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Unique Flight Features of Shuttlecock

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Abstract: *Badminton is crowd pleasing racquet sport. Unlike other racquet sport the projectile shuttlecock has highly unique flight features. These unique flight characteristics of shuttlecock have interested many researchers for number of years. Question that arise in my study are what makes the flight features of a shuttlecock so unique and how these unique features of a shuttlecock work in badminton game. Here in this paper we will highlight the versatile behavior of shuttlecock. Shuttlecock glides with a pure drag trajectory. Trajectory of shuttlecock is completely different from the parabola. So the first section concerns the trajectories of the shuttlecock at the scale of badminton court. Shuttlecock always flies keeping its snout ahead. In second section we will study how the canonical shape of shuttlecock helps it to flip after the impact with racquet. The third section will cover the study, how the flight of shuttlecock depends upon its geometry. And finally we will study how these flight features of shuttlecock influences the game of badminton.*

Key Words: Shuttlecock, Badminton, Unique flight features, Racquet, Aerodynamics of shuttlecock, Drag etc.

1. Introduction:

1.1 Badminton:

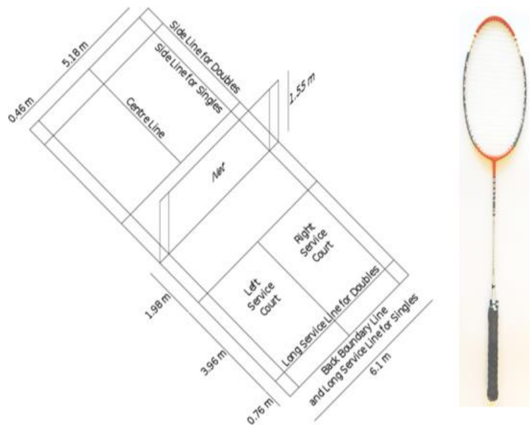
Badminton is popular racquet sport. Since 19th century badminton is played with shuttlecock. The name of the game badminton was derived from the Duke of Beaufort's Badminton House in Gloucestershire. Badminton is played either by two single opposing players or between a team of two doubles. Each player stands on the opposite halves of a rectangular court. This rectangular court is around 13.5 meters long and 5.2 meters wide. This rectangular court is divided be a net of height 1.55 meters as shown in fig 1(a). In the game badminton players score points by striking the shuttlecock by their racquets. After the impact by racquet, shuttlecock passes over the net and lands in the half court of the opponent player. Each player can strike the shuttlecock only once before it passes over the net dividing the rectangular court. A session ends during the game when shuttlecock hits the floor of court or any one of players, judges or umpire commits an error. It was observed that a badminton game lasts about one hour in each set of 20 min. The tactic behind the game badminton consists of an appropriate shuttlecock trajectory, which passes over the net and falls in the half court of opponent player and to minimize the time for reaction of opponent players.

1.2 Racquet:

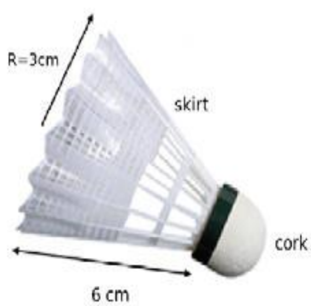
Racquet is an equipment that we use in game badminton consists of a handle and an open loop across which a web of catgut is stretched tightly as shown in fig 1(b). It is used to strike the shuttlecock. The frame of racquet was traditionally made of wood and strings of animal intestine known as catgut. The traditional racquets of wooden frame were limited by strength and weight. After that wooden frames were replaced by laminated wood to improve stiffness. Now most of the racquets are made of material like carbon fiber, titanium alloys or ceramics. Carbon fiber has outstanding strength to weight relation and it gives excellent transfer of kinetic energy. Catgut has been replaced by synthetic material like nylon polyamide and other polymers. Racquets can be restrung when it is required, which may be after every match for the professionals. There are wide varieties of designs of racquets but the size and shape of the racquets are limited by commandments of badminton. Nowadays nanomaterial like carbon nanotubes and fullerene are being added to racquets to give them superior stability.

