On drag and lift forces acting at flow past rotating bodies

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Abstract
Results of investigation of forces acting at flow past rotating sphere and prisma are presented. Experiments were performed in the wind tunnel, where special stand enables to rotate models and to measure components of aerodynamic forces. Dependencies of lift coefficient and drag coefficient on spin are evaluated. A theoretical model of flow effects on rotating bodies is prepared.

Keywords
Drag force, Lift force, drag coefficient, lift coefficient, experimental measurement, wind tunnel, volleyball, flight, prisma, rotation, revolutions, spin, Fourier analysis,

1 Introduction

Understanding the flight of rotating bodies is a wide topic in aerodynamic science already for a long time. Firstly it was I. Newton, who described flight of tennis ball in 1672. Almost two centuries later, in 1852 was whole theory on rotating sphere written down by German physicist H. G. Magnus [1] – nowadays it is known Magnus effect theory.
In the turn of centuries it was primarily R.D. Mehta [2], [3], who published most studies on sports ball aerodynamics. Most of papers are focused to explain the flight of football, baseball, tennis ball, etc. however there have been made also studies focused to volleyball [4]. Some observations have been also made, which tried to describe dependence of drag, respectively lift coefficient and Reynolds number for rotating sphere, [5].
This study is focused to describe drag and lift forces on different volleyballs based on measurement, compare results with previous made works and find the objective instrument, how to evaluate aerodynamic quality of sports balls, specially volleyballs.
In the last part of the paper is described theoretical model, which is dealing with flow past rotating prisma. Fourier analysis was made and amplitudes and frequencies were found. Also rotating prisma will be observed in the wind tunnel. Goal is to compare results from mathematical calculation and real measurement.

1.1 Description of experiment

Experiment was conducted in the 1,8 m-diameter low-speed wind tunnel in laboratories of Aerospace Research and Test Establishment in Prague.
Stand for measuring drag force F_D and lift force F_L on volleyball {Figs. 1, 2, 3} was made as it was required by dimensions of wind tunnel test section. Forces of drag and lift were measured by four independent scales, which were installed on the base stand in the laboratory. Scales were connected with ball-holding frame by string. Data were collected by Labview program to the PC, where data were later used by Matlab based program, which computed and plot all required results – computation of coefficient $\{C_D, C_L\}$ and plot of dependences $\{C_D = C_D(Re), C_L = C_L(Re), C_L = C_L(s)\}$.

Scheme of the experiment stand is shown and described on the Fig. 3.

