TRANSVERSAL DRAG FORCES DURING THE BALL'S FLIGHT

Otmar Kugovnik[1]**, Matej Supej**[1] **and Bojan Nemec**[2]

[1]*Faculty of Sport, University of Ljubljana, Slovenia*
[2]*Institute Josef Stefan, Ljubljana, Slovenia*

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Abstract:

The problem of a tactically well performed straight service in volleyball is under investigation. The aerodynamical forces acting on the ball and the vortex wake behind the sphere are the main subjects of the research work. These parameters determine the tactics in volleyball service, because they can “spoil” the expected trajectory of the ball and consequently disturb the defences.

Two different wind tunnels in diameter 1.8 m and 3 m, respectively, with distinguished turbulence intensities were used for measuring the interval of critical Reynolds' numbers for two volleyball balls with different roughness of the surface. The longitudinal and the transversal forces were also measured for five airflow velocities ranging from 8 m/s to 25 m/s. It was found that the transversal forces acting on the ball are two orders of magnitude smaller than the frontal drag force. It was also noticed that the position of the seams, in regard to the direction of the airflow velocity vector, is crucial for the determination of the transversal forces components. All the facts stated above give the reason for the deviation of the ball away from its expected ballistic trajectory.

The periodic nature of the phenomena enabled the performance of the discrete Fourier transformation on the transversal forces. It turned out that the error made with the Fourier transformation when taking only the first four summands is negligible compared to the measuring error.

Key words: *volleyball, straight service, ball flight, vortex wake behind the sphere, Fourier transformation, transversal forces*

TRANSVERSALE ZUGKRÄFTE WÄHREND DES BALLFLUGES

Zusammenfassung:

Das Problem des taktisch gut ausgeführten geradlinigen Aufschlag im Volleyball wurde untersucht. Im Mittelpunkt der Untersuchung standen die auf den Ball wirkenden aerodynamischen Kräfte und der Luftwirbel hinter der Sphäre. Diese Parameter entscheiden die Taktik beim Volleyballaufschlag, denn sie können die vorgesehene Ballflugbahn „verderben“ und folglich die Verteidigung hindern.

Zwei verschiedene Windtunnels, 1,8 m und 3 m im Durchmesser, mit ausgeprägten Turbulenzintensitäten wurden zum Messen des Intervalls der kritischen Reynoldsschen Zahl für zwei Volleyball-Bälle von unterschiedlicher Oberflächenrauheit benutzt. Longitudinale und transversale Kräfte wurden auch für fünf Fluggeschwindigkeiten im Bereich von 8 m/s bis 25 m/s gemessen. Es wurde festgestellt, dass die auf den Ball wirkenden transversalen Kräfte um zwei Größenordnungen kleiner als die frontale Zugkraft sind. Es wurde auch beobachtet, dass die Nahtstellen bezüglich der Richtung des Fluggeschwindikeitsvektors für die Bestimmung der Komponenten transversaler Kraft wesentlich sind. Alle angeführten Tatsachen stellen den Grund für die Abweichung des Balles von der vorgesehenen Flugbahn dar.

Die periodische Natur dieser Phänomene ermöglichte, die diskrete Fouriersche Transformation an den transversalen Kräften durchzuführen. Es wurde festgestellt, dass der Fehler bei der Fourierschen Transformation, wenn nur die ersten vier Summänden in Betracht genommen sind, im Vergleich zum Messfehler unbeträchtlich ist.

Schlüsselwörter*: Volleyball, geradliniger Aufschlag, Ballflug, Luftwirbel hinter der Sphäre, Fouriersche Transformation, transversale Kräfte*

Introduction

The ball's flight in the gravitational field is a well known phenomenon (Daish, 1972a; 1972b). The air resistance is the expected contribution to the ball's non-parabolic trajectory in a longitudinal direction. But despite these changes, air resistance is also the reason for the so called unexpected longitudinal as well as the transversal deviation of the ball's trajectory away from the parabolic curve. A server in volleyball that knows how to give the ball proper direction and velocity by an initial strike at the center of the ball can quite accurately define where the unexpected deviations will be the greatest. According to the previous facts he can also minimize the time that the defender has at his/her disposal to react to this change in the ball's flight with adequate motor control (McGown, 1994; Štulrajter and Panek, 1987). This way a tactically well performed service may disturb the defence up to the point where the player is unable to take or return the ball properly.

