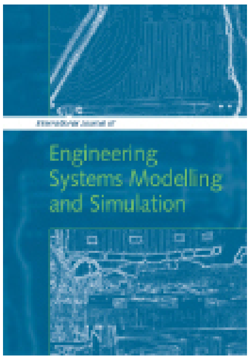

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Aerodynamic properties comparison between natural feather, nylon, and synthetic shuttlecocks

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Abstract: This study compared the aerodynamic properties between the natural feather, nylon, and foam shuttlecocks under various pitch angles, α using computational fluid dynamics (CFD) during steady-state flight conditions. The velocity varied within 10–60 m/s and α =10°, 20°,30°. The drag coefficient for feather/foam was approximately constant at 0.56. Other aerodynamic properties including the lift and moment coefficients were also investigated. The lift coefficient obtained for nylon and feather/foam were 0.38 and 0.30 at α = 30° (30 m/s). All models had shown a negative sign for the moment coefficient, which indicates the aerodynamic centre is always behind the centre of gravity. Therefore, it will give stability to the shuttlecock during the flight. The nylon shuttlecock showed a higher drag coefficient compared to others due to its larger gap area and an increased wake behind the shuttlecock.

Keywords: aerodynamic properties comparison; natural feather shuttlecocks; nylon shuttlecocks; synthetics shuttlecocks; computational fluids dynamics; CFD; drag coefficients; lift coefficients; steady-state flight.

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Hazim Moria is an accomplished academic and researcher. He holds a PhD from RMIT University, Australia. He is recognised for outstanding contributions, with a diverse educational background spanning mechanical engineering. He has excelled in roles such as an Associate Professor at Yanbu Industrial College, Saudi Arabia. His expertise extends to research, with notable awards like the Young Investigator Award in ISEA 2011. His administrative prowess includes leadership as the head of Planning and Development at Yanbu Technical Institute and Royal Commission Yanbu Colleges and Institutes. Hazim's commitment to excellence is evident in his memberships with esteemed engineering associations, further solidifying his standing in the academic community.

1 Introduction

Badminton is one of the world's most common sports for all, regardless of age or experience. The sport began in China and developed in England. The sport has actively participated in Asian countries such as Malaysia, China, Indonesia, Japan, the Republic of Korea, and certain European countries such as Denmark, Sweden, and the UK. Playing badminton involves not only technical skills but also understanding projectile physics. A shuttlecock's design and material can have a major impact on its trajectory and the dynamics of how a player hits a shuttlecock. Additionally, studying the shuttlecock flight will enable the manufacturer to create those with consistent flight patterns with cheaper material to imitate the feather shuttlecock.

Numerous attempts have been made to create a feather replacement shuttlecock, but none of them has been successful. Natural feather shuttlecocks remain the most favourable choice among players, especially professionals, due to their performance. The development of the synthetic grew wider due to the decrease in the demand for natural feathers, which can be inconsistent in supply and quality. Also, the bird's feather shortage has risen for several years and remains a concern in the future. Shortage of feathers supplies can be affected by many factors, such as waterfowl disease, exports, etc. Recently, India faced a serious shuttlecock shortage when the government banned all China feathered products. China has produced more than 90% of shuttlecock worldwide. As a result, the price is rising due to high demand.

The manufacturer has recently developed a shuttlecock made of foam plastic and carbon fibre. This shuttlecock is claimed to have the same flight and elasticity as the natural feather by adding carbon fibre to the feathers' surface to increase the shuttlecock's resilience. Feather and synthetic shuttlecock used the same drag induction principle by having features along with the conical skirt, even if they are different in design and construction. Therefore, the study's objective is to determine the aerodynamic properties comparison between natural feather, nylon, and carbon fibre shuttlecock under a range of spend and pitch angles using computational fluid dynamics (CFD). A great understanding of aerodynamic and flight trajectory would benefit players and help the manufacturer produce cheaper and consistent in-flight patterns. Alam et al. (2010a) conducted a study on variants type of the shuttlecock brand under wind tunnel. The shuttlecock where all observed at 60, 80, 100, and 120 km/h speeds. Based on the result, it is known that all shuttlecock's drag coefficient, CD average increases with increases of Reynold Number and lower with lower Reynold number. However, synthetic and feather shuttlecock showed decreased drag coefficient, CD value as the speed exceeded 80 km/h. Further mentioned in his paper, the average drag coefficient for feather shuttlecock obtained is 0.62 (over 100 km/h) and 0.49(60 km/h). Meanwhile, synthetic shuttlecock gave result of 0.59 (over 100 km/h) and 0.54 (60 km/h). Thus, it is concluded that the reduced drag coefficient of synthetic shuttlecock is due to skirting deformation at high speed (Alam et al., 2010b).

