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EXPERIMENTAL ANALYSIS OF AERODYNAMIC PERFORMANCE OF FLAPPING WINGS NANO AERIAL VEHICLES

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Abstract

The aerodynamics of flapping wings is ultimately concerned with the relation between motion kinematics and the time-history of aerodynamic forces and moments. However, an important intermediate quantity is the evolution of the flow field – and in particular of flow separation. Nature's solution to large time-varying pressure gradients, for example those due to aggressive motions, is to form and eventually to shed vortices. We are interested in understanding and exploiting these vortices – for example, in delaying vortex shedding to promote lift in situations where flow separation is in any case inevitable. From the engineering viewpoint, the question is to what extent closed-form models and conventional numerical/analytical tools can estimate the aerodynamic force history, with an eye to eventually running large parameter studies and optimizations. Our paper contains results of water tunnel experiments on flapping wings aeromechanics. The idea of investigation is to optimize the wing trajectories, and to find methods providing stability and control. In the paper, we present, also, conception and methodology of tests. The investigation is dividing into two parts: preliminary and principal tests. The aim of initial part is to extract quasi – state characteristic for wings of different platforms shapes. This characteristic will be used to generate initial kinematics of movement of wing. It will be initial point of further tests. The purpose of the main experiment is to find the best way of movement for wing taking account all of unsteady phenomena (interaction between vortices, wing – wing interference, etc.). Finally, we want to identify efficient way of controlling nano-microelectromechanical flying insect (entomopter).

Keywords: *aerodynamic performance, flapping wings micro aerial vehicles, water tunnel measurements*

1. Introduction

The development and acquisition of a new class of military system known as Nano Aerial Vehicle (NAV) is possible in the not so distant future as a result of technological progress in a number of areas such as aerodynamics, micro-electronics, sensors, micro-electromechanical systems (MEMS) and micro-manufacturing. A NAV, according to DARPA's definition, will be smaller than 7.5 cm and will weigh less than 10 grams. The potential of NAVs opens up new possibilities in the formulation of military strategies with respect to information superiority in urban operations. It is expected that their main attributes will be low cost, low weight, little to no logistical footprint, mission versatility, covertness and precision. Their distinctive flight envelope will include hovering, perching and other high-agility manoeuvres. The real mission niche for these insect-size aircraft may well be in the indoor setting where there is currently no reconnaissance asset available for military use. There is strong evidence that for very small craft, flapping-wing performance is superior to other options due to dynamic effects that create much higher average lift at low Reynolds numbers. The aerodynamics of flapping wings is ultimately concerned with the relation between motion kinematics and the time-history of aerodynamic forces and moments. However, an important intermediate quantity is the evolution of the flow field, and in particular of flow separation. Nature's solution to large time-varying pressure gradients, for example those due to aggressive motions, is to form and eventually to shed vortices. We are interested in understanding and exploiting these vortices, for example, in delaying vortex shedding to promote lift in situations where flow separation is in any case inevitable. From the engineering viewpoint, the question is to what extent closed-form models and conventional numerical/analytical tools can estimate the aerodynamic force history, with an eye to eventually running large parameter studies and optimizations. In this work, we focused on low Reynolds number water tunnel experiments with the emerging theme that often the prediction of aerodynamic force history is easier than resolving the underlying flow field. We outline several attempts to bridge from classical problems in unsteady aerodynamics, such as dynamic stall 1, to more topical questions in flapping-wings. We focus on Reynolds numbers in the range of 3,000 – 50,000, covering flapping wing applications from large insects to medium birds [3-5].

Many researchers have already pointed, that for flapping wings cases doing tests in water have many advantages [1, 2]. For high-rate unsteady experiments in air, inertial and structural effects are a problem, because physical motion rates must be large to achieve the desired dimensionless rates. Experiments in water solve the inertial but not the structural difficulties, because the physical motion rates are now fairly small, but apparent-mass effects greatly reduce the frequency response of the test paper mounting scheme. We suggest as a working compromise the use of dye injection in water to preliminarily validate numerical predictions, and then use of computations for parameter studies, finally closing the loop with detailed quantitative velocimetry in experiments, once the computations have identified the most interesting cases.

Accurate rendition of laminar to turbulent transition is important for proper computation of the flow field, with similar consequences for facility flow quality on the experimental side; that is, laminar flow assumptions can lead to spurious prediction of flow separation, and vice versa. However, at high effective angles of attack, separation becomes inevitable and effects of Reynolds number, boundary layer physics and so forth become far less acute. Therefore, we have the somewhat paradoxical conclusion that massively separated problems are easier to compute than the more classical problems of attached flow. As an example, we consider a study of airfoil pitch-plunge and pure-plunge, with the former a moderate separation and the latter a deep dynamic stall case, with a strong leading edge vortex.

