Comparison of Aerodynamic Properties of Badminton Feather and Synthetic Shuttlecocks [†]

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† Presented at the 13th Conference of the International Sports Engineering Association, Online, 22–26 June 2020.

Abstract: The purpose of this study is to investigate the difference in aerodynamic properties between the feather shuttlecock and the synthetic shuttlecock. In particular, we focus on the aerodynamic stability of the two types of shuttlecock during impulsive change of an angle of attack (flip movement). Wind tunnel experiments are performed by using two types of the badminton shuttlecock (feather and synthetic shuttlecocks) to measure the fluid forces, and to visualize the flow fields around the shuttlecock. It is confirmed that the pitching moment coefficient at a near-zero angle-of-attack for feather shuttlecock is larger than that for synthetic shuttlecock. The results indicate that the feather shuttlecock demonstrates high stability in response to the flip phenomenon.

Keywords: badminton shuttlecock; wind tunnel experiment; aerodynamic stability; fluid forces

1. Introduction

Badminton is one of the most popular sports in the world. At world competitions and the Olympics, representative players from Asian countries have won many medals. Badminton is famous as the sport with the fastest initial velocity of a batted ball among all ball-related games. The initial velocity immediately after smashing may reach up to 408 km/h (113 m/s). In addition, as an airborne projectile, a shuttlecock has high deceleration characteristics. For example, when a shuttlecock is projected at an initial speed of 67 m/s, it rapidly decelerates to 7 m/s in 0.6 s [1]. The shape of the shuttlecock has a substantially truncated cone shape; furthermore, a cork simply fixed with feathers from birds such as water birds is attached by adhesive, making it extremely aerodynamically stable. Badminton shuttlecocks rotate counter-clockwise about the major axis in flight (autorotation) as viewed from downstream because they have a skirt structure with a diverging array of stems with overlapping feathers. The turnover stability of a series of feather and synthetic shuttlecocks was measured to compare the performance of synthetic shuttlecocks to that of feather shuttlecocks [2]. Experimental and theoretical values for the oscillating period of a shuttlecock during the flip phenomenon were measured by the actual hit test [3,4]. It is reported that the aerodynamic stability in the feather shuttlecock is high (Transactions of the JSME (in Japanese)), but the aerodynamic stability in the synthetic shuttlecock has not yet been clarified. By examining this reason, aerodynamics closer to the feather shuttlecock can be obtained even with the synthetic shuttlecock. In the present study, the behavior of the shuttlecock during the flip movement was evaluated in order to investigate the influence of the synthetic shuttlecock skirt gaps on the aerodynamic stability.

2. Experimental Apparatus and Methods

Figure 1 shows the experimental apparatus and the experimental setup for the fluid force measurements and flow visualization system. The wind tunnel experiment was carried out in a low-turbulence wind tunnel at the Institute of Fluid Science, Tohoku University, Japan. The test section was octagonal and 0.29 m by 0.29 m (height by width); experiments were performed in an open area in the center of the test section. The turbulent intensity was 0.4% or less of the main shuttlecock. The coordinate system is right handed and the coordinate origin is defined as the center of mass of a shuttlecock. The velocity is denoted by the components (u, v, w) in the directions (X, Y, Z). The test model was the feather shuttlecock and the synthetic shuttlecock (NEW OFFICIAL and MAVIS2000, YONEX Co., Ltd., Tokyo, Japan). YONEX feather shuttlecock is the official choice for the world's leading international tournaments. The shuttlecock test models are shown in Figure 2, and the representative dimensions are given in Table 1. The surfaces of each of the shuttles was painted black to suppress halation during the visualization experiment. The aerodynamic forces on the shuttlecock were measured by using a three-component force balance (LMC-3501-50N, NISSHO-ELECTRIC-WORKS Co., Ltd. Tokyo, Japan) and strain amplifiers (DSA-100A, NISSHO ELECTRIC WORKS) connected to a shuttlecock support. The balance was able to simultaneously detect the lift, drag, and pitching moment. The equipment used for motion analysis experiments were high-speed cameras (FASTCAM SAX 2, Photron Ltd., Tokyo, Japan) and metal halide lights (HVC-SL, Photron Ltd.). The Reynolds number *Re* was defined as

