ISSN : 0974 - 7435 Volume 8 Issue 10

BioTechnology

An Indian Journal

FULL PAPER

BTAIJ, 8(10), 2013 [1325-1330]

The mathematic simulation of "banana kick" in football based on mechanical model

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ABSTRACT

In the rapidly developing modern football, the set piece is regarded as an important tool to score by all nations teams. In all kinds of set pieces, the swerving kick has the most precision. Because its flying path is like a banana, so it is also called "banana kick". By detailed analyses in basic mechanics and fluid mechanics to the motion of the ball, this paper tries to provide the factors that form the "banana kick", with study on mechanical parameters' influence on the state of motion of the ball. Results reveal that: Banana kick simulated with Mathematic by parameter equations based on mechanics model, is able to explain the classical theories about the flying path of football in mechanics and fluid mechanics, and serves the fundamental theories for this sport.

KEYWORDS

Mathematical modelling;
Football, fluid mechanics;
Mathematic Simulation.

INTRODUCTION

Spinning and fast, the banana kick has become an important skill to score in football. In the match between France and Austria, 12th World Cup, one French player managed to present a banana kick that rounded the wall and went into the far corner of the net, solidifying the victory for his team. The magic of the banana kick was out of imagination then. After 12th World Cup, the swerving ball has become a popular skill.

Many researches are done in China on the relating mechanics theories and techniques about spinning ball. In this sport, there are already top players who can perform this skill to an extraordinary level with good and effective technique. However, their techniques are not necessarily eligible as basic theories for research. Previous studies have already improved the football technique with scientific study and correct analytic method. In the meantime, same contribution can be done by mechanics and fluid mechanics analysis, making this field of study possible for further advances.

This paper does away with previous methods on this topic, and adopted the kinematic mechanics, a natural science, as the tool of study football sport. It provides in detail the momentum and acting force analysis when the body contacts the ball, as well as the flying path and placement analysis of the ball in motion. The flying path is simulated from the perspective of football mechanics. All of the above present accurate descriptions on the relation between the kicking force on the ball and its flying path. It is hoped this paper can help the popularization of football and training of players.

Also, it is expected that by this study, teaching can be better done in classes of this sport and physics can be closer to everyday life, including the game of football.

BERNOULLI'S PRINCIPLE AND MAGNUS EFFECT

Bernoulli's principle

It can be learned by an experiment. Take two pieces of paper, just like Figure 1.

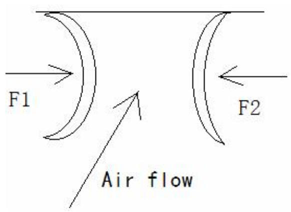

Figure 1：Diagram of Bernoulli's principle

Put two pieces of paper in parallel in front of one's face closely. When air is blown into the space between two pieces of paper, one would find that, instead of going further from each other, two pieces of paper go closer. The reason is that the air flow in between is on a higher speed than outside air flow, so two pieces of paper are subject to pressure F_1 and F_2 which make them go closer. In equation, it is:

$$\frac{1}{2}\rho v^2 + \rho gz + p = k \tag{1}$$

It is called Bernoulli's equation. The equation shows that when the flow speed v is high, the pressure P is small. While v is low, the pressure P is large.

Magnus effect

Take this left-going ball as an example. See figure below:

When the ball goes in anticlockwise spin as shown in Figure 2, the air above the ball is affected by the spin and moves leftward. And because the ball goes leftward too, so the air has relative velocity to the right to the ball. Two velocities above will partially offsets each other as they are on opposite direction, which makes the air flow velocity smaller and pressure higher above the ball. While for the air below the ball, it is moving rightward. The ball goes leftward so the air has relative velocity to the right to the ball as well. Two velocities are on same direction, making the air below the ball goes quicker and has lower pressure. As a consequent to the pressure difference of the two, the ball will drop to the ground earlier than normal. This kind of ball is called top spin in banana kick. If the ball goes left in clockwise as shown in Figure 3, it is called back spin.