Similarly, Chan and Rossmann (2012) also experimented with comparing the flight performance of feather and synthetic shuttlecock under a range of speed and pitch angles ($\alpha = 0°, 10°, 15°$) in a subsonic wind tunnel. The paper stated that the drag coefficient, CD for feather shuttlecock reduced with increasing Reynolds Number (Hasegawa et al., 2013). Meanwhile, the lift coefficient remained constant along with Reynold number's range. The drag coefficient, CD obtained in his paper, was slightly higher than previous studies and tended to converge near 0.48–0.5 for Re > 190,000 (Alam et al., 2010a). Chan and

Rossmann (2012) preferred another parameter such as lift coefficient and pitching moment in his study. As a result, it is found that all three parameters were linearly dependent on the angle of attack. It is acknowledged that the plastic shuttlecock deformed drastically at high speed during the wind tunnel experiment. As a result, plastic shuttlecock travelled faster after a high-speed launch condition due to drag's surface area to act on being minimised by this deformation.

On the other hand, Hasegawa et al. (2013) have carried out a study by using a low turbulence wind tunnel to measure the aerodynamic properties of feather shuttlecock within the range of wind speed (10–60 m/s) and pitch angle (0°–25°). They also considered other aerodynamic characteristic such as lift coefficient and moment coefficient. Two types of shuttlecocks were used, feather shuttlecock with gaps and feather shuttlecock without gaps. There was no major difference between rotating and a non-rotating shuttlecock. Non-rotating shuttlecock with gaps showed that the drag coefficient increases with a higher Reynolds Number. However, as the Re > 86000, the drag coefficient was reported to decrease gradually (Hasegawa et al., 2013). Meanwhile, the drag coefficient for rotating shuttlecock with gaps is significantly over Re = 210,000. On the opposite side, the shuttlecock's drag coefficient without gap was slightly lower than the shuttlecock with a gap. Based on the result obtained, the drag coefficient decreased gradually with an increase of attack angle up to 20°. Meanwhile, as the attack angle goes beyond 20°, the drag coefficient also increased (Hasegawa et al., 2013). The drag parameter is vital for determining flight behaviour characteristics.

Verma et al. (2013) used computational approaches on feather, synthetic and gapless shuttlecock to determine the aerodynamic characteristic. The experiment has been carried out at various speed, and the difference in pressure between the inside and the outside of the skirt was found the main reason for drag. The effect of the twist angle of the feather was also tested using CFD, and the drag coefficient, CD decreased as the twisting angle goes beyond 12°. Nevertheless, according to Lin et al. (2014), these features are irrelevant to the synthetic shuttlecock model since the skirts are typically constructed in one piece.

In contrast, Kitta et al. (2011) performed a study of the flow around the gap and a gapless shuttlecock. A feather shuttlecock skirt was covered to create a gapless shuttlecock by covering it with tape. A high-speed camera (FASTCAM-SA3, Photron Ltd) was used to measure the skirt deformation and was analysed by image processing techniques. It was observed that shuttlecock with a gap has a higher value of drag coefficient than the gapless one. Besides, it is also mentioned that spin does not has a direct effect on drag.

