4, DKH Inc, Tokyo, Japan) was used to manually digitize the anatomical body landmarks. The direct linear transformation (DLT) method (Abdel-Azis & Karara, 1971) was used to obtain the three dimensional coordinates of each landmark. The performance area was calibrated with a net root mean square error of 5 mm. Fig. 5 shows the coordinate system defined for the present study, where the y-axis is taken horizontally in the direction of the ball flight, the x-axis is in depth direction, and the z-axis is taken in vertical direction.

In this regard, it was necessary to correct the distortion of the image as seen through a wide-angle lens. The correction of the depth perception arising from the image taken with camera No. 1, which was set immediately behind the goal, was attempted at the digitization stage.

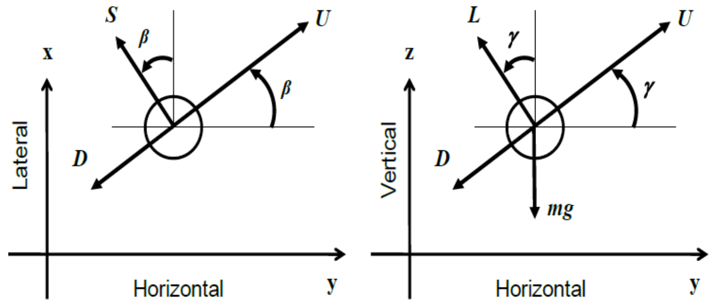

Fig. 5: Coordinate system defined in this study.

Each of the following parameters was calculated: ball (wind) velocity (*U*), force acting in the direction of the wind (drag (*D*)), force acting perpendicular to the wind direction (lift (*L*)), and force acting sideways as viewed from the front (*S*), as shown in Eqs. (1) to (3). Also, the aerodynamic forces acquired in the experiment were converted into the drag coefficient (*CD*), the lift coefficient (*CL*), and the side force coefficient (*CS*), as shown in Eqs. (4) to (6).

$$S= m(ax\cos\beta - ay\sin\beta) \qquad (1)$$

$$D=-m[(az + g)\sin\gamma + ay\cos\gamma] \qquad (2)$$

$$L= m[(az + g)\cos\gamma - ay\sin\gamma] \qquad (3)$$

In the above equations, *S* is side force, *D* is drag force, *L* is lift force, *U* is the flow velocity, *m* is the mass of the ball, and *g* is the gravitational acceleration.

$$C_D = \frac{D}{1/2\rho V^2 A} \qquad (4)$$

$$C_L = \frac{L}{1/2\rho V^2 A} \qquad (5)$$

$$C_S = \frac{S}{1/2\rho V^2 A} \qquad (6)$$

In the above equations, ρ is the density of air (ρ=1.2 kg/m3), *V* is the flow velocity, and *A* is the estimated area of the soccer ball (*A* = π × 0.112 = 0.038 m2).

RESULTS AND DISCUSSION

Flight trajectory:

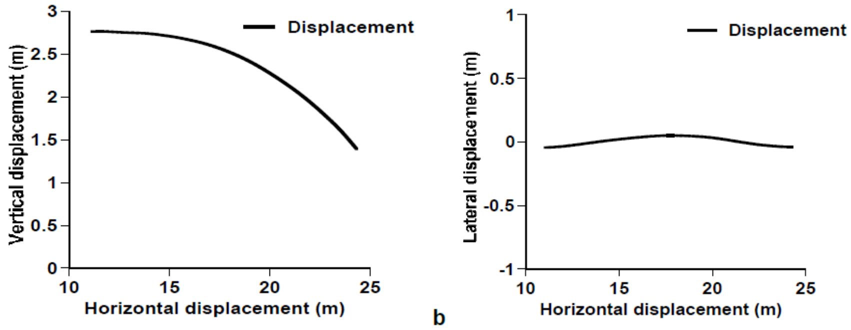

Fig. 6: An example of the flight trajectory (knuckle ball) by the kick robot from side view (a) and top view (b).

