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Aerodynamic Properties and Flow Behavior for a Badminton Shuttlecock with Spin at High Reynolds Numbers

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Abstract

The shuttlecock used in the game of badminton has astonishing aerodynamic characteristics. The shuttlecock which has an open conical shape is the smallest ballistic coefficient and exhibits the largest in-flight deceleration of any airborne sporting implement. The ballistic coefficient of a body is a measure of its ability to overcome air resistance in flight and is inversely proportional to the deceleration. To evaluate correctly the forces acting the shuttlecock, it is necessary to know the in-flight properties determined from the aerodynamics. The purpose of this study is to investigate the relationship between aerodynamic properties and flow fields for a shuttlecock with spin rotation at high Reynolds numbers. Particle image velocimetry (PIV) was used to aid in understanding the flow field in the near field of the shuttlecock edge for the wind tunnel test. The effect of shuttlecock deformation on aerodynamic properties was also investigated because it is presumed that aerodynamic forces are affected by the deformation of the shuttlecock skirt. The drag coefficient for the shuttlecock with no gap is significantly smaller than that for the ordinary shuttlecock (with gap). For the ordinary shuttlecock, the air flows through the gap in the shuttlecock skirt, and this flow is related to high aerodynamic drag. That is, the high aerodynamic drag of a badminton shuttlecock is causes by the gap in the shuttlecock skirt.

Keywords: Drag; badminton shuttlecock; spin rotation; flow visualization

1. Introduction

The shuttlecock used in the game of badminton is the very interesting subject of research from an

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aerodynamic point of view as the sport of badminton is one of the oldest and most popular sports in the world. The popularity of the game is so immense that over 160 countries have officially joined the Badminton World Federation. 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 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 rang 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 until the development of injection moulding as a manufacturing process had advanced enough to facilitate the production of synthetic shuttlecocks. In the future, it is possible that shuttlecocks may 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. Several researchers have measured the aerodynamic drag acting on a series of feather and synthetic shuttlecocks under a wide range of wind speeds to compare the results of synthetic shuttlecocks with feather shuttlecocks[2,3] and computer simulations of shuttlecock trajectories have been reported[4]. Knowledge of aerodynamic properties of shuttlecocks can greatly assist both amateur and professional players to understand the flight trajectory as players require considerable skills to hit the shuttlecock for the full length of the court. However, the mechanism of inducing high drag in flight for shuttlecocks has not been clarified yet.

In the present study, measurements of aerodynamic forces and flow visualization experiments were conducted in order to investigate the relationship between fluid forces and vortex behavior 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 are affected by the deformation of the shuttlecock skirt. The shuttlecock rotates about the shuttlecock's major axis in actual flight, and the experiments were performed on 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

Figure1 shows the experimental apparatus used to estimate forces acting on shuttlecocks in a wind tunnel. 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 center of mass of a shuttlecock, and the distance of the center of mass from nose tip X_0 was 31.4 mm. The models were conducted using a real-size model of a shuttlecock. The test models of shuttlecocks are shown in Figure 2, Figure 3 and representative dimensions are given in Table 1. The angle of attack α indicates the angle between the axis of symmetry and the velocity vector in the X-Y plane and defines the angle of the cork in line with the flow as α=0°. 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 the lift, drag and 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 ~ 260000. The flow visualization experiments were performed at Re=210000 (U_0=50 m/s) to make the flow pattern visible around the shuttlecock with the Particle Image Velocimetry (PIV). A high speed camera (PIVCAM10-30; TSI) and a Nd-YAG laser (MiniLaseⅡ- 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, where the gap is completely covered with a smoothed clear tape with no porosity, was 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.

