# A STUDY OF FLIGHT DYNAMICS AND AUTOMATIC CONTROL OF AN ANIMALOPTER

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## Abstract

*The key problem is to construct the proper computational models for the simulation of controlled animalopter motion. In the paper investigating control efficiency of stabilization of an animalopter plane motion is also presented. The following assumptions are made: the motion may be decomposed into flapping and feathering; each wing is rigid and rotates about the common axis; aerodynamic forces coming from airfoils have periodical character; the wing vortices are generated at the trailing edge only; the shape of the wake is determined from calculations via a time-stepping procedure. The modified strip theory and modified panel method are used for computing the unsteady flows of animalopter flight. A linear dependence of aerodynamic force on feathering angles is assumed. In the proposed model the control of the motion is performed by rudder deflection and by feathering angle amplitude. Synthesis of control has been conducted on the basis of nonlinear inverse dynamics. In order to verify applied calculating models, experimental investigations in wind tunnel at Institute of Aeronautics and Applied Mechanics of Warsaw University of Technology have been performed.*

## 1 Introduction

Animal propulsion by means of flapping wings has been the focus of considerable interest in the late nineties. This is due to the relatively high efficiency obtainable by such mode of flight. Flapping flight for micro-robots [13] (known also as MAVs or micro-flyers) is not only an intriguing mode of locomotion but provides manoeuvrability not obtainable with fixed or even rotary wing aircraft. The MAV is of comparable size of small birds and big insects. In order to obtain satisfying explanation of animal flight features, it is necessary to create adequate physical, mathematical and computational models. The key to do this is the understanding how complex motions of animal's wings generate aerodynamic forces [14]. However, very little is still known about flight dynamics and automatic control of flying micro-robots.

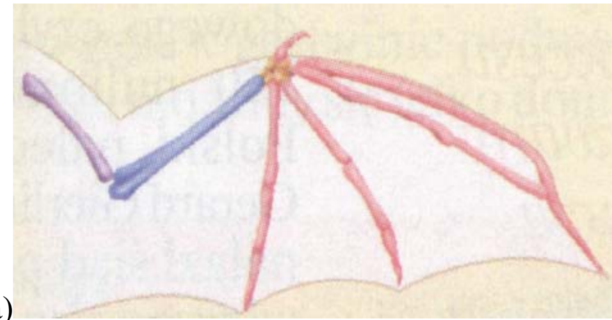
Another important problem is the control of motion. Stabilising control is made difficult because the wings do not have typical control surfaces such as ailerons. The influence on the motion is possible only through changing amplitudes and frequencies of flapping and feathering of wings. Thrust of animalopter depends on local angles of attack, and these depend on parameters of flapping and feathering

Fig. 1. A bird during hovering flight (cf. [5])

The primarily goal of our work is to design the software simulation for micromechanical flying robots (so called animalopters). The animalopter flight simulator should be an end-to-end tool composed from several modular blocks, which model: wings aerodynamics, the body motion, and control algorithms. Of course, the investigation of animalopters is obviously guided by the real flying animal studies (Fig. 1).

## 2 Flight mechanics of animalopters

It is well-known fact that larger flying creatures fly principally by gliding or slow beating, where as smaller ones fly by strong beating at high frequency. Thus, the range of beating frequency and the Reynolds number varies greatly.

a) 

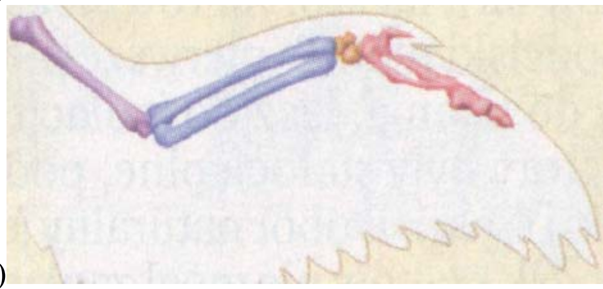
b) 

Fig. 2. Morphology of: bat wing a), and bird wing b)

The beating motion of wings is exclusively used in the powered flight of birds and insects. In flying, this is the only way by means of these flying creature can counter the gravity forces and propel themselves against aerodynamic drag. Therefore, detailed analyses of kinematics are central to an integrated understanding of animal flight [2, 10, 17]. The musculoskeletal system (Fig. 2 from [5])) is an ultimate downstream "decoder" of neural signals, converting the activity of motor neurons into the kinematics we observe as the behaviour of an animal [3].