Even though there has been considerable analysis of bird and insect flight mechanisms, no machine at the size level of a hummingbird has been demonstrated. There is more to designing insect-size vehicles than just scaling down the dimensions of UAVs. The aerodynamics of an insect-scale aircraft in the low Reynolds number regime differs significantly from the aerodynamics of mini vehicles, such as UAVs. There has been considerable analysis of the mechanisms of bird and insect flight providing insight into the design of small-scale flapping-wing aircraft. Insect flight has been successful in nature for millions of years, and relied on unsteady aerodynamics to produce high lift coefficients and excellent manoeuvrability. Insects fly by oscillating (plunging) and rotating (pitching) their wings through large angles, while sweeping them forwards and backwards.

The dramatic lift-boosting unsteady aerodynamic phenomena that are exploited by insect flapping wings are however not yet fully understood. The main likely aerodynamic phenomena occurring in insect-like flapping are:

a) bound leading edge vortex, persisting during each half-cycle and shed at the end of it,
b) effects of wing pitching, plunging and sweeping present all the time,
c) wing interaction with its own convected wake, due to its forward-backward sweeping.

It has also been qualitatively found that insects achieve their high flight performance using active flow control.

The aerodynamic performance of insects has motivated the development of aerodynamically scaled flapping mechanisms. These devices allowed progress in gathering experimental data on insect aerodynamics, but were generally too bulky for NAVs. Although the mechanism was completed, there are still significant uncertainties in the modelling and understanding of the relevant aerodynamics. The technical difficulties relate to the complex unsteady motion required to produce high lift and the effects of flow at low Reynolds number.

The aerodynamic modelling and experimental evaluation of flapping wings at a low Reynolds umber (Re) have identified several key areas of interest. Researchers have described the importance of the leading-edge vortex (LEV) that is formed by small flapping wings and its effects in stall-delay during the flapping cycle, yielding very high lift coefficients for this Re regime. The ability of birds and insects for expertly regulate the movement of the LEV on lifting wings gives them fine control during flight at very low speeds. Others have investigated both experimentally and computationally, the performance of flapping wings at low Re numbers and concluded that a more complete understanding of dynamic stall performance is required. Elsewhere cameras installed on birds have monitored their behaviour in flight. Interesting phenomena related to feathers on different section of the wing are seen to provide the fine control and agility associated with bird flight.

Although flapping-wing products may be purchased in hobby stores and university teams may fabricate aero models with flapping wings, the insect-size aircraft for military applications still has a long way to go. DARPA has just launched their *Phase I NAV program*, which is focused on developing a system that will have the power, navigation, communications and mechanisms needed to provide lift, thrust, and hover capabilities. The design and analysis capability within the scientific community has progressed to a point where it can handle simple cases such as pure-plunge of airfoil. The understanding of the issues for the full 3-D motion representative of insect wing beat kinematics appears now to be within reach and is the objective of this project. This is an essential step towards engineering realization of the functionality of insect flight.

2. Problem Statement

The aim of work is to investigate how basic geometrical and kinematical parameters, such as aspect ratio of wing, stroke amplitude and Reynolds regime effect on resultant aerodynamic forces. Results will be used to find initially optimal considered dimensions of electromechanical entomopter, what will be helpful at the beginning of design process. In general, the aim of present work is similar as in work [3] and [4], but results are based on experimental measurements.

To achieve comparable view of influence of mentioned geometrical parameters on resultant forces, to numbers of similarities were taken into account: Reynolds number, which for 3D flapping motion is expressed as follows:

$$\mathrm{Re} = \frac{4 f \Phi R^2}{\upsilon AR}, \tag{1}$$

where:

aspect ratio $AR = \frac{(2 \cdot R)^2}{S}$

and reduced frequency, which in this case it can be expressed by equation:

$$k = \frac{\pi}{\Phi \cdot AR}. \tag{2}$$

Basic parameter was stroke amplitude. Simultaneously to varying amplitude, the flapping frequency was changed respectively to equation:

$$f = \frac{\mathrm{Re} \cdot \upsilon \cdot AR}{4\Phi R^2} \cdot \tag{3}$$

In consequence, mean Reynolds number was constant for one measurement series.

In general, time history of wing angular position (stroke angle) can be expressed:

$$\varphi(t) = \frac{\Phi}{2} \sum_{i=1}^{N} \left[A_i \cos(2i\pi f(k)t) + B_i \sin(2i\pi f(k)t) \right]. \tag{4}$$

If instead frequency *f* will be put equation 3, above expression will take a form:

$$\varphi(t) = \frac{\Phi}{2} \sum_{i=1}^{N} \left[A_i \cos(i\pi \frac{\mathrm{Re} \cdot \upsilon\lambda}{2\Phi R^2} t) + B_i \sin(i\pi \frac{\mathrm{Re} \cdot \upsilon\lambda}{2\Phi R^2} t) \right] \cdot \tag{5}$$

Basing on above we can find, that both maximal and average angular velocity are constant during each series, because theirs value can be obtained from following expressions:

$$|\omega|_{\max} = \frac{\mathrm{Re}\,\upsilon\lambda\pi}{4R^2}, \quad |\overline{\omega}| = \frac{\mathrm{Re}\,\upsilon\lambda}{2R^2}, \tag{6}$$

where linked parameters (frequency and amplitude) are absent.

