INVESTIGATION OF FLIGHT OF MICRO AERIAL VEHICLE WITH FLAPPING WINGS

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Abstract. Micro aerial vehicles design represents a challenge that lasted for years and the fact that they operate in a low Reynolds range, which make the unsteady aerodynamic effect more influential, made the direct computational fluid dynamics simulation expensive in time and money, and an alternative method especially in the early phase of the design would be very beneficial and rentable. In this work, the flight of a flapping wings operated micro aerial vehicle is investigated by the simulation of the mechanical equations of motion to have an approximation of the motion behavior and the flying condition of the vehicle, at the same time this model can be electronically implemented to make the MAV auto-controlled by imposing some criteria. The equations were developed in a cylindrical coordinates system, and simulated using the software Mathcad, and some of the constants related to the size of the vehicle are changed to match different range of existing flying animals from insects to birds, a concept of two different drag coefficients was used successfully to model the flapping wing. It was found that for smaller sizes and higher flapping frequency, the model does not fly, however for a bigger vehicle, and a simplification of parameters, it gave good approximation, and the model can be used for auto-control by a predefined flying path. Beside the main simulation work a small experimentation on a model wing covered in feather was conducted in a subsonic wind tunnel in order to present a practical alternative that economize energy by reducing the drag in upstroke.

Keywords: flapping wings, classical mechanic, MAV.

Introduction

Flying, a dream that man have always been dying to achieve (literally dying) and he always found inspiration in nature, in birds and insects, and there is no doubt that those creatures had developed the most efficient way of flying, but even with the huge advance in analysis and simulation method and recent developments in high-speed videography, we could not reproduce a flying machine as efficient as those animals and especially insects which have stimulated a great deal of interest among physicists and engineers because at first glance, their flight seems improbable using standard aerodynamic theory, and despite the great advance in fixed wing vehicles, flapping wings vehicles still have lots of secrets for the engineers.

Such way of generating lift was examined very closely by aviation pioneers from Abbas Ibn Firnas to Leonardo di Vinci who, inspired by the nature, tried to project the bird’s flapping wings on humans to realize the immortal dream of flying.

Nowadays, researches are conducted on the small scale flapping wings, and this because of the need to a much smaller and more maneuverable aerial vehicle, that is indeed needed in many combat or reconnaissance situations and has other practical applications like search-and-rescue missions, law enforcement and even package delivery, something that the available unmanned aerial vehicle (UAV) does not provide, which increased the need for MAVs (micro aerial vehicles) and NAVs (Nano aerial vehicles), these vehicles are efficient, agile, and can carry a camera or other sensing equipment.

Research and design of such vehicle was encouraged by several organizations like DARPA (Defense Advanced Research Projects Agency) [1], that initiate the MAVs project which aimed to solve the technical barrier that prevents from the realizations of such machine.

Definition of MAV

They are affordable, fully functional, militarily capable, small flight vehicles in a class of their own. The definition employed in DARPA's program limits the craft to a size less than 15 cm (about 6 inches) in length, width or height. In addition, gross takeoff weight of no more than 100g.

Four types of configurations [2] exist in this category: fixed-wing, rotary-wing, and flapping wings, the fourth class is without propulsion and is called passive.

Recent years experienced some advance in the MAV field and there were several promising flapping wing operated vehicles, like the one Festo Company revealed in March 2011, the SmartBird (Fig. 1), an autonomous ultra-light unmanned aerial vehicle with a focus on better aerodynamics and high maneuverability [5], and BionicOpter ‚a dragonfly-like" AV (Fig. 2) a little bit bigger to be called MAV due to its 63 cm wing span and 44 cm long, it has an ultra-light weight of 175 g, and probably the most amazing thing about it is its 13 degree of freedom.

