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EXPERIMENTAL STUDY AND NEURAL NETWORK MODELLING OF AERODYNAMIC AND DYNAMIC CHARACTERISTICS OF FLAPPING WINGS MICRO AERIAL VEHICLE

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Abstract

The article is close connected with building flying object, that fly like an insect (entomopter). Present work concerns on concept of aerodynamic model using artificial neural networks. Model is used in simulations of flight of entomopter. Aerodynamic model based on experimental data. Necessary data are taken from experiment performed in water tunnel on entomopter model. For this case dynamic test are required. Measurements are ducted during sinusoidal motion of whole model. Modelled object is dipterous. Each wing can perform various spherical motions (wing is rotated around point). The motion of the wing in this case was two-dimensional; it was rotated around two axis. As a model, specially trained neural network is used. For training are used data from measurement. Presented in this article approach is based on artificial neural networks. In this article, innovative concept of model, describing unsteady aerodynamics of entomopter was proposed. It was shown that it could be easily implemented as mathematical model. 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. Test has to reproduce real conditions as close, as it is possible. In reality, it is challenging to design test that will reproduce similar motion.

Keywords: *entomopter, flapping wings aerodynamic neural network modelling*

Nomenclature

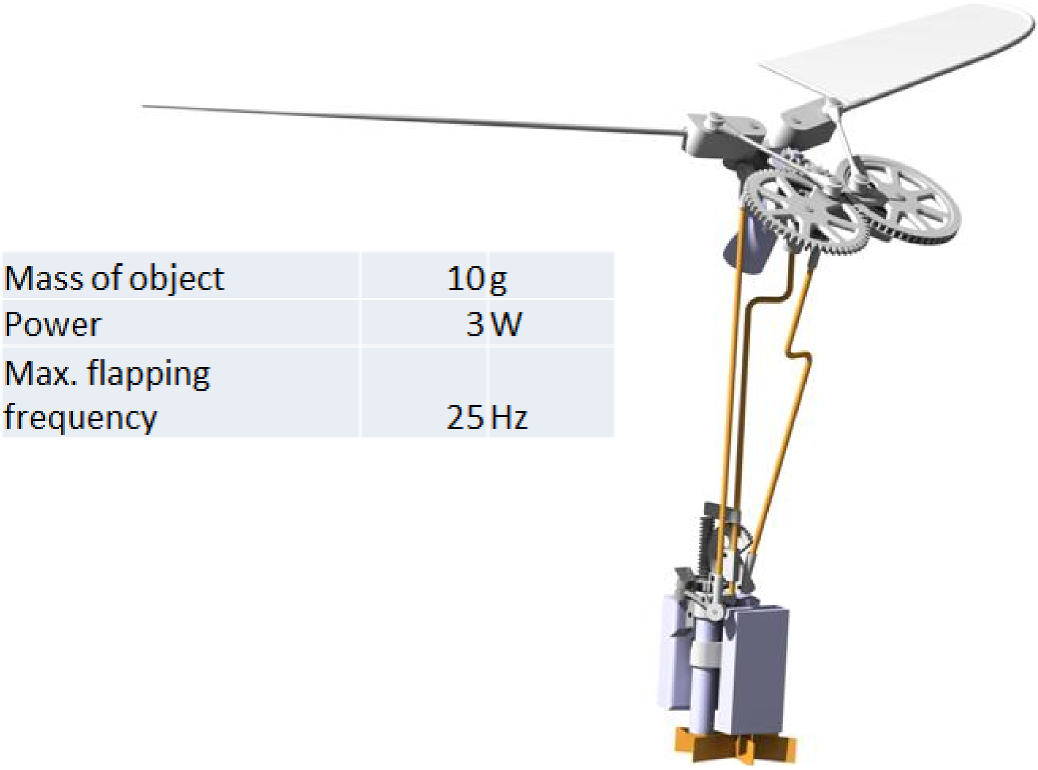
Cs, Cc – Fourier series coefficients,
C_F – aerodynamic force coefficient,
f – Flapping frequency,
N – normal to mean stroke plane component of hydrodynamic force,
T – tangent to mean stroke plane component of hydrodynamic force,
m – mass of entomopter,
v – flight velocity,
u – horizontal component of flight velocity vector,
w – horizontal component of flight velocity vector,
dv/dt – rate of change of flight velocity,
α – angle of attack of entomopter,
Q – pitch angle of whole object,
q – rate of change of pitch angle,
R – distance from centre 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

