# AERODYNAMIC PARAMETERS FOR DESCRIPTION OF FLIGHT OF ROTATING VOLLEYBALL

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**Abstract:** This work deals with description of effect of revolutions on the flight of a rotating volleyball with airstream in defined side angle of attack. The description is based on results of measurements in an aerodynamic tunnel. The flight is described by using dimensionless aerodynamical characteristics such as coefficients of Drag, of Lift and of Side force and coefficients of moments – Roll, Pitch, Yaw with parameters of Reynolds number *Re*, spin *s* and side angle of attack $\beta$. The real conditions of flight of a volleyball, which were simulated ($Re = 1.5 – 4.2 \times 10^5$) all fall within the region of critical *Re*. All collected results are prepared to be used in the system of 3D ballistic equations. The system of ballistics and data from the experiment can solve all types of flights of a volleyball including the special cases: influence of side wind, flight of ball without rotation.

**Description of experiment:** The experiment was performed in 1.8m diameter wind tunnel with open test section (the intensity of turbulence up to 1%) in the Aerospace Research and Test Establishment, Department of Aerodynamics, Prague, Czech Republic. The 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 (ccheme of the experiment is in Fig. 1.):

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: $M_Y = F_4 \cdot f - F_3 \cdot f$ Pitch: $M_Z = (F_3 + F_4) \cdot b - F_5 \cdot c$