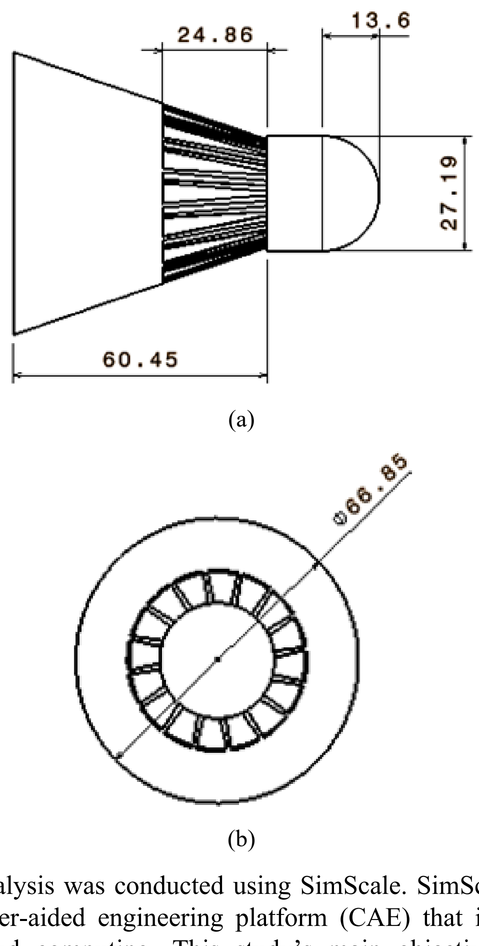
Meanwhile, Hart (2014) focused on understanding the badminton shuttlecock's aerodynamic properties but using CFD simulation. The purpose of his study was to predict the complex flow field associated with the bluff body aerodynamics of the shuttlecock by using Reynolds Averaged Navier Stokes (RANS) simulation in comparison with scale resolving simulation (SRS). Unlike the model resolved by the SRS model. It was found that RANS can predict the time-averaged flow phenomenon. Jahi et al. (2015) also accepted that the RANS model performs well for external flow around bluffed body with complex geometries in his paper. The model used two transport equations to enhance simulation sensitivity.

2 Methodology

2.1 Geometric model of shuttlecock

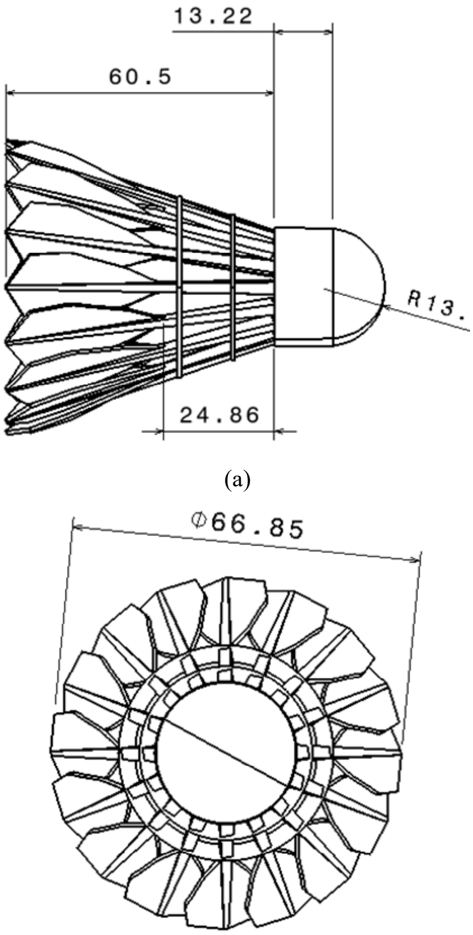
There are three types of shuttlecock models used in this study, feather, nylon, and foam. All models are designed using CATIA V5 software. The distance between the cork's nose to the middle of the diameter, L, is 87.27 mm in length. Meanwhile, the maximum diameter of the skirt D is 66.85 mm. The feather and the synthetic shuttlecock consist of 16 panels attached to the cork. There is no specific instrument used to make a measurement. Thus, the dimensions of these shuttlecocks are determined by the general measurement.

Figure 1 (a) Front view of nylon shuttlecock dimensions
(b) Side view of nylon shuttlecock with dimensions



The analysis was conducted using SimScale. SimScale is a computer-aided engineering platform (CAE) that is based on cloud computing. This study's main objective is to compare the aerodynamic properties between feather, nylon, and foam shuttlecock under the range of wind speed and pitch angles. SimScale is used to obtain the drag, lift, and pitch moments. The shuttlecocks were simulated at velocity inlets of 10, 20, 30, 40, 50, and 60 m/s with pitch angles between 10°–30°. The analysis was simulated as an incompressible fluid flow since the Ma value is below 0.3. Besides, the k-ω SST turbulence model is assigned to the simulation with a SIMPLE algorithm for pressure velocity coupling.