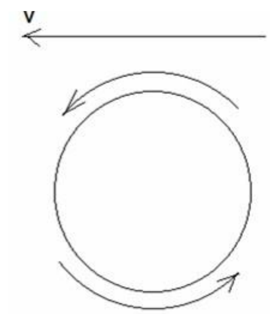

Figure 2 : Ball goes forward while in anticlockwise spin

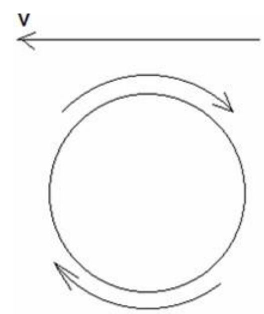

Figure 3 : Ball goes forward while in clockwise spin

MECHANICAL ANALYSIS FOR SPINNING BALL IN MOTION

Forces on the spinning ball

Translation principle can be applied to the spinning ball. The acting force(L) which deviates from the centre will produce moment of force(M) to make the ball spin and force to induce translation motion(F), as shown in Figure 4.

According to mechanics principles: Moment of force of spinning M=acting force (F) × arm of force

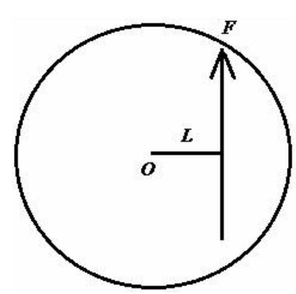

Figure 4 : Moment of force of Spinning.

(L). It can be deduced that the speed of spinning is determined by the strength of the acting force and the length of arm of force. For a fixed centre of the ball and acting force, the longer the arm of force, the stronger the rotary force, and vise versa.

Following are acting forces on the ball when it is in the air:

(a) gravity on the spinning ball

$$G = mg \quad (2)$$

In above, G is the downward gravitational force; m is the mass of ball; g gravitational acceleration

(b) air resistance on the spinning ball

$$F = c\rho AV^2 / 2 \quad (3)$$

In above, F is the air resistance on football; c is the drag coefficient, which is related to the shape of the ball; ρ is the density of air; A is the area of cross section

(c) Magnus force on the spinning ball

$$L = 8\pi\rho a^3 v / 3 \quad (4)$$

$K = c\rho A / 2$, $G = 8\pi\rho\omega a^3 / 3$ are introduced to facilitate calculation.

Then

$$F = Kv^2 \; L = Gv \quad (5)$$

Moment of air resistance on centre of ball is little and can be omitted. Because of angular momentum conservation, it can be deduced from equation (2) that the air resistance of the ball is in direction proportion to its horizontal velocity squared. This resistance will make the horizontal velocity decrease faster.

In the other hand, the anelasticity makes that the friction moment on inside of the ball is in direct proportion to coefficient of viscosity of air and angular velocity gradient. The coefficient of viscosity of air is small; therefore the moment of anelasticity makes the angular velocity decrease very slowly. When the ball goes forward in spin, the viscosity of air results in that the air on the surface of the ball goes spin with the ball and thus

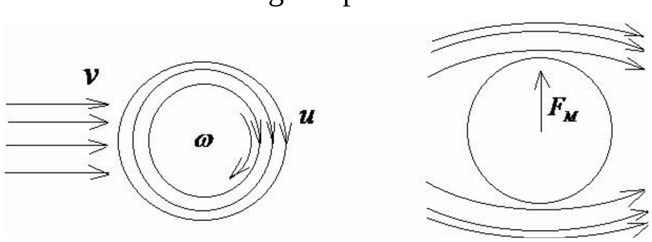

Figure 5 : Diagram of air current on horizontal cross section of ball

form general circulation around the ball. As shown in Figure 5.

In Research on Law of Football Motion, Long Geqi of Zhejiang Normal University adopts Magnus effect and air resistance theories to find the law of motion of spinning ball, and points out that the flying path of a spinning ball is a space curve.

Law of motion of spinning ball

When an object is in spin, it will take the fluid in direct contact with it into spin. As shown in Figure 6, A and B indicate the ball and its spin direction of its boundary layer. The direction of air in boundary layer on ball's left is the same of that of air current, while for the right side it's in opposite direction. This difference results in the pressure difference of two sides. A low pressure area will form at the left side, where the air flow direction is the same with the air current, and for the right side there will be a high pressure area. The result of the pressure difference of two sides is that the ball is subject to a resultant force from right to left, which will make the ball deviate from the straight path.

