Aerodynamic properties of a shuttlecock with spin at high Reynolds number

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Abstract

The badminton shuttlecock has the smallest ballistic coefficient and exhibits the largest in-flight deceleration of any airborne sporting implement. In the present study, measurements of aerodynamic forces are performed at high Reynolds numbers, and the effect of shuttlecock deformation on aerodynamic properties was also investigated. A shuttlecock skirt has an array of diverging stems, whose ends are at the convergent end of the skirt, joined together in an end-ring. Furthermore, the shuttlecock rotates about shuttlecock’s major axis in actual flight, and the experiments are performed by the shuttlecocks with and without rotation (spin). The effect of the flow passing through the gap between slots (stiffeners) located at leg portion of the shuttlecock skirt on aerodynamic characteristics is also demonstrated by using no-gap shuttlecock model, which is completely covered with cellophane tape. The free rotation rate of a shuttlecock increases with increasing Reynolds number, and the drag coefficient gradually decreases over \( Re = 86000 \) for the shuttlecock with no rotation. On the other hand, the drag coefficient for the shuttlecock with rotation is almost constant over the whole range of Reynolds number in the present study because the deformation of shuttlecock skirt for the shuttlecock with rotation becomes smaller than that for the shuttlecock with no rotation. However, there is no significant difference in drag coefficient between the shuttlecocks with and without rotation in contrast to the difference in drag coefficient between the shuttlecocks with and without gap. The drag coefficient for the shuttlecock with no gap is significantly smaller than that for the ordinary shuttlecock (with gap). For an ordinary shuttlecock, the air flows through the gap in the shuttlecock skirt, and this flow is related to high aerodynamic drag.

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1. Introduction

The sport of badminton is one of the oldest and most popular sports in the world and has been the subject of research from the point of view of aerodynamic. The popularity of game is so immense that over 160 countries have officially joined the Badminton World Federation (BWF) - a governing body of the game. Its initial name “International Badminton Federation” was renamed as BWF. The shuttlecock has the smallest ballistic coefficient and exhibits the largest in-flight deceleration of any airborne sporting implement. In other words, the aerodynamic characteristics of badminton shuttlecocks are significantly different from balls used in other racquet sports. The centre piece of the game is no doubt a shuttlecock which is made of either natural feathers with an open conical shape. Being a bluff body, the shuttlecock generates significant aerodynamic drag and complex flight trajectory. Initial velocities of shuttlecocks in the range of 67 m/s are reduced in only about 0.6 sec to near the terminal velocity of roughly 7 m/s [1].

Unlike most racquet sports, a badminton shuttlecock is an extremely high drag projectile and possesses almost parabolic flight trajectory. The hand-manufactured feather shuttlecock was the only available badminton projectile, when the development of injection moulding as a manufacturing process had advanced enough to facilitate the production of synthetic shuttlecocks. Recently, it is not out of the question that shuttlecock may indeed be manufactured with the use of carbon fibre technology. However, top class players still prefer the feather shuttlecock and consequently these are used in all major badminton competitions. These players believe that the synthetic shuttlecock still does not behave like a feather shuttlecock. The aerodynamic drag of a series of feather and synthetic shuttlecocks under a wide range of wind speeds was measured to compare the results of synthetic shuttlecocks with feather shuttlecocks [2] [3]. The shuttlecock trajectories by the computer simulation was reported [4], and 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. However, for shuttlecocks, the mechanism of inducing high drag in flight has not been clarified yet.

In the present study, measurements of aerodynamic forces and flow visualization experiments are carried out in order to investigate the relationship between fluid forces and vortex behaviour around a shuttlecock at high Reynolds numbers (200 km/h). The effect of shuttlecock deformation on aerodynamic properties was also investigated because it is presumed that flight mechanics is affected by the deformation of shuttlecock skirt. The shuttlecock rotates about shuttlecock’s major axis in actual flight, and the experiments are performed by the shuttlecocks with and without rotation (spin). Furthermore, the effect of the flow passing through the gap between slots (stiffeners) located at leg portion of the shuttlecock skirt on aerodynamic characteristics is also demonstrated. Therefore, the shuttle was set up in the wind tunnel to examine the fluid force that acted on the shuttlecock, and the flow field was made visible with the measurement of the fluid force.