Figure 2 (a) Front view of feather and foam shuttlecock with dimensions (b) Side view of feather and foam shuttlecock with dimensions



(a)

(b)

2.2 *Domain and boundary condition*

The computational domain for all types of shuttlecocks is rectangular, where the flow inlet is located 5 L upstream of the 15 L shuttle downstream of the shuttle. Also, the 9D radius length is used to avoid missing any important flow features. On the other hand, a fixed velocity condition is assigned to the upstream boundary with a zero-gauge pressure at the downstream boundary. The outer surface domain is assigned to be modelled as a 'No-slip' wall and symmetry condition. The shuttlecock also was modelled as non-rotating. For this study, the fluid within the domain is specified to be air at the ideal temperature of the badminton game at 16°C, ρ = 1.222 kg/m^3 and μ = 1.817e-5 kg/(m.s). The computational domain was cut in half to minimise the number of elements as well as to reduce the simulation time. Approximately 1–2 million elements with 400–600 thousand nodes were used for the simulations.

Figure 3 Rectangular fluid domain enclosing the shuttlecock profile (see online version for colours)

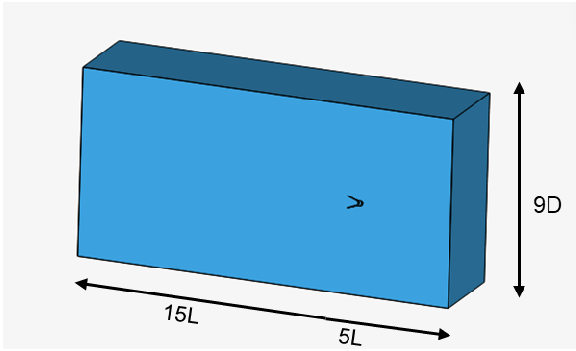
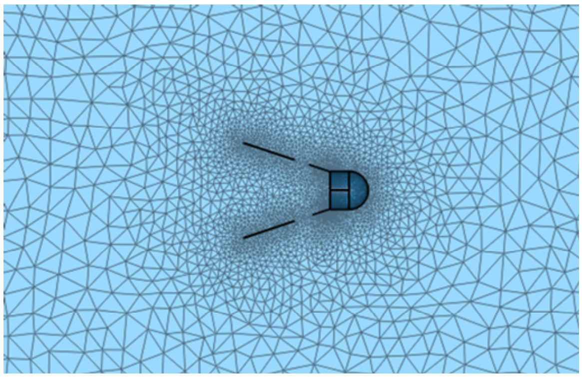


Figure 4 Close up mesh structural of shuttlecock (see online version for colours)



3 Result and discussion

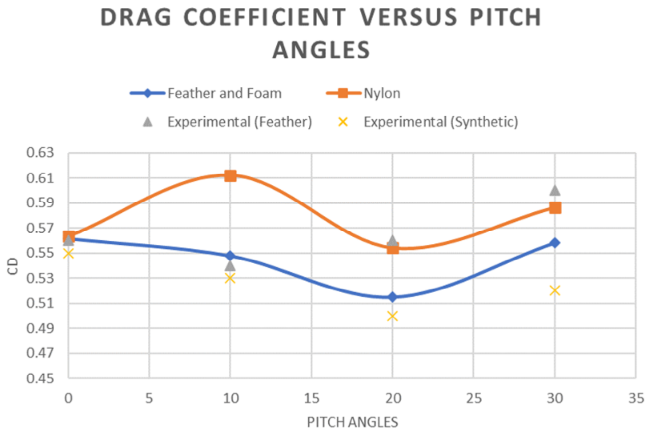
Flow past synthetic and feather shuttlecock were investigated for 45,000 < Re < 268,000 corresponding to an inlet velocity of 10–60 m/s. All shuttlecock models have the same dimensions and boundary conditions in the simulation. Reynolds number is a dimensionless quantity, measuring the fluid's flow condition and defined as $Re = \frac{\rho V d}{\mu}$.

In this study, the foam shuttlecock has the same CAD model as a feather. The research reveals that foam and feather shuttlecock has the same aerodynamic characteristics. Aerodynamics does not affect the material density of a solid object. When an object travels through a fluid, fluid resists movement. The object is subjected to aerodynamic force in the opposite direction called drag. Lift and drag depend linearly on the object's size where the cross-section produces drag around the object by the pressure variance. Furthermore, airflow and air properties also influence aerodynamics. The drag coefficient is defined as $CD = \frac{F_d}{0.5 \rho U_\infty^2 A}$, where F_d is the drag on the shuttlecock and A is the reference area, $A = \frac{\pi D^2}{4}$. Besides, lift and moment coefficient is also defined as $C_L = \frac{F_L}{0.5\rho U_\infty^2 A}$ and $C_M = \frac{F_M}{0.5\rho U_\infty^2 A}$ respectively.

