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TITLE:	FLUID DYNAMICS RESEARCH
VOLUME/ISSUE/PAGES:	3/1-4 231-237
DATE:	September 1998
AUTHOR OF ARTICLE:	Wei Quing-ding
TITLE OF ARTICLE:	VORTEX-INDUCED DYNAMIC LOADS ON A NON-SPINNING VOLLEYBALL
ISSN:	0169-5983
DELIVERY:	E-mail Link: smackenz@stfx.ca
REPLY:	E-mail: smackenz@stfx.ca

This document contains 7 pages. This is NOT an invoice.

Fluid Dynamics Research 3 (1988) 231–237
North-Holland

Vortex-induced dynamic loads on a non-spinning volleyball

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Abstract. An experiment on vortex-induced dynamic loads on a non-spinning volleyball was conducted in a wind tunnel. The flow past the volleyball was visualized, and the aerodynamic load was measured by use of a strain gauge balance. The separation on the volleyball was measured with hot-film. The experimental results suggest that under the action of an unstable tail vortex system the separation region is changeable, and that the fluctuation of drag and lateral forces is the same order of magnitude as the mean drag, no matter whether the seam of the volleyball is symmetric or asymmetric, with regard to the flow. Based on the experimental data a numerical simulation of volleyball swerve motion was made.

1. Introduction

The aerodynamic features of sports balls have been researched by many aerodynamicists [1]. It is well known that the swing, swerve and curve motion of a sports ball is producted by a Magnus effect or that it has been attributed to asymmetric boundary layer separation caused by a spinning ball or by a ball seam which is placed asymmetrically about the velocity direction of the ball. The problem is whether, if the ball were not spinning and the ball seam were symmetric about the velocity direction of the ball, there would be some aerodynamic loads under which the ball may swing, swerve or curve. Our experiment and calculation indicate that the answer is in the affirmative.

2. Experimental setup and procedure

The test was conducted in the 2.25 m-diameter low-speed wind tunnel at Peking University. The model is a real volleyball supported by a tail supporting strut with a 6-component strain gauge balance (fig. 1).

The separations on the ball were measured by the use of a hot-film mounted flush with the surface of the volleyball. The visualization of flow past the volleyball was conducted with the titanium tetrachloride method. Visualization of the structure of the vortex system in the wake of a ball 6.0 cm in diameter was conducted in a water channel with electrolysis-precipitate method as well.

The test wind speed is about 7–25 m/s. The Reynolds number is about $1-3.6 \times 10^5$. The turbulence intensity in the wind tunnel test section is less than 0.2%.

3. Experimental results and discussion

3.1. *The structure of the vortex system in the wake of a volleyball*

Figs. 2a and b show the wake of the flow past the volleyball whose seam is symmetric about the main flow. It is clear that the wake is changeable and is a swing (a, inclined up; b, inclined

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Fig. 1. Model volleyball and tail supporting strut.

down). An experimental visualization of the flow past a sphere was conducted in a water channel to research the structure of the vortex system in the wake of a sphere on which the turbulent separation was set off by a trip wire. The test Reynolds number was about 1.5×10^3.

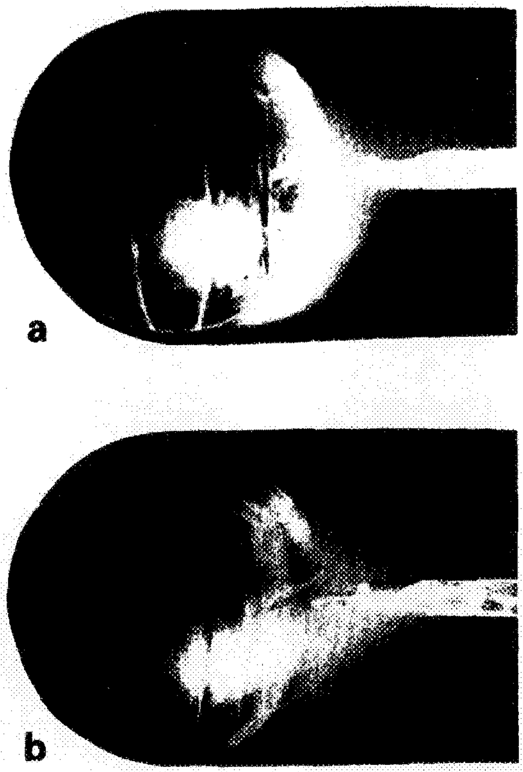

Fig. 2. The wake behind a volleyball, $R = 2 \times 10^5$.