The motion of an animal wing may be decomposed into: *flapping*, *lagging*, *feathering* (the rigid body motions) and also into more complex deflections of the surface from the base shape (*vibration modes*).

This requires a universal joint similar the shoulder in a human. A good model of such joint is the articulated rotor hub (Fig. 3). *Flapping* is a rotation of a wing about longitudinal axis of the body (this axis lies in the direction of flight velocity), i.e. "up and down" motion. *Lagging* is a rotation about a "vertical" axis, this is the "forward and backward" wing motion. *Feathering* is an angular movement about the wing longitudinal axis. During the feathering motion the wing changes its angle of attack. *Spanning* is an expanding and contracting of the wingspan. Not all flying animals implement all of these motions. Unlike birds, most insects do not use the spanning technique.

Flapping flight is possible with only two degrees of freedom: flapping and feathering. In the simplest physical models heaving and pitching represent these degrees of freedom. This kind of motion can be generated principally by a flapping (up and down) motion of the wing, but not by a feathering (pitch-up and pitch-down) motion. The mode and frequency of the beating motion differ among different species and are strongly dependent on body size and shape.

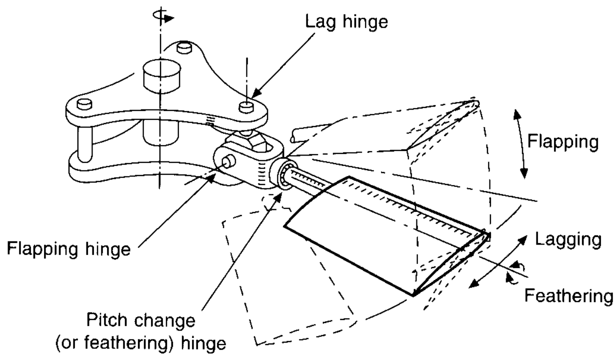



Fig. 3. Articulated rotor hub

A typical difference in beating motion between birds and insects is observed in the way they use the aerodynamic forces, lift and drag. Birds rely entirely on lift because the Reynolds number of their wings is high enough. However, insects use drag as well as lift thanks to the low Reynolds number and high frequency beating of low aspect ratio wings.

## 3 Mathematical model of animalopters

The motion equations of an animalopter can be determined by applying Newton's Second Law to the rate of change of linear momentum and angular momentum of the animalopter. For any point they are as follows:

$$m\begin{bmatrix}\dot U\\ \dot V\\ \dot W\end{bmatrix}+m\dot{\mathbf{J}}_\Omega\begin{bmatrix}x_c\\ y_c\\ z_c\end{bmatrix}+m\mathbf{J}_\Omega\begin{bmatrix}\dot x_c\\ \dot y_c\\ \dot z_c\end{bmatrix}+ \qquad (1)$$

$$+m\mathbf{J}_\Omega\begin{bmatrix}U\\ V\\ W\end{bmatrix}+m\mathbf{J}_\Omega\mathbf{J}_\Omega\begin{bmatrix}x_c\\ y_c\\ z_c\end{bmatrix}=\begin{bmatrix}F_x+G_x\\ F_y+G_y\\ F_z+G_z\end{bmatrix}$$

$$\dot{\mathbf{J}}_S^w\begin{bmatrix}U\\ V\\ W\end{bmatrix}+\dot{\mathbf{J}}_B^R\begin{bmatrix}P-\dot\delta\\ Q+\dot\gamma\\ R\end{bmatrix}+\dot{\mathbf{J}}_B^L\begin{bmatrix}P+\dot\delta\\ Q+\dot\gamma\\ R\end{bmatrix}+$$

$$\mathbf{J}_s\begin{bmatrix}\dot U\\ \dot V\\ \dot W\end{bmatrix}+\mathbf{J}_B\begin{bmatrix}\dot P\\ \dot Q\\ \dot R\end{bmatrix}+\mathbf{J}_S^w\begin{bmatrix}\dot U\\ \dot V\\ \dot W\end{bmatrix}+\mathbf{J}_B^R\begin{bmatrix}\dot P-\ddot\delta\\ \dot Q+\ddot\gamma\\ \dot R\end{bmatrix}+$$