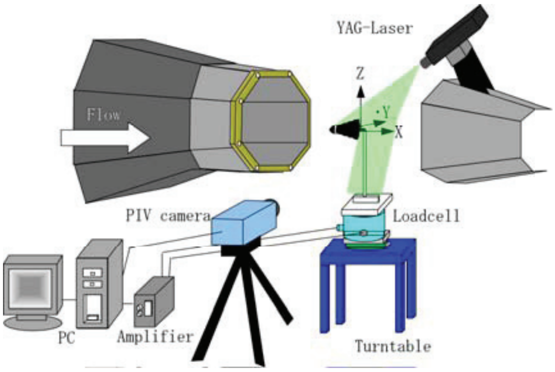

Fig. 1. Experimental apparatus

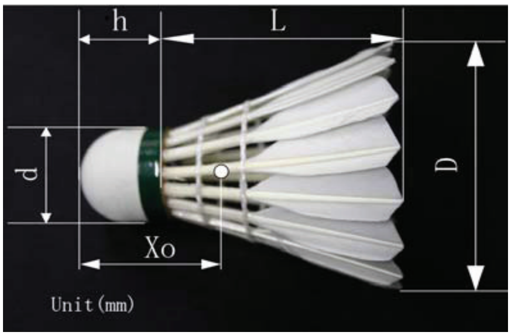

Fig. 2. Shuttlecock geometry (ordinary type with gap)

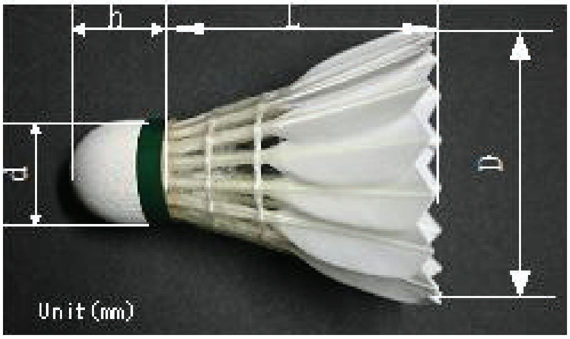

Fig. 3. Shuttlecock with no-gap

Table 1. Shuttlecock dimensions

Type	The total length [h+L] mm	Length of shuttle [L] mm	Length of Cock [h] mm	Width at the end of skirt [D] mm	Width of cock [d] mm	Mass g
NEW OFFICIAL	85.0	60.0	25.0	66.0	26.4	5.4

3. Results and discussion

3.1. Aerodynamic characteristics

The rotation rate of a shuttlecock about its major axis is shown in Figure.4 where square symbols 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 Fig.4 that the relationship between the rotation rate and Reynolds number has almost the same tendency for all shuttlecocks. The drag coefficient C_D variation with Reynolds number was shown in Figure.5. 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. In addition, the value of the 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. The shrink ratio of the shuttlecock skirt δ for all shuttlecocks was indicated in Figure.6, and the shrink ratio was defined as

$$\delta = D' / D \tag{1}$$

where D' was the diameter of the 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 is promoted and the diameter of the skirt becomes smaller than the original one. On the other hand, for the shuttlecock with rotation, the diameter of the 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 generated by the high rotational speed of the shuttlecock at high Reynolds number. Rotation of shuttlecock leads to a 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.

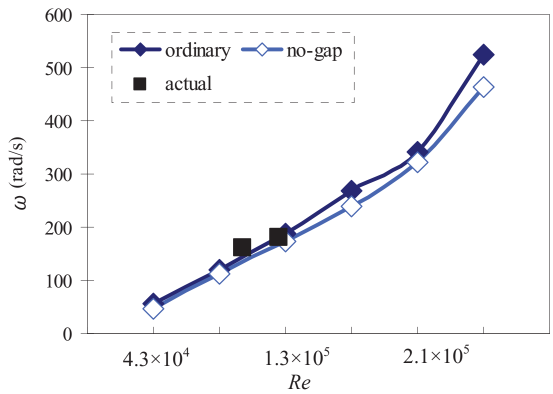

Fig. 4. Rotation rate (auto rotation)

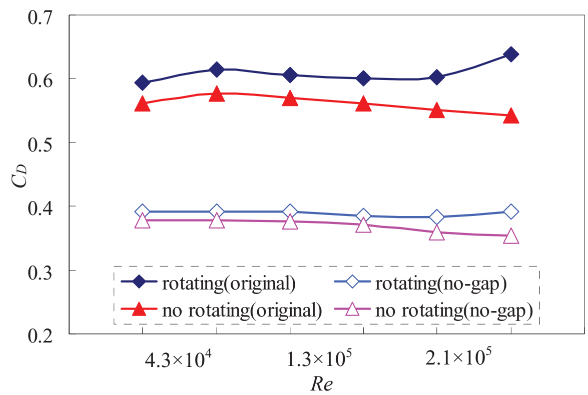

Fig. 5. Drag coefficients (α=0°). Filled and open symbols denote shuttlecocks with and without gap, respectively