3. Experimental Set-Up

The experiments were conducted in the RHRC water tunnel (Fig. 1) [6, 7]. The water tunnel has an open surface test section with a vertical return circuit. Much care was exercised in ensuring that the turbulence screens were always free of trapped air bubbles and that a constant temperature of 22C~ 24C was maintained. The uniformity of the velocity field in the empty tunnel has been validated by the PIV measurements at all Reynolds number conditions of interest.

The 3DOF system controlled three angular motions: pitch motion (γ), dihedral motion (θ) and sweep motion (φ). The standard terminologies and nomenclatures used in fixed wing aerodynamics are adopted here. The body axes system is shown in Fig. 3. Three angles are taken as the motion parameters, i.e. feathering angle (γ), flapping angle (θ) and stroke angle (φ), corresponding to feathering motion angle, elevation angle and position angle in some bioflight literature [3-5].

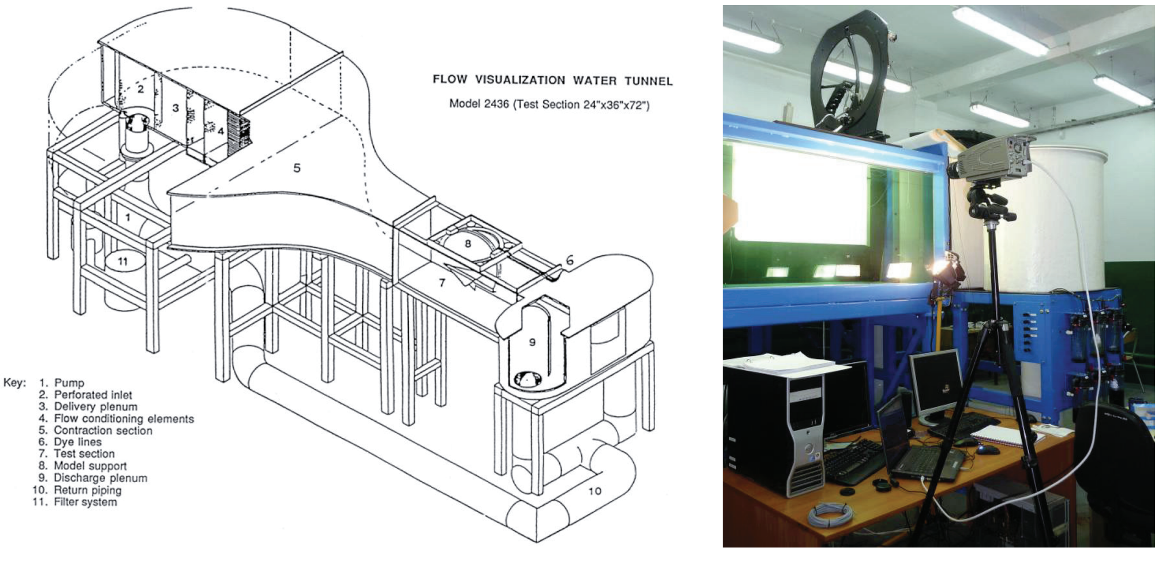

Fig. 1 Rolling Hills Research Water Tunnel Model 2436 [7]

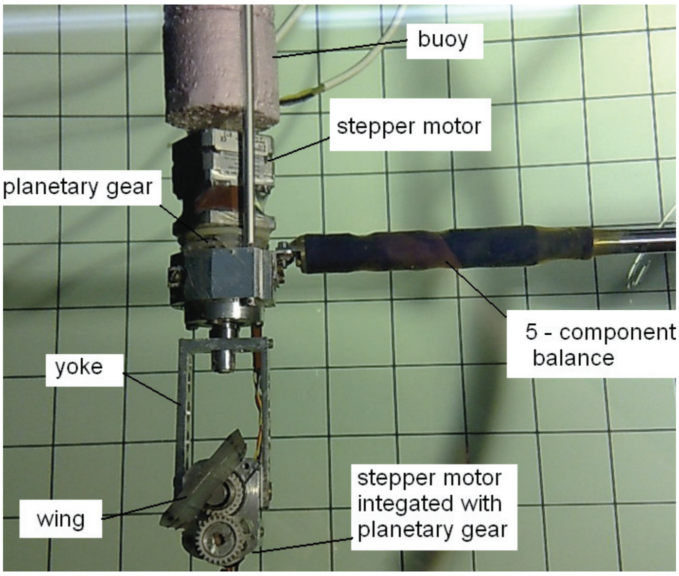

Fig. 2. Mechanism used in experiment

The time' history of motion can be described by three equations and in case of this investigation are as follows:

$$\varphi(t) = \frac{\Phi}{2}\cos(2\pi ft),$$
$$\theta(t) = 0,$$
$$\gamma(t) = \frac{\Gamma}{2}\sin(2\pi ft) + 90^{o}. \tag{7}$$

In current experiments wing had only 2DOF, so θ angle was constant and equal 0. Two others angles are changing accordingly with sinusoid. Amplitude of pitching angle (Γ) was always constant and equal 90 degrees. As already was mentioned, only sweep motion amplitude and flapping frequency were varied. In Tab. 1. values of these parameters are for which the measurement was made.