$$+\mathbf{J}_B^L\begin{bmatrix}\dot P+\ddot\delta\\ \dot Q+\ddot\gamma\\ \dot R\end{bmatrix}+\mathbf{J}_\Omega\mathbf{J}_S\begin{bmatrix}U\\ V\\ W\end{bmatrix}+\mathbf{J}_\Omega\mathbf{J}_B\begin{bmatrix}P\\ Q\\ R\end{bmatrix}+ \qquad (2)$$

$$+\mathbf{J}_\Omega\mathbf{J}_S\begin{bmatrix}U\\ V\\ W\end{bmatrix}+\mathbf{J}_\Omega\mathbf{J}_B^R\begin{bmatrix}P-\dot\delta\\ Q+\dot\gamma\\ R\end{bmatrix}+\mathbf{J}_\Omega\mathbf{J}_B^L\begin{bmatrix}P+\dot\delta\\ Q+\dot\gamma\\ R\end{bmatrix}=$$

$$=\begin{bmatrix}M_{0x}+y_cG_z-z_cG_x\\ M_{0y}+z_cG_x-x_cG_z\\ M_{0z}+x_cG_y-y_cG_x\end{bmatrix}$$

where:

$F_x$, $F_y$ $F_z$ – coordinates of aerodynamic forces in *Oxyz* system (Fig. 4); *P, Q, R* – coordinates of angular velocity of *Oxyz* system; *U, V, W* – coordinates of velocity of the chosen animalopter point; $x_c$, $y_c$, $z_c$ – coordinates of the mass center in *Oxyz* system;

$$\mathbf{J}_\Omega=\begin{bmatrix}0&-R&Q\\ R&0&-P\\ -Q&P&0\end{bmatrix},\ \mathbf{J}_S=\begin{bmatrix}0&-S_z&S_y\\ S_z&0&-S_x\\ -S_y&S_x&0\end{bmatrix}$$

$S_x$, $S_y$, $S_z$ - static moments animalopter without wings; $\mathbf{J}_S^w$ - matrix of static moments of animalopter's wings; $\mathbf{J}_B$- inertial moment of animalopter without wings; $\mathbf{J}_B^R, \mathbf{J}_B^L$ - inertial moments of right and left wing, respectively;

$\delta=\delta_0\sin\omega t$, $\dot\delta=\delta_0\omega\cos\omega t$, $\gamma=\gamma_0\sin(\omega t+\lambda)$, $\dot\gamma=\gamma_0\omega\cos(\omega t+\lambda)$

where:

γ - feathering angle of wings; δ - flapping angle of wings; ω - frequency of wing motion respect to the body; λ - phase shifting between feathering and flapping.

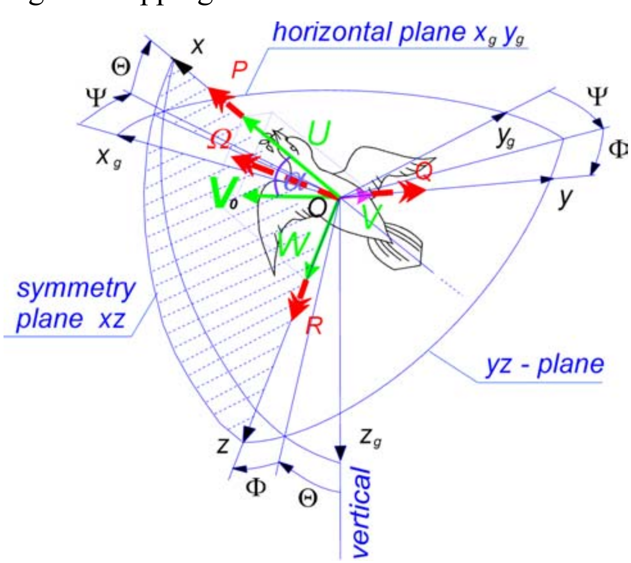



Fig. 4. Systems of co-ordinates

We assume that aerodynamic forces are nonlinear functions of angle of attack α, feathering angle γ, flapping angle δ, and their derivatives:

$$F_x=\frac{1}{2}\rho V_0^2SC_x[C_L(\alpha,\beta,\mathbf{u}),C_D(\alpha,\beta,\mathbf{u})]$$

$$F_y=\frac{1}{2}\rho V_0^2SC_y(\alpha,\beta,\mathbf{u})$$

$$F_z=\frac{1}{2}\rho V_0^2SC_z[C_L(\alpha,\beta,\mathbf{u}),C_D(\alpha,\beta,\mathbf{u})]$$

$$M_{0x}=\frac{1}{2}\rho V_0^2SbC_l(\alpha,\beta,\mathbf{u}) \qquad (3)$$

$$M_{0y}=\frac{1}{2}\rho V_0^2ScC_m(\alpha,\beta,\mathbf{u})$$

$$M_{0z}=\frac{1}{2}\rho V_0^2SbC_n(\alpha,\beta,\mathbf{u})$$

where: $C_L$ - lift coefficient; $C_D$ - drag coefficient; $C_y$ – side force coefficient; $C_l$, $C_m$, $C_n$ – coefficients of aerodynamic moments;

$\mathbf{u}=[\delta(t),\gamma(t),\delta_H(t)]^T$ - control vector.

## 4 Modeling of aerodynamic loads

Traditional aerodynamics studies [11] have mainly focused on the qualitative observation of vortical flow around a flapping wing and, in turn, have not taken up the quantitative calculation on the aerodynamic forces and moments acting on the flapping wing. The analyses have often neglected critical components of flapping flight such as unsteady fluid dynamics. Usually unsteady flow is defined as that in which aerodynamic characteristics depend on time. Among various unsteady flows the linear, harmonic flows are especially important. The linearity means that amplitudes of oscillations are small and that separation does not take place. For such flows it is sufficient the aerodynamic characteristics are presented versus a frequency parameter. Time does not appear explicit in the function describing these characteristics.

There are few computational fluid dynamics (CFD) studies. Smith et al. [20] by using an unsteady panel method, calculated the aerodynamic forces of flapping wings of a tethered moth. The results showed good agreement with the experimental data obtained in the vertical force but not in the horizontal force. It is not clear whether the discrepancy was due to the lack of suction force or not. Liu et al. [12] by using a finite volume method, studied the unsteady aerodynamic of the flapping wing of a hovering hawkmoth. They analyzed the mechanism of generation of the leading-edge vortex during one complete flapping cycle. The calculated vertical force was produced mainly during the downstroke and the latter half of the upstroke, with little force generated during pronation and supination.

The above CFD-based results are very important for understanding the statement that the unsteady effects of the wing motion generate an extremely large lift. Nevertheless, a modelling of aerodynamic loads by means of CDF methods is a challenge, specifically when we want to incorporate these loads in nonlinear equations of motion. Therefore, to calculate forces and aerodynamic moments effected on animalopter's wing we have used the modified panel method [7] and the modified strip theory [1, 18]. The choice of these methods was dictated by an easy application and low cost of calculations, which makes it possible realize the shown problem on PC computers.

## 5 Results of numerical calculations of aerodynamic characteristics

Since the wake is force-free, each wake panel moves with the local free-stream velocity. This velocity is the result of the wing motion and the velocity components induced by the wake and the body. A view of the wake developed over one cycle is shown in Fig. 5.

