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Aerodynamics of badminton shuttlecock: Characterization of flow around a conical skirt with gaps, behind a hemispherical dome

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ABSTRACT

The effects of gaps on flow properties were studied for a thin walled conical structure behind a hemispherical dome-badminton shuttlecock. Computational fluid dynamics was applied to six different profiles with differing gap sizes. The gaps increased the drag force over a gapless conical skirt by up to 45.2% using the design dimensions. This is termed the critical gap size. Below the critical gap size, drag increases with as gap widens. Beyond the critical gap size, larger gaps resulted in reduced blunt body effect, reduced drag, and increased skirt porosity. Bleeding caused the formation of air jets that diminished the recirculation typical of wake behind a blunt body. Analysis of the pressure profiles showed that gaps increased the differential pressure between the inner and outer surface, thereby producing more drag. The gaps also resulted in spikes along the pressure profiles. Some of the numerical results were validated against wind tunnel experiments and showed good agreement. Variation of only 3.2–4.7% was observed between the numerical and experimented drag data of the gapless cone.

1. Introduction

The shuttlecock used in a badminton game has the drag characteristics of a blunt body. Aerodynamically, the shuttlecock is equivalent to a semi-porous thin wall cone attached behind a solid hemispherical dome. This property gives the shuttlecock very high deceleration rate, where shuttlecock velocity in the same game can range from 5.5 m/s to over 80 m/s. Based on the guidelines from Badminton World Federation (BWF, 1988), a badminton shuttlecock comprises of a 16 feather skirt attached to a base and weigh between 4.74 g and 5.50 g. The skirt can be replaced by synthetic materials but flight characteristics should remain similar. Since flight of a shuttlecock is highly dependent on the drag properties, the synthetic skirt must retain the same drag properties. The synthetic skirt must also weigh as light as a feather skirt to retain the flight performance, especially the trajectory and turnover. The challenge then, is innovating a skirt design that can reproduce feather performance. Through the decades of badminton sports, there have been numerous attempts from the industry at the creation of an alternative to the natural feather shuttlecock. However, none was successful and even till today, feather shuttlecocks remain the top choice. Despite that, the development of a synthetic shuttlecock remains attractive for various reasons. These include the possible increase in consistency from batch to batch of shuttlecock, the decrease in demand of natural waterfowl feathers that can be unpredictable in supply and quality, improved durability, and lowered production cost. The availability of good synthetic shuttlecocks will make badminton more affordable and attractive as a recreational sport because top grade feather shuttles remain a costly consumable in the game.

The first step in development of synthetic shuttles is to understand the fundamental differences between it and the feather counterpart. Numerous previous works explored the differences between synthetic and feather shuttlecocks. Cooke (1992, 1996, 1999, 2002) was one pioneer of such works. Her works include trajectory studies to compare the flight path, wind tunnel studies to evaluate flow field differences between synthetic and feather shuttles, and the design process changes required for development of synthetic shuttlecocks. More recently, Alam et al. (2009) compared the drag coefficient between feather and synthetic shuttlecocks in the wind tunnel. The average drag coefficient observed for the 10 types of shuttlecocks was 0.61 at flow speed over 100 km/h. It was proposed that the skirt deformation of synthetic shuttles at high speed was the cause in lowered drag. The work by Chan and Rossmann (2012) reinforced this idea by observing the transient deformation under steady state flow in wind tunnel. It was observed that even with spin, synthetic skirts are unable to maintain the circular geometry at high speed. In contrast, feather shuttles were able to resist deformation. The feathers

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shuttlecocks were also observed to have higher spin rate at the same free stream speed. Differences between feather and synthetic shuttlecocks have also been observed through flow simulation. Verma et al. (2013) applied computational fluid dynamics (CFD) to evaluate the differences between synthetic and feather shuttlecock. The various planar cuts and plots presented gave insight to local flow conditions around the badminton shuttlecock skirt. Through CFD, the effect of twist angle of feathers was studied. It was found that increasing the twist angle beyond 12° lowered the drag. However, such properties are less relevant for design of synthetic shuttles, because synthetic skirts are typically molded as one-piece design. Study of the effect of gaps on feather shuttlecocks by Kitta et al. (2011) may be more applicable in the design of synthetic skirts. This is because gap designs, which play a critical role in synthetic skirts, are seldom discussed in open literatures. The work compared the drag coefficient of feather shuttlecocks with and without gaps. It was observed that the presence of gaps significantly increased drag. Kitta et al. (2011) also observed that spin has no direct effect on drag. The drag change from spin was induced by the skirt expansion under the centrifugal force of spin.