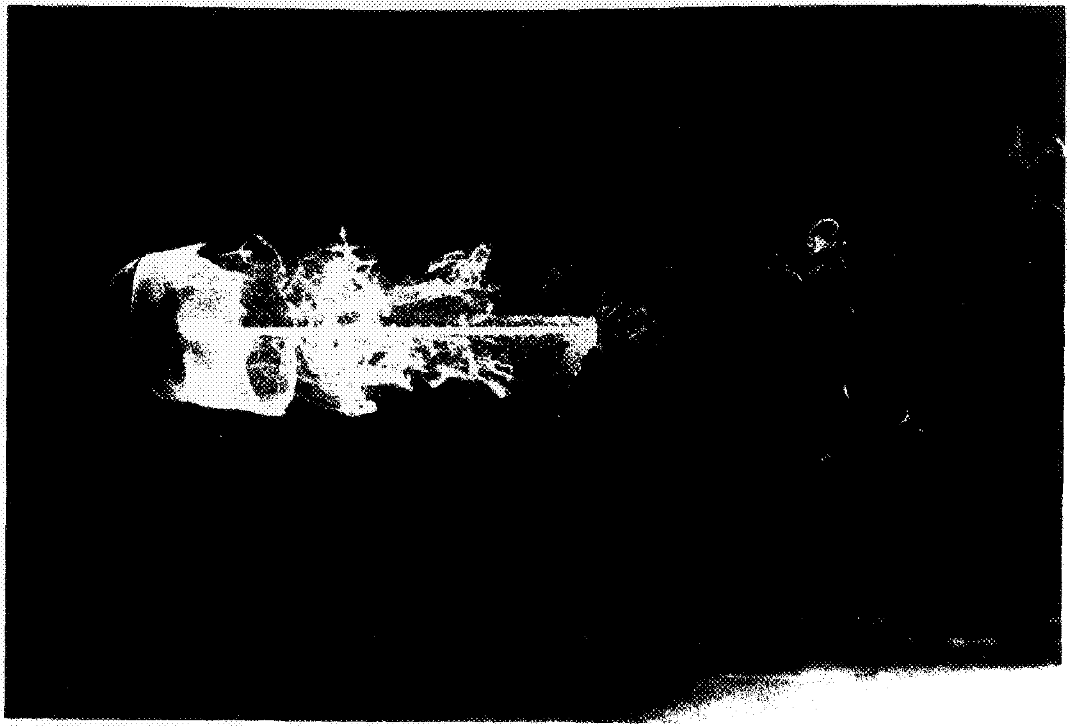

Fig. 3. The wake behind a sphere, $R = 1 \times 10^5$.

Fig. 3 shows a picture of the visualization. The diagram is shown in fig. 4. It is clear that the structure of the vortex system in the wake of a sphere has the following characteristics:

(1) There is an annular vortex sheet behind the separation line. The vortex rings are shed from the vortex sheet unceasingly.

(2) There is a reverse flow region in the annular vortex sheet. In this region the flow is very irregular and complex including various vortices. The shedding vortex rings are incorporated into this region and deform.

(3) In a phenomenon pointed out by S. Taneda, the wake oscillates irregularly, and some pairs of longitudinal vortices often appear in it [2].

The structure of the vortex system in the wake of a volleyball is similar to the above; however, it is more complex and more instable. Its instability effect in turn on the separation on a sphere. From this induced loads on the sphere occur. Fig. 5 shows asymmetric separation and pressure distribution on it.