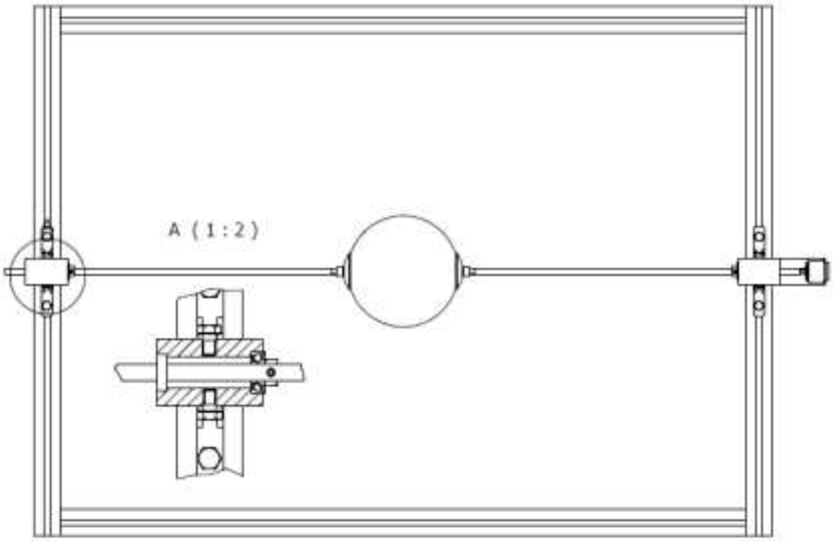

Fig. 1- Frame, which holds the ball

Fig. 2- Wind tunnel test section

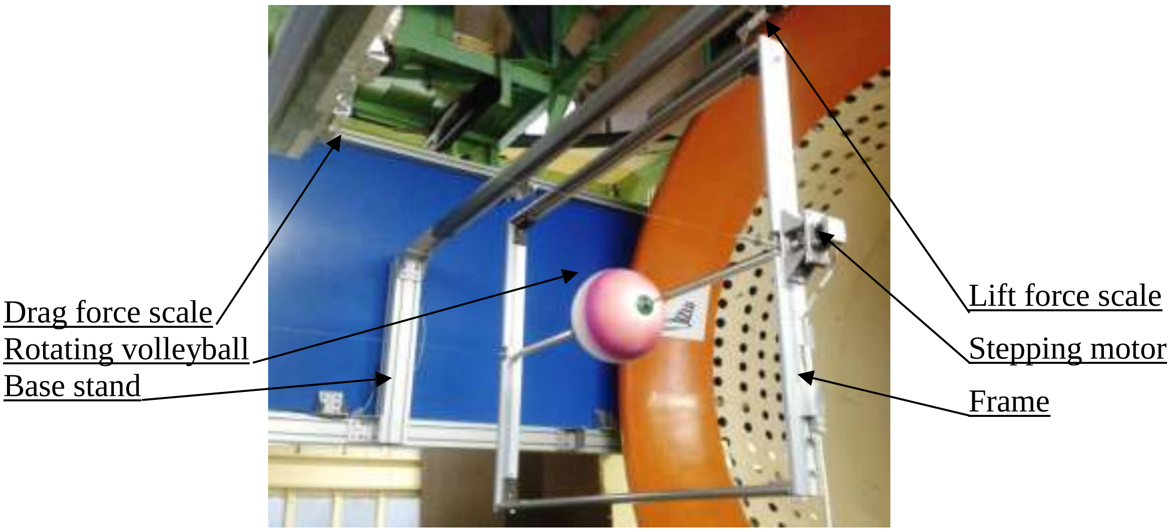

Fig. 3 - set description

Procedure of the test was made in air-flowing velocities of 10 – 32 m/s and revolutions in range of 5 – 12.5 revolution per second (revolutions and speed are coming from real observation of volleyball services – was observed by specialists from Faculty of Physical Education and Sport, Charles University). Reynolds number is 1.4 – 4.6 x 10^5.

1.2 Results of experiment

Measured dependence of drag force, respectively lift force on velocity v [m/s] and revolutions n [rps] is shown on the Fig. 4, respectively Fig. 5. It is evident for both dependences that at increasing revolutions, force grows and with growing airstream speed grows force again. Drag force F_D and lift force F_L are similar in trends obviously, but absolute value of drag force component F_D is higher.