Current work was ducted in accordance of research project: founded by NCBiR. The objective of project is to investigate the possibilities of build and use micro class flying object in entomopter configuration. New object is constructed. Its construction was introduced in recently papers [1]. Basic parameters are exposed in Fig. 1. The object is dipterous. As a power source, micro electric motor is used. As a power transmission, a crankshaft system is used. Total angle range of main wing motion is 140º. Flapping frequency is within range 10-20 Hz and average Reynolds number varies between 11000 and 23000. Structure of entomopter is classical. Innovative is stabilizing system. Pitch control is performed by tilting whole engine unit with wings. Change of angle ζ will cause change of aerodynamic moment related to centre of gravity

The current work concerns on the concept of flight mechanics modelling. Most of approaches use simple aerodynamics models based on newton equation. 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 art approach is based on artificial neural networks. Neural network modelling 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 logic block, which for flight conditions, as an input; give aerodynamic forces and moments as results. Such model can be used for prediction of performance of object during flight, flight mechanics analysis, or data for autopilot. 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]. 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 modelling reader can find in [5]. This article describes the second way.



Mass of object	10 g
Power	3 W
Max. flapping frequency	25 Hz

Fig. 1. Concept of entomopter

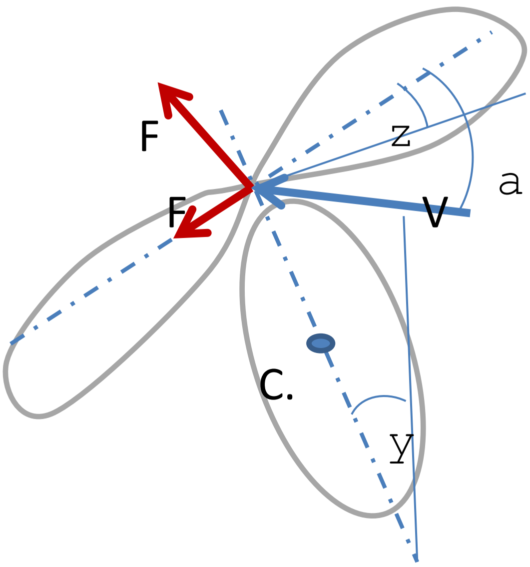


Fig. 2. Idea of controlling system

2. Idea of aerodynamic model

Fig. 1. shows general idea of aerodynamic model using neural network is shown. As input parameters flight speed (v), acceleration (dv/dt), angle of whole entomopter (a) 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.