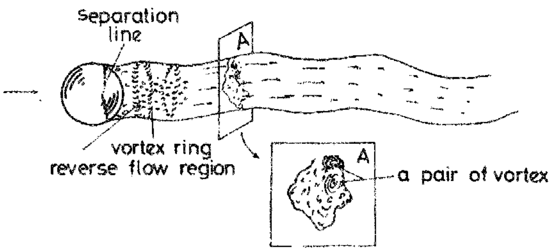

Fig. 4. The structure of the vortex system in the wake behind a sphere.

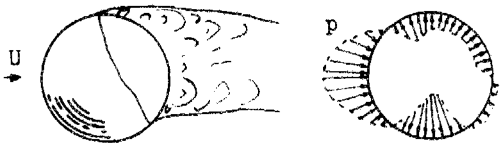

Fig. 5. A schematic diagram of asymmetric separation on a sphere (left) and corresponding pressure distribution on it (right).

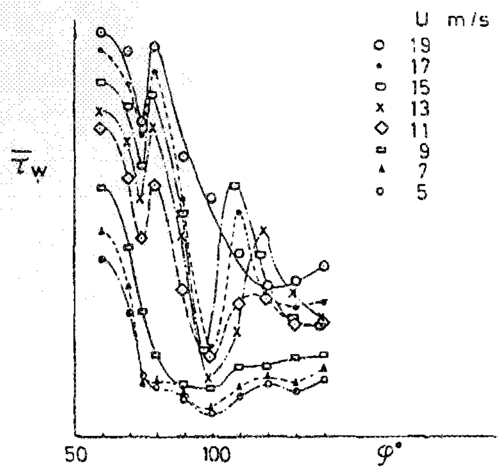

Fig. 6. The variation of mean surface stress $\overline{\tau}_\omega$ on a volleyball with longitudinal angle φ. (ordinate is relative)

3.2. *The separation of flow past a volleyball*

Fig. 6 shows the variation of the mean surface stress $\overline{\tau}_\omega$ on a volleyball with the longitudinal angle φ of the volleyball. It makes clear that when the flight velocity of a volleyball is more than about 10 m/s, the separation on the volleyball is turbulent separation. The mean position of separation measured with cold-hot films is about 95° for the laminar boundary layer and about 115° for the turbulent boundary layer (fig. 7).

3.3. *Aerodynamic drag*

The drag and the region of fluctuation of drag on the volleyball is shown in fig. 8. It is clear that the range of the drag fluctuation is the same order of magnitude as the mean drag even if the seam of the volleyball is symmetric about the main flow. Fig. 9 compares the drag and its fluctuation in a symmetric situation with that in an asymmetric situation. The two values of the mean drag have some difference. but the ranges of the drag fluctuation do not change much.

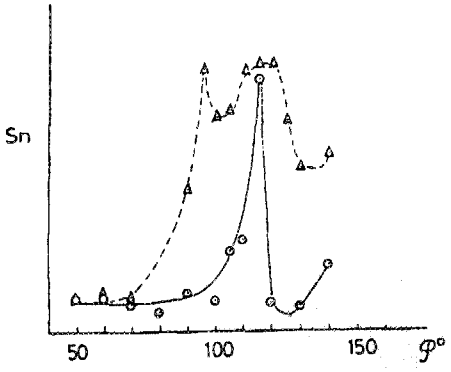

Fig. 7. The mean position of separation on a volleyball (measured with cold-hot films) triangle-laminar flow. circle-turbulent flow. Sn-reverse flow signal. (ordinate is relative)

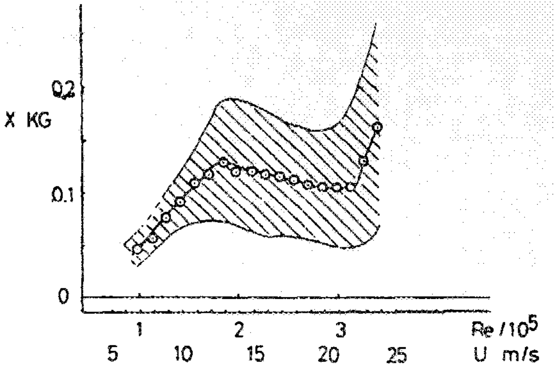

Fig. 8. The aerodynamic drag on a volleyball and the region of fluctuation of the drag on it (shadow). The seam of the volleyball is symmetric about the main flow.