1.3 Shuttlecock:

A shuttlecock is a high drag projectile with an open canonical figure of weight around five grams. The property of shuttlecock to break the spherical symmetry unlike other sport balls allows it to flip after the impact with racquet and to fly the cork of shuttlecock ahead. A shuttlecock flies with a pure drag trajectory. The cone of shuttlecock is formed by around sixteen overlapped feathers laced together by thin threads. One end of these feathers are attached firmly together to round base cork, giving the shuttlecock its beautiful flowery shape and aerodynamics properties. The cork is covered with a thin leather or synthetic material. The feathers of shuttlecock create much higher drag and cause the shuttlecock to decelerate more rapidly. The approximate cross- sectional area of skirt of feather is given by $S = \pi r^2 = 30\ cm^2$ as shown in fig 1(c). During the game shuttlecock can move at very high velocity of around 100meters per second. The speed of 117 meters per second was achieved by Malaysian Tan Boon Heong that has been recorded in Guinness book of wood records as fastest smash of the world. These huge velocities of shuttlecock make the badminton one of the fastest sports among all.



(a) (b)



(c)

Fig1 (a) Figure of badminton court. (b) A badminton racquet. (c) An example of feathered shuttlecock

1.3.1Types of Shuttlecocks:

Players in game badminton use commonly two types of shuttlecocks. Shuttlecocks are also abbreviated as shuttle or birdie in game badminton. The professional players prefer to play with feathered shuttlecock whereas recreational players may be seen playing with synthetic shuttle.

1.3.1(a) Feathered Shuttlecock:

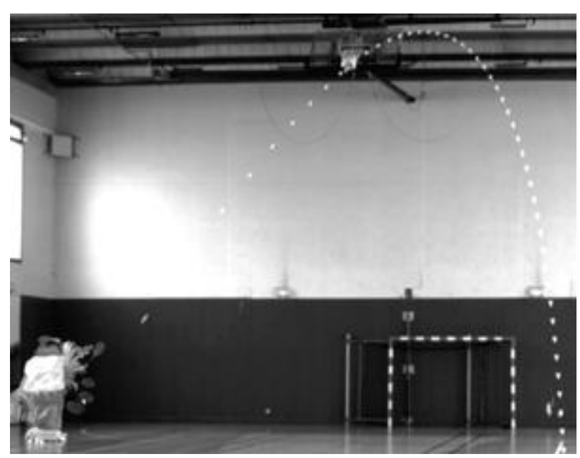
Feathered shuttlecocks are made from the feathers of only the left wings of ducks or geese. Feathered shuttlecocks are very light in weight only around 4.5 to 5.5 grams. Shuttles have 14-16 feathers with each feather 70 mm in length, laced together to give a look of skirt. The diameter of round base cork is around 25-28 mille meters and diameter of the skirt of the shuttle is around 54 mille meters. Feather shuttlecocks are very delicate and don't last for many rounds. Expert players prefers feathered shuttle because they claim that feathers are easy to control and put a smaller amount strain on shoulders, so they don't need to be hit much harder with the racquet. In tournaments only feathered shuttles are used as it poses lower drag coefficient at lower speed and high drag coefficient at higher speeds. Feathered shuttles are preferred as they are capable of rapid acceleration and deceleration. Using a fathered shuttle, a player can hit bang at higher speeds, which allows the less time for the opponent to react.

1.3.1(b) Synthetic Shuttlecock:

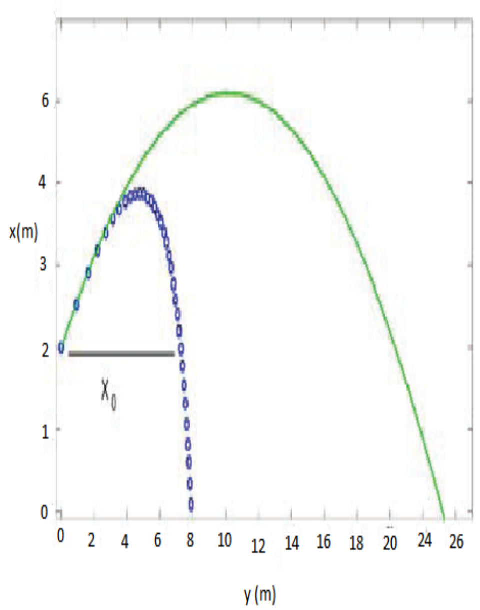
Synthetic shuttlecocks have advantage that they last much longer as compared to feathered shuttlecocks. Synthetic shuttlecocks have complex aerodynamics behavior than a feathered shuttlecock. They can not move as quickly but are far better for maintaining whatever speed they gain.

