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Magnus effect on a rotating soccer ball at high Reynolds numbers

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ABSTRACT

The Magnus effect on a prototype model soccer ball rotating perpendicular to the flow direction at Reynolds numbers in the range of $0.96 \times 10^5 < Re_D < 4.62 \times 10^5$ was investigated by means of aerodynamic force measurements and of a flow field survey. Experiments were performed using a rear sting support where the soccer ball was split into two halves that were driven by a motor inside of them. In the non-rotating state the variation of force coefficients with Reynolds number and boundary layer separation points are within the range that is found for real soccer balls. In the rotating-state, considerable changes of the mean force coefficients with Reynolds number Re_D and spin parameter SP occurred, which can be attributed to the altered boundary layer separation. These changes also lead to significant changes of size and deflection of the wake zones in the lateral direction. A negative Magnus effect occurs in the critical Reynolds number range. Positive Magnus force is induced when the boundary layer is either laminar or turbulent on both sides of the rotating model soccer ball.

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1. Introduction

Curved ball trajectories contribute much to the attraction of many ball games; therefore, sports equipment manufacturers have become greatly interested in understanding and improving the aerodynamics of their balls. The flight of the famous free-kick taken by Roberto Carlos in the 1997 Soccer Confederations Cup was explained by Asai et al. (1998) from a scientific point of view. The basic flow phenomenon responsible for the sideways deviation of a ball rotating around an axis perpendicular to the flight direction from its initial straight path is commonly known as the ordinary Magnus effect. Less known is the negative Magnus effect due to the reversal of the side force that occurs in a certain range of Reynolds numbers and spin parameters.

Both flow phenomena were mainly studied for spherical bodies with homogeneous surface characteristics. For a smooth sphere the physics of both, the ordinary and negative Magnus effect, were described in detail by Kray (2009) and summarized by Kray et al. (2012). In a recent paper, Muto et al. (2012) studied the boundary layer flow on a rotating sphere at few different Reynolds numbers and spin parameters by means of large-eddy simulation in more detail. In the non-rotating state they found a good agreement between their drag curve and the one given by Wieselsberger (1922), where the latter is known to have been strongly affected by support interference (Flachsbart, 1927). As the critical Reynolds number region of Muto et al. (2012) was shifted to a lower Re_D than in the drag curve of Achenbach (1972), whose study may be considered as a fundamental investigation on sphere aerodynamics, it may be concluded that the discrepancy is caused by inadequate reproduction of the transition in the boundary layer.

Apart from the Reynolds number mismatch, the basic findings of Muto et al. (2012) agree well with the findings of fundamental studies of the Magnus effect on rotating spheres (Davies, 1949; Taneda, 1957; Sawatzki, 1960; Tsuji et al., 1985; Tanaka et al., 1990): In the subcritical and supercritical boundary layer regimes, where the boundary layer was either subjected to fully laminar or fully turbulent separation, the Magnus force increased with increasing circumferential velocity. In the critical flow regime negative Magnus force was observed. The reason was laminarization of the boundary layer on the downstream-moving side and corresponding upstream shift of the separation point, whereas transition to turbulent boundary layer on the upstream-moving side shifted the separation point downstream, compared with the non-rotating case.

The Magnus effect for rotating sports balls, however, has been less investigated. Briggs (1959), Watts and Sawyer (1975), Watts and Ferrer (1987) as well as Alaways and Hubbard (2001) conducted such research for baseballs, whereas Aoki et al. (2002) investigated rotating golf balls. To the best of authors' knowledge, for rotating soccer balls, only a few studies are available which

