A cylindrical methodology for the study of fabric aerodynamics

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Abstract

The understanding of aerodynamic behavior of sports garments in high speed sports can lead to achieve higher efficiency and performance in order to understand the aerodynamic behavior of fabrics used in speed sports garments, prior studies have mainly used the vertical cylindrical methodology in wind tunnel environments. However, using the vertical cylindrical methodology, the aerodynamic behavior of sports garments cannot be fully realistic as athlete’s all body parts are not positioned vertically all the time. Limited information is available on cylindrical methodology that can provide aerodynamic characteristics of fabrics under inclined positions. Therefore, the primary objective of this study is to develop a cylindrical methodology that can be used for both vertical and inclined positions. The suitability of the developed method for the fabrics is investigated using a wind tunnel. The results indicated that the developed methodology suited well and provided detail aerodynamic information about the fabric used.

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1. Introduction

Aerodynamic behavior of sport fabrics can play a significant role in a wide range of speed sports including cycling, downhill-skiing, speed-skating, ski-jumping, sprinting and swimming. The winning time margins are progressively being reduced with the integration of advanced technologies as well as vigorous training regimes. The winning margin can be further decreased by understanding such aerodynamic behavior especially the drag and lift properties of athlete’s physical body positions and their outfits (garments) \cite{1-4}. Elaborate understanding of the aerodynamic behavior of physiological parameters (such as athlete body position and geometric shape of body parts) as well as fabric parameters (surface roughness, course/wale orientation in knitted fabric, and weft/warp orientation in woven fabric, seam configuration and placement) in high speed sports can lead to higher efficiency and achievement.

The human body shape is complex and can be considered as a bluff body. Researchers such as Hanavan \cite{5}, Hatze \cite{6} and Yeadon \cite{7} studied the human body anthropometric behavior and subdivided the human body into multiple cylindrical, conical and other shapes in order to represent the body with simplified anthropometric dimensions. Although this human body representation is well studied for biomechanics applications, several other researchers such as Hoerner \cite{8}, Pugh \cite{9} and Brownlie \cite{10} studied the aerodynamic characteristics of human bodies based on simplified human body. Kyle et al. \cite{11,12}, Oggiano et al. \cite{13}, Strangwood \cite{14} and Moria et al. \cite{15} have mainly focused on the aerodynamic behavior of fabrics using vertical cylindrical methodology in wind tunnel environments. Chowdhury et al. \cite{16} evaluated aerodynamic properties (drag and lift simultaneously) of the simplified human body parts under a range of angles of attack (\( \alpha \)) to simulate athlete’s body positions. Hence, the experimental setup used by Chowdhury and others can only measure the drag and lift of

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cylindrical within a limited range of angles of attack (30° to 90°). However, in many sports the body parts’ position can lie below the 30° angle of attack and beyond the 90° angle of attack. Therefore, it is necessary to develop an experimental arrangement that can evaluate aerodynamic behavior of the cylinder. In this study, a new cylindrical arrangement has been designed and developed to measure the aerodynamic parameters (lift and drag) from $\alpha = 0°$ to $90°$.

2. Methodology

With a view to investigate aerodynamic behavior of fabrics experimentally under a range of angles of attack (0° to 90°), a 90 mm diameter ($d$) and 220 mm length ($l$) cylinder was developed. The cylindrical arrangement consists of cylinder, rotating mechanism, strut with airfoil canopy. The cylinder was made of PVC material and used filler to make it structurally rigid. The test cylinder was connected to the hinge that was supported by the strut. The hinge was designed in such a way that the angle of attack of the test cylinder can be varied. The airfoil canopy was also covered the strut during the test to minimize the aerodynamic interference. The strut was vertically mounted on a six components load sensor (type JR-3) which has a sensitivity of 0.05% over a range of 0 to 200 N. The Model of inclined cylinder experimental arrangement is shown in Fig. 1(a). The aerodynamic forces and their moments were measured for a range of Reynolds numbers based on cylinder diameter and wind speeds (30 to 140 km/h). As shown in Fig. 1(b), each test was conducted as a function of angles of attack from stream-wise ($\alpha = 0°$) to span-wise ($\alpha = 90°$). The tunnel was calibrated prior conducting the experiments and air speeds inside the wind tunnel were measured with a modified National Physical Laboratory (NPL) ellipsoidal head Pitot-static tube (located at the entry of the test section) which was connected through flexible tubing with the Baratron® pressure sensor (manufactured by MKS Instruments, USA). The sensor was used to measure all three forces (drag, lift and side forces) and three moments (yaw, pitch and roll) at a time. Each set of data was recorded three times for 30 seconds time average with a frequency of 20 Hz ensuring electrical interference is minimized. Multiple data sets were collected at each speed tested and the results were averaged for minimizing the further possible errors in the raw experimental data.

In order to validate the results, initially the cylinder without fabric was tested. Then a knitted fabric used in sports garment fitted around the test cylinder without tension (e.g., normal fit) was investigated. The fabric sample was joined together by a seam which was placed at the rear of the cylinder to minimize the effect of seam [15].