2. Trajectories of a Shuttlecock:

Being a cheery body, a shuttlecock produces high aerodynamic drag and a steep flight trajectory. The flight trajectory of a shuttlecock is significantly different from the balls used in most racquet sports due to very high initial speeds that decay rapidly due to high drag produced by the feathered skirt. The parabolic flight trajectory is twisted greatly and thus fall of shuttlecock has much sharper angle than rise. By understanding of trajectory of shuttlecock speed, time, direction and path can be predicted and this information can be helpful for training of players.



(a)



(b)

Fig2 (a) High clear chronophotography. Each frame are separated by 20 milliseconds.
(b) Trajectory of shuttlecock (blue circles) compared with the parabola (green line)

2.1 Experimental study of shuttlecock's trajectory:

Trajectories of shuttlecock were studied by high speed cameras [1]. A similar work was done by A.J. Cooke [2][3]. One of the observations captured by high speed camera is shown in fig 2(a). It is clear from the fig 2(a) that initially trajectory of shuttlecock is a straight line. After that high deceleration of the shuttlecock was observed because of air friction at high Reynolds number. Gravity curves the trajectory when the speed is enough low and finally the weight become dominant and the shuttle falls closely vertical. Comparison of experimental observed trajectory of shuttlecock with the expected trajectory in pure gravitational limits without air friction is shown in fig 2(b). Unlike parabola, the observed trajectory of shuttlecock is highly asymmetrical and range is significantly lower. The deviation in trajectory is due to the natural spin of the shuttle because of its canonical shape as well as the significant amount of drag due to air friction. As the shuttle approaches its highest it start deviate from the parabolic path. The shape of trajectories was drawn by Tartaglia when he looked at the cannon balls trajectories [4].

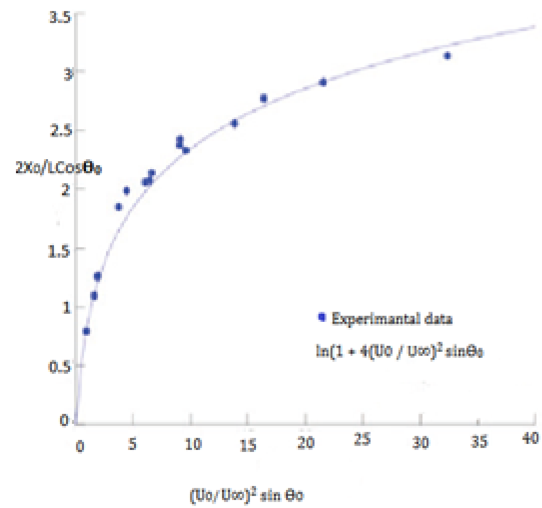


Fig3. Reports of experimental observations showing that non dimensional range of shuttlecock depends upon non dimensional square velocity.

2.2 Theoretical study of shuttlecock's trajectories:

Air applies no lift on shuttlecock and drag coefficient of shuttlecock is constant for Reynolds number of typical game. The dynamics for shuttlecock will be expressed by the following equation [5]

$$m\frac{d\vec{U}}{dt} = m\,\vec{g} - \frac{1}{2}\varrho S C_D\, U\vec{U} \qquad (1)$$