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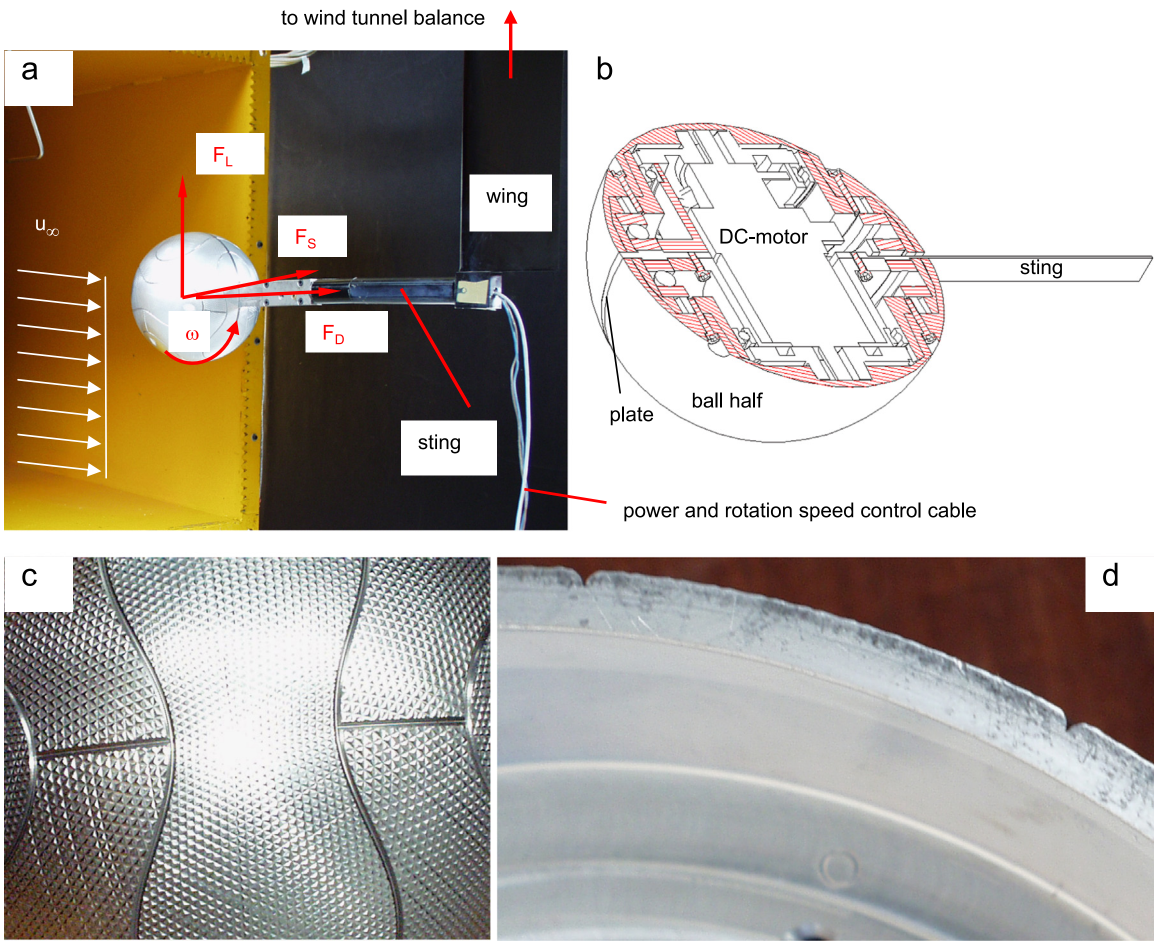

Fig. 1. (a) Installation photograph of the ball-halves set-up with the textured 14-panel model; (b) spinning mechanism including constructional details; (c) textured surface with pimples; and (d) cutout of a ball half used for assembly with the spinning mechanism.

present aerodynamic force coefficients (Seo et al., 2004; Carré et al., 2005; Asai et al., 2007; Oggiano and Sætran, 2010; Passmore et al., 2011). In some of these studies only Magnus data is given, as the drag coefficient was strongly increased by the flow interference of the driving rod. As all of them show, to a great extent, support interference due to the penetration by shafts or by wires at the ball equator, and as the results disagree among each other, the measured force coefficients as a function of Reynolds number and spin parameter cannot be considered as reliable. Such data are, however, needed to gain a better understanding for ball trajectories encountered in today's game of soccer.

The Magnus effect should not be confused with the so-called 'knuckling effect', which is an unstable flight condition, where the direction of side forces changes when the ball is non-rotating or slowly rotating with very low frequencies in the range of 0–2 Hz (Asai et al., 2006, 2007). Asai and Kamemoto (2011) found that the large-scale undulations in the vortex trail were related to the fluctuation frequency of the lift force acting on the knuckle ball with a statistically high correlation. Most of this research focused on the Teamgeist ball, the official 2006 World Cup soccer ball. Murakami et al. (2012) found that the knuckle effect is caused by large-amplitude lateral forces with frequencies of about 0.5–1.0 Hz at supercritical Reynolds numbers. The unsteady lateral forces are generated by the rather random, dynamic behavior of a pair vortex structure that, after being occasionally created, rotates, collapses and then is recreated. This finding differs from the assumption of quasi-steady changes of lateral forces in response to the variation of the relative position of the ball seam lines to air flow during slow ball rotation, which may cause large deflections from the straight flight path (Barber et al., 2009, Passmore et al., 2011). Barber et al. (2009) conclude that when the rotation frequency increases above 2 Hz (at a flight velocity of 30 m/s corresponding to a spin parameter of approximately 0.1), ball trajectories are more predictable. This is the case when the Magnus effect takes over and causes 'curve balls', where the fluctuation of lateral forces is much lower than for 'knuckle balls' (Asai et al., 2008).

In the following, experimental data on a prototype model soccer ball are presented, comprising Magnus, drag and side forces as measured in a wind tunnel. After describing the experimental set-up and defining the analyzed quantities and their associated uncertainties, results are shown for the non-rotating and rotating case as a function of Reynolds number and spin parameter. The presented force coefficients are useful to better understand and predict ball trajectories. Further applications where drag and Magnus force data are needed are rough spherical objects, e.g. as particles in water and air (Brown and Lawler, 2003) or as compact wind-borne debris in the atmospheric boundary layer flow (Holmes, 2004), where rotation strongly affects objects' trajectory.

2. Experimental set-ups and instrumentation

The experimental set-up used to determine the aerodynamic coefficients of non-rotating and rotating soccer balls for a broad range of Reynolds numbers and spin parameters was very similar to the hemisphere set-up described by Kray et al. (2012), with soccer ball halves replacing the hemispheres. This set-up has proven to be

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