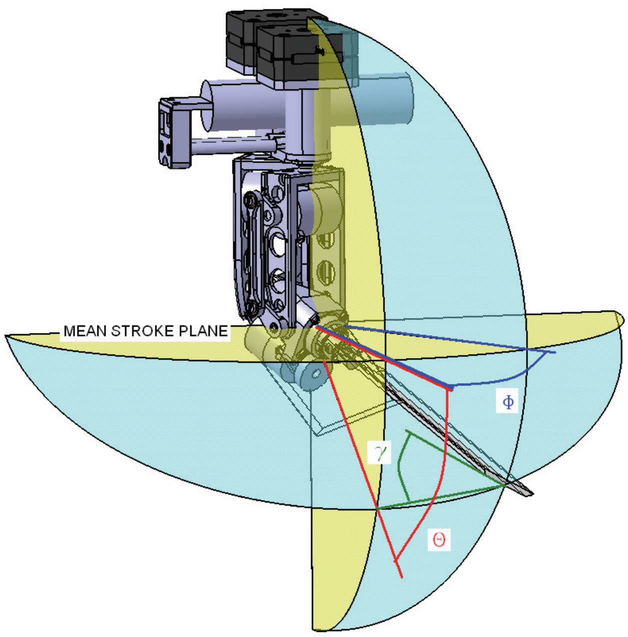

Fig. 3. Coordinate system

Tab. 1. Plan of experiments

Φ, deg	f, Hz						
	AR= 6.5			AR= 8.7			
	Re=3800	Re=5500	Re=7200	Re=3500	Re=5500	Re=6200	Re=7000
30	N/R	0.408	0.529	0.362	0.546	0.610	0.679
35	N/R	0.356	0.459	N/R	0.456	0.525	0.592
40	0.025	0.311	0.403	0.217	0.402	0.462	0.521
45	0.022	0.276	0.360	N/R	0.380	0.413	0.467
50	0.020	0.250	0.324	0.2212	0.325	0.373	0.355
60	0.017	0.208	0.272	0.1859	0.272	0.314	N/R
70	0.014	0.181	0.234	0.1613	0.236	0.272	0.306
80	0.013	0.156	0.207	N/R	0.206	0.240	0.269
90	0.011	0.140	0.184	0.125	0.184	0.215	0.240

In experiments were used two wings (Fig. 4), which are characterized different aspect ratio (AR=6.5 and AR=8.7). The distances between wing tip and centre of rotation and between wing root and the same centre point are equal for both wings. Wings were made as 3 mm thick flat plates tapered on leading and trailing edges. Inside the wing were made three 0.9 mm diameter dye jets, two on leading edge.

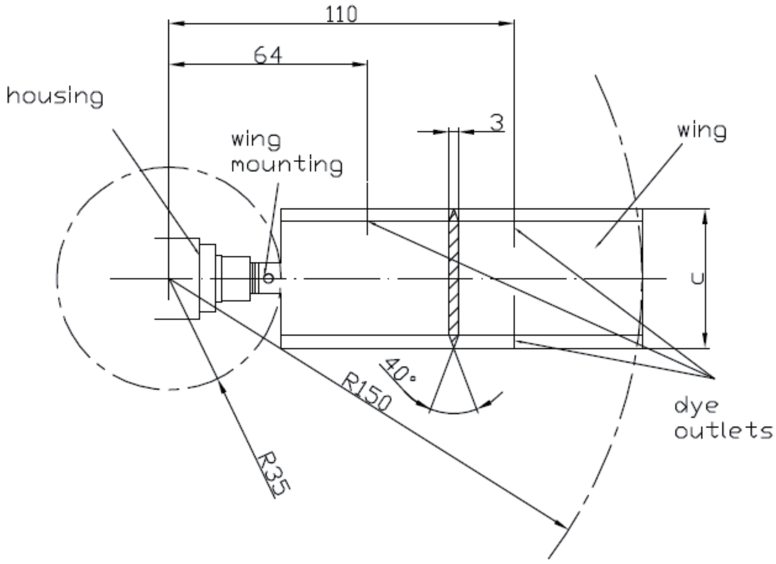

Fig. 4. Wing geometry

4. Results of Water Tunnel Tests

In respect of flow, field nature one period of wing motion can be divided into two parts:

1 – angular rotating (Fig. A),

2 – changing direction of rotation (Fig. 5B).