To understand the nature of the unexpected deviation of the ball's trajectory we proposed the theoretical model for the velocity distribution in the vortex wake around and especially behind a sphere. The model for the airflow passing the radially symmetric obstacle is based on (Swain, 1950) the Prandtl's theory of the length of the mixing vortex wake and the hypothesis that the shape of the boundary layer is determined with the equation:

$$r = \alpha \cdot x^{1/3} + \beta \cdot x^{-1/3},$$

where the coefficients α and β are experimentally measured. The coordinate system x, r, z is shown in Fig.1.

With further assumptions (see Fig. 1):

- far away from the ball with diameter d is the relative velocity of the airflow equal to $u_\infty + v$ where $v \ll u_\infty$,
- the changes of the transversal velocity are much smaller than the changes in the longitudinal velocity,
- the equation of motion in the perpendicular direction z and r to the main airflow (direction x) is negligible,
- the velocity pulsation v' in the direction of the r axis is equal to

$$v' \approx \frac{d(2b_w)}{dt} \approx u_\infty \frac{d(2b_w)}{dx}$$

where $2b_w$ is the diameter of the vortex wake, and solving the continuum equation and the equation of the momentum conservation (Schlichting, 1968; Swain, 1950) we finally obtained results we wanted:

$$b_w = \left(\frac{105^{1/3}}{2}\right)\beta^{2/3}(c_x d^2 x)^{1/3} \quad \text{and}$$

$$\frac{u'}{u_\infty} = \frac{105^{1/3}}{54}\beta^{-4/3}\left(\frac{x^2}{c_x d^2}\right)^{-1/3}\left(1-\left(\frac{r}{b_w}\right)^{3/2}\right)^2,$$

where $u' = u_\infty - u$. The values b_w and u'/u_∞ can be determined only if we measure the drag coefficient c_x and the constant β.

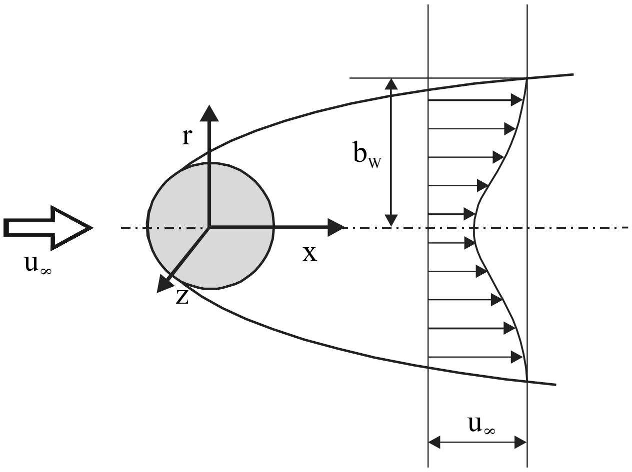

Figure 1. The coordinate system (x, r, z) for the velocity distribution in the vortex wake centered in the center of the sphere, where $2b_w$ is the diameter of the vortex wake and u_∞ velocity of the airflow distant from the ball.

Materials and methods

On the basis of the described phenomena we were interested in measuring the transversal, as well as the longitudinal drag forces acting on the sphere, which were in our case two volleyball balls. They distinguished each other especially with different roughness of the surface and a slight difference in diameter and in mass. The maximal heights of the surface roughness were $\delta = 2.2$ mm and $\delta = 1.2$ mm, respectively.

The drag coefficients values for both balls were determined in two aerodynamic wind tunnels with measurement space diameter $\phi = 1.8$ m and $\phi = 3$ m respectively. The differences were also in hydrodynamic properties: the longitudinal turbulence intensity was in the first one $\varepsilon = 1.3\%$ and in the second one $\varepsilon = 0.7\%$, maximal airflow velocities were $v_m = 55$ m/s and $v_m = 45$ m/s, respectively.

The right oriented coordinate system with its origin in the centre of the ball was defined so that the x axis is pointed in the direction of the air flow. To determine the values of the aerodynamic forces three-component tensiometric aerodynamic scales V-02A were used. The balls were glued onto a metal cap with equal curvature at the surface of the balls as can be seen in the Figure 2.