$$Re = U_0 \, d_s / \nu, \tag{1}$$

where the rear-end diameter ds of the blade portion is the maximum width of the shuttle and the representative length, the free stream velocity U_0 is the representative speed, and ν is the kinematic viscosity of air. The wind speed U_0 was set at 10 to 30 m/s corresponding to the Reynolds number *Re* based on the skirt diameter ds of 4.3×10^4 to 1.3×10^5. The angle of attack $\alpha = 0°$ indicates the state that the cork of the shuttlecock was set in the upstream direction in this experiment. The direction of the moment was found to be positive in the clockwise direction, and a manual rotary stage was used to manipulate the angle of attack as the static fluid force was measured. The fluid force coefficients were obtained using the freestream U_0, the projected area of shuttlecock S, and the air density ρ, each fluid force (the lift, drag, and pitching moment).
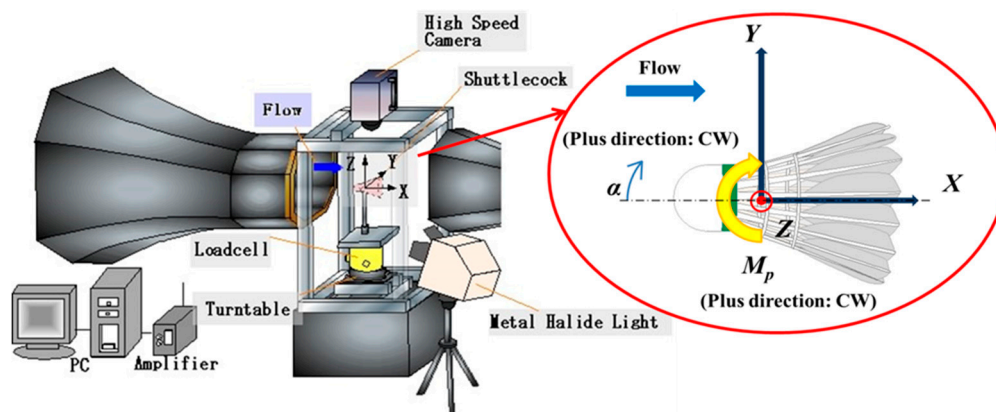

Figure 1. An overview of the wind tunnel experimental setup.

Table 1. The dimensions of two type shuttlecock.

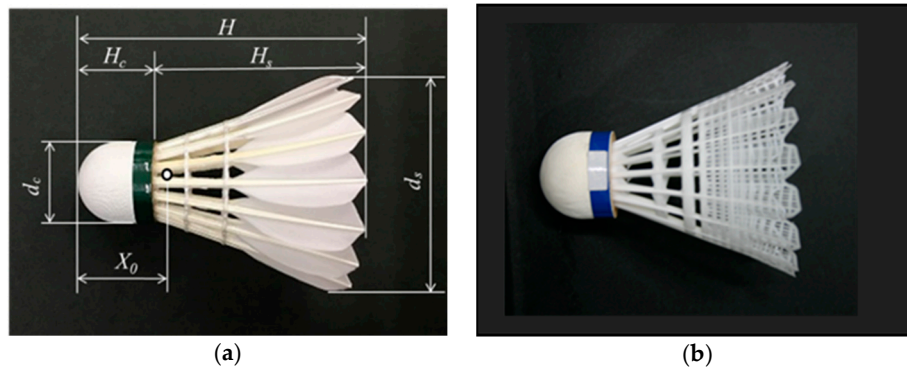| Shuttle Type		Feather	Synthetic
The total length [mm]	H	85.0	80.0
Length of shuttle skirt [mm]	H_s	60.0	57.2
Length of cork [mm]	H_c	25.0	22.8
Diameter of skirt [mm]	d_s	66.0	66.0
Diameter of cork [mm]	d_c	26.4	26.4
Mass [g]	m	5.3	5.3
Distance of center of mass [mm]	X_0	31.4	28.4

| (a) | (b) |

Figure 2. Shuttlecock geometry, (**a**) feather shuttlecock; (**b**) synthetic shuttlecock.