During rotation, the leading edge vortex is creating and growing. Irrespectively from reduced frequency value, develop of LEV looks in the same manner. Vortex created on inner sections is tight and remain attached to the wing. In addition, soon after turn, it starts moving spanwise (Fig. 7). Vortex created on outer sections has clearly different structure. Firstly, it is also tight, but it detaches at once from the wing surface, in the same time it is winding up around vortex from inner section (Fig. A.) As a graphically description the flow field shape of LEV looks like horn. Above description, confirm strong influence of spanwise flow on flow field around wing. In general, results of visualization are very similar as in related works [10, 11]. In comparison with flow around oscillated airfoil (pith and plunge motion) [one, 2], there is many similarities, but there is also one remarkable difference. In pure pith and plunge, LEV is flat; while in rotational motion are three-dimensional.

Trailing edge vortex was quite difficult to observe especially for very low frequencies. Nevertheless it was observed, that the form of it remain unchanged. From time to time small vortexes are shedding to wake (Fig. 8a).

Flow around the wing during direction change strongly depends from reduced frequency. During this moment, the wing is passing through its aerodynamic trail what is well seen on Fig. 5B. Increasing frequency causes increased of acceleration of the wing. In effect, induced velocity, which is tangent to wing trajectory, also is increasing. Differences manifest in form of starting vortex (Fig KB), which creates during each change of direction. For higher frequencies, starting vortex became much more distinct and remains longer, while for low values it became virtually unseen.

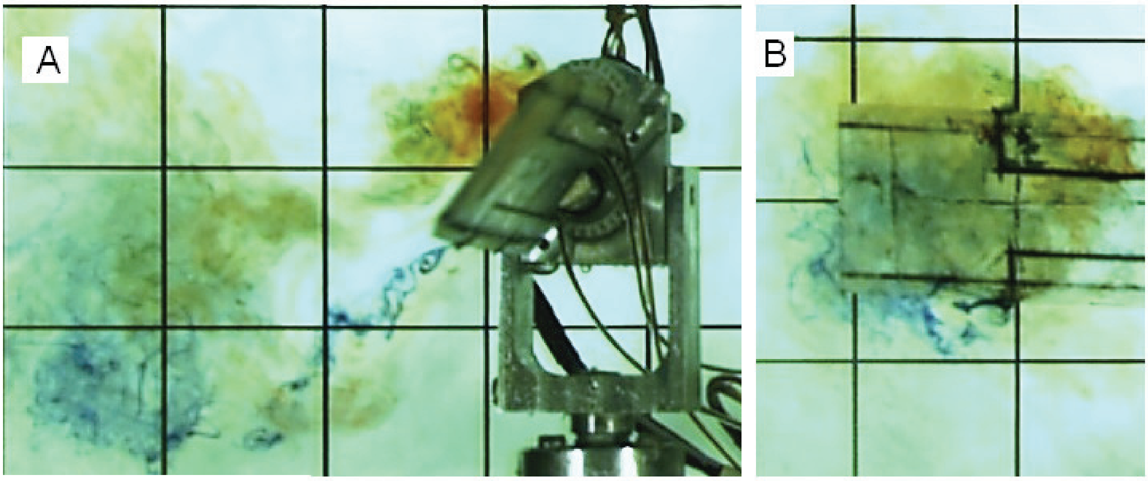

Fig. 5. Flow field during rotation (A) and during direction change (B)