2. Experimental Apparatus and Method

The overview of the wind tunnel experimental set up is shown in Figure 1. The wind tunnel experiment was carried out by a low-turbulence wind tunnel at Tohoku University, Japan. The test section was octagonal, 0.29 m wide by 0.29 m high, and experiments were performed in the middle of the open part of the test section. The origins of coordinates $X$, $Y$, and $Z$ were defined as the centre of mass of a shuttlecock, and the distance of centre of mass from nose tip $X_0$ was 31.4 mm. The models were conducted using a real-size model of a shuttlecock. The shuttlecock is shown in Figure 2, with representative dimensions given in Table 1. The angle of attack $\alpha$ indicates angle between axis of symmetry and velocity vector in the $X$-$Y$ plane and defines the state that the cork was suitable for the
direction of the upstream as $\alpha = 0^\circ$. Shuttlecocks rotate about the major axis in flight (autorotation) because of a skirt structure having a diverging array of stems with overlapping feathers, and in the present study, all measurements were taken in the cases with and without rotation. Aerodynamic forces acting on a shuttlecock were measured by using a three-component balance (LMC-3501-50N, NISSHO-ELECTRIC-WORKS) connected with the shuttlecock support stick. The balance could simultaneously detect all of the lift and drag, pitching moment. The wind speed $U_0$ was set at 10 to 60 m/s corresponding to the Reynolds number $Re$ based on the skirt diameter $D$ of $43000 \sim 260000$. The smoke flow visualization experiments were performed at $Re=86000$ ($U_0=20$ m/s) to make the flow pattern visible around the shuttlecock and the Particle Image Velocimetry (PIV). A high speed camera (PIVCAM10-30; TSI) and an Nd-YAG laser (MiniLase II-30; NEW WAVE RESERCH Ltd) were used to capture the smoke pattern. In addition, analysis of the flow field was executed with analytical software (INSIGHT, TSI Ltd) for the PIV. Furthermore, in order to investigate the effect of the flow through the gap in the shuttlecock skirt on aerodynamic characteristics, the shuttlecock with no gap, which is completely covered with a smoothed clear tape with no porosity, is also installed. The deformation of shuttlecock skirt was measured by a high speed camera (FASTCAM-SA3, Photron Ltd), and the deformation was evaluated by image processing techniques.

![Schematic diagram of experimental setup](image1.png)

![Shuttlecock geometry](image2.png)

**Table 1. Shuttlecock dimensions.**

| Type            | The total length (H) | Length of shuttle (L) | Length of Cock (h) | Width at the end of skirt (D) | Width of cock (d) | Mass (M) | Position of centre of mass (Xo) |
|-----------------|----------------------|-----------------------|--------------------|-------------------------------|-------------------|----------|-------------------------------|
| NEW OFFICIAL    | 85.0 mm              | 60.0 mm               | 25.0 mm            | 66.0 mm                       | 26.4 mm           | 5.4 g    | 31.4 mm                       |

### 3. Results and Discussion

#### 3.1. Aerodynamic characteristics

Figure 3 shows the rotation rate of a shuttlecock about its major axis, and square symbols in Figure 3 denote the rotation rate measured by the actual flight data when the shuttlecock had reached quasi-steady
state rotation after the effects of the racket impact had disappeared. The rotation rate increases with increasing Reynolds number. The rotation rate for the ordinary shuttlecock follows the same trends as the rotation rate for the shuttlecock without gap. It is seen from Figure 3 that the relationship between the rotation rate and Reynolds number has almost the same tendency for all shuttlecocks. Figure 4 shows the drag coefficient $C_D$ variation with Reynolds number. There is no significant difference in drag coefficient between shuttlecocks with and without rotation. The drag coefficient for the ordinary shuttlecock without rotation increases in the case of $Re$ less than 86000 and gradually decreases over $Re=86000$. On the other hand, the drag coefficient for the ordinary shuttlecock with rotation increases abruptly over $Re=210000$. The drag coefficient variation with Reynolds number for the shuttlecock without gap has the same tendency of that for the ordinary shuttlecock. On the contrary, the value of drag coefficient for the shuttlecock without gap is significantly smaller than that for the ordinary shuttlecock.