3. Results and Discussion

3.1. Behavior of Each Shuttlecock during Flip Movement and Static Aerodynamic Characteristics

Flight of a shuttlecock can be described by steady and unsteady states. Most of the flights become the steady state, however the transient unsteady state is critical because it determines the initial condition of stabilized flight. The rapid angular change during the unsteady state is the flip movement. The behaviors of the feather shuttlecock and the synthetic shuttlecock during flip movement are shown in Figure 3. The wind speed U_0 were 10 and 30 m/s ($Re = 4.4 \times 10^4$ and 1.3×10^5). It can be seen that the shuttlecock freely rotates about the Z axis at the instant that the fixation of the shuttlecock support needle screw is released. Additionally, the initial angle of attack of each shuttlecock was set as $\alpha = 145°$ in order to prevent initial instability. Figure 3 also shows that the attitude of each shuttlecock eventually converged to about $\alpha = 0°$. The turnover stability of each shuttlecock during the flip movement was measured by using a high-speed camera; the observed decrement of the angle of attack indicates the clockwise rotation of the shuttlecock during the flip movement. The horizontal and vertical axes denote elapsed time and angle of attack of the shuttlecock, respectively. The oscillating period during the flip movement for the feather shuttlecock was found to be shorter than that for the synthetic shuttlecock. To evaluate the stability of the shuttlecock, we defined a dimensionless stabilization time. The stable angle of attack was defined from the behavior of the shuttle measured by the high-speed camera. The time from the start of the shuttlecock to the stable angle of attack was defined as the stable time. In order to compare the stability of the feather shuttlecock and synthetic shuttlecock, the stability time ratio C_{stb} ($=t_s/t_f$) was calculated. Here, t_s and t_f are the stability time of the synthetic shuttlecock and the feather shuttlecock. When the value of C_{stb} exceeds 1, it indicates that the feather shuttlecock has a shorter stabilization time than the synthetic shuttlecock, and the feather shuttlecock is more stable. Comparing the stable time ratio in the different Reynolds numbers, $C_{stb} = 1.2$ when $Re = 1.3 \times 10^5$ and $C_{stb} = 1.1$ when $Re = 4.4 \times 10^4$. As Re numbers increase, the stable time of each test shuttlecock decreases. In any Re numbers, the feather shuttlecock reaches the stable time in a shorter time than the synthetic shuttlecock. The arrow in the Figure 3 indicates the overshoot angle (O.S.) of shuttlecock variation across $\alpha = 0°$. The first overshoot angle is larger for the synthetic shuttlecock than for the feather shuttlecock. The second

