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The Using of Fluid Mechanic in Badminton Shuttlecocks' Design

Mubai Chen

Zhangjiagang IVY Experimental School, Suzhou, China
chenmubai262@gmail.com

Abstract. Today, badminton has become one of the world most popular sports, which is accompanied by a large demand on badminton shuttlecocks. The shuttlecock's special skirt hem structure makes its fluid mechanics greatly different from tennis and football. This thesis systematically overviews the use of Bernoulli's equation and Reynolds number in shuttlecock design and the reasons for the shuttlecock's special movement in the air. First, it records that the Reynolds number of badminton is around 10^4 to $10^5$and its drag coefficient remains nearly a constant number(≈0.6-0.7) over a wide range of speed.Second, the article shows the Bernoulli pressure difference around the shuttlecock, caused by its auto rotation, leading to curvilinear flight trajectory. Future research should concentrate on using the knowledge of fluid mechanics to produce shuttlecocks that have a smooth flight trajectory and steady moving speed at a lower manufacturing cost. The thesis aims to conclude recent shuttlecock's designing features and point out future research directions for shuttlecock designers.

Keywords: Bernoulli's equation, reynolds number, drag coefficient, auto rotation

1. Introduction

As we all know, badminton is the fastest racket sports in today's world. A recent research in2021 showed the highest moving speed of badminton shuttlecock can even achieve 137m/s in a second [1]. This amazing speed is attributed by its special open racket head structure made from natural goose feathers, or human made Polyamide (PA), Thermoplastic Polyurethane (TPU) and Polyethylene Terephthalate (PET). This structure makes badminton shuttlecock has a very different fluid mechanic behavior from other balls. In general, badminton shuttlecock's flying trajectory is determined by two classical fluid mechanic concept:Bernoulli's equation and Reynolds number. Bernoulli's equation can explain the relationship between velocity and pressure. This is the reason why badminton shuttlecock may make a turn or floating in the air. It is usually caused by the difference in pressure around the shuttlecock. While Reynolds number can help to make a judgement on the fluid state (laminar flow or turbulence), This factor can determine the characteristic of fluid resistance and drag force, which can help to improve the behavior of shuttlecocks in specific condition. Following this introduction, Section 2 presents the basic definitions of Bernoulli's equation and Reynolds number. Section 3 then examines how Reynolds

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number influences shuttlecock flight, while Section 4 focuses on the role Bernoulli's equation plays in its trajectory. Section 5 compares the aerodynamic behaviour of shuttlecocks with that of other sports balls, and Section 6 discusses practical implications before providing a brief summary.

2. The using of Bernoulli's equation and Reynolds number in shuttlecock

Bernoulli's equation is P $+\frac{1}{2}\rho v^2+\rho g h=C$. In this equation, P means static pressure. Static pressure is the pressure exerted by a fluid at rest or the pressure acting perpendicular to the flow direction, independent of the fluid's velocity. It is measured by a wall tap normal to streamlines [2]. ρ means fluid density(kg/ m^3). v means the fluid velocity. $\frac{1}{2}\rho v^2$ means dynamic pressure. Dynamic pressure is the kinetic energy per unit volume of a flowing fluid.It represents the additional pressure produced by fluid motion. g is gravity and h is height.C is a constant.The value of the equation is proving when fluid velocity is fast, the pressure of the fluid will be low.But it can only be affective in following conditions:steady flow,incompressible fluid,inviscid flow and single streamline.The equation can be used to explain Magnus effect in some balls' trajectory. Some sports balls have a curved flight path when spinning at a high speed, this is caused by the pressure difference on both sides of the ball.

Reynolds number represents the ratio of inertial forces to viscous forces in a fluid flow [2]. It is used to predict the transition from laminar flow to turbulent flow. It can be expressed as: $Re=\frac{\rho v L}{\mu}=\frac{v L}{v}$ .In the equation, ρ is fluid density, v is fluid velocity, L is characteristic length, μ is dynamic viscosity, ν is kinematic viscosity.If Re<2300, it is laminar flow,if Re>4000,it is turbulence.The Reynolds number can measure the air condition around the badminton shuttlecock and resistance exerts on it.

When the badminton ball is moving, the two concepts will both effect on it. Bernoulli's principle determine the air pressure distributed around the shuttlecock and Reynolds number determine the condition of the air flow close to the it.

Through the past research, the badminton shuttlecock is at turbulence flow (Re> 10^4) at a full speed, according to The Physics of Badminton [3]. For many objects, its drag coefficient usually is not a constant and will show obvious fluctuations with the change of Reynolds number. It is usually called absence of drag crisis. Smooth sphere's drag coefficient will fall dramatically when Re $\approx 4\times 10^5$ [4]. However, badminton shuttlecock is different. According to reference [5], not only spinning but also statically fixed badminton shuttlecocks 's drag coefficient do not depend on the change of Reynolds number. This is because of the shuttlecock skirt structure. The structure looks like a parachute, when it moves at a high speed, the air impacts the head of the shuttlecock and forms a high pressure area. While the porous feather allow some air pass through it and form a stable low pressure area. The structure will lead to a big pressure difference in resistance between front and back, and overshadow the tiny effects caused by Reynolds number's change. This means the speed of badminton shuttlecocks will not show a sudden heap, and the deceleration of it will be more smoothly.

