World Journal of Engineering and Technology, 2016, 4, 256-262
http://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Theoretical and Engineering Approach to Human Power Ornithopter Design

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How to cite this paper: Zverkov, I., Kryukov, A. and Evtushok, G. (2016) Theoretical and Engineering Approach to Human Power Ornithopter Design. *World Journal of Engineering and Technology*, **4**, 256-262.
http://dx.doi.org/10.4236/wjet.2016.43D031

Received: July 11, 2016
Accepted: October 22, 2016
Published: October 29, 2016

Abstract

The article considers the issues on preliminary calculation of human-powered ornithopter general performances. The model of "simple ornithopter" is introduced. Giving an example of simple ornithopter interaction with the environment, the formula of relation of ornithopter theoretically available propulsion to kinematic and physical parameters of its horizontal flight parameters is derived. The tasking is performed for the following stages of calculation and design of the human-powered ornithopter.

Keywords

Human-Powered Ornithopter, Simple Ornithopter, Ornithopter Propulsion, Wing Aerodynamics

1. Introduction

The task of engineering and design of flapping flight aircraft has engaged the attention of scientists and engineers. Anyone may see with one's own eyes the birds, using that flight principle, can, on the one hand, fly and alight in tough terrains, and on the other hand, they can perform long passages, an in the end, the flight of bird is almost inaudible. Thus, for long time, the mankind has dreamed to fly as the birds, but scientific and practical approach to solution of that task was found just recently. Leonardo da Vinci, in his works, [1], perhaps, was the first who presented a description of some man-powered flapping device that, probably could get off the ground by use of that power. By now, after 300 years, the mankind got quite advanced branch of industry, *i.e.* the Aviation. Using propeller propulsion force or jet blast, airplanes fly successfully enough within wide range of speeds. However, advancement in ornithopters designing is very modest. Nowadays, there are only two ornithopters that flew manned more or less successfully.

The first flight with use of additional engine was performed in 2009 [2] by a group form University of Toronto Institute for Aerospace Studies. The second attempt of the man-powered flight was performed in 2010 by the group of the university above [3]. Despite that, in recent times, a lot of works have been published, that are devoted to studying of flapping wing, and no more manned ornithopters were constructed.

In authors' opinion, it is related to the fact that duplication of natural structures in ornithopters is rather complicated task, both as to theoretical model development, and building of real engineering structure. Therefore, this work proposes, on the one hand, to use the ornithopter simple kinematic model, and, on the other hand, to reveal the correlation between general ornithopter kinematic and physical parameters and the propulsion that construction is available to provide. It will allow the engineers, without conducting of expensive aeronautical and time-consuming full-scale and numerical experiments, to determine the main parameters of future manned ornithopter driven by man-power.

2. The Model of Simple Ornithopter

In **Figure 1**, the model of simple ornithopter and the forces affecting it are presented. Let the basic axis system is oriented as follows. ***Y***-axis is against gravity direction, ***X***-axis is along the direction of horizontal ornithopter flight. Let's introduce some simplifications which will permit to reveal the main interaction of the ornithopter with the environment.

1) Let the weight of the ornithopter is located in its center of gravity and the position is steady regarding the hull regardless of the wing position. F_g force is directed straight down. It is equivalent to acceptance of the assumption that the wing is weightless.
2) Wing lift is definitionally perpendicular to the wing movement trajectory, which deviates at γ angle during flapping motion.
3) Aerodynamic drag force of the ornithopter F_x is applied in the center of gravity and does not depend on position and value of wing lift.