The average drag coefficient value for feather/foam and nylon shuttlecock increases with Reynolds number and lower with lower Reynolds number from the simulation. Feather shuttlecock model has a constant value of about 0.56 over the 86,000–223,000 range of Reynold numbers. Previous research has repeatedly mentioned that synthetic shuttlecock results in a lower drag value compared to feather Alam et al. (2009) and Woo and Alam (2018). However, few other studies also found that the shuttlecock drag coefficient decreases as porosity increases (Alam et al., 2015). Typically, the nylon shuttlecock is more porous on the skirt body than the feather and creates smaller drag coefficient values. However, the synthetic shuttlecock's drag coefficient value is slightly higher than the feather in the analysis.

A study conducted by Lin et al. (2014) clearly stated that drag increases as the gap around the shuttlecock widen. Therefore, the drag coefficient increase might be due to the difference in the gap size of the shuttlecock skirt for the nylon model. Thus, there is a slight variance in CAD for both models because of no proper measuring instrument in determining the shuttlecock dimension and complexity of the shuttlecock feature. The gap between the nylon feather is more widen compared to the feather in this study. Hence, the drag coefficient for feathers is expected to be lower compared to nylon.

Figure 5 C_D versus pitch angles at 30 m/s (see online version for colours)



A study by Nakagawa et al. (2020) reveals that the drag coefficient obtained using wind tunnel for feather and synthetic models are around 0.5–0.6. The drag coefficient curve for feather shuttlecock is much higher than synthetic shuttlecock at all attack angles in their study. However, Figure 5 shows the opposite result in the drag coefficient due to the nylon model's skirt's gap size. The result from the experiment was plotted along with the simulation result obtained to see the difference clearly (Figures 5, 6 and 7).

Figure 6 C_L versus pitch angles at 30 m/s (see online version for colours)

On the other hand, the lift coefficient linearly increases with the attack angle, as indicated in Figure 6. At =0°, the lift coefficient values are near zero. The variation of the curves might be due to the difference in porosity, which changes the effective frontal area. The lift coefficient obtained for the nylon shuttlecock is 0.30 at $\alpha = 30°$ while feather/foam gives a value of 0.38 at a velocity of 30 m/s.

Figure 7 C_M versus pitch angles at 30 m/s (see online version for colours)

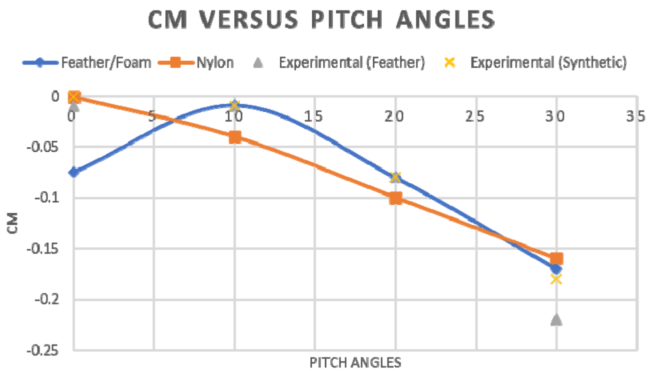


Table 1 Comparison between experimental and simulation for C_D at 30 m/s

Pitch angles	*Exp. (Feather)*	*Sim. (Feather)*	*Error (%)*	*Exp. (Nylon)*	*Sim. (Nylon)*	*Error (%)*
0	0.56	0.56	0	0.55	0.56	1.79
10	0.54	0.55	1.82	0.53	0.61	0.13
20	0.56	0.52	7.69	0.50	0.55	0.09
30	0.6	0.56	7.14	0.52	0.59	11.86

As can be seen in Figure 7, the moment of pitching is always negative, thereby restoring the moment. Both models show the same trend where the moment coefficient increase with pitch angles. Therefore, the shuttlecock is always stable. Unlike aircraft or other flying objects, shuttlecock lift forces are rarely studied since they are typically fly without an angle of attack and moment. Shuttlecock has an axisymmetric body, which has caused them to experience minimal lift or moment. However, the lifting and pitching moment can significantly enhance the trajectory simulation's accuracy.