When badminton shuttlecock is moving up, even without any spins, it will also have a small lift force. The Bernoulli's principle can explain this phenomenon. This is because the velocity of the upper side of the shuttlecock is bigger than the lower side's velocity. According to the Bernoulli's equation, the fluid pressure is lower if the fluid velocity is higher. So the upper is side has a smaller pressure compared to the lower side. As a result, there will be a small lift force exert on the shuttlecock. Furthermore, the lift force is different when the shuttlecocks have different attack angles. According to reference [6], the lift force will increase by the increase in angle of attack.

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In some international badminton competitions, the badminton show a curved trajectory in the air and confuse opponents. This is because the player hit the shuttlecock at the edge side of badminton racket and make the shuttlecock start self spinning at a high speed.The quick spinning will make the velocity of one side of the shuttlecock increase and the opposite side decreases. According to Bernoulli's principle, there will be a pressure difference on the two sides and caused a lateral force act on the shuttlecock. So, the shuttlecock will display a curved trajectory.

Many special features of shuttlecock is caused by a particular trait:the center of mass is few centimeters in front of its center of pressure. According to The Physics of Badminton [3], the distance of two centers is about 3cm.The position of two centers make shuttlecocks have static stability. So, when the shuttlecocks have angle of attack in the moving and unequal distribution of air pressure, the shuttlecocks will generate a restoring moment. This can correct the moving direction and make the shuttlecocks' trajectory looks direct in vertical plane.

In the final part of the trajectory, shuttlecock decelerates in horizontal and falls vertically. Figure 1 shows the structure of feather badminton. It always find that the badminton shuttlecock seems float in the air and make it difficult to hit the shuttlecock. This phenomenon is because Reynolds number decreases to transition area from turbulence. According to reference [7], through wind tunnel experiments, the drag coefficient of shuttlecock will change when Re ≈ 86000,which is the final part of the trajectory. The change will lead to a sudden change in air resistance. So the trajectory of shuttlecock will be difficult to predict.

There are also many sports ball in the world, but most of the balls choose the traditional sphere structure, only have the differences in size, mass and materials. For tennis ball, it has Reynolds number in 10^4 ~10^5 [8]. For footballs, they have different Reynolds number between 2.2×10^5~3.3×10^5 [9]. Not only these two,thousands of balls have different Reynolds number from shuttlecocks. Besides, the change of drag coefficient of other sports balls are quite different from shuttlecock. For example, shuttlecock's c_D is nearly a constant number, but football's will change in a larger range and appear drag crisis [10]. The feature can make shuttlecock's deceleration is easier to predict compare to other sports balls. Moreover, shuttlecock has restoring torques caused by its skirt structure that most sports balls do not have,this makes the trajectory of shuttlecock more stable than others.

Figure 1. The structure of feather badminton

Today, company manufactures shuttlecocks with 16 feathers. The design is not only because of symmetry, but also many considerations about Reynolds number. If the quantity of feather is smaller, Re will decrease and make drag coefficient fluctuates largely. If quantity is bigger, the weight will increase and make the shuttlecock has too big inertia, which make it easy to hit the shuttlecock beyond the field. These are not good for a comfortable playing experience. Usually, high quality shuttlecocks' feathers are made from goose feather. Compared to human made feathers, it has a rougher surface. This contributes to a bigger Bernoulli's effect that make the hits have certainty.

In some dry areas, people usually steam the shuttlecocks. This is because shuttlecocks do not have enough wetness, the feathers are too dry and brittle. After adding suitable amount of water, the feathers will be soft and smooth. However, this method will change the trajectory of the ball as the shape of shuttlecocks have been different, which hinders to see the players steam the shuttlecocks in big competitions.

The Reynolds number can also explain the players' strategy. It is normal see some players hit high clear in the competition to disrupt the opponent's rhythm. This uses the feature that shuttlecocks have low Re at low velocity. And the shuttlecocks will display floating effect that will move farther. While some players choose smash to get score a point. This is based on the stable resistance at high Re number at high speed to let shuttlecocks move in a direct line.

3. Conclusion

The article explains the use of Reynolds number and Bernoulli's principle in shuttlecocks. When the shuttlecocks are in turbulence, the drag coefficient can be regarded as a constant($\approx 0.6-0.7$).The shuttlecocks also have curved trajectory caused by self spinning ,and the pressure difference generated will form storing torques to stabilize its trajectory.Many differences between shuttlecocks and other sports balls is because of its unique skirt structure.The research find that the researches in shuttlecocks at low Re and transition area is not thorough.The writer hopes more researches will be developed in human made feature materials and more accurate experiments in low Re wind tunnel tests.Overall ,Bernoulli's principle and Reynolds number are the basic tools for delving shuttlecocks. They are also the perfect example of connections between physics and sports.

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