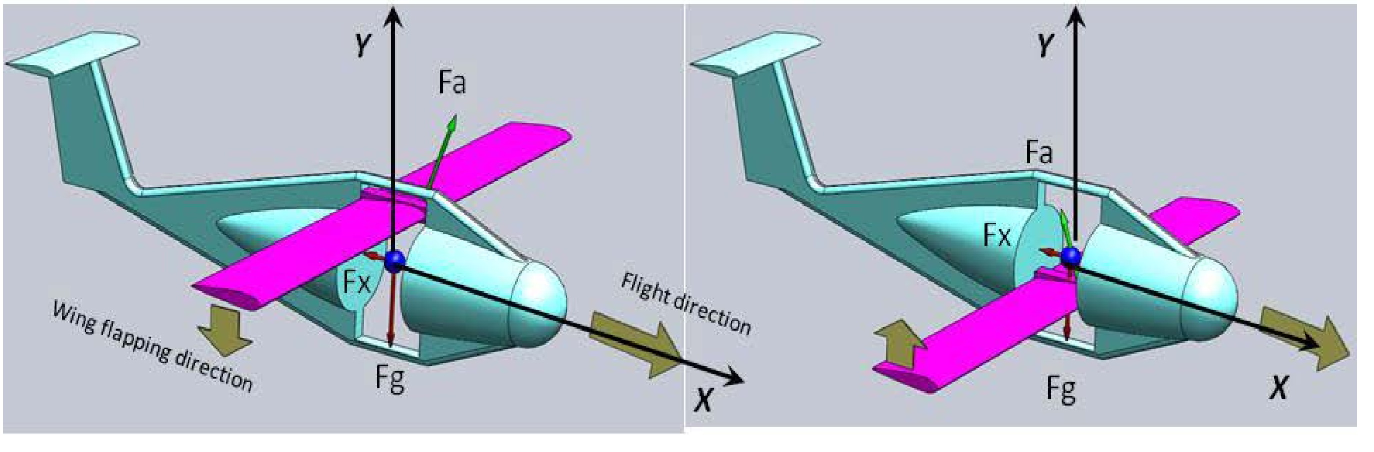

Figure 1. The schem of simple ornihtopter.

4) The angle of wing trajectory to horizontal is $\gamma < 20^{\circ}$ max. That assumption is necessary for the analysis of simplest motion cases and allows using the following approximations for transformation of wing lift in F_{ay} vertical component and F_{ay} horizontal component.

$$F_{ay} \approx F_a \tag{1}$$

$$F_{ax} = F_a \bullet tg(\gamma) \approx F_a \bullet \gamma \tag{2}$$

5) The ornithopter wing is always pre-stall streamlined. Strouhal number ***St*** taken by the amplitude of swing

$$St = \frac{Hf}{U_\infty} < 0.1 \tag{3}$$

where: ***f***-flapping frequency.

3. Formula for Simple Ornithopter Propulsion

Now, let's turn to bidimensional representation of simple ornithopter movement. In order to fulfill the conditions of straight and level flight, it is necessary that the wing lift onto the vertical axis is to be equal to gravity affecting the ornithopter. However, the analysis of birds filming or video recording shows that body of a bird or the ornithopter has periodic acceleration both in vertical and horizontal planes. Therefore, we will consider the flight of simple ornithopter as the straight one if, at the same moment of the flapping cycle, the ornithopter is at the same height and moves with the same speed. We accept the position, when the wing is at the top dead point, as the initial height (**Figure 2**).

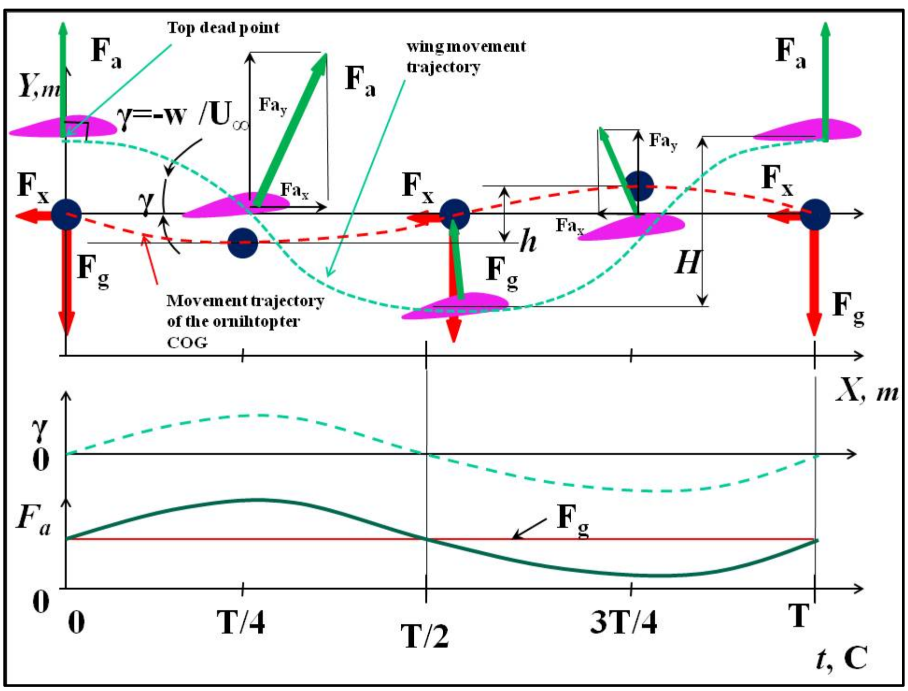

Figure 2. The diagram of forces affecting to the ornithopter during a cycle.

