Flight trajectory simulation of badminton shuttlecocks

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Abstract

The aerodynamic behavior of badminton shuttlecocks differs considerably from other ball, racket or projectile sports. Being a bluff body, the shuttlecock generates high aerodynamic drag and steep flight trajectory. Despite the popularity of the badminton game, scant information is available in the public domain about shuttlecock aerodynamics and its flight trajectory. The primary objective of this work was to construct the flight trajectory of a synthetic and feather shuttlecocks for a range of wind speeds under non-spinning condition based on aerodynamic data obtained experimentally.

1. Introduction

Badminton is one of the oldest and popular sports in the world. Today over 160 countries have officially joined the Badminton World Federation (BWF) - a governing body of the game. Currently according to the BWF estimates, the game is played by over 200 million people worldwide and over thousand players participate in various competitions and tournaments around the world. The projectile of Badminton game is the shuttlecock. It is made of either natural feathers or synthetic rubber with an open conical shape (described and shown later). The cone comprises of 16 overlapping goose feathers embedded into a round cork base which is covered generally with a thin goat leather or synthetic material.

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Unlike most racquet sports, a badminton shuttlecock is an extremely high drag projectile and possesses a highly skewed parabolic flight trajectory. Most amateur players use synthetic shuttlecock as it lasts longer and costs less (cheaper) compared to feather shuttlecock which is predominantly used by the professional players and have high initial velocity. Generally, three types of synthetic shuttlecocks (distinguished by color code) are available in the market. They are: a) Green shuttlecock (for slow speed), b) Blue shuttlecock (for middle speed), and c) Red shuttlecock (for fast speed). Frequently, the red shuttlecock is used in colder climates and the green shuttlecock is used in warmer climates.

In spite of the enormous popularity of Badminton game, the aerodynamic behavior of the shuttlecock is not clearly understood and well studied. Its flight trajectory is significantly different from the balls used in most racquet sports due to very high initial speeds (highest speed is 332 km/h by Chinese player Fu Haifeng in 2005) that decay rapidly due to high drag generated by feathers or rubber skirts. While some studies by Alam *et al.* [1, 2], Mehta *et al.* [3], Smits and Ogg [4] and Seo *et al.* [5] were conducted on spherical and ellipsoidal balls, no study except Cooke [6] and more recently by Alam *et al.* [7] was reported in the public domain on shuttlecock aerodynamics. The knowledge of aerodynamic properties of shuttlecocks can greatly assist both amateur and professional players to understand the flight trajectory as player requires considerable skills to hit the shuttlecock for the full length of the court. The parabolic flight trajectory is generally skewed heavily thus its fall has much steeper angle than the rise. The understanding of aerodynamic properties can significantly influence the outcome of the game. Therefore, the primary objective of this work is to experimentally determine the aerodynamic properties of a series of shuttlecocks (synthetic and feather made) under a range of wind speeds, and compare their aerodynamic properties and built flight trajectories for a synthetic and feather shuttlecocks.

Nomenclature

F_D	Drag Force
C_D	Drag Coefficient
Re	Reynolds Number
V	Velocity of Air
ν	Kinematic Viscosity of Air
ρ	Density of Air
A	Projected Area
d	Shuttlecock Diameter

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2. Experimental Procedure

A brief description of badminton shuttlecocks, experimental facilities and set up is given in the following two sub sections.

2.1. Shuttlecock description

As mentioned previously, the feather shuttlecock is made of 16 goose fathers with a skirt diameter of 65mm, mass is around 5.2 grams (g) and total length is approximately 85mm. Figure 1 shows general

features of a standard feather shuttlecock. A typical feather shuttlecock and synthetic shuttlecock are shown in Figure 2.

As part of a larger study, twenty new shuttlecocks were initially selected. However, only 10 shuttlecocks (five feather shuttlecocks and five synthetic shuttlecocks) were used in this study. These 10 shuttlecocks are: a) Grays nylon, b) Grays plastic, c) Grays volante, d) Mavis – Yonex 500, e) RSL standard, f) Grays volant en plumes, g) Yonex mavis 350, h) RSL silver feather, i) Arrow 100, and j) RSL classic tourney. The dimensions of all these shuttlecocks can be found in Alam *et al.* [1].
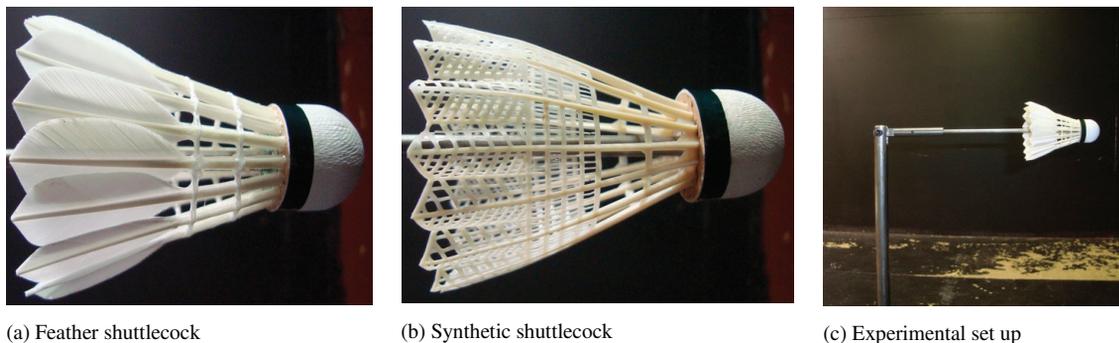

(a) Feather shuttlecock   (b) Synthetic shuttlecock   (c) Experimental set up

Fig. 1. Types of shuttlecock [1].

