DESIGNING A BADMINTON SHUTTLECOCK; VALIDATION OF VIRTUAL DESIGN BY 3D PRINTED THIN-WALLED FUNCTIONAL PROTOTYPE

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ABSTRACT: This paper focuses on the additive manufacturing of a prototype badminton shuttlecock skirt that was designed through computational fluid dynamics (CFD). The fabricated prototype weighs 3.81 g and has wall thickness of between 0.5 mm to 0.65 mm. The prototype was tested functionally in the wind tunnel to validate the numerical results. CFD and wind tunnel testing was also applied to a reference feather shuttlecock for validating the flow simulation framework. Experimental and numerical results of the feather shuttlecocks showed good agreement. While the high speed testing of the prototype showed skirt deformation, the low speed results of the prototype demonstrate the feasibility of functional prototyping through additive manufacturing.

1. INTRODUCTION

Badminton shuttlecocks are fascinating. Having an aerodynamically blunt shape, and weighing just 5 g, a shuttlecock experiences large rate of deceleration in flight. According to regulations from the Badminton World Federation (BWF, 1988), a shuttlecock should weigh between 4.74 g to 5.50 g, while having a skirt diameter of 58 mm to 68 mm. Typically, most shuttlecocks for tropical climate (speed 76) are around 5 g and have diameter of 64 mm to 67 mm. There have been numerous previous works to understand the flight of badminton shuttlecocks. Goff (2013) reviewed some work on aerodynamics of sports projectiles, including shuttlecocks. The lack of computational fluid dynamics (CFD) work on badminton shuttlecocks was highlighted.

Indeed, there have been many publications on CFD analysis of blunt bodies, but few for shuttlecocks. One of the early work was by Frank et al. (2000) who applied CFD to understanding of shuttlecocks, concluding that it is a valuable tool in flow visualization. However, it was also noted that more computational power was required for improved accuracy. Verma et al. (2013) compared the flow field of feather and synthetic shuttlecocks by CFD. Due to advancement in computational power, grid independence was easily achieved. The effect of gaps on shuttlecock

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skirt was also studied through numerical methods in Lin et al. (2013a, 2014) where a virtual and rapid prototyping framework for design iterations of shuttlecock design was proposed.

Prototyping of synthetic badminton shuttlecock skirt are traditionally done with established molding methods, such as injection molding and compression molding. While the actual molding process is accomplished within a short time, fabrication of the mold is time consuming. This means, the prototyping process can be costly in time and resource, especially when design iterations, which often require new molds, are considered.

This paper evaluates the feasibility of applying additive manufacturing to shuttlecock prototyping for faster design iteration cycles. In the current work, a shuttlecock skirt was designed and evaluated using CFD. The numerical result was then validated against the experimental result obtained from testing the 3-D printed prototype in the wind tunnel. This serves as a basis for future additive manufacturing of shuttlecock prototypes that can be fully functional and tested. Numerical and experimental test procedures were also evaluated by using a standard feather shuttlecock. Such workflow of design changes through CFD, followed by experimental validation on additive manufactured prototypes is also applied in other fields, such as design of an agriculture irrigation emitter by Celik et al. (2011). The difference for badminton shuttlecock is the constraint on weight and structural strength when building the thin walled functional prototype.

2. METHODS

2.1 Prototype design

After various design iterations using the virtual prototyping framework suggested in (Lin et al., 2013a), the obtained skirt design is as given in Figure 1. With a length of 58mm and a diameter of 66.1mm, this skirt design follows closely to that of a conventional full size shuttlecock. The features include:

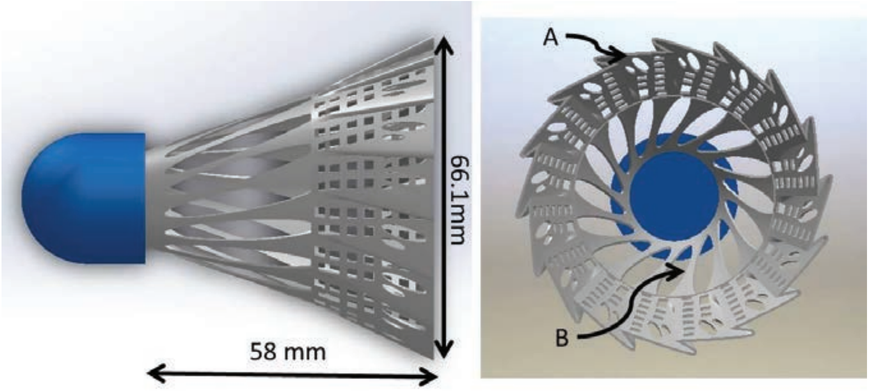

Figure 1 Virtual design of the shuttlecock skirt design.

- Oval shaped gaps along the skirt for generation of pressure difference between inner and outer surface on skirt to fulfill drag criteria.
- Folds (A) on the skirt, aft of the gaps (B), for generation of spin torque.

- Cut patterns along the folds for increased local pressure difference between the upper and lower surface to enhance spin rate.
- The cut patterns also control the weight and center of gravity, which determines the turnover stability (Lin et al., 2013b)

Through the design of these shuttlecock features, feasibility of replicating such details through additive manufacturing is tested. Subsequent functional testing of these prototypes will determine if additive manufacturing is suitable for fabricating fully functional prototypes of new shuttlecock designs.

2.2 CFD method

Domain size for flow simulation is as referenced from Verma et al. (2013) and also implemented in Lin et al. (2013a). Located 150 mm upstream of the shuttlecock, the inlet of the domain has a diameter of 310 mm and is defined as a velocity inlet boundary. Flow outlet, defined as 0 Pa static pressure condition, is 500 mm downstream of the shuttlecock. Boundary wall of the fluid domain is a cylindrical free-slip wall, while the shuttlecock is defined as a non-slip smooth wall.

All simulations were conducted with the shear stress transport (SST) turbulence model on ANSYS® CFX. The velocity inlet was simulated at 6 m/s, 10 m/s, 15 m/s, 20 m/s, and 25 m/s for the proposed virtual design. Flow was not increased beyond 25m/s because the fabricated prototype was expected to be unable to sustain such flow without significant deformation. Simulation was also conducted on a reference feather shuttlecock, where the feather profile was digitized from a Li-Ning A+90 shuttlecock.

Unstructured mesh of tetrahedral elements was generated with ANSYS® ICEM for the fluid domain. Ten layers of prism, the recommended minimum for SST turbulence model (Ansys, 2010), were also generated around the shuttlecock profile as boundary layer. The generated mesh for the proposed skirt design had 5.4 million elements. Grid refinement produced a second mesh of 8.2 million elements. Comparing the numerical drag forces of both grids obtained at 6 m/s and 20 m/s, it was determined that grid independency was obtained with the 5.4 million elements grid. Drag force at 6 m/s is 0.0532 N and 0.0529 N for the 5.4 million elements mesh and 8.2 million elements mesh respectively. At 20 m/s, numerical drag is 0.595 N for the applied mesh and 0.591 N for the refined mesh.

For the feather shuttlecock profile, a grid setup of 4.7 million elements produced a drag force of 0.0492 N at 6 m/s flow rate. Grid refinement to 6.8 million elements only resulted in a 2.2 % reduction in drag force to 0.0481 N. The 4.7 million element mesh was determined to be sufficiently accurate.

2.3 Prototype fabrication

The production of a mold for traditional prototyping methods may require a week or more. While subsequent molding of each piece of prototype with methods such as injection or compression molding is accomplished in minutes, it is seldom that a large quantity of prototype is required at the design iteration stage. Therefore, the advantage in large quantity production using traditional molding methods may not apply.

In contrast, a tray of three prototypes of the design in Figure 1 can be fabricated within 4 hours when using an Objet™ Eden 350V with FullCure™ 720 model material and FullCure™ 705 support material. Through elimination of a mold, the application of additive manufacturing to prototyping of shuttlecock skirt greatly reduces the time and cost involved in development of badminton shuttlecocks. The prototype skirt for wind tunnel testing was manufactured with the above mentioned Objet™ system.