overshoot angle is extremely small for the feather shuttlecock compared to the synthetic shuttlecock. This tendency was the same with different *Re* numbers. Interestingly, both the feather shuttlecock and the synthetic shuttle have almost the same value for the overshoot angle, even when the *Re* number is different. From the above, it was found that the feather shuttlecock is more stable during flipping movement than the synthetic shuttlecock. The feather shuttlecock also has a small overshoot angle and decays quickly during overshoot. In other words, the overshoot behavior was suppressed for the feather shuttlecock.
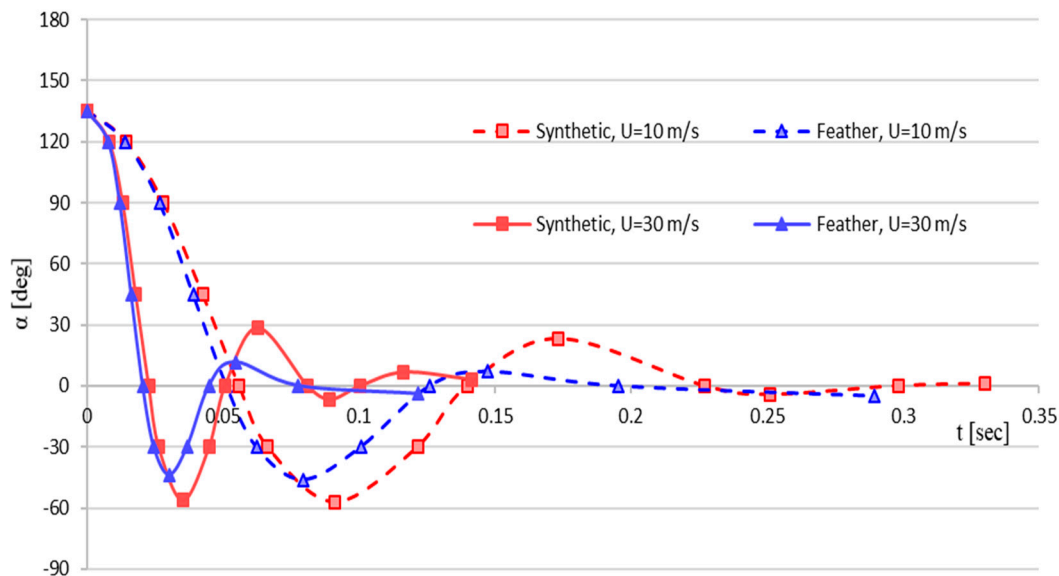

Figure 3. Time evolution of the angle of attack during the flip movement at U_0 = 10 and 30 m/s (*Re* = 4.4×10^4 and 1.3×10^5.). Triangular plots show the feather shuttlecock results, and square plots show the synthetic shuttlecock results. The solid line shows U_0 = 30 m/s, and the broken line shows U_0 = 10 m/s.

3.2. Comparison of Feather Shuttlecock and Synthetic Shuttlecock in Aerodynamic Characteristics

The results indicate that the feather shuttlecock demonstrates high stability in response to the flip phenomenon. In order to investigate the reasons for delayed stabilization, force measurements were carried out. The shuttlecock rotates about its major axis when in actual flight; however, since the shuttle does not spin during flip movement, the experiments were performed on shuttlecocks without rotation (spin). Figure 4 shows the static fluid force characteristics for each angle of attack. The trends observed in the fluid force results were similar between the feather shuttlecock for all Re numbers (U_0 = 10, 20, and 30 m/s). In the case of the synthetic shuttle, there was a difference in the fluid force coefficient curves due to the deformation of the skirt due to the difference in wind speed. The fluid force measurements were carried out by implementing an angle of attack α with increments of 4°. Figure 4a–c shows the lift, drag, and pitching moment coefficient curves for each shuttlecock model. It can be seen that synthetic shuttlecock for the variation of C_L curve changes less than feather shuttlecock. The C_D curve acting on feather shuttlecock was larger than synthetic shuttlecock at all angles of attack, and a particularly significant difference was seen in the region of large angles of attack (i.e., approximately $100° < \alpha < 180°$). From the results of the C_L curves and the C_D curves, it is considered that the reason why the fluid forces acting on synthetic shuttlecock are smaller than feather shuttlecock in spite of the same substantially truncated cone shape is due to the air permeability of the synthetic shuttlecock skirt. In discussing aerodynamic stability, we focus on the slope (stability derivatives) of the C_M curve near the zero cross point of the angle of attack. It can be seen that the slopes of the C_M curves are clearly different between feather and synthetic shuttlecock, and that feather shuttlecock is larger than synthetic shuttlecock. This difference in C_M can be described as a difference in the restoring force near the zero cross point of the angle of attack that