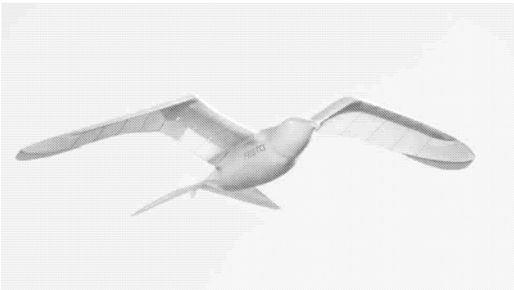

Fig. 1. **Festo's SmartBird**

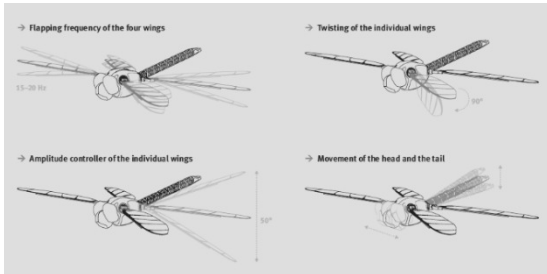

Fig. 2. **Some characteristics of the BionicOpter**

Statement of work

we performed a study of motion of a flapping wing operated micro aerial vehicle and this by simulating the classic motion equation of mechanics by changing each time one of the variables and using an approached value for the drag coefficient of birds and insects was done in the cylindrical coordinates system.

Using the same equations, we will create a control system that can be implemented electronically to steer the MAV, all of this using the Mathcad software.

With the numerical investigations using Mathcad, some experimental works will be conducted in the wind tunnel facility provided by the Riga Technical University, which will be consisting of testing the wing drag coefficient and its variation between the upstroke and the down stroke.

Numerical investigation with Mathcad

Theoretical investigation

The classical mechanic theory describes well the flight of the vehicle, the equations of motion (or equilibrium) which result from the Newton's second law are used to describe the flapping wing vehicle, and other systems of coordinates than the rectangular are used because it suits better this kind of motion in space that these vehicles usually follow.

The Newton's 2nd law stipulates that the resultant of all the forces acting on a particle is proportional to the acceleration of the particle:

$$\sum F = ma \,. \tag{1}$$

Cylindrical coordinates (r - θ - z)

The cylindrical coordinate attributes make it desirable to use in cases where the path is more complex. Every point in space is determined by the r and θ coordinates of its projection in the *xy* plane, and its z coordinate (Fig. 3).

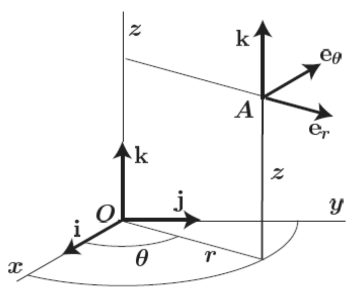

Fig. 3. **Cylindrical coordinate**

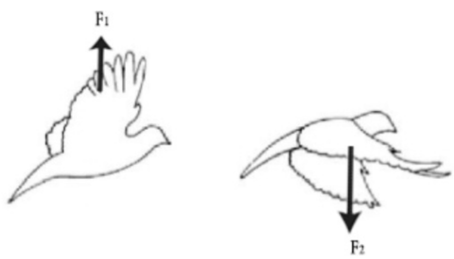

Fig. 4. **Two different forces in the upstroke (left) and down stroke (right)**

The equations of motion in cylindrical coordinates will be then:

$$\begin{aligned} \sum F_r &= ma_r = m\left(\ddot{r} - \dot{r}\dot{\theta}^2\right) \\ \sum F_\theta &= ma_\theta = m\left(r\ddot{\theta} + 2\dot{r}\dot{\theta}\right). \\ \sum F_z &= ma_z = m\ddot{z} \end{aligned} \tag{2}$$

Application on a flapping wing MAV

The equations of motion as seen before and despite their simplicity can be used to simulate the flight of a flapping wing vehicle; we used Mathcad after writing the equations in a proper syntax that we can use time increment to simulate the flight.

Lift force

Lift force is generated by the flapping of the wing itself, the original idea of this work is the consideration of the lift force more or less equal to the drag but as we observe from nature, when a wing is in the upstroke the animal uses its muscle to change the shape of the wing so it will have less drag, therefore a smaller drag coefficient C_{d1} in contrast in the down stroke the shape of the wing is optimal so for the biggest lift force which is the opposite of the drag force if we change the direction of the axis, therefore a biggest drag coefficient C_{d2} .