**Measurements conditions:**

air-flow velocity: *v = <10 – 25> m/s*, revolutions: *n = <0 – 12.5> rps*

Reynolds number: $Re = 1.5 – 3.8 \times 10^5$, spin: *s = (0 – 0.94)*

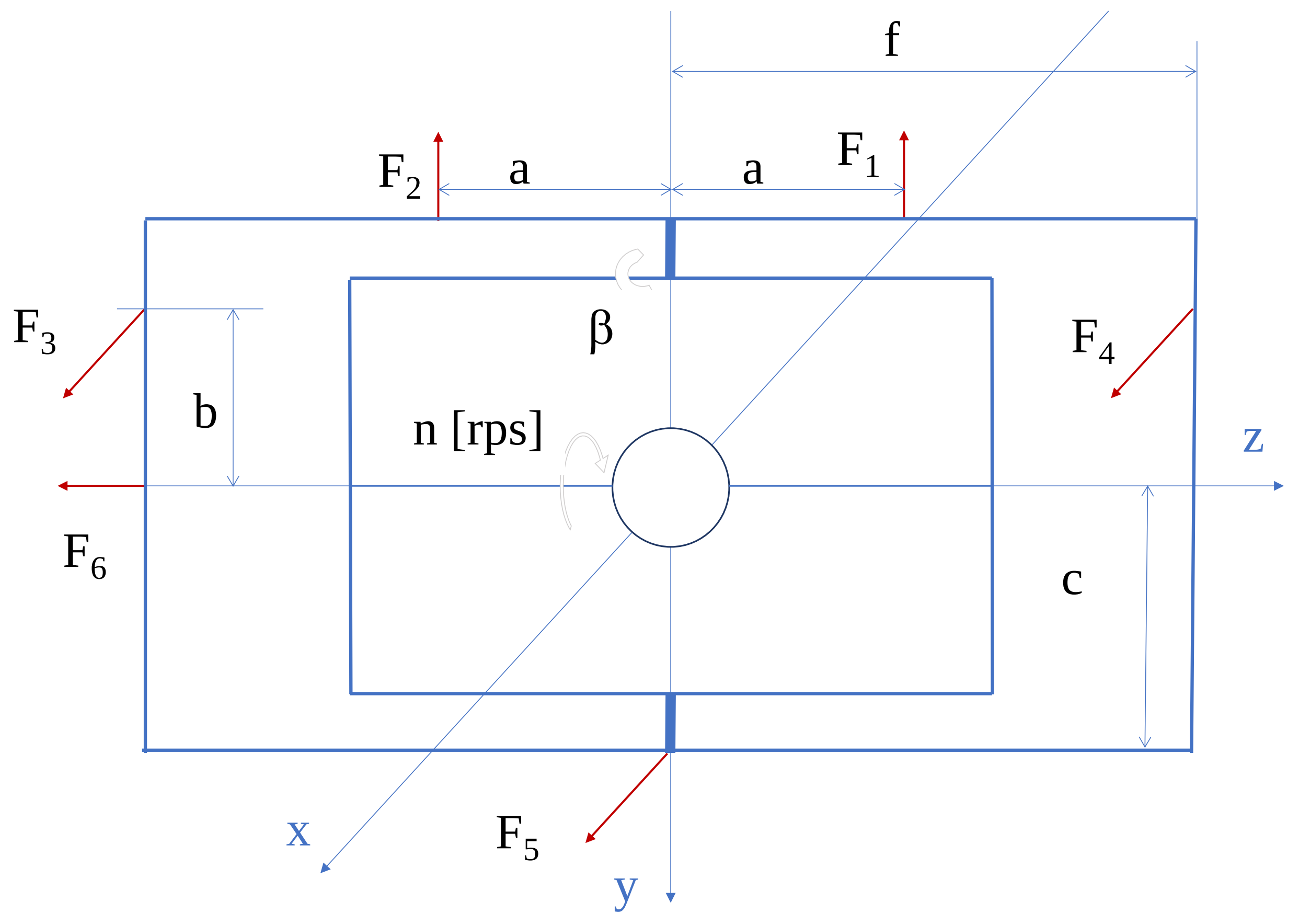

Fig. 1: Scheme of the experimental set up

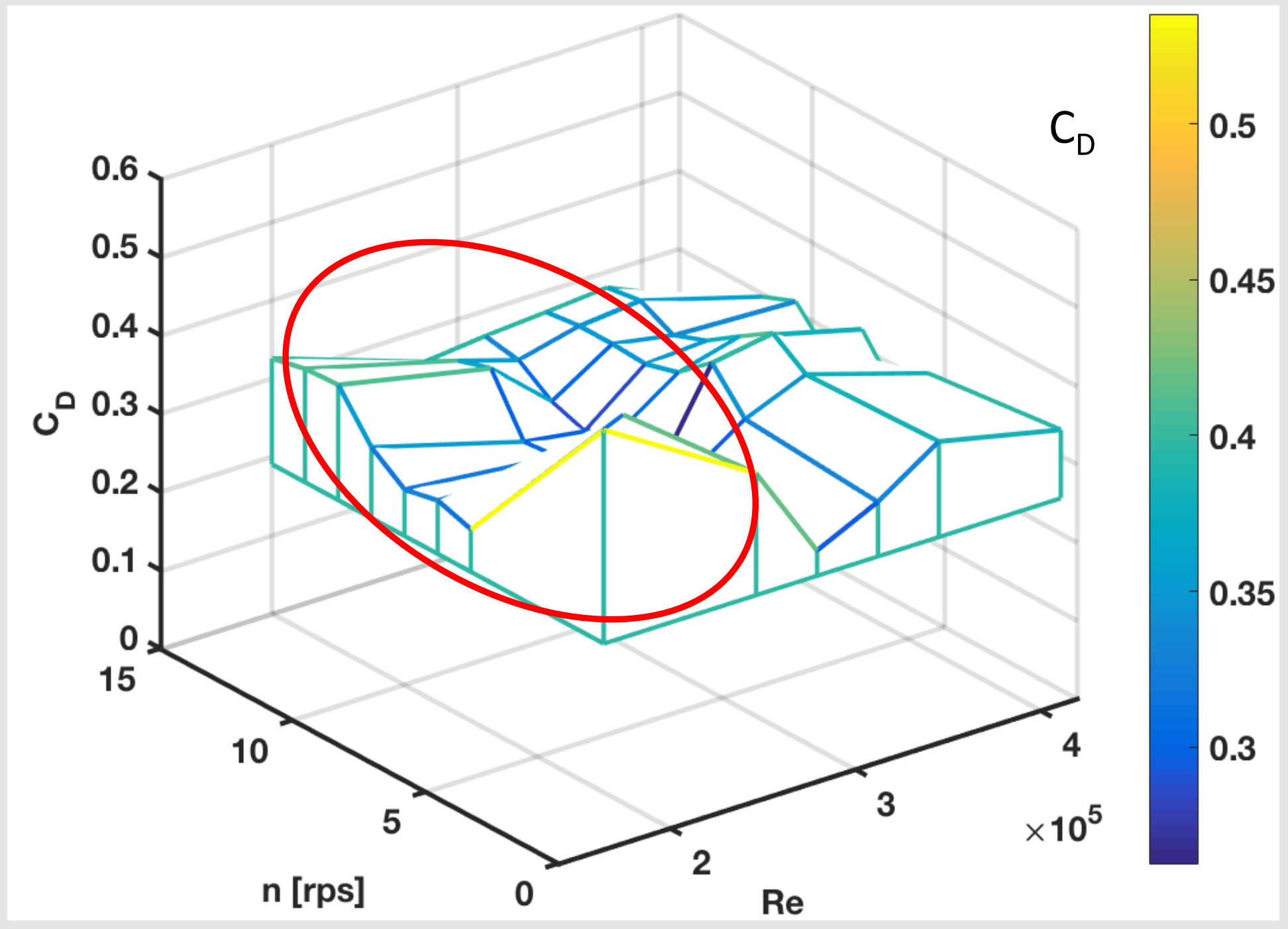

Fig. 2. The dependence of coefficients of Drag $C_D$ on Reynolds number *Re* and revolutions *n*, side angle of attack $\beta = 0°$

**Influence of revolutions *n* on transition** – in the case of side angle of attack $\beta = 0°$ the effect of Reynolds number and revolutions on coefficient of Drag $C_D$ shows that revolutions cause reduction of $C_D$ (Fig. 2 – red area) for lower Reynolds numbers (lower *Re* means here: lower half of the investigated interval of Reynolds number $Re < 2.8 \times 10^5$). This phenomena can be explained by the different shape of wake behind the sphere, which is caused by rotation of the ball.