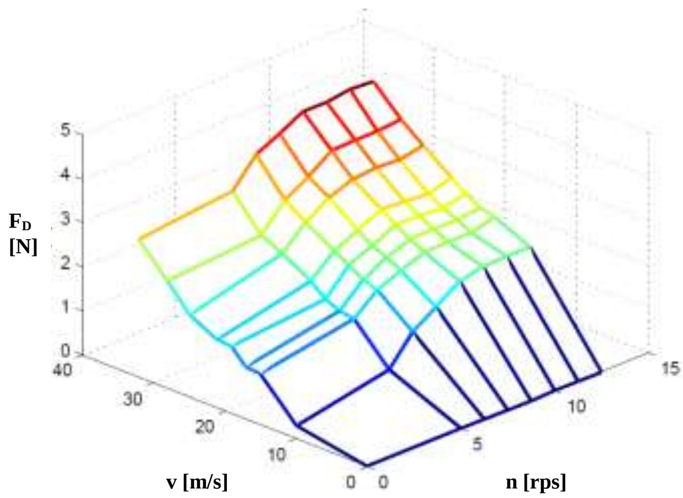

Fig. 4– Measured drag force F_D

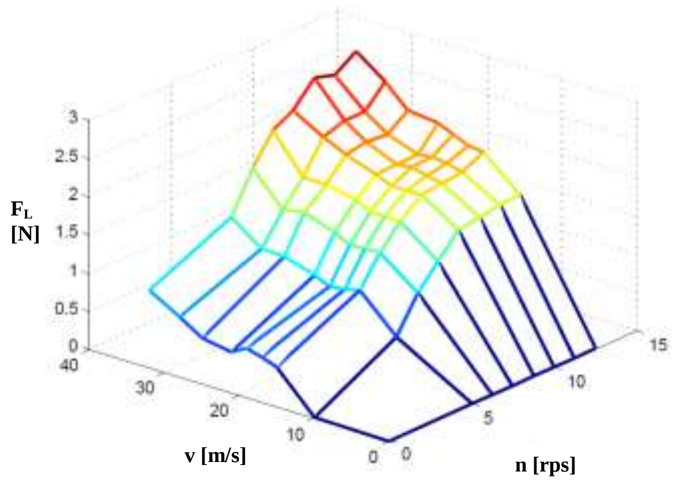

Fig. 5 – Measured lift force F_L

Drag coefficient versus speed and revolutions is shown on the Fig. 6. Highest values of C_D, C_L are obviously for highest revolutions with the lowest speed of airstream.
Lift coefficient versus spin ration is shown on the Fig. 8. Spin ratio is defined according [6]:

$$s = \frac{\pi \cdot n \cdot d}{2 \cdot v} \quad , \qquad (1)$$

where d is diameter of volleyball,
v is velocity of airstream and
n is revolutions per second.