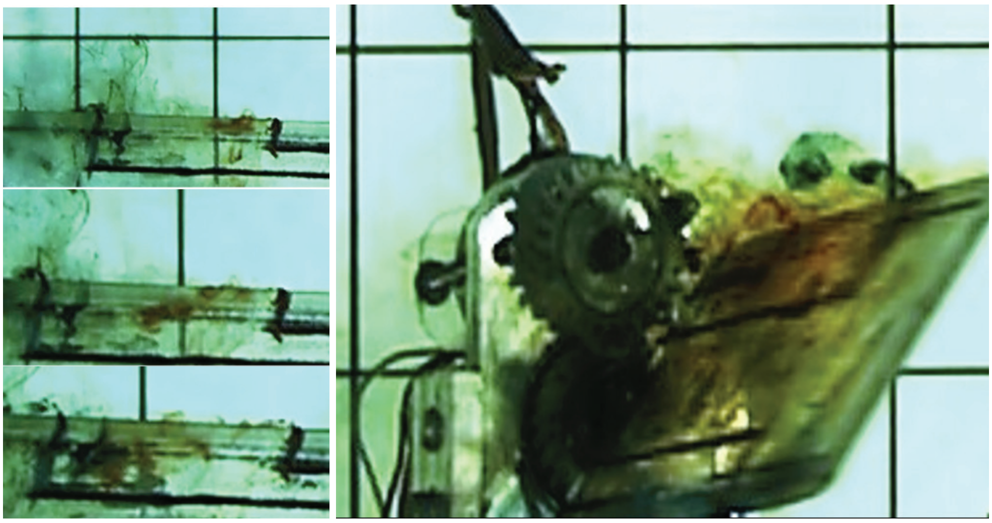

Fig. 6. Spanwise flow of LEV

Every test consists of 20 repetitions of full cycles. For all time the resultant lift force and torque measurements were performed. Sampling time was set as 50 Hz. To make results more clear software low pass filter was used after experiment. Exemplary result is shown in Fig. 9. Achieved data were divided into each period and then they averaged (*Navy*). Later, averaged time history during one period was approximated with Fourier series (*Nf*). As a background results of quasi-steady, estimation was added (*Nqs*). At the end, average value of approximated lift force was calculated (*Nav*).

Fig. 7. Trailing edge vortex and starting vortex for reduced frequency 0.15 (A) and 0.4 (B)

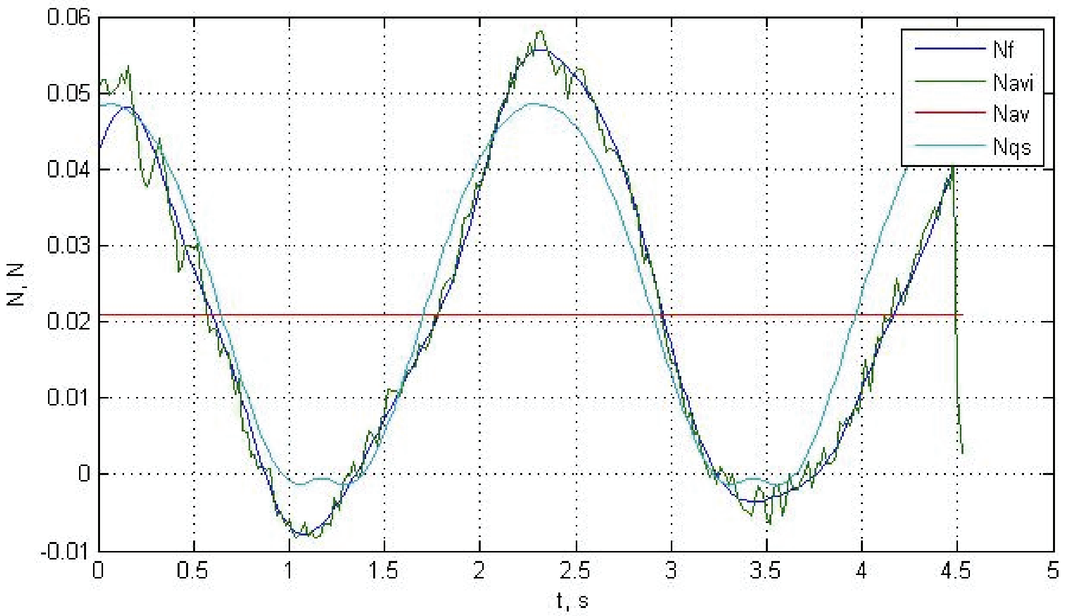

Fig. 8. Exemplary result of test Re=3500 Φ=50°

It is impossible to compare directly resultant forces from measurements series for different Reynolds number or aspect ratio. Thus, force values were recalculated into dimensionless coefficient in accordance with expression:

$$\overline{C}_L = \frac{3 \cdot N_{av}}{2\rho \cdot (\Phi \cdot f)^2 \cdot c \cdot (R^3 - R_0^3)}. \quad (8)$$

Results prepared in such a way could be compared. Value of average lift force coefficient C_L carry information about effectiveness of wing during motion. Fig. 9 and 10 show characteristics of average lift force coefficient from measurement (C_L) compared with calculated results (C_{Lqs}).

According to quasi–steady model influence of as rise of reduced frequency as decreasing aspect ratio on wing effectiveness is disadvantageous (see Fig. 10 and 11, curve C_{Lqs}). Explanation such a behaviour is simple. In both cases area of stroke plane fall, so induced velocity grows. In case of decreasing aspect ratio also, lift curve slope of airfoil decrease, so resultant force for the same angle of attack is lower.

Effectiveness of wing with aspect ratio 8.7 is increasing due to reduced frequency in cases of Reynolds numbers 5500 – 7000. Only in case of Re= 3500 is decreasing. Furthermore, for lowest Reynolds number values of coefficient taken from measurements virtually are the same as from quasi-steady calculation. For rest cases, measured values are lower and differences are decreasing with rise of frequency. It appears from experiment, that in this regime of Reynolds number and such nonstationarity of flow, so slender wing is not effective. Probably on section placed further from centre of rotation appears very fast separation, so outer part of the wing produce mostly only drag. The situation is getting better, when period is very short. The separation appears relatively late and results are better. For the time being it is only a hypothesis, it should be checked by more insightful flow visualization.