![Fig. 1. Design and experimental arrangement of the cylinder geometry to measure the aerodynamic properties (lift and drag) at different angles of attack from 0° to 90° relative to wind direction. (a) Schematic CAD model; (b) cylinder in wind tunnel.](image)

The knitted fabric sample was composed of 80 % Polyester and 20 % Spandex. The thickness of the fabric is 0.55 mm. Fig. 2 shows the fabric microstructure which was captured using a scanning electron microscope (SEM) at different magnifications. It can be seen that surface topology consists of approximately 21.10 and 167.00 μm fiber diameter and yarn size respectively. The stitch pattern was observed as V-shape. Also, the number of courses and wales per cm was found 22 and 25 respectively.
3. Results and discussion

All three aerodynamic forces (drag, lift and side force) and three moments (yaw, pitch and roll) were measured simultaneously. The aerodynamic force converted to their non-dimensional coefficients of $C_D$, $C_L$ and $C_S$ as a function of Reynolds number ($Re$). However, only coefficients $C_D$ and $C_L$ are included in this paper. The $C_D$, $C_L$ and $Re$ were calculated using equations 1, 2 and 3:

$$C_D = \frac{F_D}{0.5 \rho V^2 A}$$

$$C_L = \frac{F_L}{0.5 \rho V^2 A}$$

$$Re = \frac{V d}{\mu}$$

where, $\rho$, $V$, $A$, $d$, and $\mu$ are the air density, wind speed, projected frontal area of the cylinder, diameter of the cylinder and absolute air viscosity respectively.

The drag coefficient ($C_D$) and lift coefficient ($C_L$) variation with Reynolds number ($Re$) (varied by wind speed ranging from 30 km/h to 140 km/h with an increment of 10 km/h) at different angles of attack ($\alpha$) (0° to 90° with an increment of 15°) are shown in Fig. 3. The variations of $C_D$ and $C_L$ for the smooth cylinder are shown in Fig. 3(a). The $C_D$ and $C_L$ for the fabric under the same $Re$ are illustrated in Fig. 3(b). For the smooth cylinder, the maximum value of $C_D$ was obtained at $\alpha = 0^\circ$ whereas the lowest $C_D$ value was found at $\alpha = 30^\circ$. The magnitude of $C_D$ values reduces with the decrease of angle of attack. The $C_D$ variation with $Re$ as a function of $\alpha$ indicates that with the increase of $\alpha$, the $C_D$ value increases. It may be noted that in the calculation of $C_D$ value for the various $\alpha$, the projected frontal area was considered as: $A = l \times d \times \sin \alpha + (\pi r^2 \times \cos \alpha)$. However, for zero angle of attack, the projected frontal area was considered as cross sectional area of the cylinder (i.e., $\pi r^2$). Therefore, despite having lowest drag experienced by the cylinder at $\alpha = 0^\circ$, the $C_D$ value is highest. There is no apparent flow transition occurred for the smooth cylinder under the range of $Re$ tested. Generally, flow transition (from the laminar to turbulent regimes) for the smooth cylinder occurs at $Re \geq 3 \times 10^5$. In this study, the maximum $Re = 2.3 \times 10^5$ which covers with for most speed sports and also the maximum speed limit for RMIT industrial wind tunnel. It is interesting to note that an early flow transition has been noted for the smooth cylinder at angle of attack between 60° to 75°. However, it is not clear what triggered this flow transition. It is believed that the oblique flow generated by the inclined cylinder might cause this early transition. Further studies are required to understand this behavior. The similar behavior of the smooth cylinder for the $C_L$ was noted as shown in Fig. 3 (a). The $C_L$ behavior at low $Re$ is believed to be experimental error. The $C_D$ value at stream-wise ($\alpha = 0^\circ$) and span-wise ($\alpha = 90^\circ$) was agreed with published data (Hoerner [8], Chowdhury et al. [16], Achenbach [17] and White [18]). However, the maximum $C_L$ value was found at $\alpha = 45^\circ$ and values decrease with the further increase or decrease of angles of attack. Furthermore, the $C_L$ values at $\alpha = 15^\circ$ and $30^\circ$, the direction is negative at low $Re$, however, the $C_L$ values increases with the increase of up to 70 km/h ($Re = 1.18 \times 10^5$).
On the other hand, Fig. 3(b) shows the $C_D$ and $C_L$ as a function of $Re$ with fabric at different angles of attack from 0° to 90°. The data clearly indicate that there is a significant effect in the aerodynamic behavior on the cylinder at different angles of attack. However, the transitional effects occur at 70 km/h for $\alpha = 30°, 45°, 60°, 75°$ and 90°. Nevertheless, no flow transitional effect was noted at $\alpha = 0°$ and 15°. The minimum $C_D$ value (0.399) is obtained at $\alpha = 75°$ and 90 km/h ($Re = 1.51 \times 10^5$).