Let establish harmonical law of the wing oscillation in vertical plane.

$$\frac{H}{2}=\frac{H}{2}\cos(\frac{2\pi t}{T}) \tag{4}$$

Then, the vertical speed of the wing ***w*** may be expressed as follows:

$$w=-\frac{\pi H}{T}\sin\left(\frac{2\pi t}{T}\right) \tag{5}$$

And correspondingly angle of wing trajectory to horizontal is:

$$\gamma=-\frac{\pi H}{TU_{\infty}}\sin\left(\frac{2\pi t}{T}\right) \tag{6}$$

Let's leave other assumptions as in p.2.

As it is well known from educational materials, in the area of wing incidence, where there is no boundary layer separation, the dependency of wing lift from angle of attack is linear and may be expressed by means of formula

$$F_a=F_{a0}+K\bullet\gamma \tag{7}$$

where:

F_{a0}—is wing lift at incidence angle corresponding to level flight with average speed of U_{∞}.

K—is the coefficient of wing lift increment

γ—is angle of deviation from the horizontal of the wing trajectory.

Taking into account that in horizontal flight

$$F_a=F_g \tag{8}$$

We may record

$$F_a=F_g+K\bullet\gamma \tag{9}$$

As a result of interaction with the environment, the center of gravity of the ornithopter will be shifted subject to force.

$$dF=K\bullet\gamma=M\bullet a_y \tag{10}$$

Plugging the law of γ change at harmonic oscillations in the formula 6 to formula 10 we will get the value of center of gravity acceleration, as follows:

$$a_y=\frac{K}{M}\frac{\pi H}{TU_{\infty}}\sin\left(\frac{2\pi t}{T}\right) \tag{11}$$

where:

M—ornithopter takeoff weight.

Let's added initial conditions: $\boldsymbol{Y_0=0;\ U_{yT/4}=0}$

After the integration of equation and calculation of constants based on initial conditions, we infer the equations for vertical speed of ornithopter center of gravity (Formula 12) and movement of ornithopter center of gravity (13).

$$U_y = -\frac{2K}{M}\frac{H}{U_\infty}\cos\left(\frac{2\pi t}{T}\right) \quad (12)$$

$$Y = -\frac{T}{4\pi}\frac{K}{M}\frac{H}{U_\infty}\sin\left(\frac{2\pi t}{T}\right) \quad (13)$$

Y minimum will be obtained at T/4, and maximum at 3T/4. Consequently, peak-to-peak amplitude of center of gravity movement (***h***) may be calculated:

$$h = Y_{\max} - Y_{\min} = \frac{T}{2\pi}\frac{K}{M}\frac{H}{U_\infty} \quad (14)$$

Now let's establish the integral equation for conservation of linear momentum on X-axis.

$$\frac{1}{T}\int_0^T\left(F_g + \frac{K\pi H}{TU_\infty}\sin\left(\frac{2\pi t}{T}\right)\right)\bullet\frac{\pi H}{TU_\infty}\sin\left(\frac{2\pi t}{T}\right)dt = F_x$$

$$F_g\frac{\pi H}{T^2U_\infty}\int_0^T\left(\sin\left(\frac{2\pi t}{T}\right)\right)dt + \frac{K\pi^2H^2}{T^3U_\infty{}^2}\int_0^T\left(\sin^2\left(\frac{2\pi t}{T}\right)\right)dt = F_x \quad (15)$$

The left part of the equation (15) represents the propulsion of the ornithopter ***P***. Upon integration of the expression we will get

$$P = -F_g\frac{H}{2TU_\infty}\bullet\cos\left(\frac{2\pi t}{T}\right)\Bigg|_0^T + \frac{K\pi^2H^2}{T^3U_\infty{}^2}\left(\frac{t}{2} - \frac{1T}{8\pi}\sin\left(\frac{4\pi t}{T}\right)\Bigg|_0^T\right) \quad (16)$$