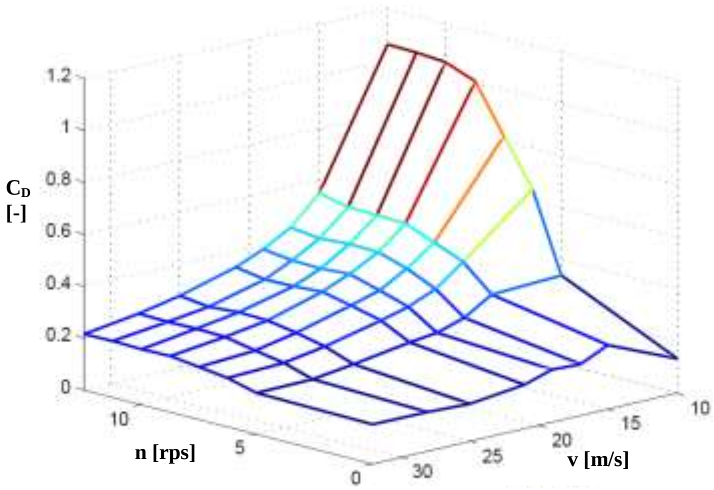

Fig. 6- Drag coefficient

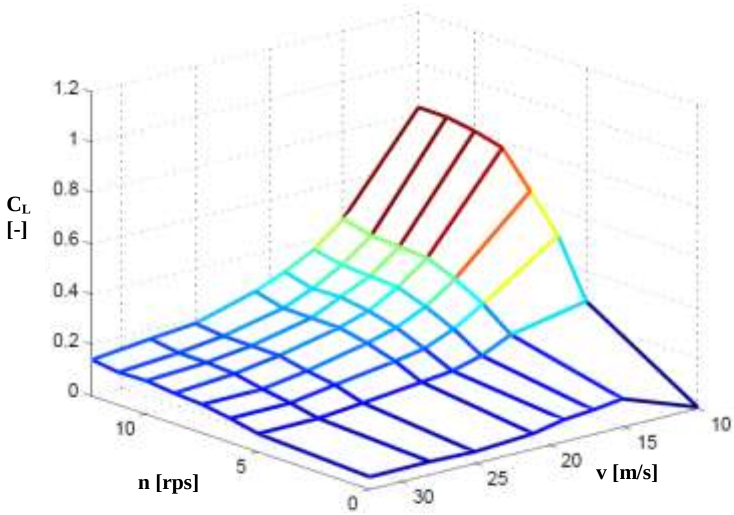

Fig. 7 - Lift coefficient

Dependence of lift coefficient C_L versus spin s is plot firstly for constant velocities v = const. (Fig. 8) and then also for constant revolutions n = const. (Fig. 9). Is predicted, that zone of existence of C_L versus s can be important factor in quality evaluation of flighing volleyball. To define more precisely the zone, where solutions of C_L vs. s are placed, the new way of plot was developed. Easily both plots (Fig. 8 and Fig. 9) were put together to one figure. The modification is visible on the Fig. 10. Results of another measurement (another type of volleyball) are presented at the Fig. 11. It is visible, that zones at both figures are different. Zone of C_L versus s at the Fig. 11 is in comparison narrower. Other criterions are described in the conclusions.

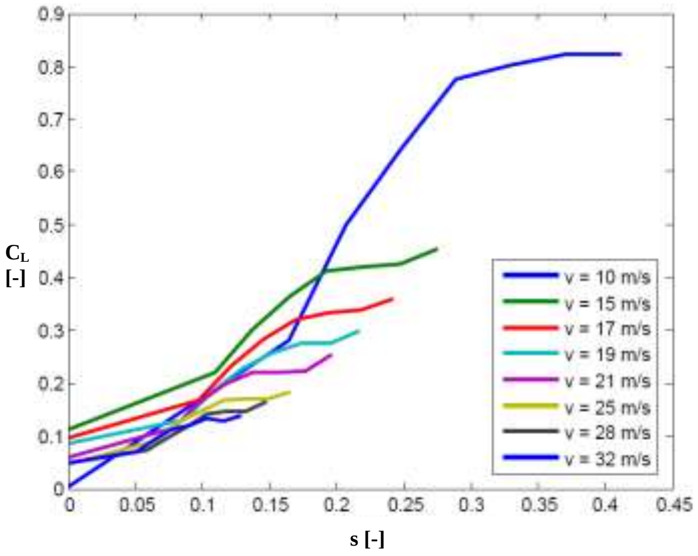

Fig. 8- Lift coefficient vs. spin, v = const.

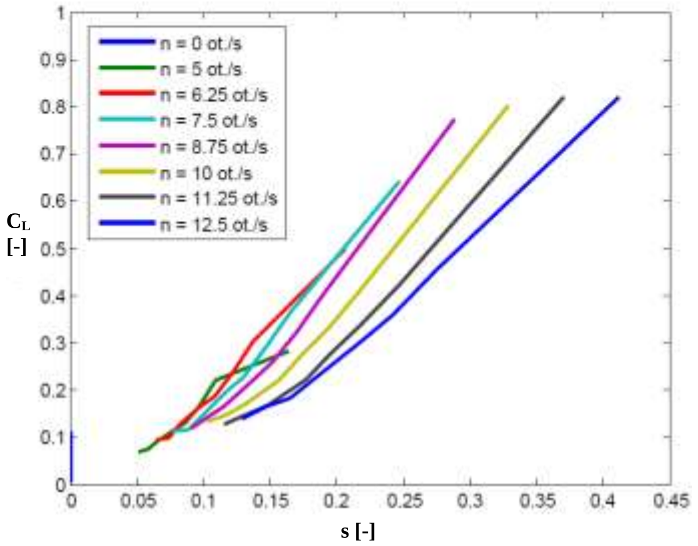

Fig. 9 - Lift coefficient vs. spin, n = const.