With the introduction of this two drag coefficient approach we will have two forces (Fig. 4) and knowing that the lift force expression is:

$$F_L = \frac{1}{2}\rho C_l A V^2, \tag{3}$$

where V – velocity;
S – lifting area (both wings);
C_L – lift coefficient.

The difference between the two strokes is the direction of the force; therefore we used this difference in sign and introduced an expression to switch between the coefficients such as:

$$0.5 - 0.5 sign(\cos(\omega t)), 0.5 + 0.5(\cos(\omega t))$$

These two expressions can be introduced before each drag coefficient so it will activate one coefficient a time the first expression equal 0 when the cosine is positive and the second equal 1 the opposite happens when the cosine is negative.

Finally, for the velocity we assumed that the flapping is done by an actuator or motor and this is following sinusoidal motion, the path would be A·sin(ω), therefore the velocity can be expressed as the first derivative: $A \cdot \omega \cdot \cos(\omega t)$ but due to the fact that this amount is squared in the force expression, another sign related expression is needed, so the expression of the velocity is:

$$V^2 = (A\omega\cos(\omega t))^2 sign(\cos(\omega t)) \tag{4}$$

where ω – Angular frequency;
A – Amplitude.

Therefore, the expression of the lifting force will be as following:

$$\begin{aligned} F = \frac{1}{2}((0.5 - 0.5\,\mathrm{sign}(\cos(\omega t))C_{d1} + 0.5 + \\ + 0.5\,\mathrm{sign}(\cos(\omega t))C_{d2}) \cdot S\rho(A\omega\cos(\omega t))^2 \cdot \mathrm{sign}(\cos(\omega t)) \end{aligned} \tag{5}$$

Damping force

Another force that we should be considering is the damping force giving the harmonic "vibration" and its expression is:

$$F_d = -b\frac{dx}{dt} \tag{6}$$

where b – damping coefficient;
x – depends on the axis.

Without forgetting the gravity force which acts only in the vertical axis.

To find the 3D equation we projected all these expressions on the respective polar, cylindrical and Z axis, A study case of each coordinate axis gave the following accelerations equations: the polar axis (7), the angular coordinate axis (8) and the cylindrical axis (9).

$$\ddot{r} = \frac{1}{m}(mr\theta^2 + [\frac{1}{2}((0.5 - 0.5\,\mathrm{sign}(\cos(\omega t))C_{d1} + 0.5 + 0.5\,\mathrm{sign}(\cos(\omega t))C_{d2}) \cdot S \cdot \rho \cdot (A\omega\cos(\omega t))^2\,\mathrm{sign}(\cos(\omega t))] \cdot \cos(\alpha)\cos(\beta) - b\frac{dr}{dt}) \quad (7)$$

$$\ddot{\theta} = \frac{1}{m \cdot R}(-2m\dot{r}\dot{\theta} + [\frac{1}{2}((0.5 - 0.5\,\mathrm{sign}(\cos(\omega t))C_{d1} + 0.5 + 0.5\,\mathrm{sign}(\cos(\omega t))C_{d2}) \cdot S \cdot \rho \cdot (A\omega\cos(\omega t))^2 \cdot \mathrm{sign}(\cos(\omega t))] \cdot \cos(\alpha)\sin(\beta) - b \cdot r\frac{d\theta}{dt}) \quad (8)$$

$$\ddot{z} = \frac{1}{m}(-mg + [\frac{1}{2}((0.5 - 0.5\,\mathrm{sign}(\cos(\omega t))C_{d1} + 0.5 + 0.5\,\mathrm{sign}(\cos(\omega t))C_{d2}) \cdot S \cdot \rho \cdot (A\omega\cos(\omega t))^2 \cdot \mathrm{sign}(\cos(\omega t))] \cdot \sin(\alpha) - b\frac{dz}{dt}) \quad (9)$$

To the last equation a certain criterion was added for the control of the altitude of the MAV, which is nearly the same as the one we added to be able to switch between the drag coefficients:

$$(0.5 - 0.5.sign(\cos(Z - H_m)), \quad (10)$$

where H_m – the maximum height that the MAV is supposed to reach.

Mathcad implementation

We had a set of parameters, some of them remained constant, and we tried to modify the others and analyze what happens.

