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APPLICATION OF ARTIFICIAL NEURAL NETWORK IN MODELING OF ENTOMOPTER DYNAMICS

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Abstract

This paper concerns on concept of flapping wings vehicle (FMAV) aerodynamic model using artificial neural networks. This model od aerodynamic loads was used in simulations of FMAV flight dynamics and control. Aerodynamic model was based on experimental data from water tunnel measurements. Necessary data were taken from experiments performed in water tunnel using entomopter scaling model (flapper). Measurement were ducted during sinusoidal motion of flapper body. Flapper has two wings. Each wing can perform various spherical motions, it means that each wing rotates around spherical joint. During measurements motion of each wing was reduced to a two degrees of freedom, (wing was rotated around two axis). Aerodynamic loads of entomopter wings was modelled by application of artificial neural network (ANN). The ANN was trained using measurements data.

Nomenclature

C_s, C_c	-	Fourier series coefficients
C_F	-	aerodynamic force coefficient
F	-	Flapping frequency
N	-	normal to mean stroke plane component of hydrodynamic force
T	-	tangent to mean stroke plane component of hydrodynamic force
m	-	mass of entomopter
v	-	flight velocity
u	-	horizontal component of flight velocity vector
w	-	horizontal component of flight velocity vector
du/dt	-	rate of change of flight velocity
α	-	angle of attack of entomopter
Θ	-	pitch angle of whole object
q	-	rate of change of pitch angle
r	-	distance from center of rotation to wing tip
Φ	–	angular range of motion related to mean stroke plane
γ	-	wing pitch angle
ϕ	-	*wing sweep angle*

1 Introduction, and Background of the Problem

Our current work was ducted in accordance of research project founded by National Centre of Research and Development Republic of Poland. The objective of this project was to investigate the possibilities of building and using flapping wings micro aerial vehicle (FMAV) during indoor recognizing operations. As results of this project the new flapping wings MAV (entomopter) was designed and build. Its construction was introduced in recently papers, for example [1]. Basic data of this FMAV are exposed in table 1. The general layout of this FMAV is shown in fig. 1. As a power source micro electric motor is used, and as power transmission was used a crankshaft system (fig. 1). The stroke angle of wing motion is 140°. Flapping frequency is within range 10-20Hz and average Reynolds number vary between 11000-23000. Structure of entomopter is classical. Innovative is stabilizing system. Pitch control is performed by tilting flapping wings gear.

Change of angle ζ will cause change of aerodynamic moment related to center of gravity (see fig. 2).

Fig. 1. Concept of entomopter

This paper concerns the concept of modelling of FMAV nonlinear aerodynamics loadings, with application to synthesis of control system, and flight dynamics simulation. In many previous works authors concerned simplified current our approach there were concerned the simplified model of aerodynamics loads. Authors have used strip theory, panel methods, and have applied linearization of aerodynamic forces and moments [5], [6]. Such approaches have limited capabilities of forecasting aerodynamic loads, especially during hovering or low speed flight. Nature of entomopter's flight is unsteady and non-linear. Presented in this paper approach is based on artificial neural networks. Neural network modeling has good performance in reproducing even highly non-linear phenomena. Objective of this work is to develop aerodynamic model based on artificial neural network. Aerodynamic model is the logic block, which for flight conditions, as an input, give aerodynamic forces and moments as a results. Such model can be used for prediction of performance of FMAV, simulation of flight dynamics phenomena, and synthesis of control laws. There are two possibilities of creation that's feature. First is to use aerodynamic physical model fluid flow around wing, second is to approximate collected experimental data. Of' course both solutions have advantages and disadvantages. First approach is well known in literature [2], [3], [5], [6], [7]. Comprehensive knowledge about this topic can be found in [4]. In this way aerodynamic models, that base on analytical approach are used. Description of such kind modeling reader can find in [5]. This paper describes the second way.