Table 2 Comparison between experimental and simulation for C_L at 30 m/s

Pitch angles	*Exp. (Feather)*	*Sim. (Feather)*	*Error (%)*	*Exp. (Nylon)*	*Sim. (Nylon)*	*Error (%)*
0	0.02	0.01	1	0.01	0.02	50
10	0.10	0.12	16.67	0.03	0.02	50
20	0.28	0.26	7.69	0.18	0.14	28
30	0.42	0.38	10.53	0.30	0.30	0

Tables 1, 2, and 3 compare the difference between the experimental result conducted by Nakagawa et al. (2020) through wind tunnel and the simulation result obtained by using Simscale. The variance for the drag coefficient shows an error below 20%. However, there is some major variation for lift and moment coefficient between both study approaches. It is not expected that the result from both experiments would be identical. However, the difference would highlight areas of future research.

Table 3 Comparison between experimental and simulation for C_M at 30 m/s

Pitch angles	*Exp. (Feather)*	*Sim. (Feather)*	*Error (%)*	*Exp. (Nylon)*	*Sim. (Nylon)*	*Error (%)*
0	–0.01	–0.07	85.71	–0.001	–0.001	0
10	–0.01	–0.01	0	–0.01	–0.04	75
20	–0.08	–0.08	0	–0.08	–0.10	20
30	–0.22	–0.17	29.41	–0.18	–0.16	12.5

Figure 8 Velocity profile for feather/foam shuttlecock at 0°(60 m/s) (see online version for colours)

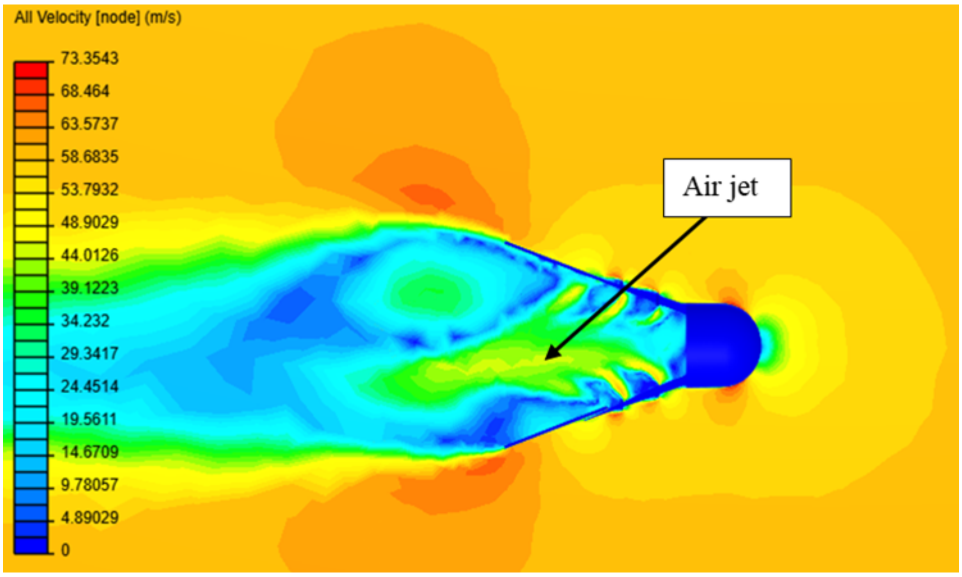


Figure 9 Velocity profile for nylon shuttlecock at 0° (60 m/s) (see online version for colours)