2.2. Wind tunnel testing

A sting mount was developed to hold the shuttlecock on a 6-component force sensor. The mounting gear and experimental set up in the test section are shown in Figure 3. The aerodynamic effect of sting on the shuttlecock was measured and found to be negligible. The distance between the bottom edge of the shuttlecock and the tunnel floor was 420 mm, which is well above the tunnel boundary layer and considered to be out of significant ground effect.

In order to measure the aerodynamic properties of the shuttlecock experimentally, the RMIT Industrial Wind Tunnel was used. The tunnel is a closed return circuit wind tunnel with a maximum speed of approximately 150 km/h. The rectangular test section's dimension is 3 m (wide) $\times$ 2 m (high) $\times$ 9 m (long), and is equipped with a turntable to yaw the model. The stud (sting) holding the shuttlecock was mounted on a six component force sensor (type JR-3), and purpose made computer software was used to digitize and record all 3 forces (drag, side and lift forces) and 3 moments (yaw, pitch and roll moments) simultaneously. More details about the tunnel can be found in Alam et al. [9].

The aerodynamic drag coefficient (C_D) is defined as: $C_D=D/0.5\rho V^2 A$, where A is calculated as projected frontal area of shuttlecock without any deformation. The Reynolds number (Re) is defined as: $Re=Vd/\nu$. The lift and side forces and their coefficients were not determined and presented in this paper. Only drag and its coefficient are presented here. In addition, the flight trajectories of a feather and synthetic shuttlecock based on C_D experimentally measured in this study using the trajectory motion equations developed by Chen *et al.* [10] have been developed. These equations are:

$$y = \frac{v'^2 t}{g} \ln\left(\frac{\sin\left(\frac{v't}{vxi}(e^{\frac{gx}{v'^2 t}} - 1) + \arctan\left(\frac{v't}{vyi}\right) \right)}{\sin(\arctan \left(\frac{v't}{vyi}\right))} \right) \qquad (1)$$

$$v' \, t = \left(\frac{mg}{b} \right)^{\frac{1}{C_D}} \tag{2}$$

$$vxi = vi\cos(\theta) \tag{3}$$

$$vyi = vi\sin(\theta) \tag{4}$$

A further detail about these equations can be found in Chen *et al.* [10].

3. Results and Discussion

Shuttlecocks were tested at 40 to 130 km/h speeds with an increment of 10 km/h. The shuttlecock was fixed relative to the force sensor (which was fixed with its resolving axis along the mean flow direction) thus the wind axis system was employed. The aerodynamic force was converted to non-dimensional parameter (drag coefficient, C_D) and tare forces were removed by measuring the forces on the sting in isolation and removing them from the force of the shuttlecock and sting. The influence of the sting on the shuttlecock was checked and found to be negligible. The repeatability of the measured forces was within ±0.01 N and the wind velocity was less than 0.5 km/h.

The C_D values for all synthetic and feather shuttlecocks were averaged. The average C_D values as a function of Reynolds numbers are shown in Figure 2. The average C_D value for all shuttlecocks is lower at low Reynolds number initially and increases with an increase of Reynolds numbers. However, the C_D value drops at 80 km/h and above. The figure also indicates a significant variation in drag coefficients between the synthetic and feather shuttlecocks at high speeds (above 80 km/h) which is believed to be due to varied geometry of skirts and deformation at high speeds. As expected, the variation in C_D is minimal for the feather shuttlecock at high speeds due to less deformation. Although the average C_D value for feather shuttlecock and synthetic shuttlecock is the same at lower speeds, the C_D value is significantly lower with an increase of speeds above 80 km/h for the synthetic shuttlecock. As mentioned earlier, it is mainly due to skirt deformation of the synthetic shuttlecock. The findings agreed well with the previously published data by Alam et al. [1, 8]. In this study, a sudden drop in C_D value is noted at 90 km/h which is little unusual. A further study is underway to clarify it.
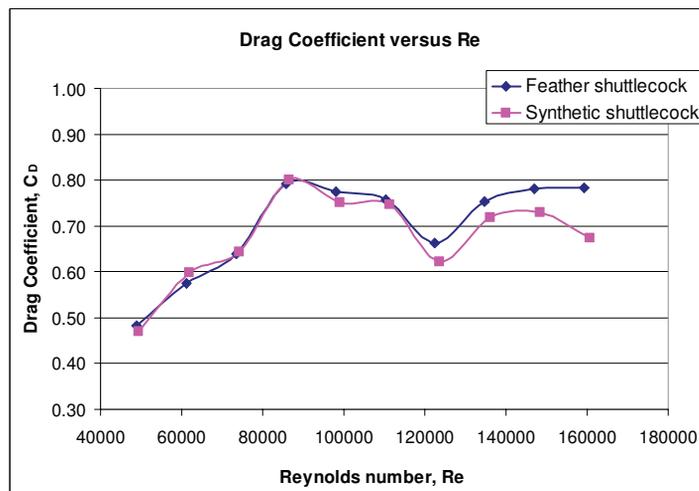