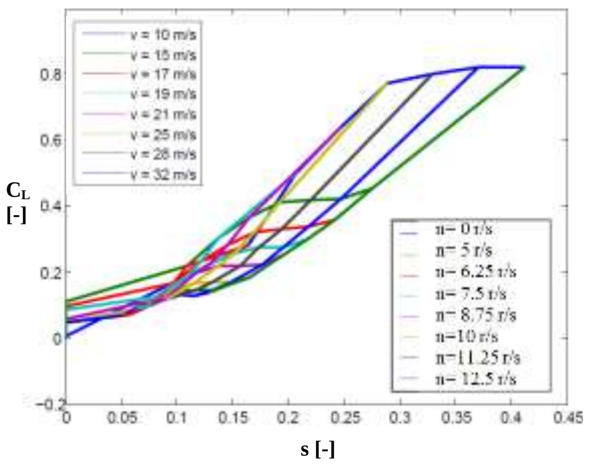

Fig. 10 - C_L vs. s measurement of volleyball No. 1

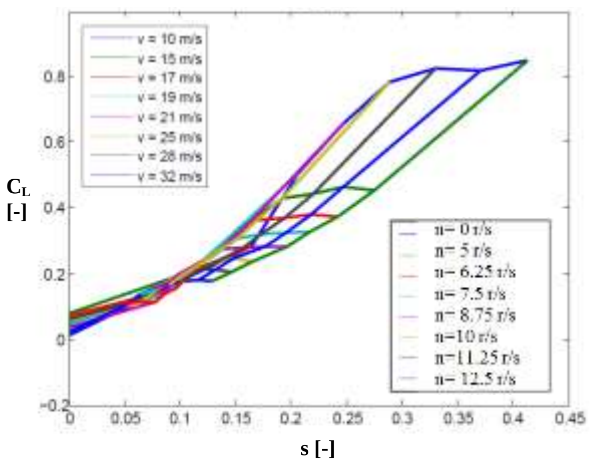

Fig. 11 - C_L vs. s, measurement of volleyball No. 2

1.3 Conclusions of Experiment

1. Dependences of C_D and C_L for flight of ball with rotation (n > 0 rps) are much more smooth than the one without any rotation (n = 0 rps). This is well shown on the Fig. 6. This fact shows, that there is occurred special mode of flight, which is called “knuckling effect“, as described in [2], [3] and [7] like unpredictable flight of ball, due to non-symmetrical separation of air stream.
2. Strong growth of C_L is marked for revolutions in between n = 5 r/s and n = 8.75 rps. Growth of C_L is not that steep for higher revolutions than n = 8.75 rps, this value (n = 8.75 r/s) looks to be a breaking point in the course of C_L vs. n. Fact was observed in all eight measurements. This conclusion can be really interesting point for volleyball praxes.
3. Zone of solutions C_L vs. s seems to be interesting instrument, for comparison of aerodynamics qualities of different balls. Compare Fig. 10 and Fig. 11, where dependences of two different measured balls are. Evaluation of ball qualities could be made as description of the zone, which is covered by solutions C_L vs. s, for example:
   1. surface,
   2. angle of resultant,
   3. highest value,
   4. thickness of zone in defined values of spin.

1.4 Acknowledgement

Experiment was made with support of cooperation in between CTU in Prague, Faculty of Mechanical Engineering with Aerospace Research and Test Establishment, Department of Aerodynamics. Cooperation is supported by project of Ministry of Education Youth and Sports called: VaVal (LM2011016 – aerodynamic tunnels).

2 Theoretical model

Rotation prism was observed theoretically in the second part of this project. Those data were taken from source [9]:

Tab.1. *– source of data, from Idelchik [9]*

α [°]	**0**	**10**	**20**	**30**	**40**	**50**
C_D	1.58	1.12	0.8	0.87	0.89	0.89

Goal of the second part of project was to applicate Fourier analysis to the periodic phenomena – rotation of prism in the flow. Expected outcome was amplitudes and frequencies of the phenomena.

2.1 Short description of Fourier analysis

Fourier analysis is a mathematical tool how to describe complicated functions. It is very practical for making frequency analysis, etc. Coefficients used in the equations have exact physical meaning – amplitude, revolution velocity, etc.
Fourier analysis is described by this system of equations:

$$f(t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos(\omega_k \cdot t) + b_k \sin(\omega_k \cdot t)), \qquad (2)$$

$$\omega_k = k\frac{\pi}{L}, \tag{3}$$

$$a_0 = \frac{1}{L}\int_0^{2L} f(t)dt, \tag{4}$$

$$a_k = \frac{1}{L}\int_0^{2L} f(t)\cdot\cos(\omega_k\cdot t)dt, \tag{5}$$

$$b_k = \frac{1}{L}\int_0^{2L} f(t)\cdot\sin(\omega_k\cdot t)dt, \tag{6}$$

physical values:

1, amplitude

$$A_k = \sqrt{a_k^2 + b_k^2}, \tag{7}$$

2, phase shift

$$\varphi_k = -atan\frac{b_k}{a_k}, \tag{8}$$

where f(t) is a function,
a_k, b_k, are coefficients,
ω_k is angular velocity,
k is coefficient, k = 1, 2, 3,…
L is half of the period,
t is the time.

