ON THE FLIGHT OF THE VOLLEYBALL

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Abstract

The paper deals with results of measurements of forces acting on volleyball. Drag coefficients evaluated from measurements in two aerodynamic tunnels are compared. The other force components i.e. lift and side force obtained by experimental investigation with angle of attack related to the axis of rotation are studied.

Keywords: aerodynamics, drag, forces, lift, measurement, volleyball, wind tunnel

1 Introduction

Flight of sports ball in the air is interesting topic for a long time. Newton described flight of tennis ball already in 1672. Whole theory of flight of rotating sphere was written in 1852 by German physicist H.G. Magnus [2]. Today, it is well known as Magnus effect theory. Nowadays, most of the studies are focused on properties of football flight, but also other sports balls were observed and articles were published, e.g. R. D. Mehta [3], [4] studies cricket ball, baseball, golf ball and also volleyball. Studies of flight of volleyball are focused on investigating the flight in the real conditions, analysed from video, as in [4], or [5]. Another way of investigating properties of the flight of volleyball is to set up experiment in the aerodynamic wind tunnel and measure forces acting on the volleyball. Many experiments are dealing with fixed ball, which can not rotate, for example [1] and [6]. Measurement of rotating ball in the wind tunnel was performed and results were published in [7].

In real conditions, sport ball freely rotates in the flight, based on initial conditions and effects of the airflow (wind). This requires more sophisticated wind tunnel set up. Exact recommendation was made in previous article [8]. Measurements were performed and results were computed. Results of $C_D$, $C_L$, $C_S$ as well as results of moments were published in [9]. Only brief overview of results is made in this article. Comparison of coefficient of drag $C_D$ is main part of this article.

2 Description of experiment

Experiment was performed in the Aerospace Research and Test Establishment, Department of Aerodynamics, Prague, Czech Republic. Measurement set up is visible in the Fig. 1.

Main aim of the measurement was to describe all forces and moments acting on the ball flying in the medium. Therefore six strain gauges (accuracy of 1% of measured forces) were used: two for lift force $F_L$, three for drag $F_D$ and one for side force $F_S$. All values, forces $F_D$, $F_L$ and $F_S$ and all moments $M_X$, $M_Y$ and $M_Z$ were evaluated according to simple equations (1) – (6). Scheme of forces is shown in the Fig. 2:

- **Drag:**
  \[ F_D = F_3 + F_4 + F_5 \]  

- **Lift:**
  \[ F_L = F_1 + F_2 \]  

- **Side force:**
  \[ F_S = F_6 \]  

- **Roll:**
  \[ M_X = F_1 \cdot a - F_2 \cdot a \]
• Yaw: \[ M_Y = F_4 \cdot f - F_3 \cdot f \] (5)

• Pitch: \[ M_Z = (F_3 + F_4) \cdot b - F_5 \cdot c \] (6)

Figure 1 - Measurement of forces acting on Beach Volleyball set up

Figure 2: Scheme of forces in the measurement
Coefficient of drag $C_D$ is defined in equation (7), $C_L$ and $C_S$ in a similar way to equation (7), and Reynolds number is defined in equation (8):

$$C_D = \frac{8F_D}{\rho v^2 \pi d^2},$$  \hspace{1cm} (7)

$$Re = \frac{v d}{\nu},$$  \hspace{1cm} (8)

where $v$ is velocity [m/s], $d$ is diameter of the ball [m], $\nu$ is kinematic viscosity [m$^2$/s], $n$ is revolution [rps].

Beach Volleyball Mikasa VLS 300 was measured. Velocity of 10 – 25 m/s, which in the case of volleyball means $Re = 1.5 \times 10^5$ – $3.7 \times 10^5$, and revolutions of 0 – 12.5 rev/s were set up. In the measurement, the side angle of attack $\beta$ was also varied (as visible in the Fig. 2), for description of forces and moments depending on different angle of attack. In this article, only drag force of nonspinning ball is described. Other values, such as lift and side forces and moments will be studied in future works more thoroughly.

### 3 Results and comparison

Results of performed experiment and comparison with another volleyballs (source of data: [1]) is depicted in the Fig. 3. Intensity of turbulence in the tunnel, where measurement was performed was 1%. Intensity of turbulence of the other results from reference [1], was lower or equal to 1%. Intensity of turbulence is comparable in both measurements.

In experiment, all components of force acting on volleyball such as lift force $F_L$, side force $F_S$ and moment $M_X$ were measured. Examples of results are shown in Fig. 4, Fig. 5 and Fig. 6: Lift coefficient $C_L$ is depicted for angle of $\beta = 0^\circ$ (Fig. 4), side force coefficient $C_S$ is depicted for angle $\beta = 0^\circ$ (Fig. 5) and moment $M_X$ is depicted for angle $\beta = 0^\circ$ (Fig. 6). In Fig. 4 it is visible that with rising revolutions, $n$ [rps], coefficient $C_L$ increases as well. However $C_S$ slightly decreases with rising Reynolds number. In the Fig. 6 according to the results it is also visible, that this is fully turbulent boundary layer regime in
separation zone, which results in intermittent breaking of symmetry in the surrounding flow, as it is visible in the zone of decrease of $M_X$ in the area of $Re$ around $3 \times 10^5$.