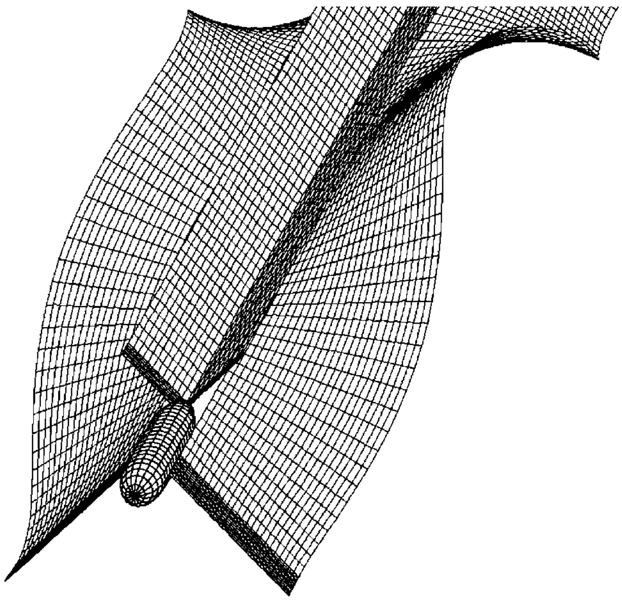


Fig. 5 Wake development after wings

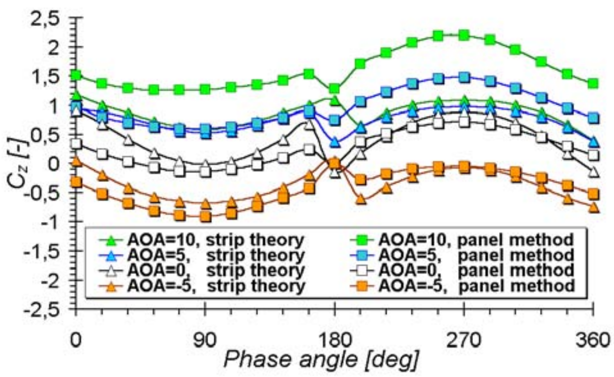



Fig. 6. Lift coefficient via two methods

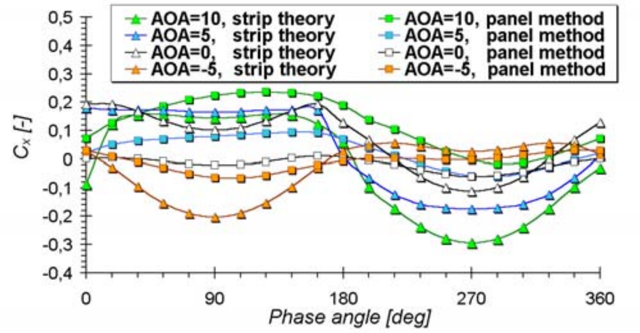



Fig. 7. Drag coefficient via two methods

Figs. 6 and 7 depicts the comparison between results of calculations obtained from panel method and strip theory calculations. Good agreement between results obtained by those methods is shown.

## 6 Experimental verification of computational models

In order to verify applied calculating models, experimental investigations in wind tunnel at Institute of Aeronautics and Applied Mechanics of Warsaw University of Technology have been performed. The mechanism of the ornithopter model is shown in Fig. 10. It allows two degrees of freedom of wing movement: a) flapping of the wing around the longitudinal axis of model; 2) feathering around the axis of the wing. The ornithopter model was equipped with the rigid wings that data are as follows (for one wing): profile Clark Y; length 0.2 m.; chord 0.08 m.; relative thickness 0.12; mass 0.25 g. The measurements were carried out at the wing flapping frequency 5 Hz.

In experiments, the total flapping angle was admitted β=40 deg around the base position 0 deg. The mean value of the feathering angle $\vartheta$ was taken in the most part of experiments as 10 deg.

Two cases of the amplitude of wing movement at 4 velocities 8, 12, 14 and 16 m/s were studied in the range of weak Reynolds numbers $4.10^4$ to $8.10^4$.

Selected results of investigations are shown in Figs. 8 and 9. Quite good agreement between calculations and results obtained from experiment is visible.

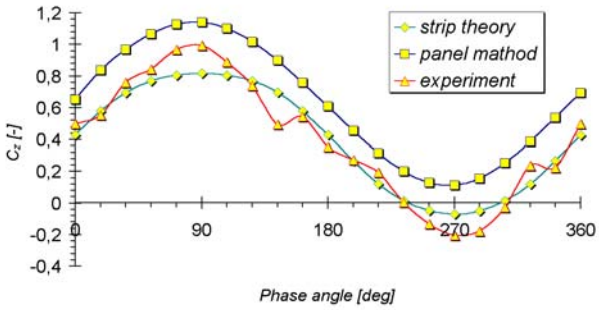



Fig. 8. Lift coefficient via calculations and experiment

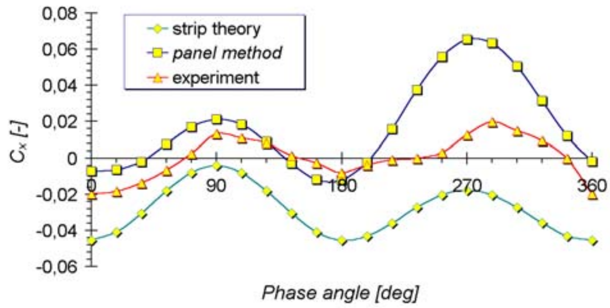



Fig. 9. Drag coefficient via calculations and experiment

Fig. 10. Scheme of moving wing mechanism

The experimental results are not contradictory with those presented by Fejtek & Nehera in [4].