2.2 Description of the calculation

Period of the phenomena is T = $\pi/2$, because as mentioned in [9] solutions are symmetric after each $\alpha = 45°$ ($\pi/4$), which is clear, because is observe four sides prism.

Numerical solution was made:

1. Vector of approximation of data was created – depict at Fig. 12.

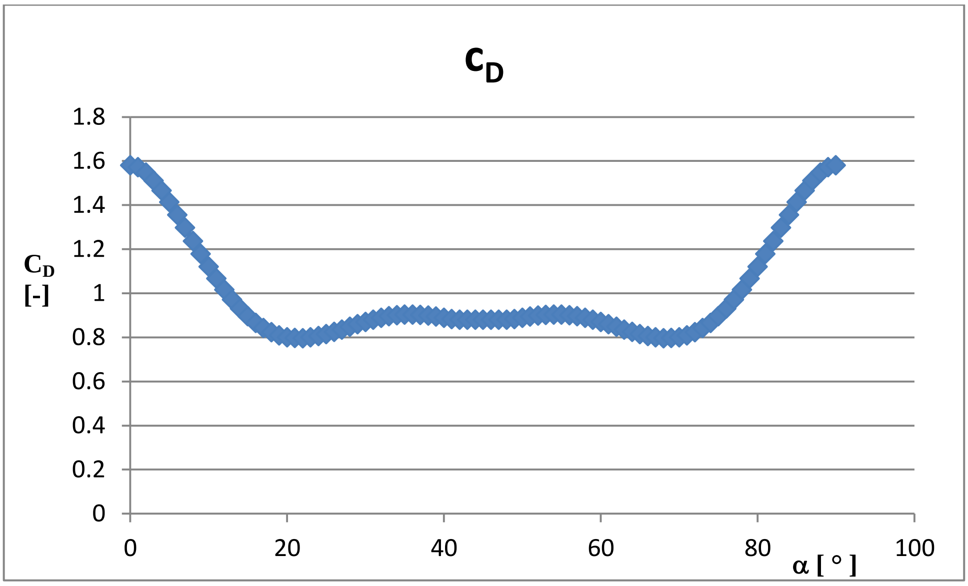

Fig. 12 - Vector of C_D versus angle α

2. Fast Fourier analysis was applied

Software Matlab was used, FFT function. Result of Amplitudes spectra are depicted – Fig. 13. Is visible at Fig. 13, that highest amplitudes are coming in the beginning of the frequency spectrum.