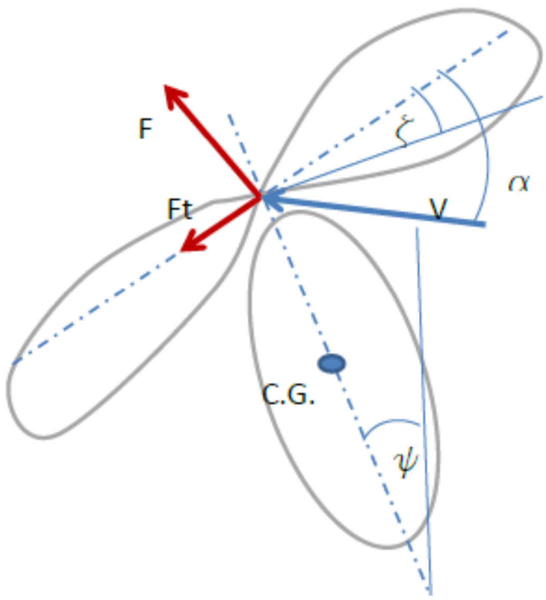

Fig. 2. Idea of controlling system

Tab. 1. Entomopter data

Entomopter mass	*m*	10 [g]
Wing mass	*wm*	1 [g]
Distance between wing tip and axis of rotation	*R*	100 [mm]
Longitudinal moment of inertia	*I*	8E-5 [kgm^2]
Reynolds number	Re	11 000 – 23 000

2 Aerodynamic Model

Figure 3 shows general idea of aerodynamic model using neural network. As input parameters flight speed (v), acceleration (dv/dt), angle of whole entomopter (α) and relative time (t). Neural network reproduce Fourier series coefficient, which represents aerodynamic loads for whole period. Network works independently from time. For each quantity separately network is created. Values of loads for appropriate time (wing position) are obtained by assembling series. Network consisted of 3 layers. First two layers have 20 neurons each. Last layer have 14 neurons, the same as number of elements in Fourier series. Sigmoid activation function was used.

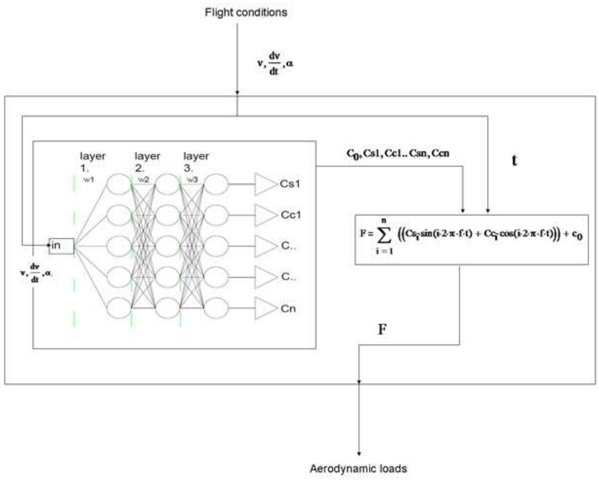

Fig. 3. Concept of neural aerodynamic model

Created neural network firstly is trained using data from water tunnel measurement. During training parameter used in measurement are put as input, and results are inserted as target values. Results of training process are values of weights and biases for each neuron. After that model is complete and ready for use. Behavior (flight parameters) of the entomopter during free flight is unknown, therefore only way to achieve unsteady model of aerodynamic is to consider each time point of analysis separately. Taking into account this simplification data from experiment with simple sinusoidal motion can be taken. Each time point of analysis of free flight corresponds with measurement point for which flight parameters: velocity of motion, angle of attack, etc. are the same (in fact with approximation of those results).

3 Experiment Set up

Experimental modeling of flapping flight long history. Wide knowledge in this topic can be found in [6]. Same recent experimental works reader find in [7],[8],[9]. For purposes of this work water tunnel experimental data were used. Dynamically scaled robot was used. It was mounted on support of water tunnel, is able to perform oscillatory motion around three axes. During this experiment such oscillatory motion were performed relative to pitch angle. Entomopter dynamic motion Frequency was the same as for the wing flapping frequency (support and wing motions were correlated) and was equal 0.2Hz. Support performed sinusoidal motion with amplitude of 10^o Phase shift (dt) between wing and support oscillations was the parameter of the experiment. Maximal velocity of pitching motion is 0.2193 rad/s, maximal acceleration during this motion is 0.0138rad/s^2.