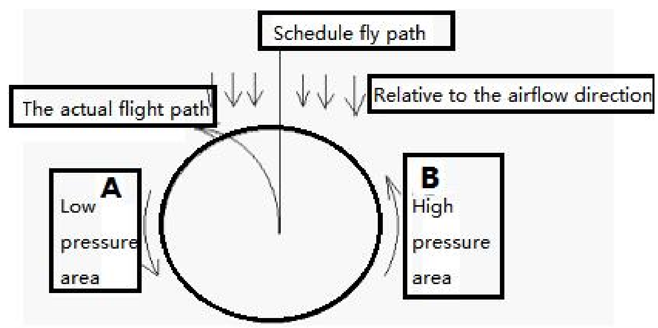

Figure 6 : The spinning results in the pressure difference and ball's deviation from straight path

When the ball goes in rapid spin, the pressure difference will form due to the air resistance. The pressure difference is constituted by the forwarding velocity and the resultant velocity of deviation velocity (by pressure difference) influenced by air resistance. In Hebei Academic Journal of Sport Institutes, Li Fuquan points out that there are three kinds of curvatures of curve when the air flow velocity is certain :(see Figure 7):

(1) When forwarding velocity is higher than spinning velocity in the former half of motion, the curvature is small and the path is close to straight line.

(2) When the deviation velocity is certain, higher forwarding velocity will result in smaller curvature.

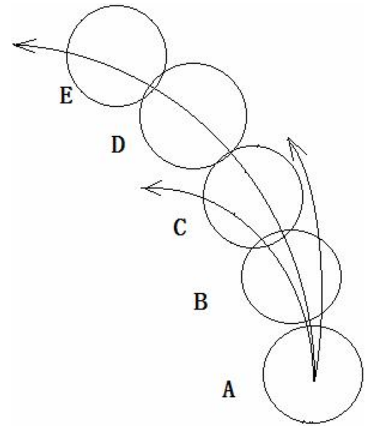

Figure 7 : Influence to Spin Direction by Air Pressure Difference

(3) When the forwarding velocity is certain, higher deviation velocity will result in larger curvature.

The flying path of the ball shows that the curvature in former half of path is smaller, in later half is larger. The forwarding distance is shortened and the dropping velocity is higher.

For the same reason, the air flow around the ball is moving around the vertical axis of the ball for in-going spinning and out-going spinning. Therefore, the difference in flow velocity results in a pressure difference. This will make the flying path of the ball deviate to the side that has smaller pressure, thus in-going and out-going spinning is made.

THEORIES OF "BANANA KICK

Conditions required for a banana kick

From the above, it can be deduced that there are two mechanical conditions required for a spinning ball: (1) The acting force (resultant force) is not on the centre of gravity————this would make the ball spin; a (2) A certain degree of deviation————the flying path of the ball changes due to the air.

Mechanical Analysis of Banana Kick

When player kicks the ball, and the acting force F goes through the centre of ball's gravity: The ball will go forward without spin (direction of acting force is the normal) and with 100% kick power. It means F1 =F×100%. This force will not make the ball spin.

When player kicks the ball, and the acting force F does not go through the centre of ball's gravity: The force forms an angle of $\alpha 1 = 30$, and eccentric distance is $X1 = 5.55cm$. The ball's (official match ball) circumference is $68 - 77cm$, and the F_2 by the tangent line will produce moment of force to make the ball rotate around the tangent of F_2 as the axis. The moment of force when kicking is:

$$\mathbf{M_1 = F_2 \times r} \quad (6)$$

In above equation, M is the moment of force, and F_2 is the tangent line component force and $F2 = F/2$; r is the radius of ball.

The component force by tangent line F_1 determines the direction and distance of the traveling of ball, and $F_1 = 86.6\% \times F$. It will make the ball goes in F_2 direction with small curvature (theoretically the curvature is $\pi/3$).

hen the acting force forms a $\alpha 2 = 60$ angle with the normal, the eccentric distance is $X2 = 9.6cm$. The F_2 by the tangent line will produce moment of force, which will make the ball spin in the direction of tangent line of F_2. The moment of force is:

$$\mathbf{M_2 = F_2 \times r} \quad (7)$$

In above equation, M_2 is the moment of force, and F_2 is the tangent line component force and; r is the radius of ball.

The component force by tangent line F_1 determines the direction and distance of the traveling of ball, and $F_1 = 50\% \times F$. It will make the ball goes in F_2 direction with large curvature (theoretically the curvature is $2\pi/3$) and short distance.

When the angle between acting force and the normal $\alpha 2 = 90$, which means the two is perpendicular, only moment of force that makes the ball spin will produce. This would not make the ball travel so a spinning ball by inner side of foot is impossible.