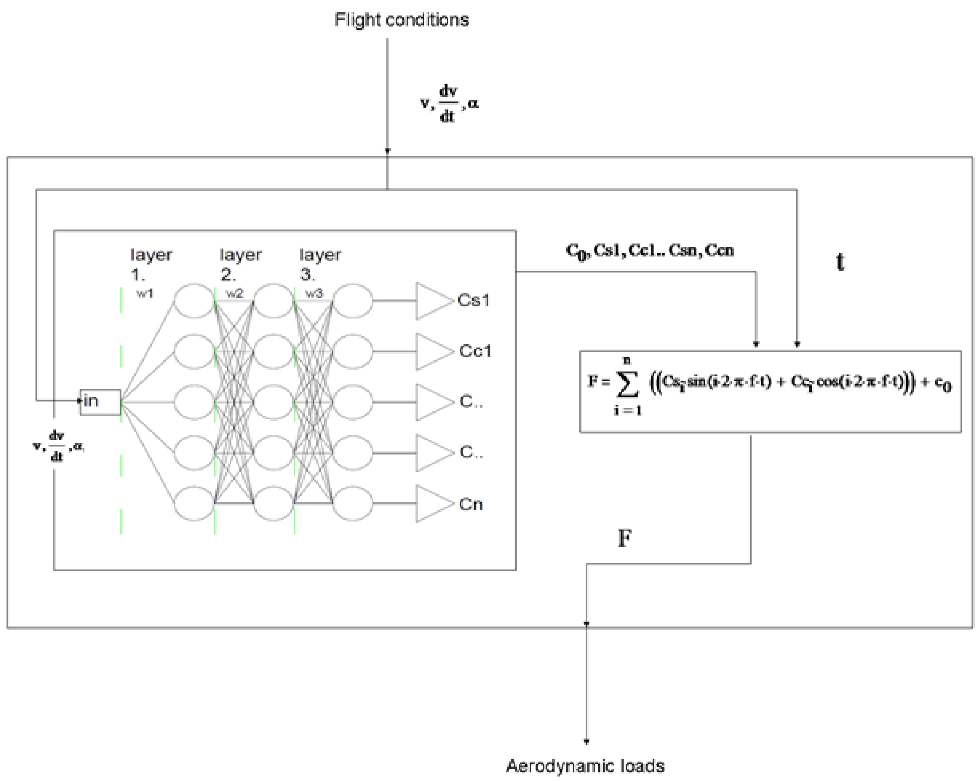


Fig. 3. Concept of neural aerodynamic model

Created neural network firstly is trained using data from 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.

Behaviour (flight parameters) of the object 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. is the same (in fact with approximation of those results).

3. Experiment set up

Experimental modelling of flapping flight has a long history. Wide knowledge in this topic can be found in [6]. Same recent experimental works reader find in [7-9]. 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 0.2 Hz. Support performed sinusoidal motion with amplitude of 10° 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 0.0138 rad/s^2. Model was offset 80 mm from support centre 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° to 90°. 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.

Used wing has planform of house fly wing (Fig. 2 right part.). Trajectory of wing motion is shown in Fig. 2 (on the left), 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. Wider description of robot and measurement system can be found in [10, 11].