Results for 6.5 aspect ratio wing are in opposite to previous. In every case, results are better than calculated. Different is also tendency of lift characteristic due to frequency. Curves gently fall with rise of reduced frequency. Nevertheless, value remains quite high (1.4-1.5). Distance between curves decreases with decreasing frequency. From investigation, appear that reduced frequency is not influencing resultant force, as it appears from quasi–steady model. Change is rather gentle. It appears also, that using wings with lower aspect ratio is more profitable.

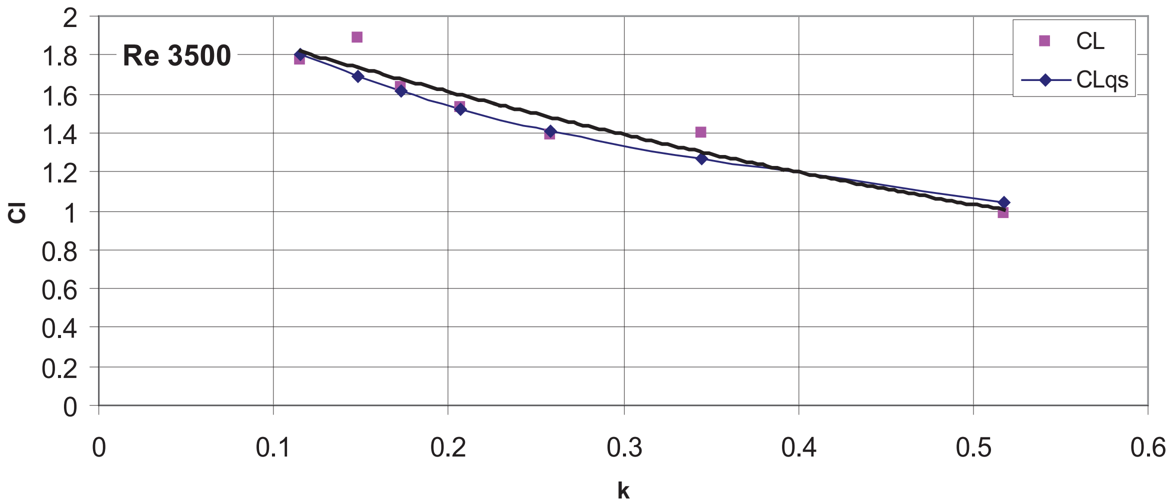

Fig. 9. An average lift force coefficient for AR=8.7 wing (Reynolds number 3500)

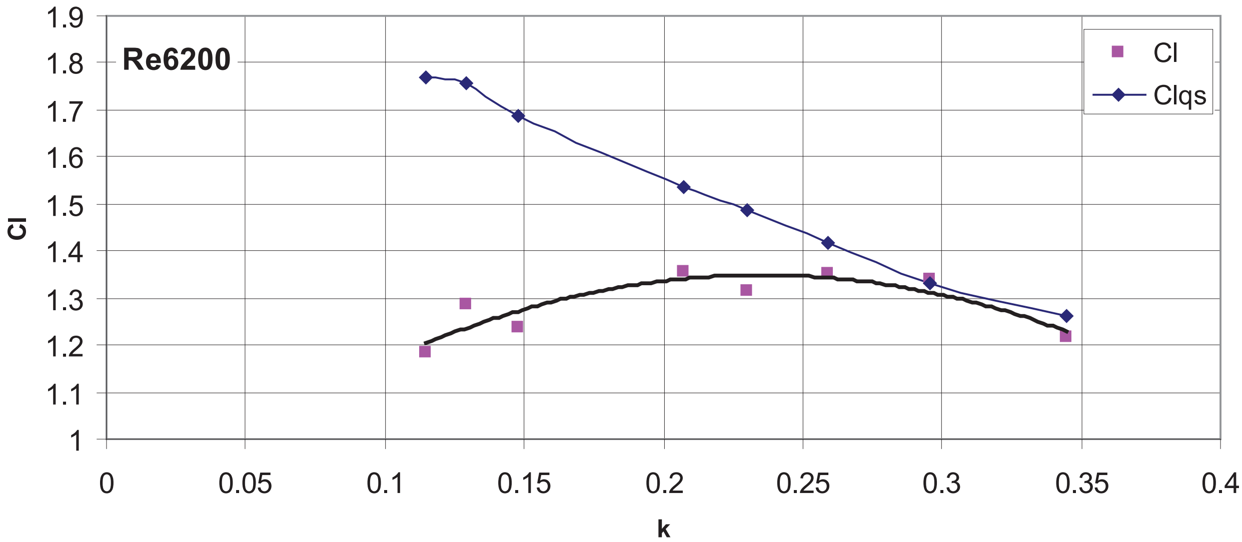

Fig. 10. An average lift force coefficient for AR=8.7 wing (Reynolds number 6200)