All results will be studied more in detail and described in future articles.

![Figure 4: Lift coefficient $C_L$, angle $\beta = 0^\circ$](image1)

![Figure 5: Side force coefficient $C_S$, angle $\beta = 0^\circ$](image2)
4 Discussion

Results of drag of all volleyballs (Fig. 3) have all the same trends: in laminar flow, drag is in between $C_D = (0.4 – 0.5)$. Turbulent flow values of drag are between $C_D = 0.1$ and $C_D = 0.2$. Trends are similar to trends of drag of a smooth sphere.

In comparison of drag of volleyballs and the drag of smooth sphere it is obvious, that dependence of drag drop of volleyball is shifted to lower Reynolds numbers. This shift is, based on data from [10] – depicted in the Fig. 7, caused by roughness of surface. As it is visible in the Fig. 8 and Fig. 9, volleyball surface is composed of pieces of synthetic leather. “seams” in between the leather pieces are the most recognizable at Mikasa VLS 300 beach volleyball.

Seams on the surface are one source of roughness of surface, but more important seems to be roughness of surface material. It is visible in Fig. 8, that Molten MTV5SLIT together with Mikasa VLS 300 are made from the smoothest material. On the other hand, material of which Mikasa MVA 200 surface is made, contains obvious dents. Dimples on the surface have clear influence on the aerodynamic characteristics, as it is well described in the case of golf ball. Effect on volleyball is not as intensive as in the case of golf ball, caused by the size of dimples on the surface in relation to the size of the ball.

Critical Reynolds number was determined from Fig. 3 and based on [11]: “critical Reynolds number is defined by $C_D = 0.3$”, for volleyballs in Tab. 1. Critical Reynolds number for smooth sphere is $3 \times 10^5$ and for golf ball it is $5 \times 10^5$.

Critical Reynolds number shows very well the effect of different roughness of surface of volleyball. Three balls (VLS 300, V5M500 and MTV5SLIT), have defined critical Reynolds number close to each other, $1.7 \times 10^5 – 1.86 \times 10^5$, while dimpled surface ball (MVA200) has critical number $2.15 \times 10^5$. Achieved results lead to task: different types of roughness should be described and influence of type of surface should be studied. According to Fig. 7, dimples on the surface of a golf ball are promoting the transition, however in tab. 1 it is visible, that for Mikasa MVA 200 (ball with dimples on the surface), critical Re is the highest in comparison to all other volleyballs. This can be explained by two aspects: 1. in the case of golf balls, promotion transition is caused by edges of dimples as described in [13], 2. It is important to define different types of surface roughness, as it is visible in Fig. 8 and Fig. 9 surfaces of balls (with or without dimples) are of different roughness.

This phenomena in case of volleyball is practically very important in the case of so called floating service, according to previous tests and the first author’s experienced in real sport activity, as it is described in [5].

The influence of turbulent intensity was not investigated, valued 1% as defined in the description of experiment, was result of detail testing of the wind tunnel.
### Influence of the experimental setup:

The way of how the ball is held in the measurement set up can influence results of the experiment. This effect was described and discussed already in 1924 [12]. In the Fig. 1, it is visible, that the ball for the measurements was held in between two small rods, which allow ball rotating, but it is not clear, what influence interaction in between rotating axe and ball has. As all studied Reynolds numbers ($Re = 1.5 \times 10^5 \ldots 3.7 \times 10^5$) are in the region of critical Reynolds number, even very small uncertainties can have influence on earlier transition into turbulent regime.

This phenomena, could be similar to horseshoe vortex model, will be studied in the CFD model.

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**Figure 7:** Drag of sphere with rough surface - Achenbach – source [10]

<table>
<thead>
<tr>
<th>Ball type</th>
<th>Critical Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mikasa VLS 300</td>
<td>$1.7 \times 10^5$</td>
</tr>
<tr>
<td>Molten V5M5000</td>
<td>$1.77 \times 10^5$</td>
</tr>
<tr>
<td>Molten MTV5SLIT</td>
<td>$1.86 \times 10^5$</td>
</tr>
<tr>
<td>Mikasa MVA 200</td>
<td>$2.15 \times 10^5$</td>
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</tbody>
</table>

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**Figure 8:** Molten MTV5SLIT and Molten M5V5000
5 Conclusion

Measurement of forces acting on volleyball was performed in the wind tunnel. Results of drag were evaluated and presented in this article. Comparison of drag coefficient of different volleyballs and smooth sphere was discussed. Surface roughness is important factor in the drag of spherical bodies. It is obvious, that influence of the surface roughness quality should be studied and defined from the point of view of fluid mechanics characteristics. This is well documented by critical Reynolds number: $Re_c = 2.15 \times 10^5$ since other studied balls have the critical Reynolds number in the interval: $Re_c = 1.7 \times 10^5 - 1.86 \times 10^5$.

Influence of experimental setup is mentioned. Study of a horseshoe vortex is recommended to describe influence of rotating axe in connection with ball.

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References