## 7 Automatic control of animalopters

To perform aerial manoeuvres, flying animals must not only generate sufficient lift to remain aloft, they must also manipulate flight forces with great precision. Although insect are known to use their legs and abdomen as control surfaces during flight [21], they steer and manoeuvre (we will call these both activities simply control) largely by altering wing motion. Thus, a central hurdle in understanding how animal's control is how modifications in stroke kinematics alter the forces and moments generated by flapping wings.

Generally, the task of control problems can be divided into two categories [15, 19]: stabilization and tracking. In stabilization problems, a regulator is to be designed so that the state of the closed-loop system will be stabilised around an equilibrium point. In tracking problems, the design objective is to construct a tracker so that the system output tracks a given time-varying trajectory. Of cause, problems such as making an animalopter fly along a specified path are typical tracking control tasks. In the paper we regard stabilisation problems as a special case of tracking problems, with the desired trajectory being a constant. However, for nonlinear systems such the model described by Eqs. (1) and (2), there are no general methods, which would be available in designing nonlinear regulators. One of the most important methods for analysing nonlinear systems is to approximate them with linear ones.

When the required operation range is large, a linear controller is likely to perform very poorly or to be unstable, because the nonlinearities in the system can not be properly compensated for [6]. Nonlinear controllers, on the other hand, may handle the nonlinearities in large range operation directly. The basic idea of modern approach is to study under what conditions the dynamics of a nonlinear system can be algebraically transformed in that of a linear system, on which linear control design techniques can be applied. This is so-called nonlinear inverse dynamics (NID) method [19].

In the NID approach the state equation should be linear with respect to the control vector $\mathbf{u}$:

$$\dot{\mathbf{x}} = \mathbf{F}(\mathbf{x}) + \mathbf{G}(\mathbf{x})\mathbf{u} \qquad (4)$$

where:

$\mathbf{x}$ is the state vector (dim $\mathbf{x} = n$); dim $\mathbf{u}$ = m.

When we want to consider a tracking problem, we must take into account the output equation

$$\mathbf{y} = \mathbf{h}(\mathbf{x}) \qquad (5)$$

and assume that our objective is to make the output $\mathbf{y}(t)$ track a desired trajectory $\mathbf{y}_d(t)$.

The system (4) and (5) will be decoupled if we use the control law in the form:

$$\mathbf{u} = \mathbf{D}^{-1}(\mathbf{x})[\mathbf{v} - \mathbf{N}(\mathbf{x})] \qquad (6)$$

where

$$\mathbf{D} = \begin{bmatrix} L_{G1} L_{\mathbf{F}}^{r_1-1} h_1 & ...., & L_{Gm} L_{\mathbf{F}}^{r_1-1} h_1 \\ \dots & \dots & \dots \\ L_{G1} L_{\mathbf{F}}^{r_m-1} h_m & ...., & \mathrm{L}_{G_m} L_{\mathbf{F}}^{r_m-1} h_m \end{bmatrix} \qquad (7)$$

$$\mathbf{v} = \mathbf{P}_0 \mathbf{y}_d - \sum_{j=0}^{r-1} \mathbf{P}_j \mathbf{y}^{(j)} \qquad (8)$$

$$\mathbf{N}(\mathbf{x}) = [L_{\mathbf{F}}^{r_j} h_j(\mathbf{x})] \qquad (9)$$

The symbols $L$ in Eqs. (7) and (9) denote the Lie derivatives, and e. g.

$$L_{\mathbf{F}} \mathbf{h} = \nabla \mathbf{h} \cdot \mathbf{F}$$

denotes the Lie derivatives of $\mathbf{h}$ with respect to $\mathbf{F}$ [19, p.226]. The upper index $r$ in the Eq. (8) is called the relative degree of the system [19, p.129]. Matrices $\mathbf{P}_j$ in the Eq (8) are chosen as ($m$ x $m$) constant diagonal matrices.