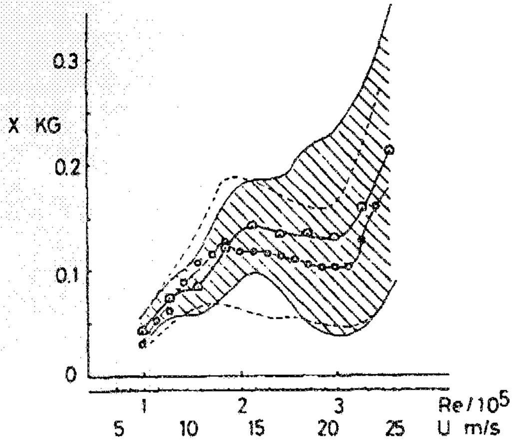

Fig. 9. The drag and the region of its fluctuation. The seam is asymmetric about the main flow (by semicircle) and is symmetric about the main flow (by circle).

3.4. *Aerodynamic lateral force*

The lateral force and the range of its fluctuation are shown in fig. 10 (seam of the volleyball is symmetric about the main flow) and fig. 11 (asymmetric and symmetric). It is clear that the range of the lateral force fluctuation is the same order of magnitude as mean drag, no matter whether the seam of the volleyball is symmetric about the main flow or not.

3.5. *The power spectra of fluctuation of drag and that of lateral force*

The power spectra of drag and that of lateral force are shown in fig. 12 and fig. 13, respectively, which suggest that the fluctuation of drag and that of lateral force can be as random fluctuation and that the energy of these fluctuations is concentrated on the low frequency region below about 10 Hz.

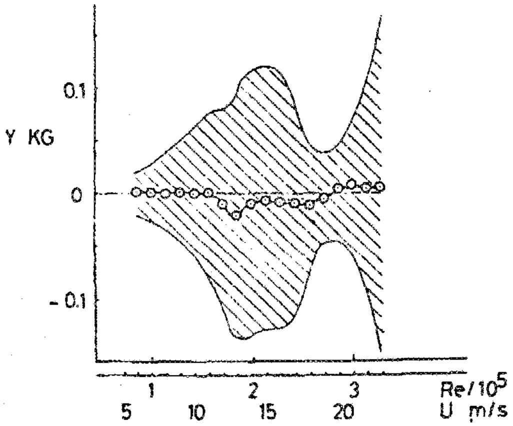

Fig. 10. The aerodynamic lateral force and the region of the lateral force fluctuation. The seam of the volleyball is symmetric about the main flow.

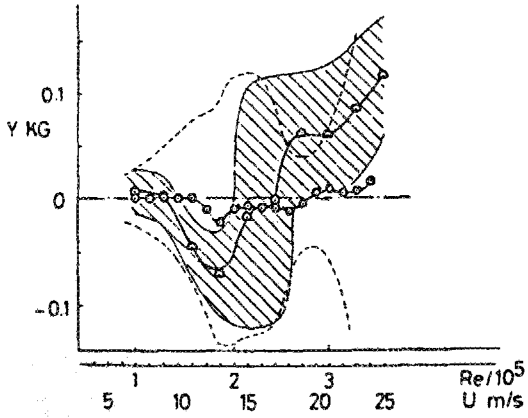

Fig. 11. The lateral force and the region of its fluctuation. The seam is asymmetric about the main flow (semi-circles) and symmetric about it (by circles).

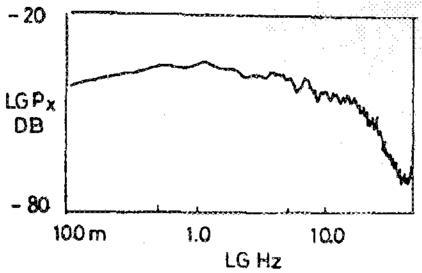

Fig. 12. The power spectra of drag of a volleyball, P_x.