The above equation contains 3 terms which are inertia, gravity and drag. As the trajectory began, the early velocity is high as the drag force. In this condition the effect of gravity could be neglected. Because of this, shuttlecock flies in a straight line and decelerates. At the point where the velocity reduces enough and drag becomes equivalent to the weight of shuttlecock, gravity curves the trajectory. And finally shuttlecock tends toward a steady state where its weight counterbalances the drag by air and its velocity becomes collinear to the gravity. In this regime velocity of shuttlecock is:

$$U_\infty = \sqrt{gL} \qquad (2)$$

Where 'L' is aerodynamic length given by:

$$L = 2m / \varrho S C_D \qquad (3)$$

Clanet and al. [6] solve analytically the equation of dynamics of shuttlecock in air and they found that range of shuttlecock depends on its initial velocity, angle and aerodynamic length.

$$X_0 = \frac{L\cos\Theta o}{2}\ln(1 + 4(\frac{U0}{U\infty})^2 \sin\Theta_0) \qquad (4)$$

Where:

m – Mass of shuttlecock.
R - Radius of cross section of shuttlecock.
S – Shuttlecock's cross section.
C_D – Drag Coefficient of shuttlecock
U – Velocity of shuttlecock
U_∞ - Terminal velocity of shuttlecock for free fall.
U_0 – Initial velocity of shuttlecock.
Θ_0 – Initial angle of shuttlecock with the horizontal.
ϱ – Density of air
L – aerodynamic length.

2.3 Comparison between theoretical study and experimental observation of shuttlecock's trajectory:

From different shoots of shuttlecock with different initial velocities and different angle, range of shuttlecock was observed. Range is the distance over which the shuttlecock is again at initial height. Fig.3 shows the results of experimental observations. It shows that non dimensional range $\frac{2Xo}{L\cos\Theta o}$ depends upon non dimensional square velocity $(\frac{U0}{U\infty})^2 \sin\Theta_0$. The aerodynamic length of the shuttlecock used in the experiment was found out by determining the terminal velocity after a long free fall. From equation (4) saturation of range for high velocities was observed. It was observed that high increase in initial velocities does not provide high increase in range of shuttlecock. Thus in condition of high initial velocities shuttlecock range scales in aerodynamic length. The measurement of this length allows us to predict about the behavior of shuttlecock in the game.

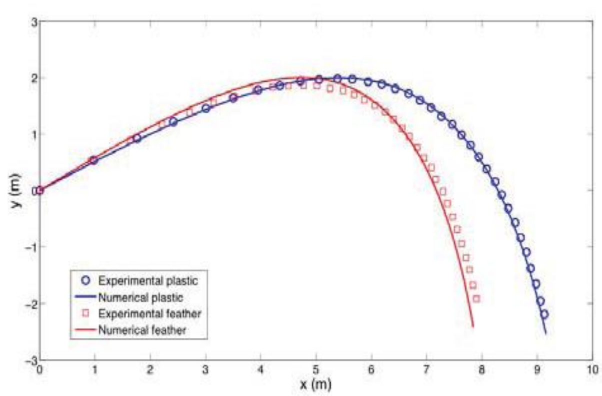


Fig4. Trajectories of Feathered and Plastic shuttlecock for same initial conditions

2.4 Comparisons between trajectories of plastic and feather shuttlecock:

Badminton performers always prefer feathered shuttlecock because of smaller and more curved trajectories of feathered shuttlecock in comparison to trajectories of plastic shuttlecock. Fig4 shows the trajectories of feathered and plastic shuttlecock for same initial settings. It can be observed from Fig4 that trajectories for feathered and plastic shuttlecock have alike shape but different range. The range of feathered shuttlecock is lower than the range of plastic shuttlecock. Equation (1) was numerically solved for both feathered and plastic shuttlecock and aerodynamic length for both kind of shuttlecock was measured. Solutions of equation (1) for both feathered as well as plastic shuttlecock are represented by the solid lines in Fig4; they are in good settlement with experimental trajectories. This results in conclusion that there is no difference in the shape of plastic and feathered shuttlecock trajectory but only in aerodynamic length so is the difference in the ranges of plastic and feathered shuttlecock.