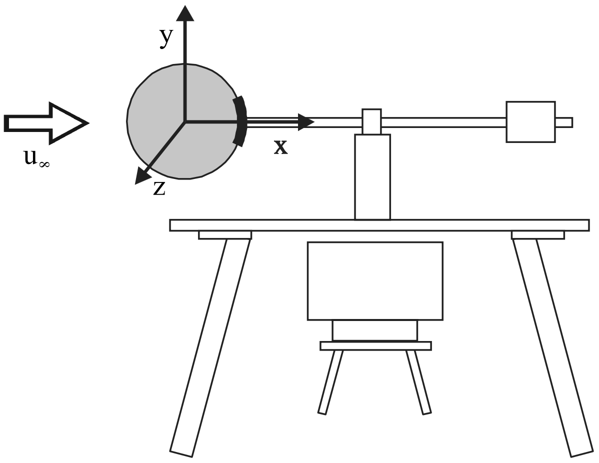

Figure 2. The tensiometric scales with the mounted ball and the coordinate system.

The millivolt output values were registered with a measurement instrument connected with the ADT-4410 and the DASIO-600 computers. The experiment was performed at normal room conditions (T = 18°C, p = 1.01344 bar) at the Institute of Aeronautics, Letnjani, Prague in Czechoslovakia.

Because the Reynolds's numbers were high enough, the quadratic drag law was used to calculate the drag coefficients directly from the output experimental data, e.g. drag forces.

Results

The frontal drag coefficient of the ball c_x is independent of the time, but depends on the velocity of the ball, the area, the distribution of roughness on the surface of the ball and the turbulence of the airflow.

The measured values of c_x are also strongly influenced by the method of the ball-fixation in the wind tunnel. The relation of the frontal air resistance is shown in Fig. 3 for the two different ball surfaces. The rougher is labelled POLAK and the smoother FIVB.

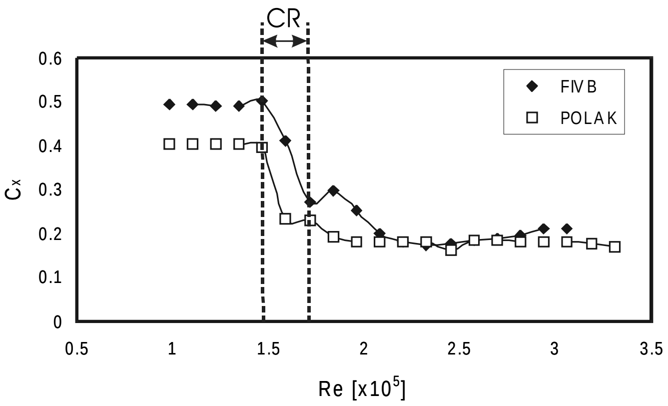

Figure3. Dependence of the frontal air resistance c_x on the velocity u_∞ for two balls (FIVB and POLAK) with different smoothness of the surface. The critical region CR is marked by two dotted lines.

The table 1 shows the maximal measured values of coefficients c_y and c_z for both balls POLAK and FIVB in the range of airflow velocities from 8 m/s to 27 m/s and from 8 m/s to 25 m/s, respectively.

Table 1. The maximal measured values of coefficients c_y and c_z for balls POLAK and FIVB with respect to the airflow velocity VAT.

VAT [m/s]	POLAK		FIVB	
	c_y	c_z	c_y	c_z
27	0.002069	0.000889	-	-
26	0.002344	0.000934	-	-
25	0.002602	0.000964	0.004123	0.001611
24	0.00253	0.000946	0.004212	0.001655
23	0.00259	0.000948	0.004099	0.001589
22	0.002626	0.000957	0.004047	0.001574
21	0.002604	0.000953	0.004141	0.001557
20	0.2598	0.000952	0.004274	0.001537
19	0.002595	0.001023	0.004358	0.001545
18	0.002574	0.001077	0.004676	0.001656
17	0.002531	0.00111	0.005403	0.001874
16	0.002584	0.001146	0.007556	0.002468
15	0.003724	0.001241	0.009252	0.002934
14	0.005312	0.0019	0.005555	0.002869
13	0.00588	0.00203	0.013161	0.004688
12	0.010786	0.003622	0.016654	0.005952
11	0.011475	0.003798	0.017388	0.00609
10	0.011365	0.003872	0.017922	0.006323
9	0.010112	0.003536	0.017901	0.00631
8	0.009352	0.003162	0.017622	0.006294

The amplitudes of the transversal forces behave similarly to the frontal air resistance in the subcritical (VAT from 8 m/s to 12m/s) and in the transcritical range (VAT from 15 m/s to 27m/s) of the airflow around the ball, despite the fact that the values are much smaller - in the subcritical range 1.1%, in transcritical around 0.8% of frontal air resistance value.