Fig. 2. Comparison between standard feather and synthetic shuttlecocks

Based on the average C_D value, a flight trajectory for feather and synthetic shuttlecocks for a range of speeds (40, 70, 100 & 130 km/h) without considering any spin effects has been developed using trajectory equations described by Chen et al. [10]. These flight trajectories are indicative only as no in-depth analysis on these equations has been conducted. The 'b' value is assumed to be 11 although a detailed analysis of 'b' value is required. The 'n' value was used from this study. These flight trajectories are shown in Figure 3. The flight trajectories agree relatively well with Cooke's findings [7]. The flight trajectories indicate that the feather shuttlecock possesses more steep curves at the end of its flight than the synthetic shuttlecock. Consequently, the horizontal distance is much shorter for the feather shuttlecock compared to the distance of the synthetic shuttlecock. Additionally, the altitude for the synthetic shuttlecock is also higher than that of the feather shuttlecock. It may be noted that the initial speed and lunch angle were the same for synthetic and feather shuttlecocks.
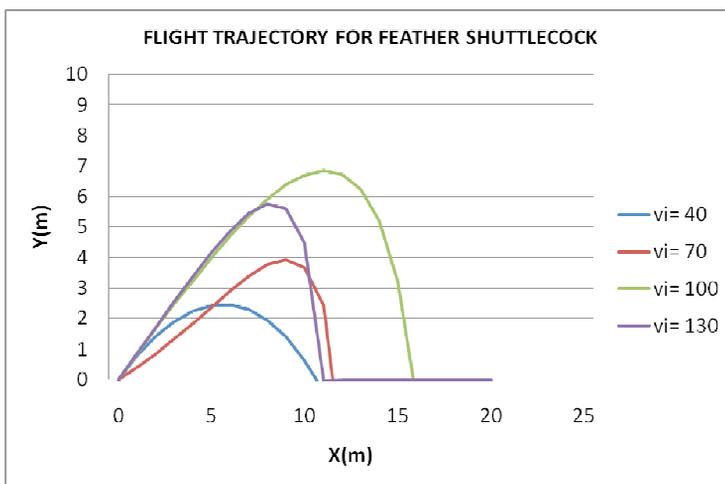
(a) Standard feather shuttlecock
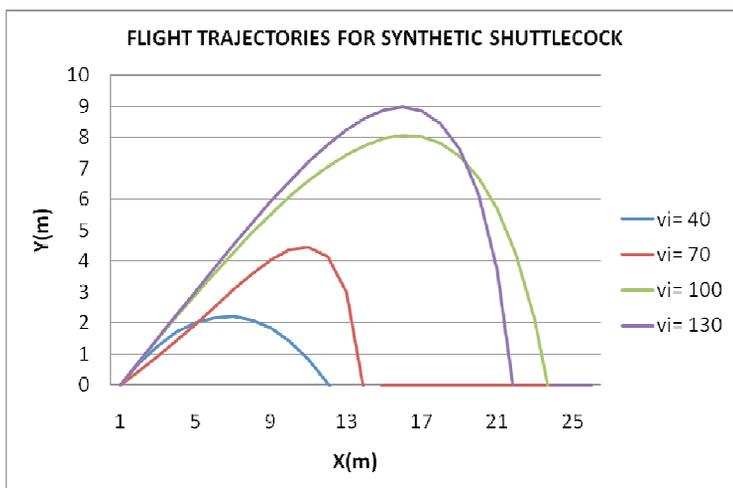
(b) Synthetic shuttlecock

Fig. 3. C_D as a function of Reynolds number.

4. Conclusions

The following conclusions have been made based on the experimental study presented here:
- The average drag coefficient for feather and synthetic shuttlecocks is approximately 0.60 below 60 km/h, however significantly higher for feather shuttlecocks compared to synthetic shuttlecocks at speeds over 80 km/h.
- The synthetic shuttlecock is subjected to higher deformation at high speeds compared to the feather shuttlecock and consequently generates the lower aerodynamic drag.
- The product, process and materials can be optimized for the synthetic shuttlecocks to avoid the deformation at high speeds so that a true replication of feather shuttlecocks can be achieved.
- The end of flight trajectory is much steeper for feather shuttlecocks than synthetic shuttlecocks due to significantly higher drag at high speeds.

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