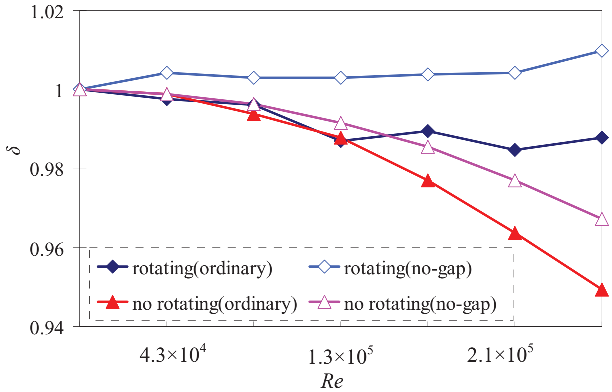

Fig. 6. Shrink ratio (α=0°). Filled and open symbols denote shuttlecocks with and without gap, respectively

3.2. Flow field in the wake of a shuttlecock

The smoke flow visualization experiments and PIV analysis were performed to make the flow pattern visible around the shuttlecock. Figure 7 shows the density maps of vorticity ω and flow vectors at $Re=2.1\times10^5$ at the edge of the ordinary shuttlecock skirt for comparing between the cases with and without rotation. The spanwise (Y-direction) vorticity is given by

$$\omega = \partial U / \partial z - \partial W / \partial x \qquad (2)$$

where U and W indicate the velocity in the X and Z directions, respectively. Figure 7 shows the side view of the separated shear layer at the end of the shuttlecock skirt by smoke-seeding the freestream for comparing between the cases with and without rotation. The vortex roll-up is observed in the near field region of the shuttlecock trailing edge and convects downstream. The counter-rotating vortex pair is appeared at the upper and under sides of the shuttlecock. There is no significant difference in the flow field between cases with and without rotation. Therefore, the drag force is not affected by the spin rotation.

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 behavior in the wake of a shuttlecock. The results are summarized as follows:

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

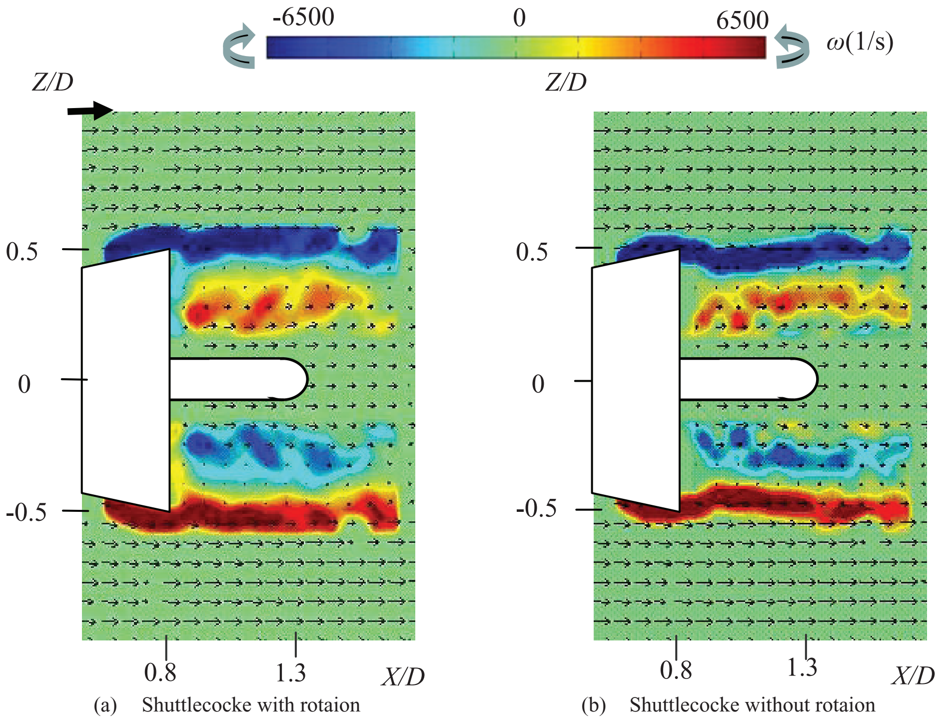

Fig. 7. Density map of vorticity in *X-Z* plan at Re=2.1×10^5 (α=0°)

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