We tested on two different ranges of dimensions the bird –like and insect-like, in the literature we found the parameters needed and in fact there is a formula developed by PENNYCUICK, that link the flapping frequency of the birds wing to the other parameter (m, S, ρ, g, b (wing span)) [6] which is written as:

$$f = m^{3/8} g^{1/2} b^{-23/24} S^{-1/3} \rho^{-3/8}, \quad (11)$$

where m – body mass;
g – acceleration due to gravity;
b – wingspan;
S – wing area;
ρ – air density.

So the expression of the angular frequency is:

$$\omega = 2\pi.m^{3/8} g^{1/2} b^{-23/24} S^{-1/3} \rho^{-3/8}, \quad (12)$$

For our bird-like MAV experimentation we used two different sizes, the first ones will be from DARPA definition the second from an actual bird which is the Dove prion.

For the insect-like configuration that is more close to the NAV we used the dimension of a dragonfly which is around 5 cm for the wing span and 350 mg for the mass.

Drag coefficient

For the drag coefficient it is mentioned in the literature that the lift to drag ratio is between 3 and 17 and the drag coefficient for birds is between 0.8 and 1.2 but the motion of the wing affects significantly the drag coefficient, therefore we tried a set of drag coefficients around the real value.

For insect like MAVs we can see from the literature that the insects wing have very a small drag coefficient around 0.06, so we used numbers around it and see the results.

However, the area of the wing depends on the Aspect Ratio, for a faster flapping frequency less aspect ratio is needed, therefore a range of area is used from an aspect ratio of 3 and bigger.

We started using the aspect ratio with the cylindrical coordinates with the following values: m = 0.155 kg, b = 0.01, S = 0.0469 m^2, D_1 = 0.4; D_2 = 0.8 and the wing span b_s = 0.635 m. However, with this parameter the MAV does not fly.

We performed more manipulations on different parameters [7], the results are illustrated in Fig. 5, 6, 8, 9. From the last graphs, it was obvious that instability occurred in the z-axis, so we changed the damping coefficient b by b1 and we varied b1. Increasing the damping coefficient (b1=0.1 and 0.15) we had nearly similar results but far more stable, as it is illustrated in the next graphs where we can see the path of flying in the (x, z) and (x, y) plan (Fig. 7, 10).

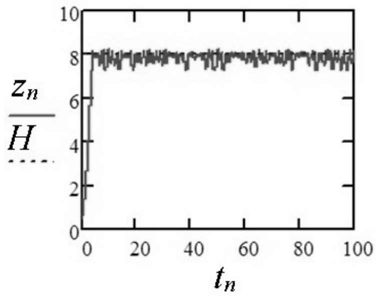

Fig. 5. **Variation of the vertical coordinates, b_1 = 0.15**

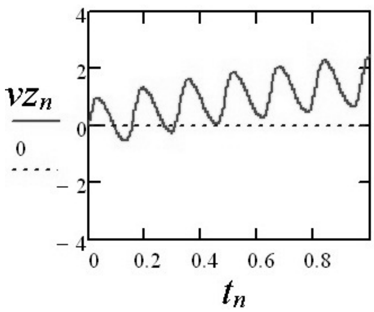

Fig. 6. **Variation of the vertical velocity, b_1 = 0.15**

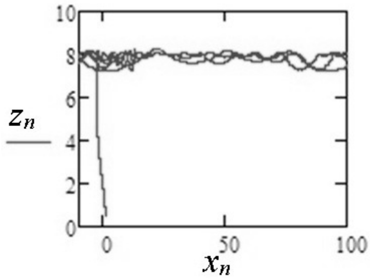

Fig. 7. **Flight path in the (x, z)**

Steering

Steering can be done by directly implementing and fixing the angles α and β or by making one or both of the angles time dependent.

Like the example we used [9] we changed the angle value by time depending functions:

$$\alpha = \frac{\pi}{2.5}.(e^{-0.01t}); \beta = 1.5.\frac{\pi}{2}(e^{-0.01t}) . \tag{13}$$

The vertical coordinates will not be affected; however, we can see the change of path in the other plans like the next graphs illustrate it.