Fig. 6-a shows a typical flight trajectory (initial velocity: 25.0 m/s) of a non-spinning ball (knuckle ball) set in motion by the kick robot. The target of analysis in the present study was the second half of the flight. As viewed from the side, the shape of the traversed flight trajectory was close to a parabola due to the influence of gravitational acceleration, and it was difficult to determine small changes in a visual manner.

On the other hand, looking at the trajectory of the knuckling effect ball as viewed from the front, a meandering of about ± 0.04 m in horizontal direction was observed, and it was found that the trajectory of the ball changes irregularly (Fig. 6-b).

Fluctuating forces:

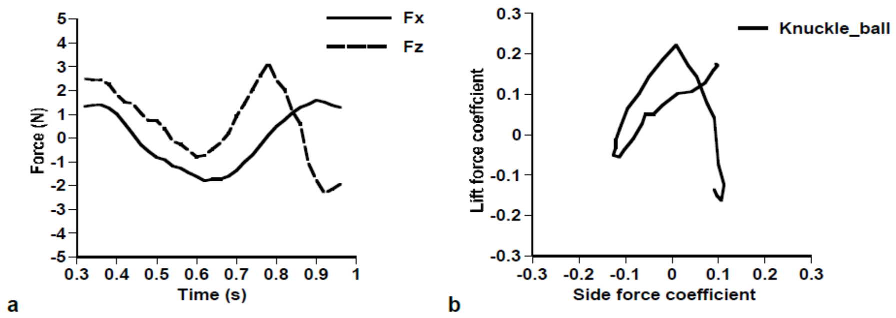

Fig. 7: An example of acting force on real flight knuckle ball (a) and the relation between the side force coefficient and the lift coefficient of that (b).

Fig. 7-a presents the force which acted on the ball as calculated from the flight trajectory, where a correction is applied by removing the forces acting in vertical direction. The force waveform reveals that there is an irregular force with a peak value of about 1~3 N acting on the ball in both up-down direction and left-right direction. A similar tendency was observed in other trials (Table 1), and it was determined that the peak of the irregular force in this experiment was about 2.0 N (s.d.=0.5 N). Hong *et al*. (2011) reported an average lift of the knuckling effect shot was 2.1 N, (s.d. = 0.4), and the irregular boundary of the lift was 1 ~ 3 N, which is similar to the irregular forces.

Table 1: Peak values of fluctuating forces in each trial.

Trial	1	2	3	4	5	6	7	8	9	10	mean	s.d.
Side Force (N)	1.1	1.6	1.7	2.9	1.5	1.4	1.3	1.6	1.8	2.1	1.7	0.5
Frequency (Hz)	2.3	2.4	1.8	1.8	3.2	3.2	3.2	3.5	2.7	2.5	2.6	0.6
Lift Force (N)	2.0	1.7	1.9	2.1	1.8	1.9	2.6	2.3	1.7	1.8	2.0	0.3
Frequency (Hz)	1.4	1.3	2.0	1.5	2.1	2.2	1.9	2.3	1.3	2.1	1.8	0.4

On the basis of these findings, it can be concluded that the emergence of irregular forces is one of the characteristics of knuckling effect balls in soccer. This irregular force acts in both up-down direction and left-right direction within a range of ± 0.3 for both the lateral force coefficient and the lift coefficient (Fig. 7-b). It is suggested that it is strongly affected by fluctuations in the vortex structure and the separation point of the backflow of the ball, although the details are as yet unclear. In addition, while the force acting on the ball was calculated from the flight trajectory in the present study, the influence of noise in the digitization of coordinates was considerable, and therefore increasing the accuracy of coordinate measurement is one of the key challenges for future research.

Conclusions:

The purpose of this study is to analyze high-speed video images of the flight trajectory of a ball in three dimensions by considering the knuckling effect as a fundamental aerodynamic property. It was determined that the peak of the irregular force in this experiment was about 2.0 N (s.d.=0.4 N). It can be concluded that the emergence of irregular forces is one of the characteristics of knuckling effect balls in soccer. This irregular force acts in both up-down direction and left-right direction within a range of ± 0.3 for both the lateral force coefficient and the lift coefficient. It is suggested that it is strongly affected by fluctuations in the vortex structure and the separation point on the ball, the details are as yet unclear.

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