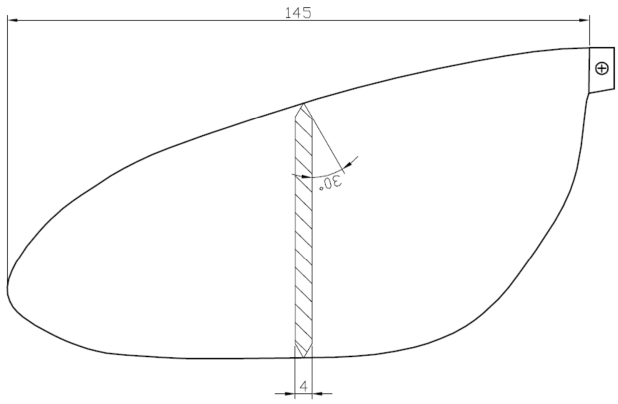

Fig. 4. Entomopter wing planform shape

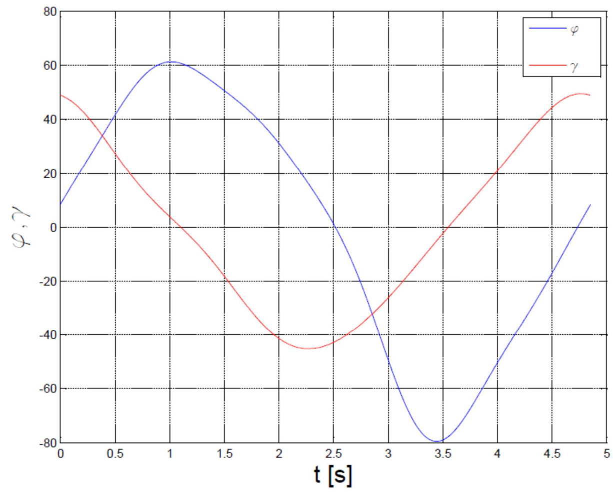

Fig. 5. Trajectory of wing motion

Model was offset 80 mm from support center of rotation. Thirteen series of measurements were performed for different position of model. Each represents entomopter motion with different angle of attack. Range of variations was -90^o to 90^o. Every series consist of 10 measurements. During test for AoA equal 0 model was offset along normal to mean stroke plane direction. As results variation in tangent to stroke plane was achieved.

Entomopter wing has planform of house fly wing (fig 4). Trajectory of wing motion is shown on figure 5, where φ is position of the wing on mean stroke plane and γ is pith angle of the wing. Forces and moments were measured in two directions using bending type balance. Force was measured in normal and tangent to stroke plane direction. Torque and pithing moment were also measured.

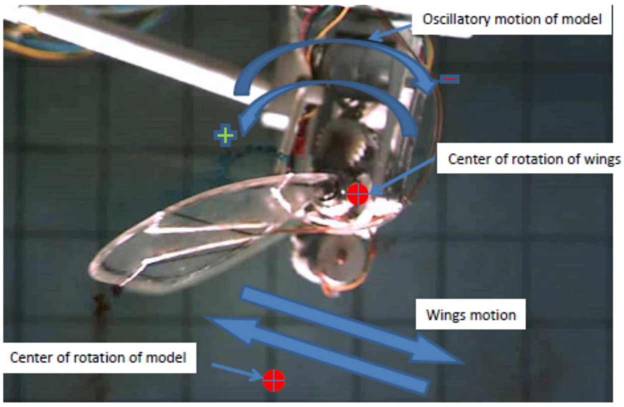

Fig. 6. Experimental setup

In fig. 6 it is shown the flapper in water tunnel measurements chamber. Wider description of robot and measurement system can be found in [1], and [11].