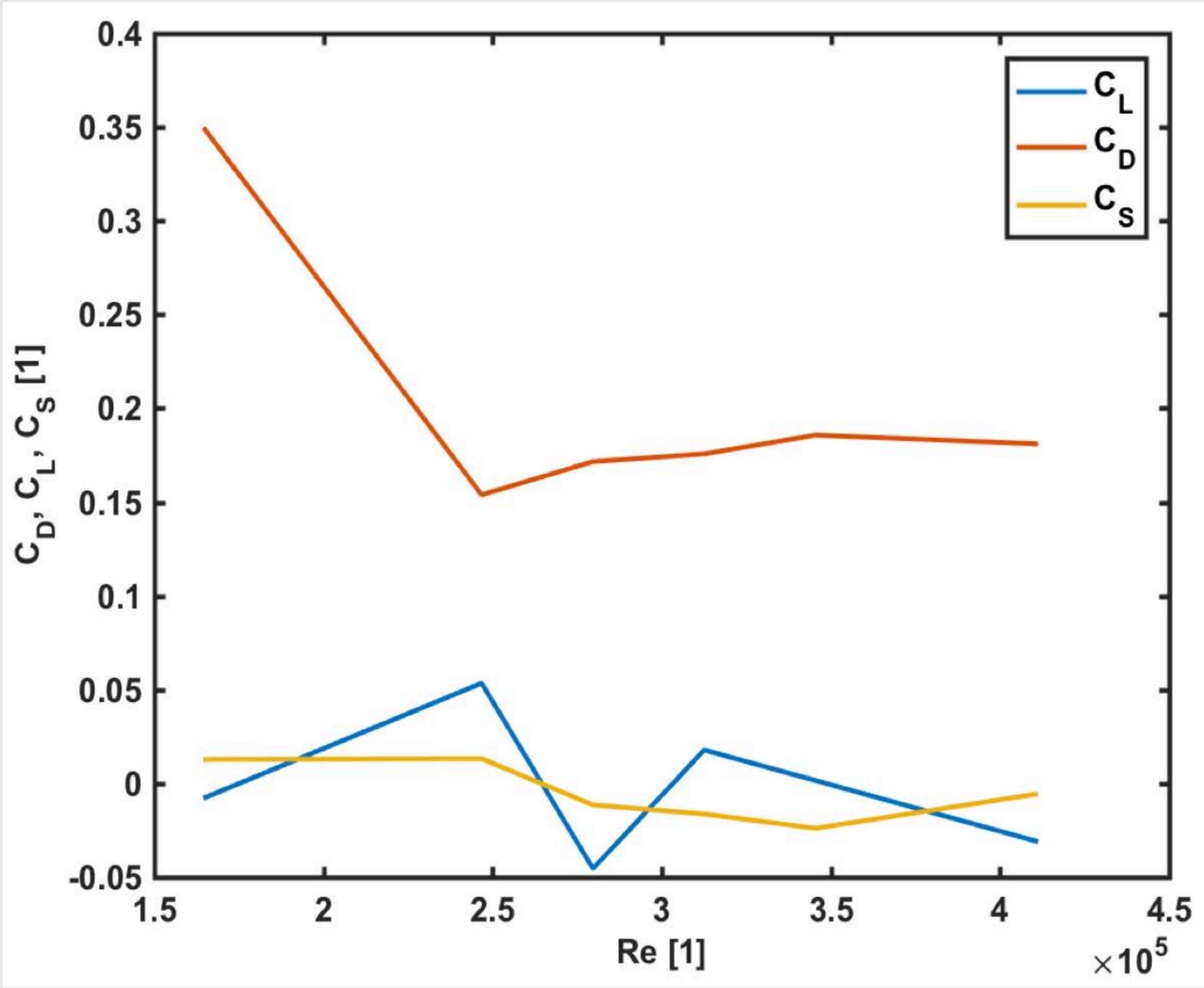

Fig. 3: The effect of Reynolds number acting on median values of coefficients of aerodynamic forces, *n = 0 rps*

In the case of **flight of ball without rotation** phenomena called knuckling effect appears. It is characterized by unpredicted changes in the path. The effect was noticed in the results of experiment. For further evaluation statistical approach was chosen: medians of six independent tests were calculated for coefficients of Drag, Lift and Side Force. It is visible in Fig. 3 that result of Drag is according the expectation (according to smooth sphere) while Lift and Side force results are very close to zero (in the area of uncertainties of the results). This confirms unpredictability of the phenomena – of knuckling effect.