![Graph showing drag and lift coefficients as a function of Reynolds number](image)

Fig. 3. Drag and lift coefficient ($C_D$ and $C_L$) as a function of Reynolds number ($Re$) at different angles of attack from 0° to 90° relative to wind direction for cylinder: (a) without fabric; (b) with fabric.
As mentioned earlier, the majority of the aerodynamic drag is generated by the body shape which is predominantly pressure drag. The projected frontal area represents a significant factor in aerodynamic drag generation. In aeronautical and many speed sports applications, the lift to drag ratio is considered fundamental. Here, lift to drag ratio relationships have plotted for the smooth cylinder as well as cylinder with the fabric under the same test conditions as mentioned earlier. The graphs are shown in Figs. 4(a) and (b). The maximum value of $L/D$ was obtained at $\alpha = 45^\circ$ for both cases whereas the lowest $C_D$ value was found at $\alpha = 15^\circ$ and $75^\circ$ for the smooth cylinder and cylinder with the fabric respectively. It also shows that the fabric surface morphology (surface structure and roughness) and the angle of attack changes the flow behavior (e.g., effect of flow regimes).

Fig. 4. The variation of $L/D$ with $Re$ at different angles of attack from $0^\circ$ to $90^\circ$: (a) without fabric; (b) with fabric.
4. Conclusions

The following conclusions have been made based on the experimental study presented here:

- Using a standard cylindrical geometry, an experimental methodology has been developed to study the aerodynamic behavior of fabrics over a wide range of angles of attack (0° to 180°). The methodology is simple, easy to setup, and aerodynamically less intrusive.
- The analyzed results indicated that the highest lift-to-drag ratio ($L/D$) was generated at an angle of attack ($\alpha$) of 45° for both the smooth surfaced and fabric covered cylinders.
- The minimum lift-to-drag ratio was obtained at higher angle of attack ($\alpha = 75°$) for the fabric covered cylinder, while the minimum value of $L/D$ was found at lower angle of attack ($\alpha = 15°$) for a smooth surfaced cylinder.

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References

[1] Barelle, C., Ruby, A., Tavernier, M., 2004. Experimental model of the aerodynamic drag coefficient in alpine skiing, Journal of Applied Biomechanics 20(2), p. 35.
[2] Grappe, F., Candau, R., Belli, A., Rouillon, J. D., 1997. Aerodynamic drag in field cycling with special references to the Obree’s position, Ergonomics 40(12), p. 1299.
[3] Lukes, R. A., Chin, S. B., Haake, S. J., 2005. The understanding and development of cycling aerodynamics, Sports Engineering 8(2), p. 59.
[4] Laing, R. M., 2002. Clothing, textiles and human performance: a critical review of the effect on human performance of clothing and textiles. The Textile Institute, Manchester.
[5] Hanavan, E. P., 1964. A mathematical model of the human body, AMRL-TR-64-102, AD-608-463, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, USA.
[6] Hatze, H. A., 1980. Mathematical model for the computational determination of parameter values of anthropomorphic segments, Journal of Biomechanics 13(10), p. 833.
[7] Yeadon, M. R., 1990. The simulation of aerial movement—II. A mathematical inertia model of the human body, Journal of Biomechanics 23(1), p. 67.
[8] Hoerner, S. F., 1952. Aerodynamic Properties of Screens and Fabrics, Textile Research Journal, 1(22), p. 274.
[9] Pugh, L. G. C. E., 1974. The relation of oxygen intake and speed in competition cycling and comparative observations on the bicycle ergometer, Journal of Physiology 241(1), p. 795.
[10] Brownlie, L. W., 1992. Aerodynamic characteristics of sports apparel. (PhD Thesis). University of British Columbia, Canada.
[11] Kyle, C. R., Brownlie, L. W., Harber, E., MacDonald, R., Shorten, M., 2004. The Mike Swift Spin Cycling Project: Reducing the Aerodynamic Drag of Bicycle Racing Clothing by Using Zoned Fabrics. UK: International Sports Engineering Association, p. 118.
[12] Kyle, C. R., Caiozzo, V. J., 1986. The Effect of Athletic Clothing Aerodynamics upon Running Speed, Medicine and Science in Sports and Exercise 18, p. 509.
[13] Oggiano, L., Troyinkov, O., Konopov, I., Subic, A., Alam, F., 2009. Aerodynamic behaviour of single sport jersey fabrics with different roughness and cover factors, Sports Engineering 12(1), p. 1.
[14] Strangwood, M., 2007. Modelling of Materials for Sports Equipment, in “Materials in Sports Equipment”. Woodhead Publishing Ltd., Cambridge.
[15] Moria, H., Chowdhury, H., Alam, F., Subic, A., 2010. Comparative aerodynamic analysis of commercial swimsuits, Journal of Sports Technology 3(4), p. 261.
[16] Chowdhury, H., Alam, F., Mainwaring, D., Subic, A., Tate, M., Forster, D., Beneyto-Ferre, J., 2009. Design and methodology for evaluating aerodynamic characteristics of sports textiles, Sports Technology 2(3-4), p. 81.
[17] Achenbach, E., 1974. The effects of surface roughness and tunnel blockage on the flow past spheres, Journal of Fluid Mechanics 65, p. 113.
[18] White, F. M., 2003. Fluid Mechanics (5th ed.). McGrow-Hill, New York.