4 Results of Measurements

Figure 7. shows changes in normal force component during one cycle. Series was made in point for AoA of flapper body equal 0. Each curve represent measurement for different condition. Value of *dt* is time shift between oscillations of support and wings. Curves differ between each other, so force depends from the oscillatory motion. The average values changing due to correlation time, as it is shown in figure 8. Data from measurement are approximated with Fourier series. After that can be used for training. Mentioned parameters of experiment are used to form input vector, while results are target of training.

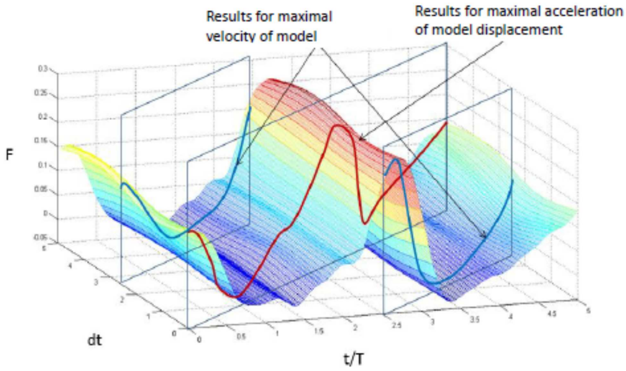

Fig. 7. Changes in normal force component – results from water tunnel measurements

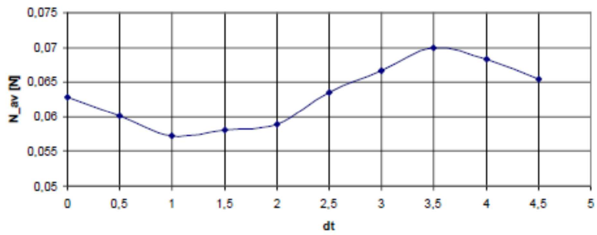

Fig. 8. The average values changing due to correlation time

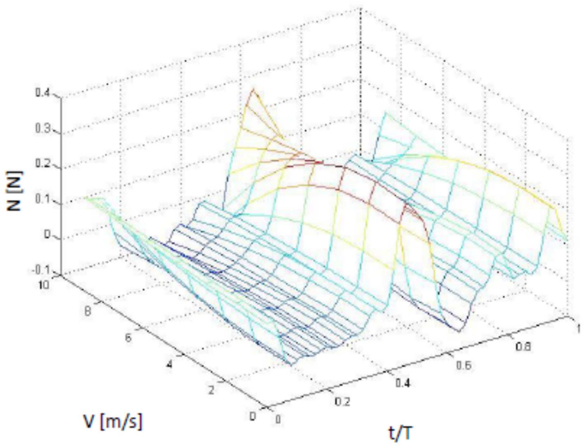

Fig. 9. Neural network representation of results from figure 7

Graph in figure 9 shows neural network representation of results from figure 7. Change of normal force progress in time during one cycle due to velocity are shown. After training with sufficient range of data, neural network will be able to predict values of loads for any condition and any time.

5 Simulation of Flight

Once aerodynamic properties are identified it is possible to simulate behavior of the FMAV during flight. For that purpose it have to be connected with model of dynamic motion. scheme of complete model for flight simulation realized in Matlab Simulink is shown in figure 10. It consist of three blocks:

- aerodynamic model,
- model of dynamic motion, and
- stabilizing block.

In this case dynamic motion block is simplified with assumption that object is rigid body. In addition model have only three degrees of freedom (horizontal, and vertical direction and pitch angle). Model assume, that stabilization is achieved by changing inclination angle of mean stroke plane due to object axis. Stabilizing block is assembled with PID controllers. Deviations of pitch angle velocities are minimalized. Linear velocities in both direction and angular velocity are achieved by solving three differential equations:

$$\frac{dw}{dt} = \frac{N}{m} - qu - g\cos(\Theta) \qquad (1)$$

$$\frac{du}{dt} = \frac{T}{m} - qw - g\sin(\Theta) \qquad (2)$$

$$\frac{dq}{dt} = \frac{M}{I} \qquad (3)$$

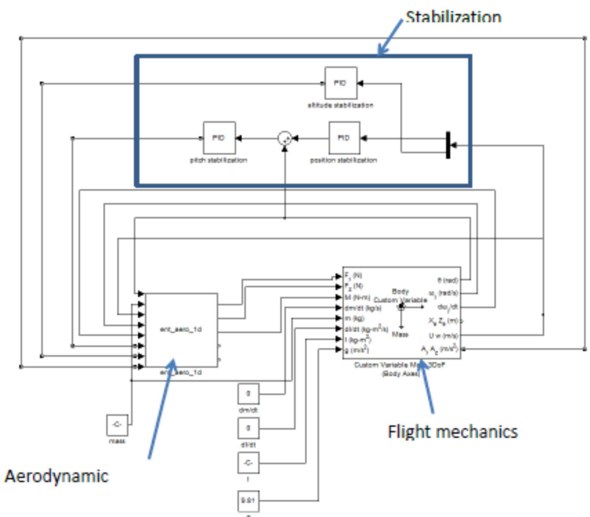

Fig. 10. Scheme of complete model for FMAV flight simulation realized in Matlab Simulink

Program need basic mass and geometric data of modeled object. Entomopter will have 10g of total mass, total wing span will not exceed 100mm. Flapping frequency is iterated during calculation satisfying zero vertical velocity of object. In figures 11, and 12 exemplary results of simulation are shown. Figure 11 presents response of neural model for aerodynamic force in normal direction. There is almost no difference between cycles, because of low values of velocities. Generally neural model have good predictions for range of change of flight parameters, that are covered in experiment. In case exceeding those boundaries predictions are often unphysical.

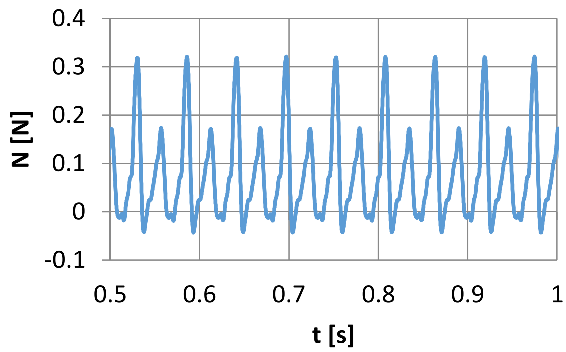

Fig. 11. Examplary results of simulation - response of neural model for aerodynamic force in normal direction

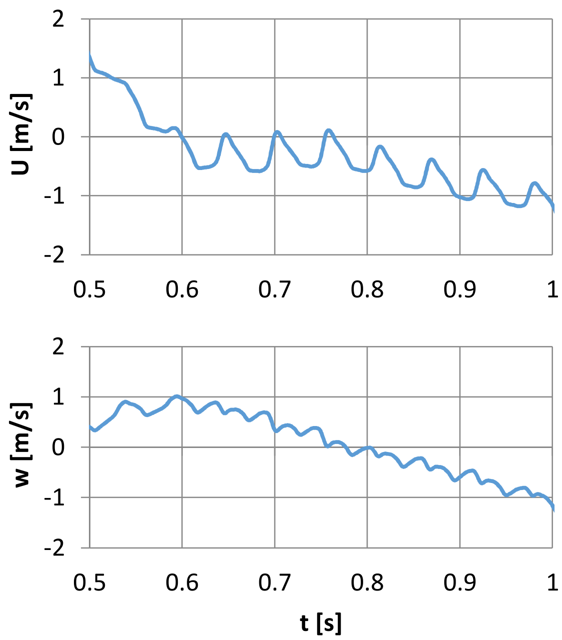

Fig. 12. Examplary results of simulation – chances of lognitudinal and vertical velocities.

6. Conclusions

In this paper innovative concept of model describing unsteady aerodynamics of entomopter was proposed. It was shown, that it can be easily implemented as mathematical model. Proposed approach have many advantages. Unsteady effects related to many state variables can be easily captured. Model can be easily adopted to predict different states of flight by networks training on appropriate data. Of course such modeling have also disadvantages. Preparing data for training needs many tests. Test must reproduce real conditions as close, as it is possible. In reality it is challenging to design test, that will reproduce similar motion, as during real flight.

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