After the definite integral is taken over the cycle, we will get

$$P = \frac{K\pi^2H^2}{2T^2U_\infty{}^2} \quad (17)$$

It is possible to derive the correlation between the amplitude of wing flap and the amplitude of center of gravity movement from the equation (14):

$$H = \frac{2\pi MU_\infty h}{TK} \quad (18)$$

Plugging (18) in the expression for ornithopter propulsion (17) we will finally get:

$$P = \frac{\pi^3MHh}{T^3U_\infty} = \frac{\pi^3MHhf^3}{U_\infty} \quad (19)$$

4. Conclusions

As is clear from Formula (19), at assumptions accepted for the simple ornithopter, the ***P*** propulsion depends only on general kinematic parameters of ornithopter movement. The main parameter is flapping frequency, as the propulsion depends on it cubically. It is necessary to remark also, that with no center of gravity movement of the ornithopter, which is caused by aerodynamic forces, propulsion development is impossible as well.

Upon completion of this research, quite simple algorithm of man-powered ornithopter construction takes shape. It can be divided conventionally in two stages:

At the first stage, the parameters of airframe structure are selected, providing horizontal flight with power expenditure of 250-300 W. As the result of that, the following parameters are to become known:

1) ornithopter takeoff weight M
2) Cruise speed U_∞
3) Wing surface area S
4) Wing aspect ratio λ
5) Wing airfoil parameters $C_l C_d$
6) F_x drag force at U_∞ speed

At the second stage, the K coefficient is calculated. Then, based of availability of structural implementation, the following parameters are chosen: flapping frequency f; amplitude of flapping H; h amplitude of center of gravity movement. According to Formula (19) the P propulsion is calculated, which is to be not less than previously calculated F_x drag force.

If it is ornithopter center of gravity movement is desired to be avoided, then biplane model (**Figure 3**) with wings moving in phase opposition. For propulsion calculation, Formula (17) may be applicable. It is necessary to take one wing amplitude of flapping as the amplitude of flapping H. At that, it is required to remember that, in this case, translational amplitude may be avoided though, reciprocal pitch motion will remain. Thus, in order to spare the pilot any oscillations caused by wings motion, it is required to fix the cockpit on horizontal hinge.

Therefore, in this article, the equation for correlation of the ornithopter propulsion with kinematic parameters of its motion in the environment is derived. An algorithm of a man-powered ornithopter designing is proposed. The recommendations on reducing of oscillatory motion of ornithopter pilot or payload are given. The obtained data is applicable in the best way and Strouhal number St < 0.1 calculated by amplitude of the flapping, but can be applied in other cases as evaluating calculations too.

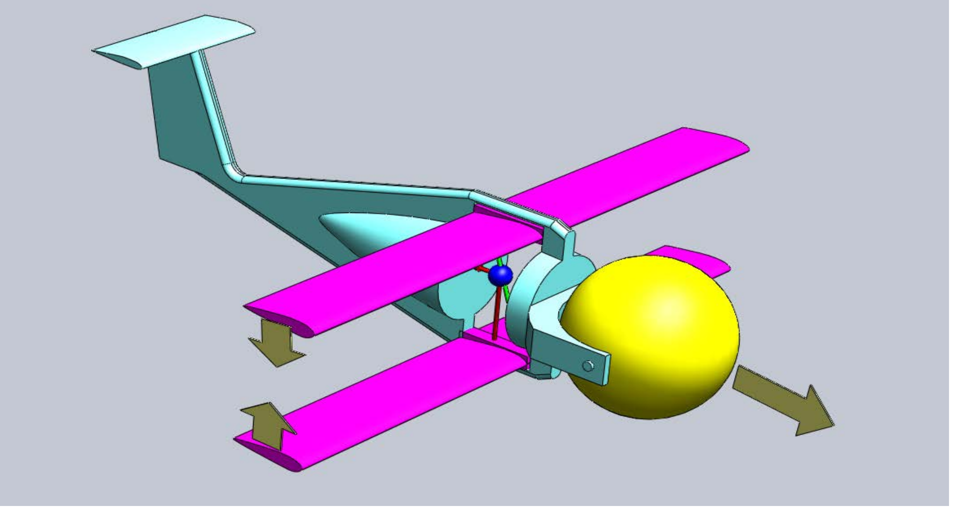

Figure 3. Example of compensating for the ornithopter center of gravity movement.

Supported

This work was supported by the Grant No. 14-08-00369 A of the Russian Foundation for Basic Research.

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