When the kicking acting force F is not on the centre of gravity of ball, the acting force can be resolvedd into the normal component force F_1 and tangent line component force F_2. The result of tangent line component force F_2 is to make the ball move forward at the velocity of V_1 ; the tangent line component forcewill result in that the ball spin at the velocity of. It can be deduced from basic mechanics formulas:

$$\mathbf{F \times t = m \times V} \quad (8)$$

$$\mathbf{V = Ft / m} \quad (9)$$

The ball's forwarding velocity is: ω

$$\mathbf{F \times t \times x = J \times \omega} \quad (10)$$

$$\omega = \frac{\mathbf{Ftx}}{\mathbf{J}} \quad (11)$$

Because the mass and rotational inertia are constant, the larger the force on the ball F and longer the time t , the higher the forwarding velocity V and angular velocity ω of rotation; vise versa, the smaller the force on the balland shorter time, the lower the forwarding velocityand angular velocity of rotation. The larger the arm of acting force, the larger the kicking angle and higher the rotation angular velocity; in the other hand, the smaller the arm of acting force, the lower the angular velocity. After combining the two motion by the combination law (parallelogram method), it can be deduced that: the higher the forwarding velocity V and rotation angular velocity, the faster the ball will travel and smaller the spinning curvature will be; on the opposite, the lower the forwarding velocityand rotation angular velocity, the slower the ball will travel and smaller the spinning curvature will be.

MATHEMATIC SIMULATION OF "BANANA KICK" PATH FORMATION

"Banana Kick" is the motion process of the resultant force of three directions. In each direction, the force can be further resolved as horizontal movement and rotation. The force on the ball when the ball is in air includes gravity and air resistance. The gravity is constant while the air resistance is proportional to the square of surface velocity of ball. The path of centre of mass is the reflection of the all above. The parameter equations (13) can be deduced from the forces on the ball after the kick:

$$\begin{cases} \mathbf{x(t)} = \frac{\mathbf{m}}{\mathbf{k}} \mathbf{v_0} \cos \alpha \left(1 - e^{\frac{-kt}{m}}\right) \\ \mathbf{y(t)} = \frac{\mathbf{m}}{\mathbf{k}} \mathbf{v_0} \cos \beta \left(1 - e^{\frac{-kt}{m}}\right) \\ \mathbf{z(t)} = \frac{\mathbf{m}}{\mathbf{k}} \left(\mathbf{v_0} \cos \gamma + \frac{\mathbf{mg}}{\mathbf{k}}\right)\left(1 - e^{\frac{-kt}{m}}\right) - \frac{\mathbf{mgt}}{\mathbf{k}} \\ \omega(t) = k\int_0^t (\omega(t) \times r)^2 dt + \omega_0 \end{cases} \quad (13)$$

In equations (13), $x(t), y(t), z(t), \omega(t)$ stand for the movement and angular velocity in three perpendicular direction. α, β, γ stand for the angles with three coordinate axes. k is the air resistance coefficient. v_0 is the kick velocity. m is the mass of football. r is the radius of football.

To simulate the path of football, the following values are set: the mass is 0.44kg; the perimeter is 0.7m; the kicking velocity is 25m/s. The angle between kicking velocity and x axis is 30o, between kicking velocity and y axis 0o, between kicking velocity and z axis 60o. The rotation angular velocity is 13.5rad/s. Air resistance coefficient is 1.2. Only the rotation around a certain axis is considered, and situation that the ball rotates in multiple direction is not considered.

The figure 8 shows that the air resistance produces a major influence. On the direction of rotation the frictional resistance and pressure resistance make the ball go back. In reality the real path of banana kick is close to the simulation. Therefore the model in parameter equations (13) is an ideal simulation to the motion of banana kick.

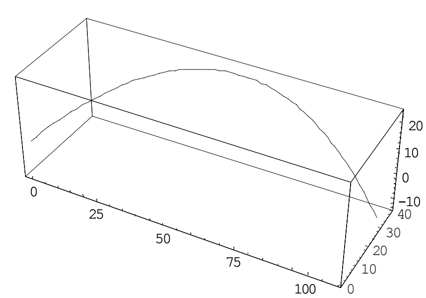

Figure 8 : Mathematic simulation path

CONCLUSION

By calculation on the formation of banana kick in football and its physical force analysis by fluid mechanics, this paper deduces the detailed calculation equations of the motion of football, which help football fans better understand the physics. At the same time, this paper put the theories in physics into practice, making a good combination of the two.

In real football, we can better understand the characteristics of flying path of football by practising on adjusting the power, direction or kicking position. The computer simulation technology made mechanics model verification easier. This is proven by the simulation path in this paper, which is critical to understand and use the spinning technique.

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