occurs when repeating an overshoot. However, because this flipping behavior is strongly nonstationary, it is necessary to consider vortex flow and unsteady fluid force in the future.
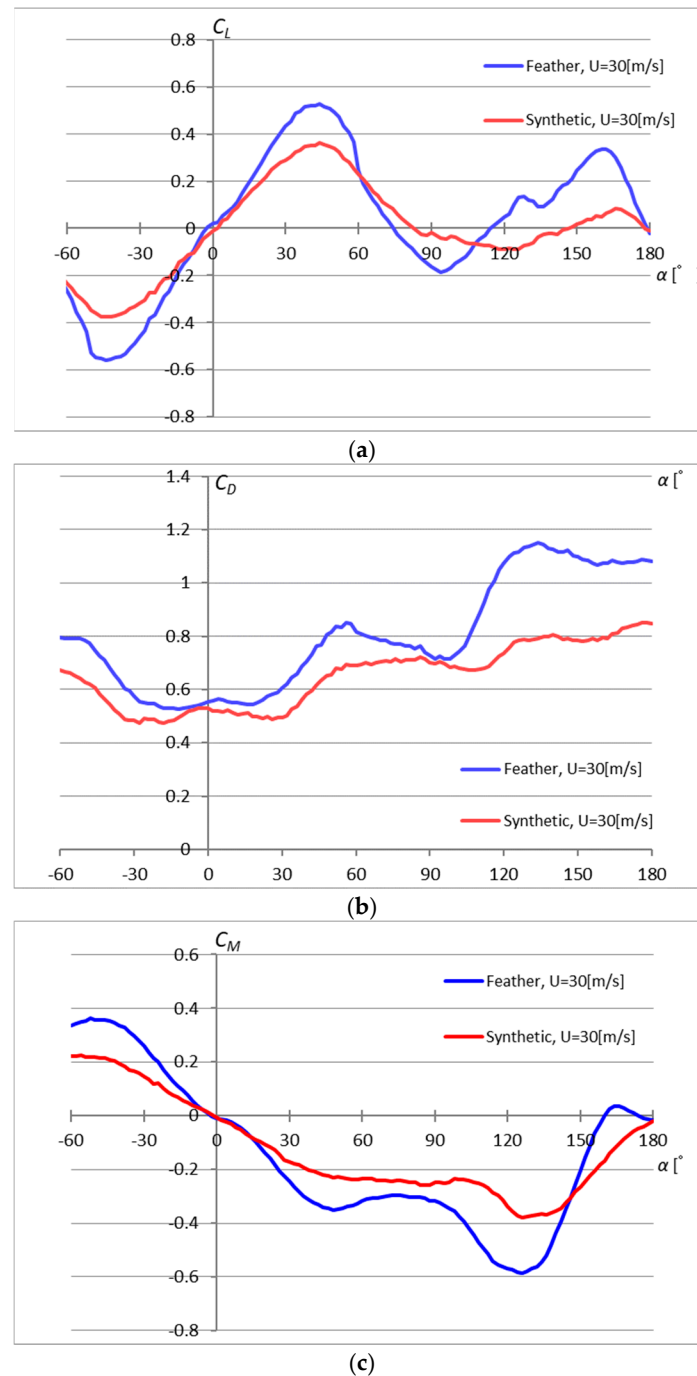

Figure 4. Aerodynamic coefficients of the feather shuttlecock and the synthetic shuttlecock as a function of the angle of attack at U_0 = 30 m/s (*Re* = 1.3 × 10^5). (**a**) Lift coefficient curves, (**b**) drag coefficient curves, and (c) pitching moment coefficient curves.

4. Conclusions

In this study, the time evolution of the angle of attack was measured for each test model during the flip movement. The results are summarized as follows:

1.　The oscillating period during the flip movement for the feather shuttlecock is shorter than that for the synthetic shuttlecock;
2.　The overshoot behavior is suppressed for the standard shuttlecock;

3.   The turnover stability of a badminton shuttlecock is affected by the existence of air permeability in the shuttlecock skirt.

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