However, none of the work explored the effect of gap dimensions. In this paper, research was carried out to investigate further the effect of gaps. The main objective is to increase the understanding of how different gap sizes affect the skirt porosity and thus, the degree of similarity to blunt body aerodynamics. In addition to drag estimation, changes from varying gap dimensions were explained through study of the wake, bleeding through the skirt, and pressure profiles along the skirt. Six simple shuttlecock models were studied in the numerical experiment: a gapless cone model and five other cone models with varied gap dimensions. The baseline result of the gapless cone model was then compared through physical experiments. This reinforces the validity of the CFD simulation. While the Reynolds-averaged Navier–Stokes (RANS) simulation that was carried out is the averaged values, it improves understanding of conical thin-walled bluff bodies which are much less studied than other solid bluff bodies. Moreover, the work will serve as a foundation for subsequent shuttlecock development, especially in virtual prototyping and transient simulation with Unsteady RANS (URANS) and Large Eddy Simulation (LES).

1.1. Numerical analysis

The reference bluff body, profile A, consists of a thin wall gapless conical cup (skirt) attached to a solid hemispherical dome (cork) shown in Fig. 1. Dimensions of the cork and skirt were referenced from Verma et al. (2013), with 0.5 mm thickness. To investigate the effect of gaps around the skirt, 5 models (profile B–F), each with a different gap dimension, were constructed. Each profile had 15 triangular gaps of X/mm width and H/mm height that extend downward along the skirt beginning from 35 mm behind the cork. The surface area of the gaps ranged from 555 mm^2 on profile B to 2636 mm^2 on profile F. Compared to the gapless cone profile A, this is equivalent to a surface area reduction of 6.59–31.31%. External dimensions remain the same as profile A. The various dimensions of cut, including the surface area reduction by virtue of the gaps, are given in Table 1.

Numerical analysis was applied to the six simple shuttlecock profiles using ANSYS™ suite. Through ANSYS™ design modeler, the CAD model of each profile was enclosed in a cylinder of diameter 310 mm, as shown in Fig. 2. Flow inlet is 135 mm upstream from the model, while outlet is 500 mm downstream. In defining the case in CFX™, velocity inlet was applied to the inlet, 0 Pa static pressure for the outlet, free-slip wall at the cylindrical wall, and no-slip wall on the shuttlecock profile. Simulation was conducted using the shear stress transport turbulence model (SST).

Table 1
Dimensions and areas of gaps for the various models.

Profile	Width (X/mm)	Height (H/mm)	Surface (area/mm^2)	Surface area reduction (%)
A	N.A.	N.A.	8420	0.00
B	2	20	7865	6.59
C	2	40	7551	10.32
D	4	40	6910	17.93
E	6	40	6268	25.56
F	7.5	40	5784	31.31

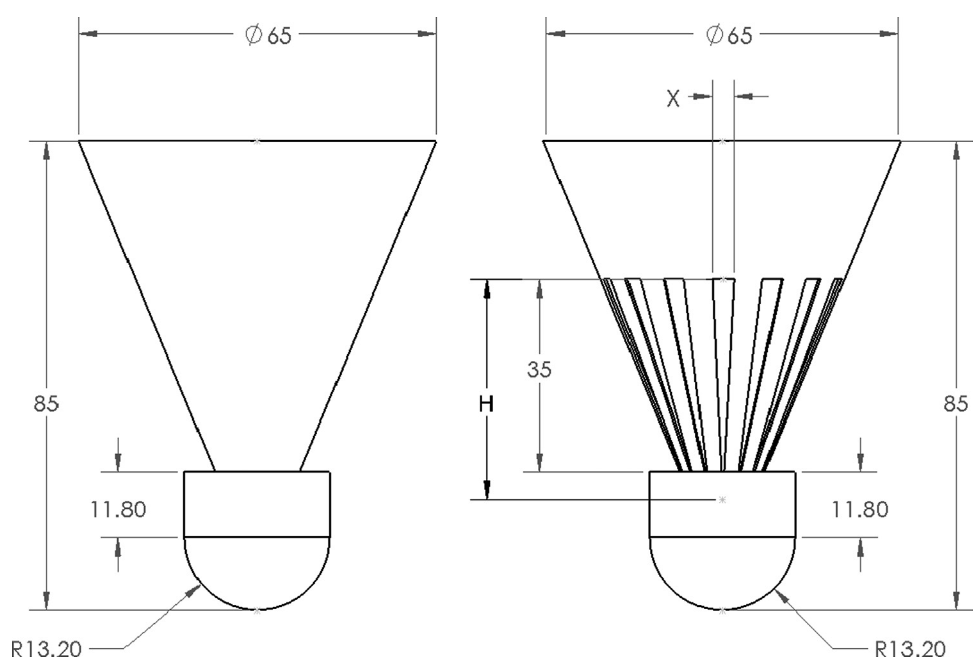

Fig. 1. Graphical description of the conical model without gap and model with gap. All dimensions are in mm.