The measurements of the transversal drag forces on the ball at five different constant velocities of the airflow around the ball: 8 m/s, 12 m/s, 16 m/s, 20 m/s and 25 m/s gave us a periodic function of time as shown in Figure 4.

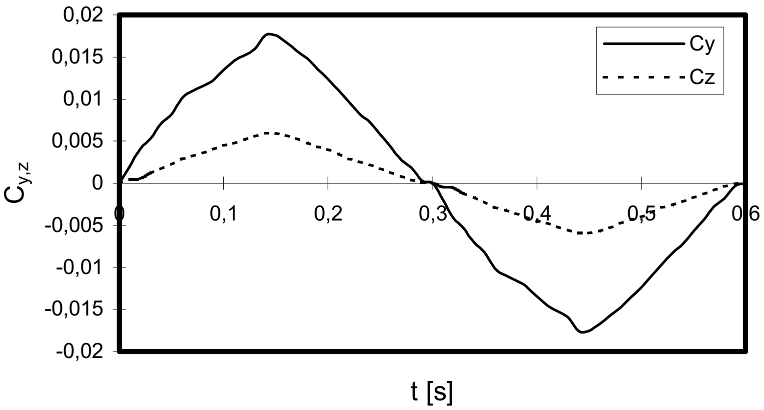

Figure 4. Periodic dependence of the transversal forces on the ball FIVB for the airflow velocity 12 m/s.

The periodicity of the transversal forces enabled us to obtain the discrete Fourier transformation from the discrete measurement data. The discrete Fourier analysis was performed on both transversal drag forces for all five airflow velocities: 8 m/s, 12 m/s, 16 m/s, 20 m/s and 25 m/s, respectively:

$$c_y(t) = \sum_{n=0}^{N-1} z_y(n) e^{2\pi \, \mathrm{int}/T} \quad \text{and}$$

$$c_z(t) = \sum_{n=0}^{N-1} z_z(n) e^{2\pi \, \mathrm{int}/T} \, ,$$

where $z_y(t)$ and $z_z(t)$ are standard Fourier coefficients determined by means of the following equations:

$$z_y(n) = \frac{1}{N} \sum_{l=0}^{N-1} c_{yl} e^{-2\pi i n/N} \quad \text{and}$$

$$z_z(n) = \frac{1}{N} \sum_{l=0}^{N-1} c_{zl} e^{-2\pi i n/N} \, .$$

In previous equations N stands for the number of measured values c_{yl} and c_{zl} in equidistant points on the periodic time interval T. The error made with the Fourier transformation when taking only the first four summands is negligible in our case compared to the measuring error.

The stochastic nature of the $c_y(t)$ and $c_z(t)$ can be seen only from the fact that any translatory shift (for example, any t_0 distributed uniformly and continuously on the interval [0,T]) of these functions is possible on the time axis.

Discussion and Conclusions

In this work the theoretical model for the vortex wake behind the sphere was given which has two free parameters that should be practically determined. Furthermore, the practical measurements showed us that the airflow acts on the ball not only in a longitudinal direction but also in a transversal direction. Especially great changes in the drag forces happen when the ball passes through the critical regimen of the airflow accurring around the ball. The stochastic asymmetric events and aforementioned results present us with the reason why the ball deviates away from its parabolic ballistic trajectory during flight. Despite the fact that the transversal drag forces are two orders of magnitude smaller than the longitudinal force, the consequence of such forces in volleyball could be quite crucial. For example, in a volleyball service with the proper speed the ball can deviate enough away from the defender's expected trajectory, so that receiving the ball is critical or even impossible when the reaction time for the defender is too short.