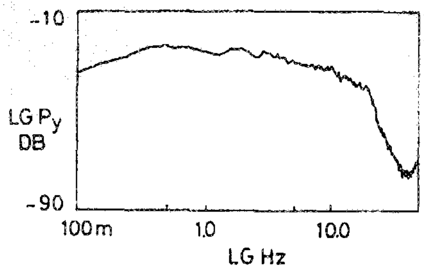

Fig. 13. The power spectra of lateral force of a volleyball, P_y.

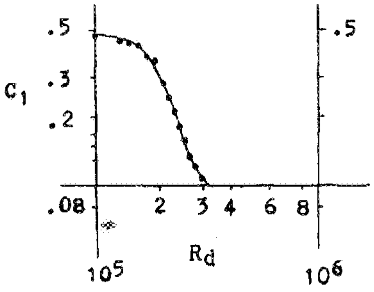

Fig. 14. Drag coefficient of a volleyball.

3.6. The numerical simulation of swerve motion of a volleyball

For describing the aerodynamic feature of a volleyball, we can represent the aerodynamic coefficient as follows:

$$C_i(v, t) = \bar{C}_i(v) + C_i'(v, t)$$

where v = velocity of volleyball, t = time, $\bar{C}_i$ = time average of C_i, C_i' = random function of v and t, $i = 1$ to 6, C_i = coefficient of drag, lift, side force, pitch moment, yawing moment and rolling moment, respectively.

$\bar{C}_i$ was given by our experiment. Actually only $\bar{C}1$ is non-zero. $\bar{C}_1$ is shown in fig. 14. C_i' was determined by statistical data – ensemble average, rms error, probability distribution function, etc.

As an example, fig. 15 shows a calculated results of a set of paths of a volleyball which was served at the same initial condition as follows:

velocity: 17.5 m/s,
angle:35°,
position: 7 m behind end line, height 2.0 m.

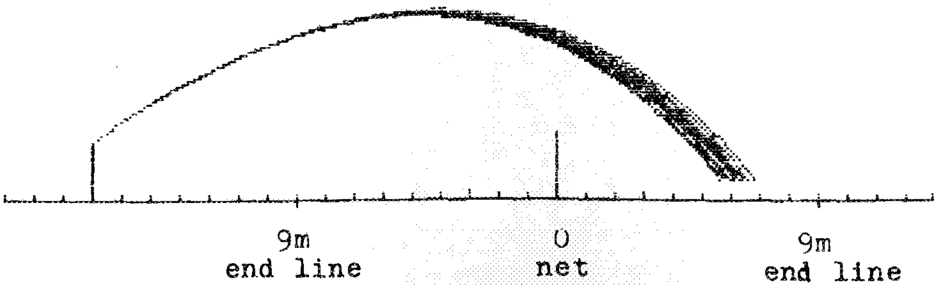

Fig. 15. A set of paths of a volleyball served at the same initial condition.

The main calculated results are as follows:

flight time: 2.063 s,
end velocity: 12.2 m/s,
standard deviation of placement: 0.29 m,
maximum deviation of placement: 1.25 m.

In this calculation only C_l' was considered.

4. Conclusions

1. When the seam of a volleyball is symmetric about the main flow which is uniform with low turbulence intensity and when the volleyball is not spinning, the wake which consists of a complex tail vortex system is irregular, and the separation of flow past the volleyball is asymmetric. As a result of this the induced dynamic loads on the volleyball occur, and cause the volleyball to swerve (a so-called floater).

2. The drag fluctuation and lateral force fluctuation is the same order of magnitude as the mean drag at the normal flight condition of a volleyball. They are random and their energy concentrates at frequency bands lower than 10 Hz.

3. By introducing the random aerodynamic coefficient the swerve motion of a volleyball can be simulated numerically.

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[1] Rabindra D. Mehta (1985) Aerodynamics of sports balls, *Ann. Rev. Fluid Mech. 17*, 151–189.
[2] Taneda S. (1986) Proceedings of Third ASIAN Congress of Fluid Mechanics, 3–14.