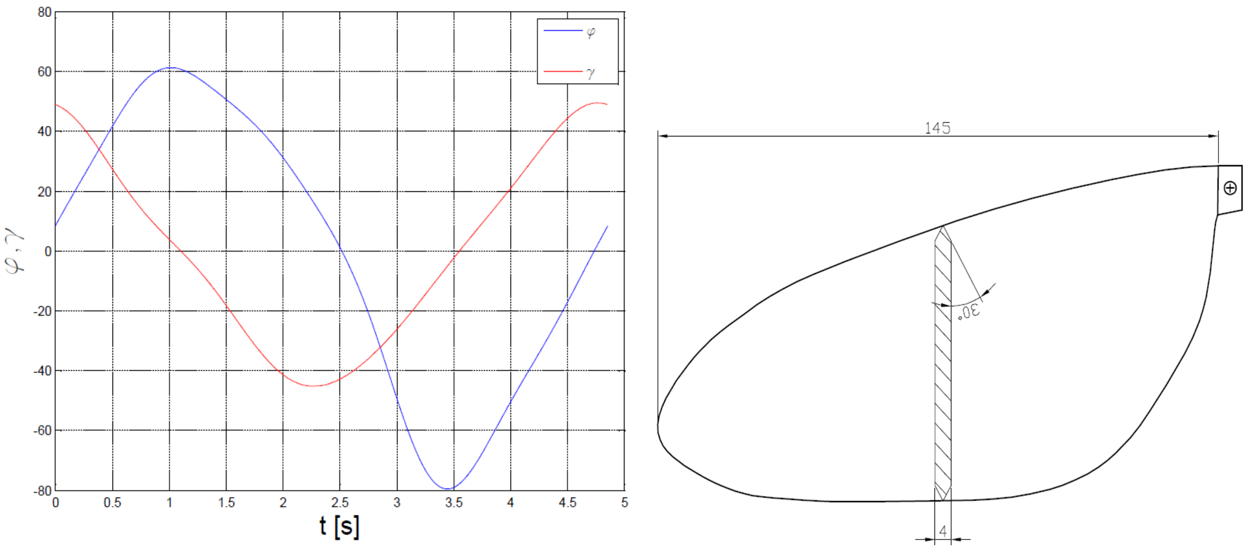


Fig. 4. Trajectory of wing motion and wing planform shape

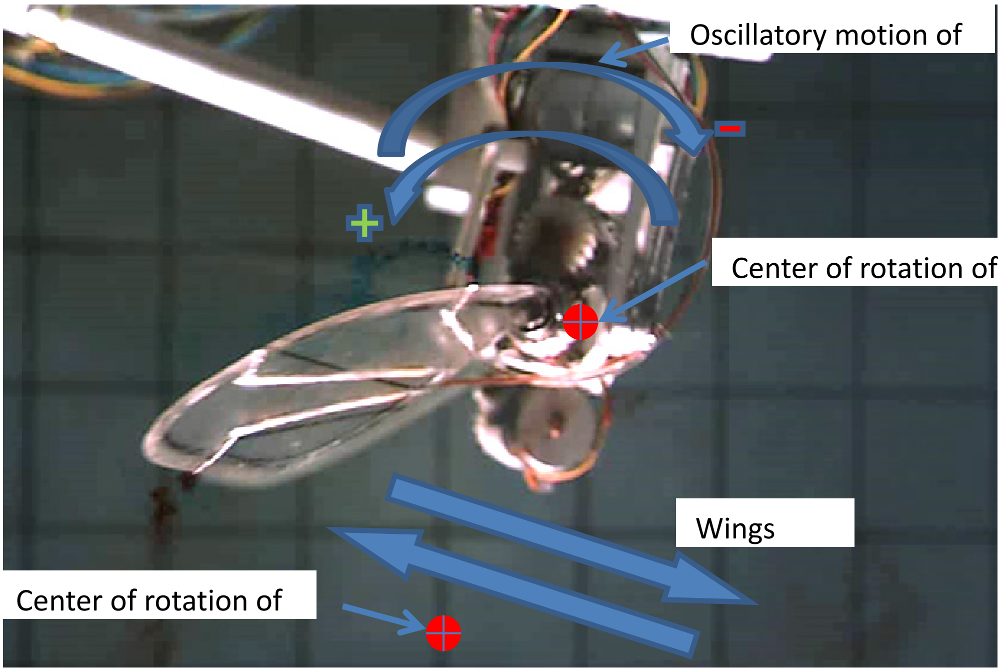


Fig. 5. Idea of experiment

4. Results of measurements

Figure 3 shows changes in normal force component during one cycle. Series was made in point for AoA equal 0. Each curve represents 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. Also average values changing due to correlation time, as it is shown in Fig. 4.