Beside the speed and, of course, the rotation of the ball also the roughness of the ball's surface influences the critical regimen of the airflow around the ball. It is reached at lower values of the Reynolds's numbers for the rougher POLAK ball. That means that the roughness of the ball is the parameter of how soon a turbulent airflow around the ball is reached with increasing velocity. We also found out that with increasing turbulence of the circulating air the range of the critical airflow is shifted to the intervals with lower velocities. We have also noticed that the positions of the seams, in regard to the direction of the airflow velocity vector, are crucial for the determination of the transversal force components on the ball F_y and F_z.

The experiment showed another interesting result that the transversal forces are on average approximately 40% lower for a rougher ball than for a smoother one, and that indeed affects the deviation of the ball away from the expected trajectory. If the transversal forces are higher, the deviations will occur faster and the amplitudes will be higher.

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Correspondence to:
Matej Supej
Faculty of sport
1000 Ljubljana, Slovenia
Phone: +386 61 140 10 77 int.255
E-mail: Matej.Supej@sp.uni-lj.si

SILE TRANSVERZALNOG AERODINAMIČNOG OTPORA TIJEKOM LETA LOPTE

Sažetak

U radu se ispituje problem taktički dobro izvedenog ravnog servisa u odbojci. Glavni su objekti istraživanja aerodinamičke sile koje djeluju na loptu i pojava vrtloženja iza lopte.

Let lopte (kugle) u gravitacijskom polju dobro je poznati fenomen. Otpor zraka očekivano doprinosi narušavanju paraboličnog oblika trajektorije leta u smjeru gibanja tijela. No, otpor zraka je i razlog za tzv. neočekivane longitudinalne, ali i transverzalne otklone leta lopte od parabolične krivulje. Odbojkaš – server, koji dobro zna kako lopti dati pravi smjer i brzinu ispravnim udarcem u središte lopte, relativno će precizno znati definirati gdje će neočekivani otkloni od pravilne putanje biti najveći. Time obrambenom igraču (primatelju servisa) skraćuje vrijeme reakcije za prijem lopte koja dolazi s neočekivanim promjenama smjera. Taktički dobro izveden servis može toliko onemogućiti obranu da više nije u stanju tako serviranu loptu ni primiti ni vratiti.

Autori su predložili teorijski model raspodjele brzine u vrtlogu oko, a osobito iza kugle kako bi se objasnila priroda neočekivanog otklona od idealne putanje leta lopte. Za izračunavanje koeficijenata aerodinamičnog otpora izravno iz sirovih eksperimentalnih podataka, korišten je kvadratni zakon aerodinamičnog otpora jer su Reynoldsovi brojevi bili dovoljno veliki.

Ispitivanje je provedeno u dva zračna tunela promjera 1.8 i 3 metra s različitim intenzitetima turbulencije. U njima se mjerio interval kritičnih Reynoldsovih brojeva za dvije odbojkaške lopte kojih površine nisu bile jednoliko glatke. Izmjerene su također i longitudinalne i transverzalne sile za pet različitih brzina strujanja zraka (raspon brzina od 8 m/s do 25 m/s). Periodičnost fenomena omogućila je primjenu diskretne Fourierove transformacije transverzalnih sila. Pokazalo se da je greška koja se javlja primjenom Fourierove transformacije kada se u obzir uzmu samo prva četiri pribrojnika, zanemariva u usporedbi s greškom mjerenja.

Dobiveno je da su transverzalne sile koje djeluju na loptu za dva reda veličine manje nego frontalne aerodinamične sile. Koeficijent frontalnog otpora ne ovisi o vremenu, ali ovisi o brzini lopte, o njenom oplošju, raspodjeli neravnina na površini kugle i o turbulencijama zračnih struja. Također je primijećeno da je položaj šavova prema vektoru brzine zračne struje presudan za određenje komponenata transverzalnih sila. Sve zajedno jest uzrok neočekivanim otklonima od očekivane balističke putanje. Osobito velike promjene sila aerodinamičnog otpora, a onda i najveći otklon od putanje, događaju se kada lopta prolazi kroz kritični režim zračnog strujanja oko lopte.

Ključne riječi: *odbojka, ravan servis, let lopte, vrtloženje iza kugle, Fourirova transformacija, sile transverzalnog aerodinamičnog otpora*