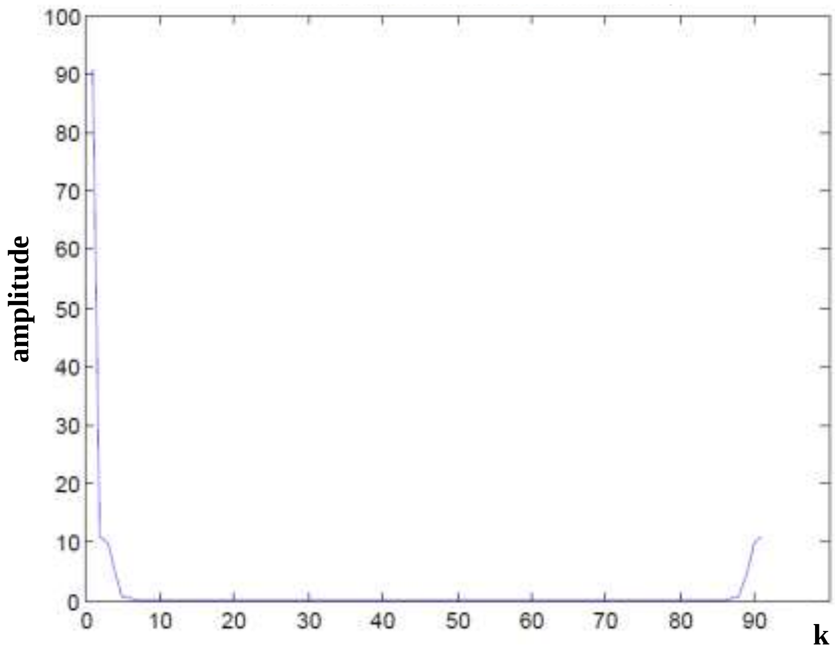

Fig. 13 - Amplitude spectrum

3. Vector of frequencies was computed

$$f = \frac{\omega}{2\pi}, \tag{9}$$

where ω is angular velocity. Dependence of amplitudes versus frequency is at the Fig. 14. From closer analysis is visible, that important for the phenomena are first three frequencies:
$f_1 = 0.636\ Hz$, $f_2 = 1.273\ Hz$, $f_3 = 1.909\ Hz$.

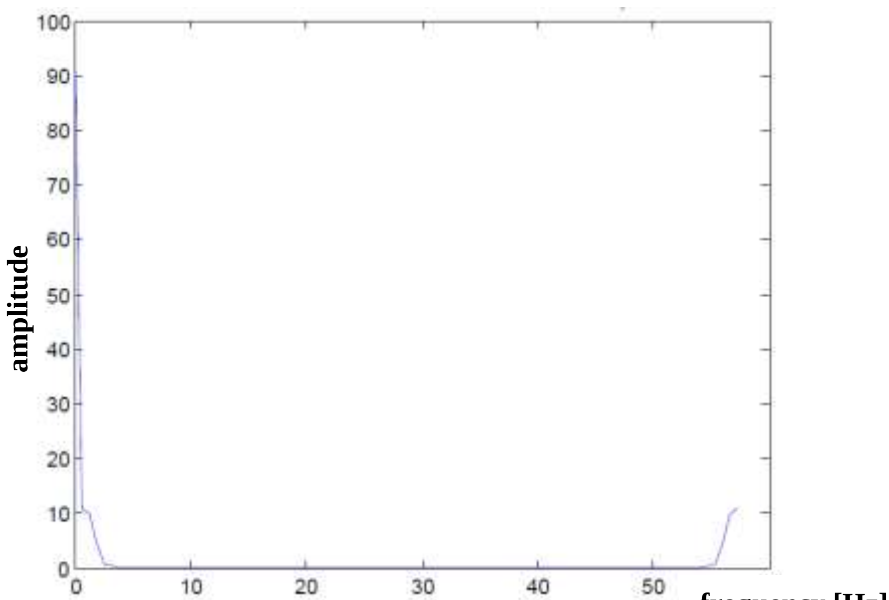

Fig. 14 - amplitudes versus frequency

2.3 Conclusion of calculation

Calculation of frequency and amplitude was made by Fourier analysis. Three frequencies were found. It is goal for next work at the topic of flow around rotating bodies to test computed results in the real measurement. Differences are expected, because calculation was made for static example. It is a plan to measure in two variants:

1. set exact angle α, let the flow to be stabilize, measure the forces F_L, F_D, then change the angle α and repeat procedure,
2. measure continuously forces F_D and F_L in the slow rotation movement (approximately ω_k = 0.1 rad/s) of the quadratic prism.

Comparison of the variants as well as comparison with the calculation results will be made.

Nomenclature

C_D	drag coefficient	(-)
C_L	lift coefficient	(-)
Re	Reynolds number	(-)
s	spin	(-)
F_L	lift force	(N)
F_D	drag force	(N)
n	revolution per second	(rev./s)
v	velocity of airstream	(m/s)
d	diameter	(m)
α	angle of rotation	(°)
ω	angular velocity	(rad/s)
a_k, b_k,	Fourier coefficients	
k	coefficient, k = 1, 2, 3,…	
L	half of the period	
t	time	(s)
φ	phase shift	(°)
f(t)	function	

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