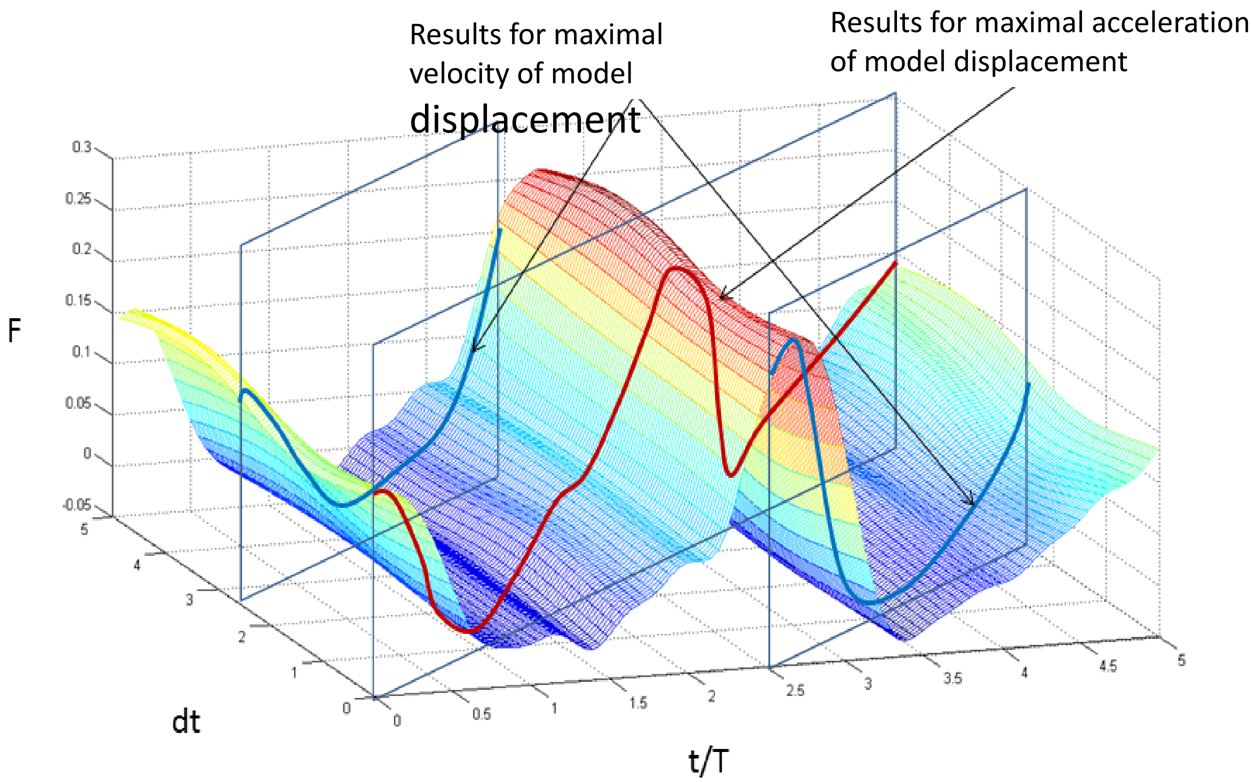


Fig. 6. Normal force measurement during one test cycle

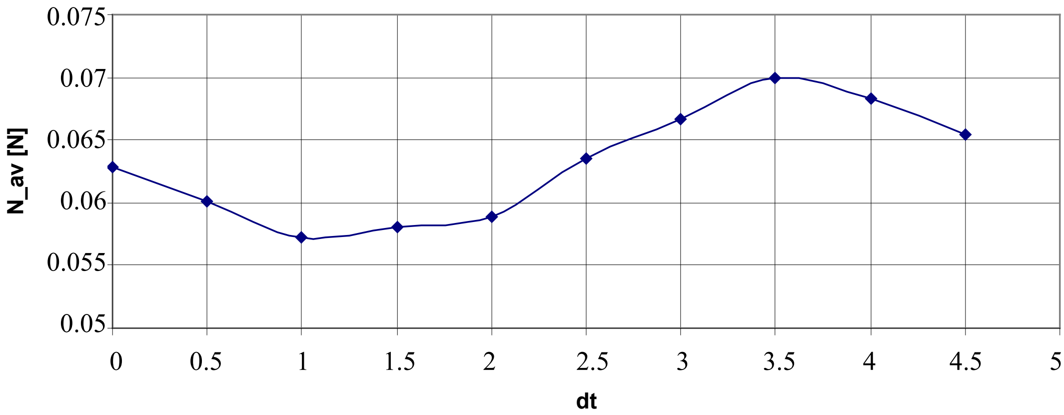


Fig. 7. Average normal force achieved in experiment

Data from measurement are approximated with Fourier series. After that, it can be used for training. Mentioned parameters of experiment are used to form input vector, while results are target of training. Graph in Fig. 8. shows neural network representation of results from Fig. 6. Change of normal force progress in time during one cycle due to velocity is shown. After training with sufficient range of data, neural network will be able to predict values of loads for any condition and any time.