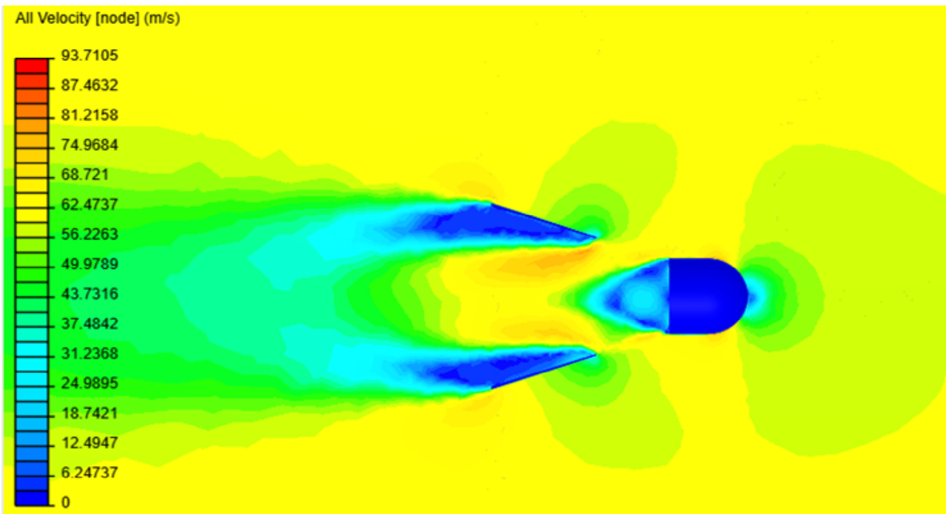


Figure 8 and Figure 9 show velocity profiles for feather and synthetic shuttlecock at Re = 267,696.00 (Velocity = 60 m/s). It is clearly seen that larger air is flowing through the gap from the shuttlecock's surrounding for nylon and weaker for feather/foam models. This flow leads to the formation of an air jet along the shuttlecock's axis. The gap in the shuttlecock skirt was found to increase the drag coefficient values (Moritz and Haake, 2006).

On the other hand, Figure 10 and Figure 11 show an annular stagnation region formed behind the skirt by air-jet, which passes through the gap behind the shuttlecock's nose. Therefore, it will reduce base pressure and increase drag (Moritz and Haake, 2006). The air movement through the feather shuttlecock interacts with the outer flow to create an unstable and irregular wake pattern. The outer flow tends to curl the shuttlecock axis inward, where it meets the fast-moving air jet that tends to curl outward into the area of stagnation behind the feather. Due to a larger gap area, the air jet is stronger for the nylon shuttlecock. Thus, the blunt-body effect is diminished and dilutes the recirculation typical of the wake behind a blunt body.

From Figure 10 and Figure 11, it is believed that the air flowing through the gap is preventing the air from outside of the skirt from recirculating back into the blockage region. This phenomenon would lead to a decrease of recirculation further downstream, expand further outward and finally increase the wake area behind the shuttlecock (Alam et al., 2015). Thus, it is believed that the larger wake area results in higher drag.

Figure 10 Velocity vector around feather shuttlecock at 0° (60 m/s) (see online version for colours)