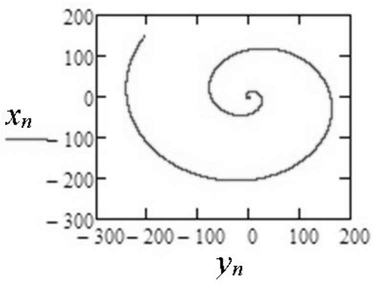

Fig. 8. **Flight path in the (x, y) plan**

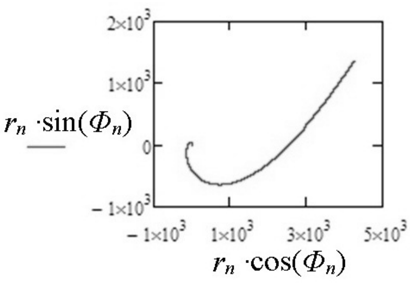

Fig. 9. **The flight path in the plan (r, Φ)**

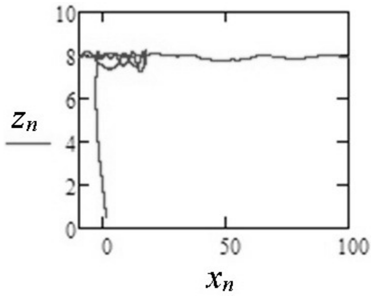

Fig. 10. **At H = 8 the MAV stops turning and takes a fixed direction**

DARPA definition MAV

For other dimension than the ones we used the first time we tried the DARPA definition m = 100g, wing span b_s = 15cm. and we tried a range of area and drag coefficients.

However, we noticed that if the frequency formula is used with smaller area, the frequency resulting will be too high and nonrealistic, on the other hand, with bigger area the MAV flies perfectly with realistic flapping frequency, but the wing ratio will be too high, because the wing span is fixed the length will be too high.

Insect's dimensions

For the insects, we tried the characteristics of a dragonfly, and we did some variation in all the parameters but the MAV only flies for very high frequency or amplitude or drag, so this model does not work for very small dimensions.

Experimental Work

The experimental work consists simply of measuring the drag force that is produced by an artificial pair of wings covered with feather (Fig. 11) from both sides, and we tried to see if the bend of the profile as well as the feather orientation affected the drag. The results are illustrated in Fig. 12.

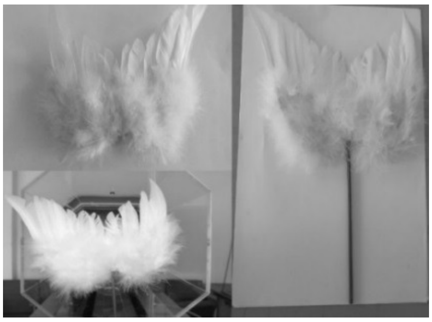

Fig. 11. **The tested artificial wing**

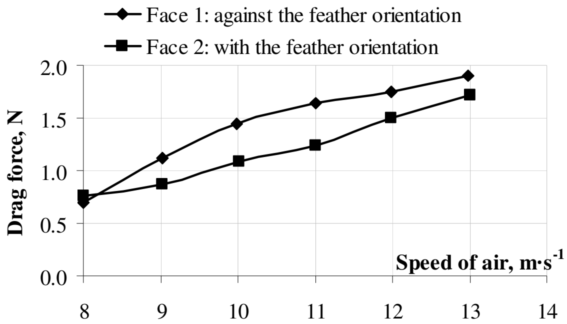

Fig. 12. **Graph that illustrates the result of the measurements performed on the wing**

It is obvious that there is a difference between the two cases, we can see that in the first case where the air flow was against the orientation of the feathers and the curve was against the flow the drag force was higher, but for the second case we can see that the force was generally less than the in first case, such difference can be used in a flapping wing vehicle in order to design lighter and more efficient wings.

Conclusions

We can summarize the results in the next points:

1. One of the major parameters that influence the MAV flying is the damping coefficients, which have great effect on the stability of the MAV especially.
2. It is possible to use some formulas found in the literature that link the flapping frequency with a group of other parameters.
3. The flapping frequencies have to be defined and limited under a certain value to keep up with the reality and the available mechanism for flapping.
4. The difference between the 2 drag coefficients plays the central role in making the MAV fly just like the amplitude.

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