In general, the shuttlecock skirt is deformed due to the flow’s dynamic pressure at high Reynolds number, and the diameter of the shuttlecock skirt is reduced. Figure 5 shows the shrink ratio of the shuttlecock skirt $\delta$ for all shuttlecocks, and the shrink ratio was defined as:

$$\delta = \frac{D'}{D}$$

(1)

where $D'$ was diameter of shuttlecock skirt after deformation. The shrink ratio increases with increasing Reynolds number for the shuttlecock without rotation. In the case of no-rotation, the deformation of the shuttlecock skirt promotes and the diameter of the skirt becomes smaller than the original one. On the other hand, for the shuttlecock with rotation, the diameter of skirt does not change with increasing Reynolds number in contrast to the no-rotation case and is enlarged over $Re=210000$, because a large centrifugal force is given by high rotational speed of the shuttlecock at high Reynolds number. The shuttlecock rotation leads to the similar effect on the deformation characteristics of the shuttlecock skirt in the cases of the shuttlecock with and without gap. Therefore, there is no significant difference in drag coefficient between the shuttlecocks with and without rotation in contrast to the difference in drag coefficient between the shuttlecocks with and without gap.

Fig. 3 Rotation rate (auto rotation).
3.2. Flow field in the wake of a shuttlecock

The smoke flow visualization experiments were performed to make the flow pattern visible around the shuttlecock. Figure 6 shows an example of instantaneous images of the side view of the separated shear layer at the edge of the shuttlecock skirt visualized by smoke-seeding the freestream for comparing between the cases with and without gap. For the ordinary shuttlecock, the periodic vortex is shed from the edge of the shuttlecock skirt and the large scale vortex exists near lee side of the shuttlecock. In other word, the vortex shed from the shuttlecock skirt becomes larger in the near wake of the shuttlecock. On the contrary, for the shuttlecock without gap, the rolled-up vortex is observed at the further downstream location due to high velocity at the corner of the shuttlecock skirt. For the ordinary shuttlecock, the air flows through the gap of the shuttlecock skirt and the surface flow on the shuttlecock skirt decreases. However, for the shuttlecock without gap, the air does not flow into the skirt and the surface flow on the skirt is faster in contrast to that for the ordinary shuttlecock. Therefore, the rolled-up vortex does not appear in the near wake region.

Figure 7 shows the density maps of vorticity $\omega$ and flow vectors at $Re=86000$. The flow field measurements in the wake of the shuttlecock were carried out by a PIV. The strong vortex is appeared near lee side of the shuttlecock in the ordinary shuttlecock case in contrast to the case without gap. For the ordinary shuttlecock, the flow in the downstream direction is observed in the wake because the air flowed through the gap in the shuttlecock skirt leads to a jet of air along the axis of shuttlecock. In fluid
dynamics, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure by Bernoulli’s principle. The flow inside the shuttlecock skirt causes a region of low pressure and induces the pressure difference between the windward side and lee side of the shuttlecock nose. The air flowed through the gap in the shuttlecock skirt is related to high aerodynamic drag.

Fig. 6 Flow visualization around the shuttlecock in X-Z plan for $Re = 8.6 \times 10^3$ ($\alpha = 0^\circ$) for (a) shuttlecock without gap; (b) ordinary shuttlecock.

Fig. 7 Density map of vorticity in X-Z plan for $Re=8.6 \times 10^4$ ($\alpha=0^\circ$) for (a) shuttlecock without gap; (b) ordinary shuttlecock.
4. Conclusions

In the present study, aerodynamic forces and flow visualization experiments were carried out in order to investigate the relationship between fluid forces and vortex behaviour in the wake of a shuttlecock. The results are summarized as follows:

(1) The value of drag coefficient for the shuttlecock without gap is significantly smaller than that for the ordinary shuttlecock.

(2) There is no significant difference in drag coefficient between the shuttlecocks with and without rotation in contrast to the difference in drag coefficient between the shuttlecocks with and without gap.

(3) The drag coefficient for the ordinary shuttlecock with rotation increases abruptly over $Re=210000$, because the diameter of the shuttlecock skirt is enlarged over $Re=210000$ due to a large centrifugal force given by high rotational speed of the shuttlecock at high Reynolds number.

(4) For the ordinary shuttlecock, the flow inside the shuttlecock skirt causes a region of low pressure and induces the pressure difference between the windward side and lee side of the shuttlecock nose, and therefore the air flowed through the gap in the shuttlecock skirt is related to high aerodynamic drag.

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