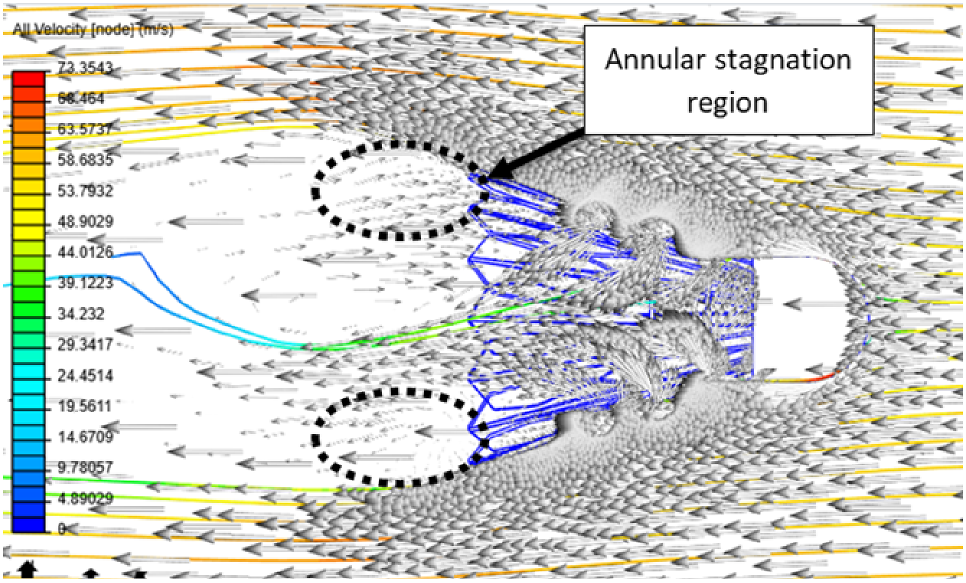
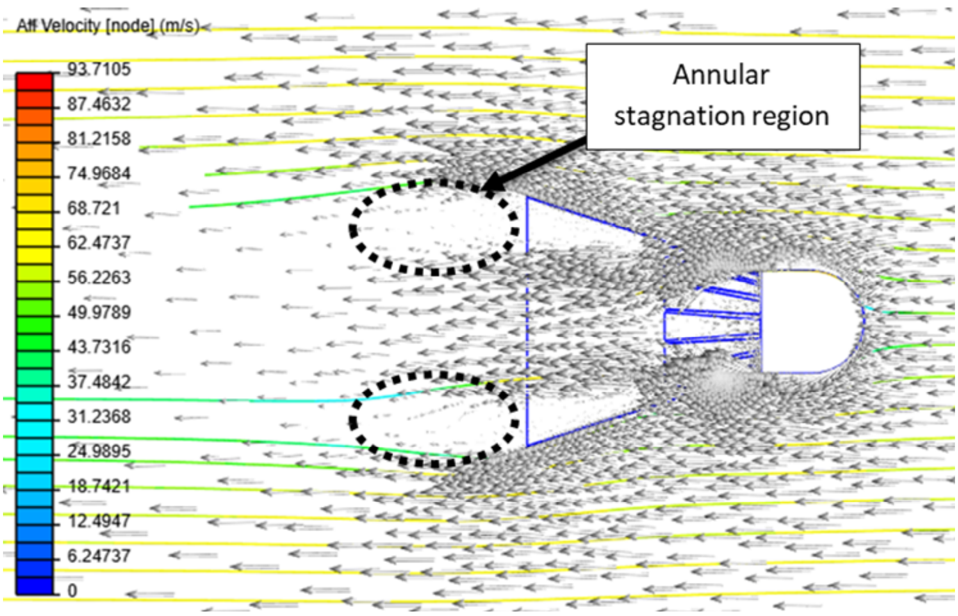


Figure 11 Velocity vector around nylon shuttlecock at 0° (60 m/s) (see online version for colours)



4 Conclusions

The study was carried out successfully met the project's objectives, such as designing shuttlecock models using CAD software, simulation of aerodynamic properties through SimScale, and comparing aerodynamic properties between feather, nylon, and foam shuttlecock within the range of speed and pitch angles.

In this study, a nylon model was constructed as a non-porous at the bottom of the shuttlecock skirt to reduce the design's complexity. However, the simulation shows that the nylon drag coefficient is slightly larger than feather/foam. The drag coefficient value of feather/foam was approximately constant at 0.56, equivalent to the Re = 223,000. Both shuttlecock models show an increase in drag, lift, and moment coefficient along with pitch angles. The lift coefficient obtained for nylon shuttlecock is 0.30, while feather/foam gives a value of 0.38 at $\alpha = 30°$(30 m/s). Both models' moment coefficient value shows a negative sign, which indicates that the aerodynamic centre is always behind the centre of gravity. Therefore, a stable shuttlecock is obtained.

The airflow from the surrounding to the core of the shuttlecock introduced air jet flow. Nylon shuttlecock models have a larger gap size compared to feather. Also, it is found out that the gap around the shuttlecock skirt increases the drag coefficient. The situation occurred due to stagnant wake air's entrainment by a strong air jet emerging from the shuttlecock gap. Moreover, the recirculation intensity and reverse flow for the nylon shuttlecock are reduced. On the other side, fair movement through the feather shuttlecock creates an erratic and irregular wake pattern by interacting with the outer flow. The outer flow tends to curl the shuttlecock axis inward. After that, it meets the stronger air-jet and tends to curl outward into the stagnation region behind the feather.

For future research, shuttlecock drawing could be carried out using CAD software with a 3D scanner. The 3D scanner can be used to accurately capture the complex shape of the shuttlecock skirt, particularly the valves, the shaft, and the rachis. Therefore, proper dimensions can be obtained, and the simulation results are more reliable. A computational analysis of the effect of skirt deformation may also be carried out. Also the use of smaller pitch angle increments (e.g., 5°) to enhance precision in data collection. However, it's essential to balance this with practical considerations, such as resource constraints and time limitations. Addressing the error margin between experimental and computational results should remain a priority, with a focus on improving models, refining experimental procedures, and conducting comprehensive error analyses to enhance the overall research quality.

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