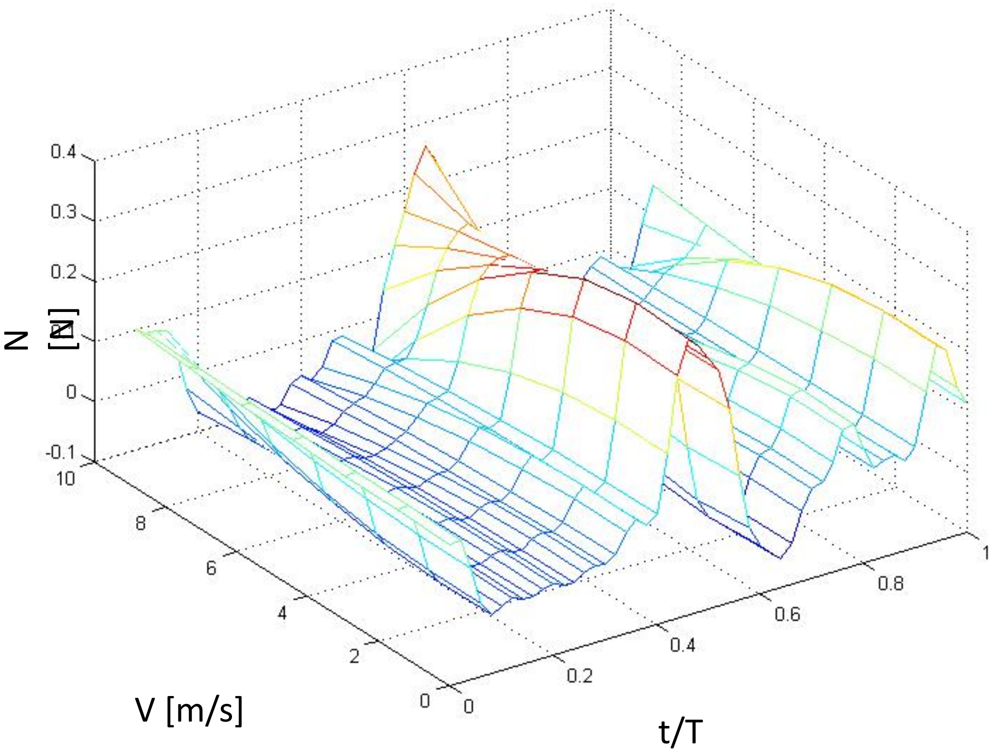


Fig. 8. Change of normal force with respect to velocity of flight

5. Simulation of free flight

Once aerodynamic properties are identified, it is possible to simulate behaviour of the object during flight. For that purpose, it has to be connected with model of dynamic motion. scheme of complete model for free flight simulation realized in MATLAB Simulink is shown in Fig. 9. It consists 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 has only three degrees of freedom (horizontal and vertical direction and pitch angle). Model assumes that stabilization is achieved by changing inclination angle of mean stroke plane due to object axis. Stabilizing block is assembled with PAD controllers. Deviations of pitch angle velocities are minimalized. Linear velocities in both direction and angular velocity are achieved by solving three differential equations:

$$\frac{d}{dt}w = \frac{N}{m} - q \cdot u - g \cdot \cos(\Theta), \tag{1}$$

$$\frac{d}{dt}u = \frac{T}{m} - q \cdot w - g \cdot \sin(\Theta), \tag{2}$$

$$\frac{d}{dt}q = \frac{M}{I}. \tag{3}$$

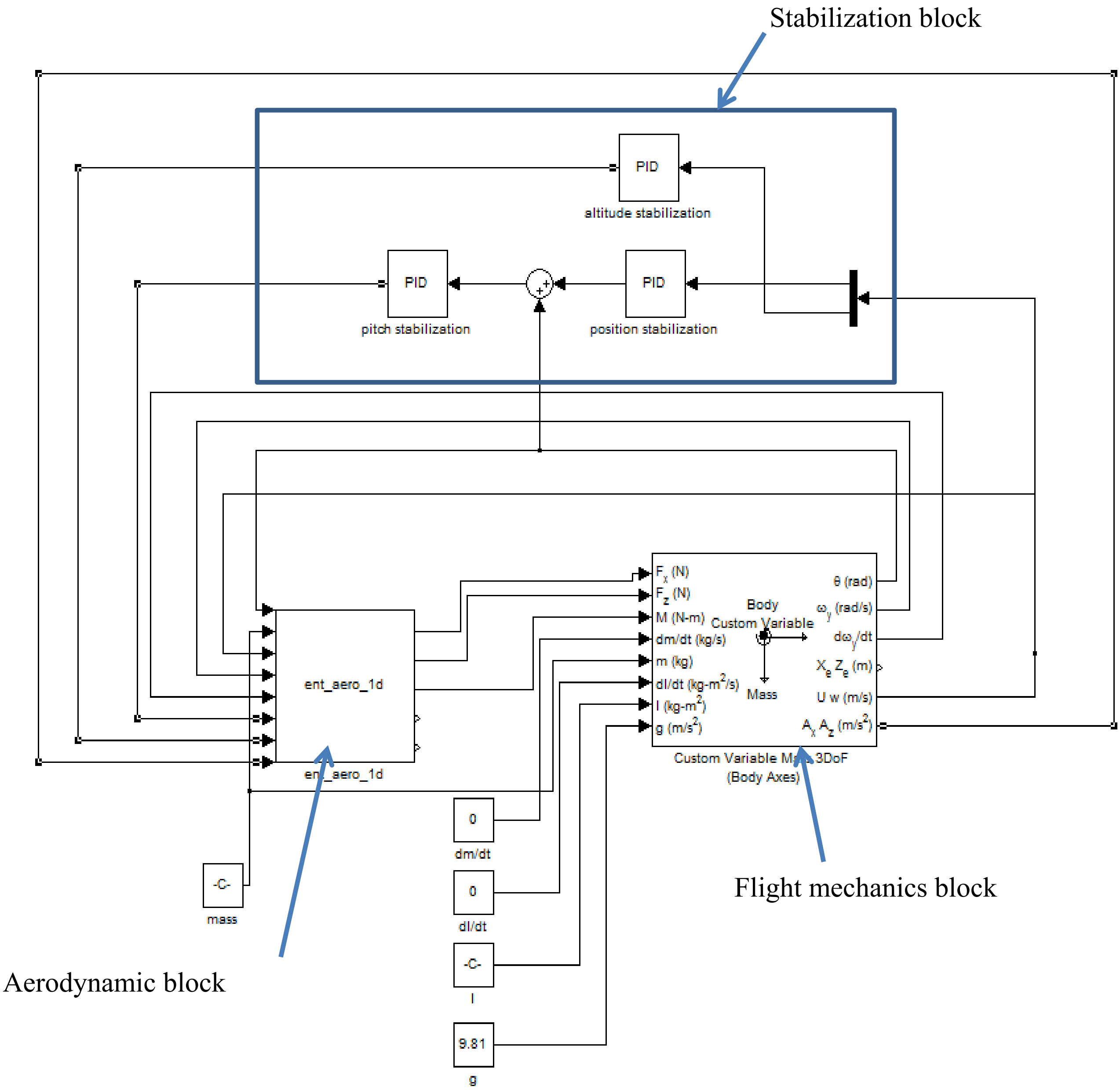


Fig. 9. Simulink model for flight simulation

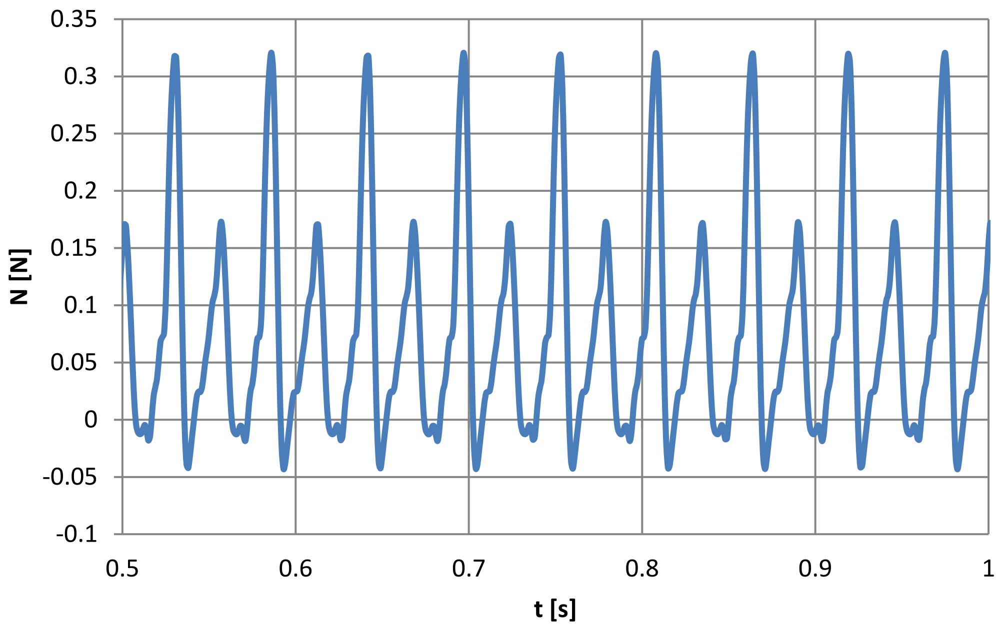


Fig. 10. Normal force during simulation of flight

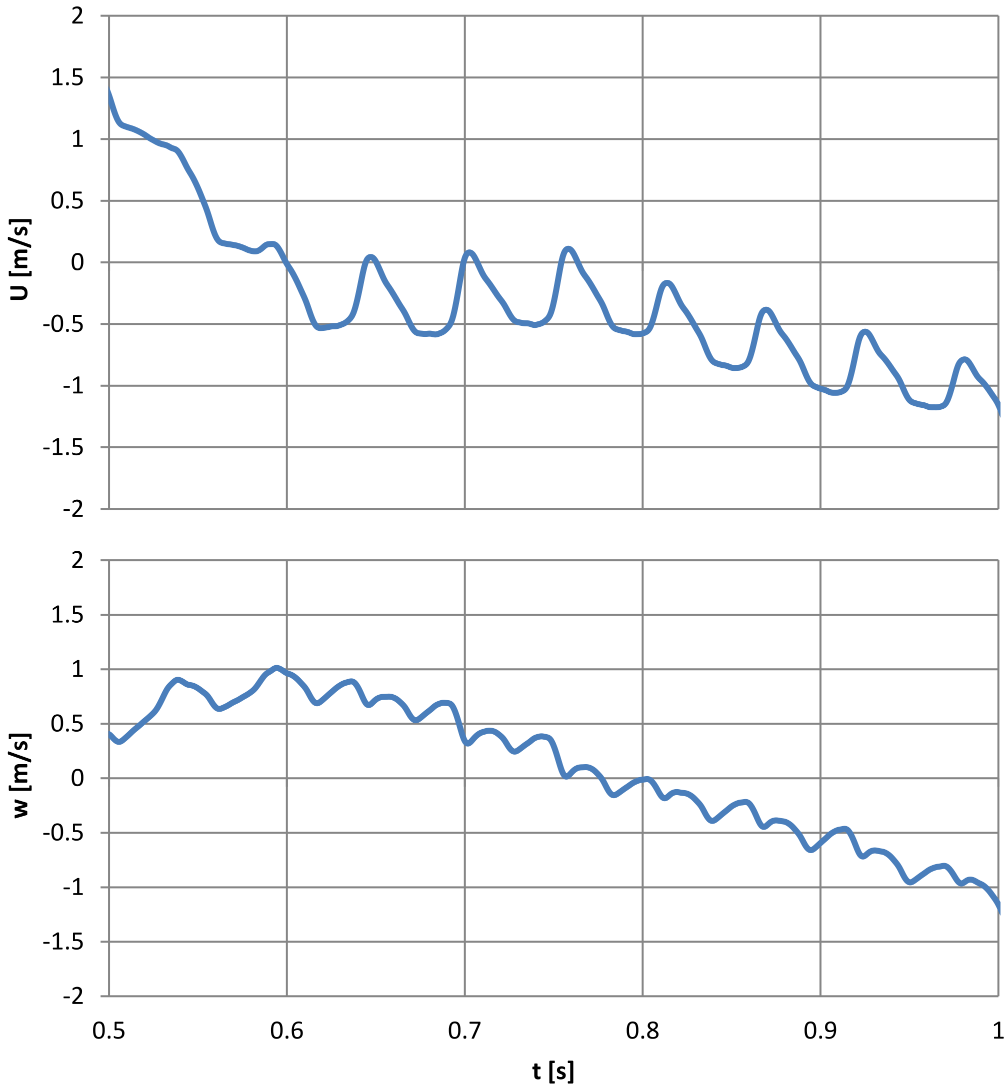


Fig. 11. Flight velocity during flight

Program needs basic mass and geometric data of modelled object. Entomopter will have 10 g of total mass, total wing span will not exceed 100 mm. Flapping frequency is iterated during calculation satisfying zero vertical velocity of object. In Fig. 10-11, exemplary results of simulation are shown. Fig. 10 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.

6. Conclusion

In this article innovative concept of model, describing unsteady aerodynamics of entomopter was proposed. It was shown, that it could be easily implemented as mathematical model. Proposed approach has 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 modelling 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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