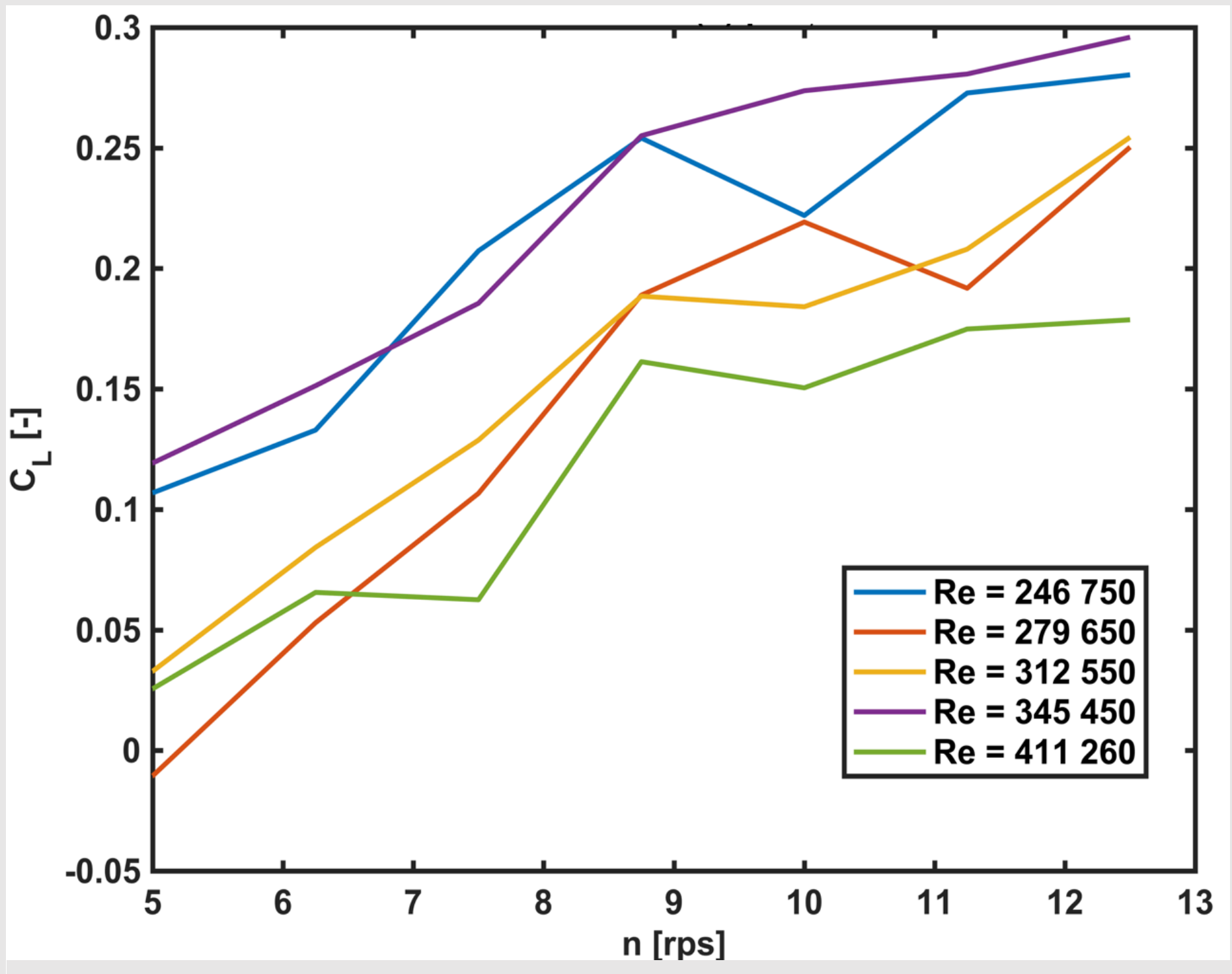

Fig. 4: Comparison of the effect of revolutions *n* on Lift coefficient $C_L$, parameter is Reynolds number *Re*, $\beta = 0°$

Based on previous experiment, published in [D2] and [D3], suspicion was stated in [D3]: *"…the growth of $C_L$ for constant velocity ($v_\infty$ = const., Re = const.) grows rapidly until n = 8.75 rps, for higher revolutions (n > 8.75 rps) the increase is very small. The explanation of this phenomenon is: there exists a border of rotation influence in growth of the lift force."*

To investigate the previous statement in more detail, Fig. 4 is depicted, where the effect of revolutions *n* on the coefficient of Lift $C_L$ for different Reynolds number is visible.

The **limit value of revolutions *n*** (is called $n_l$) is noticeable in each separate dependence for constant Reynolds number. Increasing revolutions above the limit $n > n_l$ doesn't cause increase of $C_L$, or the increase is very slow. Gradient of $C_L$ for $n > n_l$ is close to zero.

**Influence of rotation – defined by spin *s* – on Lift** was studied. The vector of velocity was divided in the case of $\beta \neq 0°$, only perpendicular component of vector *v* causes the Magnus effect which results into Lift (principal of superposition was used). The population of results of $C_L$ is depicted in the Fig. 5. The trend of the effect of spin on coefficient of Lift was statistically calculated and it is described by polynomial of third grade – dotted line in Fig. 5:

$$C_L = 0.127 \cdot s^3 - 0.4824 \cdot s^2 + 0.585 \cdot s$$

where the reliability $R^2 = 0.4799$. Dispersion of the population of $C_L$: $Var(C_L) = 0.0094$, standard deviation of the population of $C_L$: $s = 0.0967$.

It is clear from Fig. 5 that the trend of the population is rising in the interval of spin number $0 < s < 0.6$. For higher values of spin the trend stagnates. The effect of spin *s* on coefficient of Lift $C_L$ is not linear.