2.4 Wind tunnel experiment

Experimental drag of the prototype was collected in a closed loop wind tunnel at flow velocity of 6 m/s to 25 m/s. Measuring 708 mm (W) x 720 mm (H) x 2000 mm (L), the test section is much larger than the shuttlecock specimen to have influence on the result. Drag forces were measured by a Seeed Studio 500 g load cell and a Vishay P-3500 strain indicator. Figure 2 shows the prototype skirt mounted on the wind tunnel sting. The prototype design and the Li-Ning A+90 feather shuttlecock were tested.

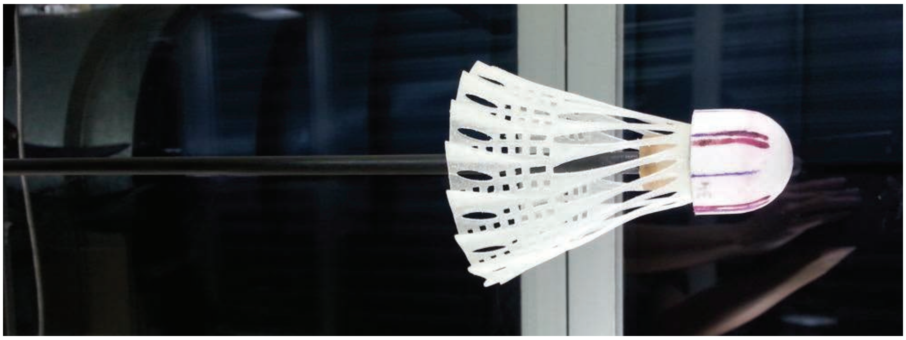

Figure 2 Prototype shuttlecock mounted on the wind tunnel sting.

3. RESULTS AND DISCUSSION

3.1 Physical properties of manufactured prototype

The physical properties of the virtual design and additive manufactured prototype are listed in Table 1 .

Table 1 Weight and wall thickness of the virtual design and manufactured prototype.

		Wall Thickness/mm	
	Weight (skirt only) /g	At A	At B
Manufactured prototype	3.81	~0.5	~0.65
Virtual prototype	2.91	0.37	0.54

Due to difference in wall thickness between the virtual and manufactured prototype, the manufactured prototype weighs 0.9 g more than the virtual design. With the 3.81 g skirt, the prototype shuttlecock weighs 6.02 g when attached to a cork. This is approximately 1 g heavier than a generic shuttlecock. While the weight difference may affect flight testing of the shuttlecock by play, it is adequate for the purpose of functional testing in the wind tunnel.

3.2 Wind tunnel experiment

Drag force measurements for both shuttlecocks are shown in Figure 3 and Figure 4. The numerical and experimental drag forces obtained for the feather shuttlecock shows good agreement in the range of the tested free-stream velocity. This supports the validity of the flow simulation method. Slight variation was observed at flow speed of 15 m/s and 25 m/s.

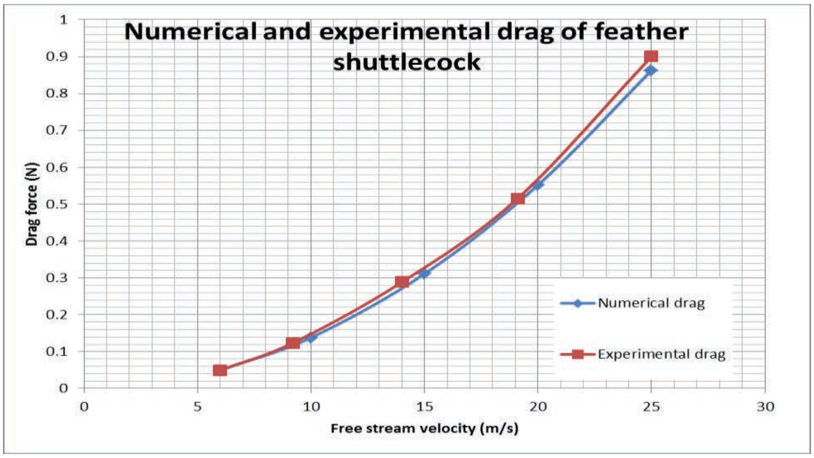

Figure 3 Numerical and experimental drag of a feather shuttlecock.