## 8 Results of numerical simulations of animalopter controlled motion

Figures 11 to 16 (the term CSA denotes the mean aerodynamic chord) present the simulation results using the lift and drag forces wings kinematics shown in Figures 6, 7, 9 and 10.

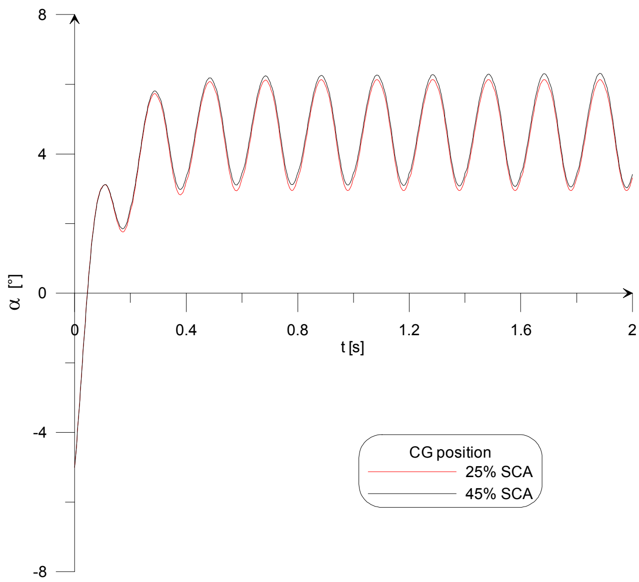



Fig. 11. Simulation of animalopter motion. Variation of angle-of-attack $\alpha$

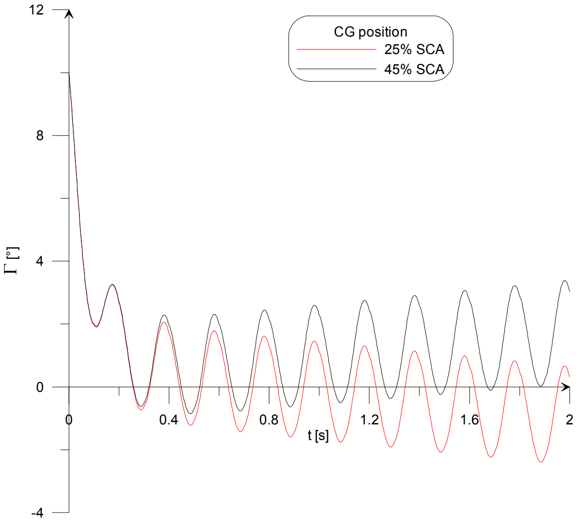



Fig. 12. Simulation of animalopter motion. Variation of pitch angle $\gamma$

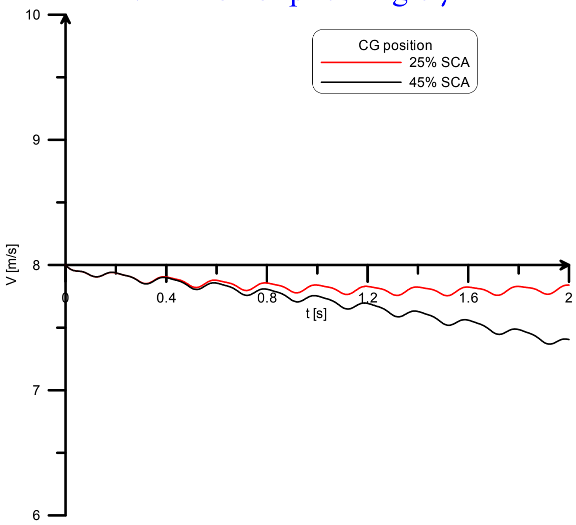



Fig. 13. Simulation of animalopter motion. Variation of airspeed $V$

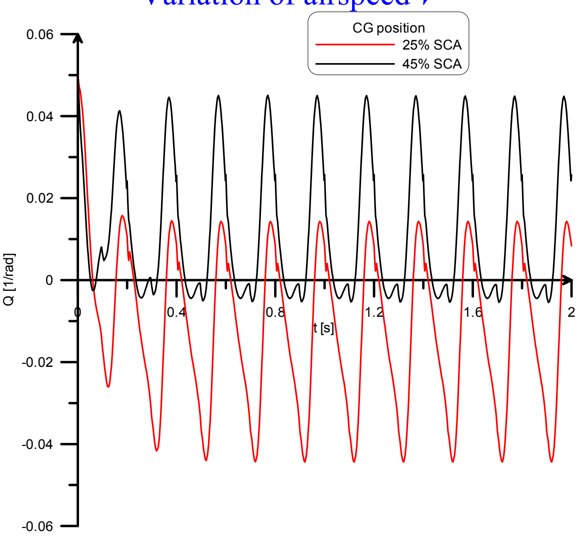



Fig. 14. Simulation of animalopter motion. Variation of pith rate $Q$

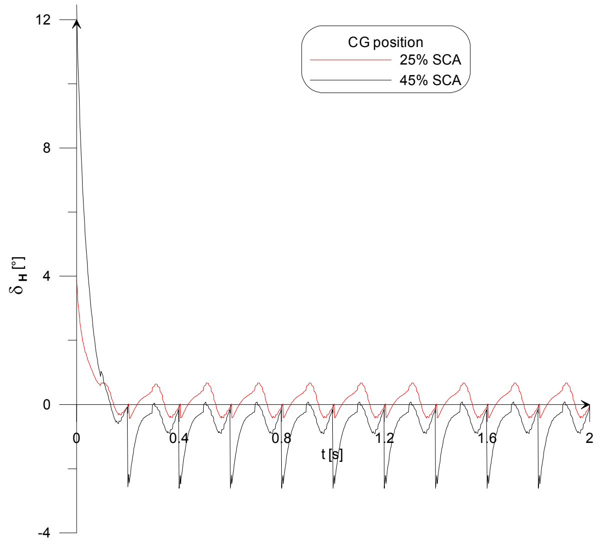



Fig. 15. Simulation of animalopter motion. Variation of tail wing deflection

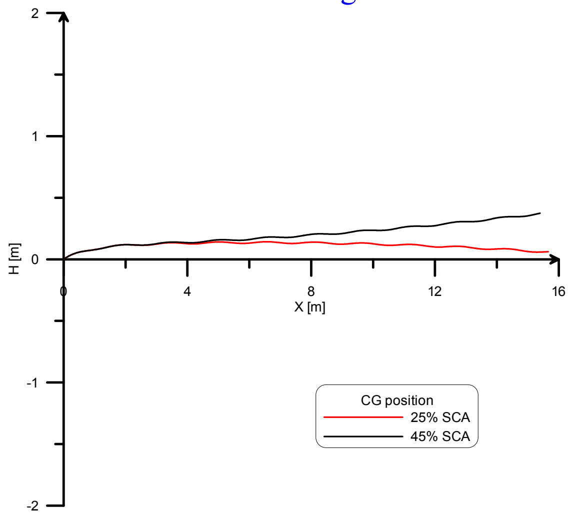



Fig. 16. Simulation of animalopter motion Trajectory of MAV's motion

The dynamics of the animalopter shows an oscillatory motion, which is the result of the time-varying nature of aerodynamic forces for animalopter flight.

To stabilize the horizontal flight mode, we have proposed and simulated a stabilizing scenario shown in Fig. 15. The trajectory of animalopter motion we present in Fig. 16.

## 7 Conclusions and future developments

Both morphology and kinematics are critical determinates of performance in flapping flight. However, the functional consequences of changes in these traits are not yet well understood. We focus on forward flapping flight and examine the effects of kinematic wing parameters on thrust and lift generation. We test the model by comparing our calculations with experimental data. We have obtained simulation results that are consistent with observations from real flying animals (especially birds and bats). Current research is directed to improve some of the models considered, aerodynamic models and control process, and to take advantage of this simulator to evaluate flight control schemes.

Flapping flight is among the most energetically expensive activities vertebrates perform. A rapid alternative way to estimate total power consumption during flight is to use a theoretical aerodynamic model to calculate the mechanical component [16]. In this context, the problem of minimum power requirements for flapping flight arises.

One integrated idea is the active flexible wing concept. This concept represents a return to the Wright Brothers' idea of wing warping or twisting by combining wing structures and flight controls to perform the desired maneuvers. But in this direction only the first steps have been made [8, 9].

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