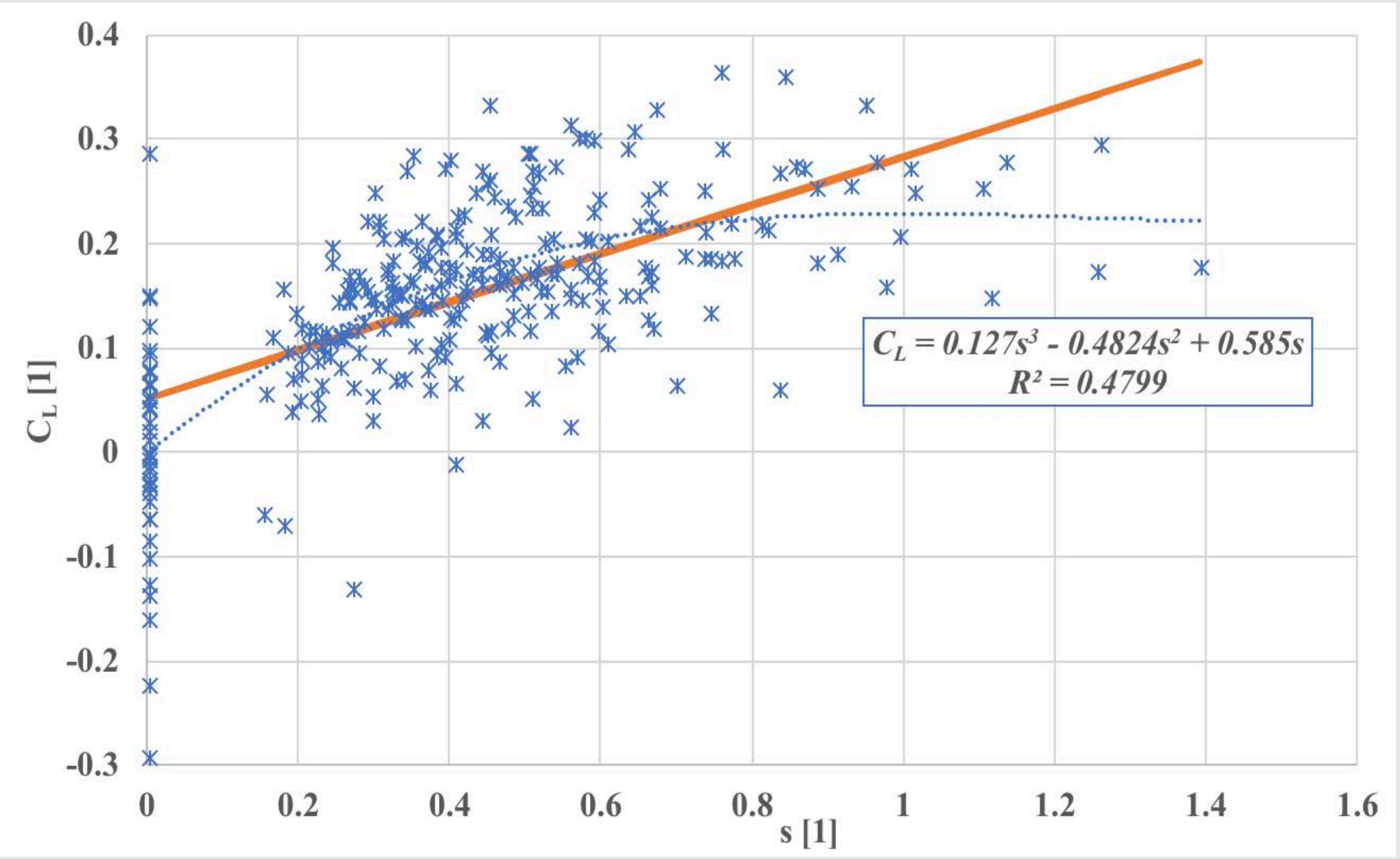

Fig. 5: Trends in the effect of spin *s* on coefficient of Lift $C_L$

**Others:**

**The coefficients of moments** Roll, Pitch and Yaw were calculated in the work. The basic meaning of the coefficients of moments is explained as partial information about the pressure distribution on the surface. The coefficient of moment compares pressure distributions on two hemispheres of the ball, therefore it is method of evaluation of symmetry of pressure distribution on the surface.

**Influence of roughness of surface** of the volleyball was studied and basic principle was confirmed: the higher roughness of surface of volleyball, the lower is value of critical *Re* – transition from laminar to turbulent flow regime.

**Uncertainties** were evaluated based on statistical approach. The conclusion is, that uncertainties don't have an intensive impact on the trends of the observed quantities, but it is important to be aware of the presence of the uncertainties.

The assignment of the case for comparison of results of experiment and **CFD calculation** was formulated. In the particular conditions, which were proposed to the CFD calculation the results are in good agreement with experiment. In the CFD was also described the influence of supporting spindle on the vorticity around the ball.

**Conclusions:** Aerodynamic parameters of flight of rotating volleyball were described and typical effects such as transitions from laminar to turbulent flow, knuckling effect, influence of rotation on Lift and others were discussed. Further more all described results of the tests ($C_D$, $C_L$, $C_S$) shell be used in equations of 3D ballistics (the 3D ballistics is proposed in thesis), then all cases of flight of ball including special cases (flight with side wind, flight without rotation) can be described by the system of equations. The knowledge gained from the investigation can be used in development of new sport-balls (testing of aerodynamical properties) and in the methodology of volleyball training (spin limit of served volleyball).

**Acknowledgement:** The experiment was made with support and cooperation between CTU in Prague, Faculty of Mechanical Engineering with Aerospace Research and Test Establishment, Department of Aerodynamics. Support by the the Project No. CZ.2.16/3.1.00/21569 Centre 3D Volumetric Anemometry is gratefully acknowledged. The wind tunnel testing in VZLU Czech Aerospace Research Centre was supported by Ministry of Education, Youth and Sports via LM2011016 Aerodynamic tunnels - Subsidy to restoration and securing of operation project

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