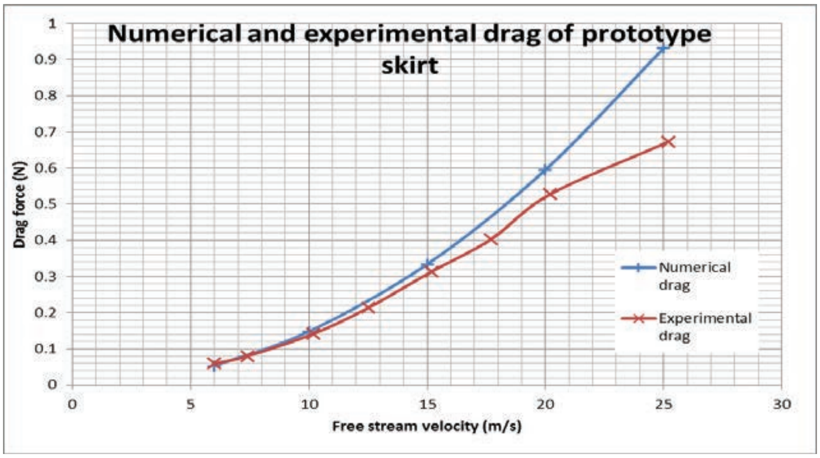

Figure 4 Numerical and experimental drag of the prototype shuttlecock skirt.

Unlike the result of the feather shuttlecock, numerical and experimental data for the prototype shows large variation at speed above 15 m/s. For instance, the numerically estimated drag at 25 m/s is 0.93 N, but experimental work only recorded 0.67 N. This is largely attributed by the deformation (skirt shrinkage) experienced, as shown in Figure 5. The skirt shrinkage observed is the result of low skirt rigidity and constrained non-spinning test condition in the wind tunnel. Kitta et al. (2011) observed that spin of a shuttlecock reduces skirt shrinkage at higher flow speed because of the spin-generated outward going centrifugal force.

While test result suggests that stiffer skirt design and material may be required for subsequent functional testing, the current work of wind tunnel testing with additive manufactured prototype proves to be feasible. Design optimization and proper material selection should be considered as the next step. The presence of sufficient spin should also aid in reduction of skirt deformation at high speed. It should also be noted that even synthetic skirts produced by traditional molding methods suffer from some deformation at speed, as seen in Cooke (1996) and Texier et al. (2012).

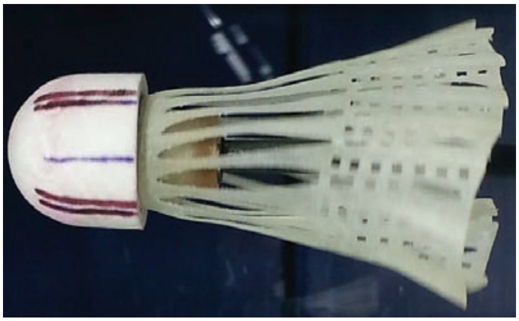

Figure 5 Skirt shrinkage observed at flow speed of 25 m/s air flow.

4. CONCLUSION

Using additive manufacturing, a shuttlecock skirt prototype was fabricated in 4 hours. While the prototype is 1 g too heavy for actual flight testing, this skirt was used to validate the numerical results. Good agreement of the experimental and numerical result was observed for low speed flow. At flow speed above 15 m/s, significant deviation was observed between the numerical and experimental result. This is likely due to the skirt shrinkage that was observed. Moreover, the good agreement of the numerical and experimental result for the feather shuttlecock suggests that error in simulation method is unlikely.

Additive manufacturing is a valuable tool in design iteration and design validation for badminton shuttlecock work. In the subsequent work, considerations in design optimization and material will be taken when building a prototype for actual flight testing.

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