3. Flipping behavior of shuttlecock :

When we talk about the flying projectiles, the shuttlecock is unusual in that because it flips on impact with a racquet as it always flies with its nose ahead. The cause of flipping of a shuttlecock unlike other projectiles is its canonical shape. These unique features of a shuttlecock have encouraged many researches on the science behind the shuttlecock trajectories over the years. Shuttlecock has distinct center of mass and center of pressure [7]. This makes the shuttlecock to flip on impact with racquet. It was found that a typical shuttlecock has its center of mass about 3.4 cm in front of its center of pressure. As cork of shuttlecock is denser than skirt of shuttlecock so the center of mass of shuttlecock is near to its cork. Aerodynamic center or center of pressure can be thought as the point where drag is exerted. In shuttlecock, aerodynamic center is near to the center of shuttlecock. When shuttlecock is not aligned with its direction of velocity the drag force by air is applied on the center of pressure and applies a stabilizing torque to the shuttlecock. This torque is responsible for the shuttlecock to flip. Thus distinguishable centers of mass and center of pressure cause the shuttlecock to exhibit its unique stabilizing aerodynamic torque and its flipping behavior.

3.1 Experimental behavior of flipping behavior of shuttlecock:

Unlike other flying projectiles a shuttlecock has flipping behavior because it lacks in spherical symmetry. During the badminton game players hits the cork of shuttlecock rather than its cork. Flip of a shuttlecock was noted by some physicists with a high speed camera which is shown in Fig5. It can be observed from the figure that shuttlecock never turns by 360^0. It was experimentally observed that shuttlecock takes 20 milliseconds to flip. Afterwards symmetry axis of shuttlecock oscillates in comparison to direction of its velocity and finally its direction stabilizes along direction of its velocity and its time of around 200 milliseconds.

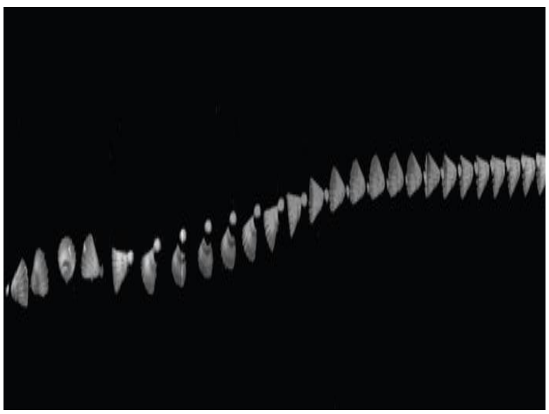


Fig5. Recording of flipping of shuttlecock by high speed camera after an impact with racquet. Here the racquet comes from the left of fig.

4. Influence of shape of shuttlecock on its flight:

Now we will discuss here how the shape of shuttlecock affects the aerodynamics of a shuttlecock. Here we will existence of optimal opening angle of shuttlecock for faster flipping motion. To find the ideal value of shuttlecock opening angle experiment was performed by Cohen [8] with same mass and diameter but with different opening angles. To reduce the length scale these experiments were performed in the water. Reynolds number was also reduced but was kept > 10^3 and flipping time and stabilizing time were recorded and plotted for different opening angles. Dependency of flipping and stabilizing time on shuttlecock opening angle was observed. The shuttlecock is extended for small opening and moment of inertia of skirt is high. In this regime it is hard to set shuttlecock in motion and flipping and stabilizing time is high. For large opening angles, shuttlecock is tiny. This will also results in large flipping and stabilizing time. Between these two conditions, there is a choice of shuttlecock opening angles for which spinning time will be less. The shuttlecocks which flip fast fit in this intermediate range of opening angle.

5. Conclusion:

The following are the conclusions that have been made on the basis of study presented here are:

1. Being a cheery body, a shuttlecock produces high aerodynamic drag and a sharp flight trajectory. The parabolic flight trajectory is twisted greatly and thus fall of shuttlecock has much sharper angle than rise.
2. Trajectories for feathered and plastic shuttlecock have comparable profile but different range. The range of feathered shuttlecock is inferior to the range of plastic shuttlecock.
3 Because of the canonical shape of shuttlecock it has distinguishable center of mass and center of pressure and it always flies with its cork ahead and flip after the impact with racquet.
4. There exist optimal opening angles for which shuttlecock can flip faster.

Acknowledgement:

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