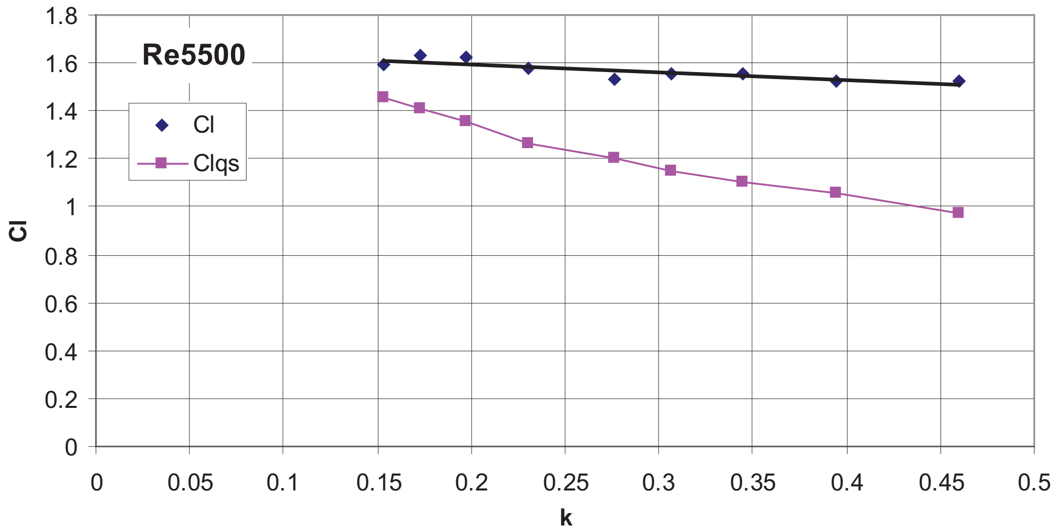

Fig. 11. An average lift force coefficient for AR=6.5 wing (Reynolds number 5500)

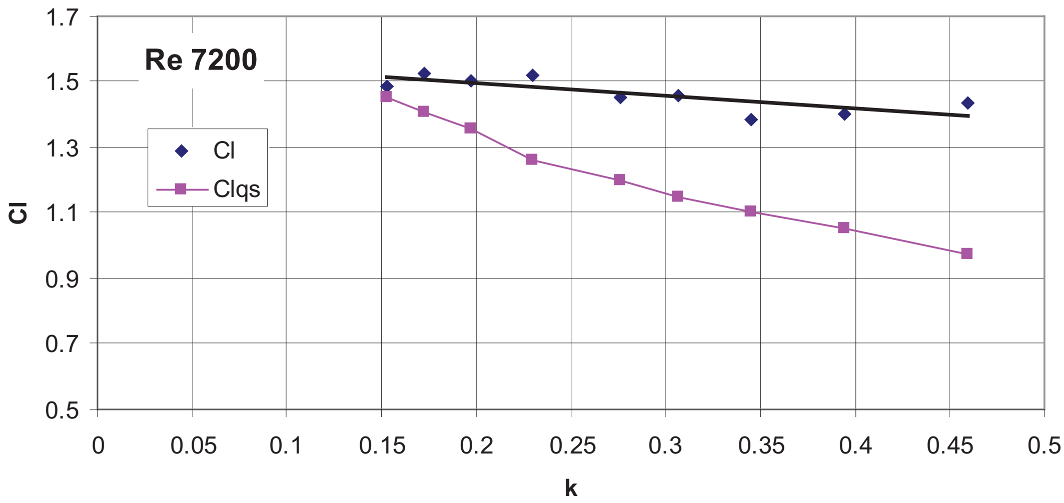

Fig. 12. An average lift force coefficient for AR=6.5 wing (Reynolds number 7200)

5. Conclusions

We conducted on water tunnel experiment an insect like wing performing two degree-of-freedom motions. Experiments give very important tips, which will be useful during designing and developing process of electromechanical entomopter prototype. Tests proved, that linkage between geometrical and kinematics parameters is very strong and both parameters influence resultant forces. Furthermore, results have explained, why in insects world short wings are so popular. Unfortunately, the range of variability of investigated parameters was quite narrow. In near future experiment will be continued. Wings with smaller aspect ratio will tested and torque (which was also measured) will be analysed.

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Nomenclature

c – chord length,
$\overline{C_L}$ – average lift coefficient,
f – flapping frequency,
k – reduced frequency,
N_{av} – average normal force,
Re – Reynolds number,
R – distance between centre of rotation and wing tip,
R_0 – distance between centre of rotation and wing root,
S – wing surface area,
Γ – amplitude of pitching (feathering) oscillation,
Φ – amplitude of stroke motion,
γ – pitch (feathering) angle,
φ – stroke angle,
θ – flapping angle,
λ, (AR) – aspect ratio,
ρ – fluid density,
υ – kinematic viscosity,
ω – angular velocity.