Modeling and simulation of an ornithopter with forward and elevating flight

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Abstract
This paper presents a modeling based 2 links solid pendulum and the open loop simulation of an ornithopter like FESTO’s smart bird after discovered the successful parameters. The elevation control of smart bird is not frequency control of faction like FESTO’s smart bird but faction and gliding time like golden eagle or hawks. The forward control of smart bird is done by twist of root of wings. It is a difficult point that the range of the parameter in which it can fly is narrow at both solver of Simulink and Excell. Then, the balance value is different according to solver.

Keywords: Ornithopter, Smart bird, Modeling, Simulation, 2 links solid pendulum

1. Introduction

The robot that flaps and flies like the bird is called Ornithopter, has been developed, and there is an academic society which is named Ornithopter Society, (Flapping Wings Newsletter, 2016), too. There was a smart bird plan by air pressure equipment maker FESTO in Germany considerably before. Then, a real machine was produced in 2011, the demonstration was done with TED (Technology Entertainment Design). It was remarkable (Atmarkit and TED.com, 2015, Youtube-TED channel, 2017) as shown in Fig. 1. Especially, observation of Fig.1(a) is important for knowing structure of wings which are 2 links, and observation of Fig.1 (b) is important for knowing how to move wings to fly well. In order to obtain lift, the wings of 2 links need not only flap up and down while stretching and folding, but also to twist the wings in order to move forward, and they need to obtain not only the levitation force component but also the propulsive force component.
Smart bird has several features to fly forward. Hold active servo, meandering joint and twisted wings and swing with vertical flapping.

On the other hand, Robotic Bird (Fig. 2) of (Birdkit.com, 2016) performs elevation control utilizing the elasticity of thin aerodynamic wings. The elevation angle is controlled by the vertical asymmetric operation time of the flapping of the wing, the pitch control and the amplitude change of the flapping, and the aileron is performed by the asymmetric operation of the left and right wing.

The parameter of periodic wing flapping of the microcomputer operation can be adjusted with the wireless control.
In addition, the ornithopters of the size of insects have been researched and developed, and a lot of presentations have come to be done recently in JSME etc..

With regard to these real machines which were produced by various trial and error of Takumi, researches on mathematical models of flying robots were positively conducted in each country before and after actual machine manufacture, and were first announced (J. Oliver Linton, 2007).

Investigation, design, and/elevation simulation research (Simulink) on the double hinge wing were executed, and have been announced recently (Y.H. Choi, J.E. Joung, D.H. Lee, 2012).

The purpose of this research is to construct an aerodynamic mathematical model for levitation and advancement of a certain ornithopter and to simulate and to confirm that it is possible to raise, lower and advance even in a flapping model using twisted double link hinge wing though it differs from a past physical mathematics model.

2. Simple elevation mathematical model equations using double link hinge wings and simulation

2.1 Simple elevation model

Here, the motion of the angle of the two-link hinge wing were modeled as shown in Fig. 3. The deflection angle of the first link is defined clockwise (CW) from the horizontal axis and the argument of the second link is defined as the CW around the left wing from the extension of the first link. The hovering model is a drag balance model, and lift for raising and lowering cannot be applied. When manipulating the combination of the angles of the wings, the drag decreases when the wing lifts and the drag increases when the wing goes down, so the body with the wings floats. As shown in Fig. 4, by twisting the wings from the base as shown in Fig. 4, the horizontal component of the drag force of the wing is generated, and due to the reaction, the body moves forward.

Another way to change the effective area for effective force in the case of the upper and lower positions of the flapping action is to attach a check valve to the wing, to change the tension on the front surface and back surface, and the like.

To forward, there is a method of twisting the wing from the base by the servos, and a method of twisting by a big flapping after connecting the left wing and right wing using a string through the head.

The elevation model formula of 2 link hinge wing is shown on the next right side.

\[
\alpha(t) = -g + \frac{1}{M} (D_1(t) + D_2(t)) \\
v(t) = v_o + \frac{1}{s} \alpha(t) \\
H(t) = H_o + \frac{1}{s} v(t) \\
D_1(t) = 0.5 \rho C_d v_1^2(t) S_1 \cos \theta_1(t) \\
D_2(t) = 0.5 \rho C_d v_2^2(t) S_2 \cos \left[ \theta_1(t) + \theta_2(t) \right] \\
v_1(t) = 0.5l_1 \omega_1(t) + v(t) \\
v_2(t) = 0.5l_2 \omega_2(t) + v(t)
\]
where \( s \) is differential operator, \( 1/s \) is integrator operator (then right hand side and left hand side of Eq.(2) and Eq.(3) are the same dimensions), \( \alpha \) is vertical upward acceleration, \( g \) is gravitational acceleration, \( M \) is mass, \( D_1 \) is a drag (air resistance) of link1, \( D_2 \) is a drag (air resistance) of link2 which are cross-sectional area components perpendicular to the air flow of the wing surface area, \( v \) is vertical upward velocity, \( v_0 \) is initial vertical upward speed, \( s \) is differential operator, \( H \) is height, \( H_0 \) is initial height, \( \rho \) is air density, \( C_d \) is a drag coefficient, \( S_1 \) is unilateral surface area of link 1 in the vertical direction, \( S_2 \) is unilateral surface area of link 2 in the vertical direction, \( l_1 \) is length of link 1, \( l_2 \) is length of link 2, \( v_1 \) is vertical upward velocity of center of link1, \( v_2 \) is vertical upward velocity of center of link2, \( \omega_1 \) is vertical upward angular velocity of link1, \( \omega_2 \) is vertical upward angular velocity of link2, \( \theta_1 \) is the angle of link1, \( \theta_2 \) is the angle of link2, on the ornithopter. It is assumed that the body was a thin plate and the cross section area for vertical drag was omitted.

2.2 Simulation results

Figure 5 shows the trend of the flapping angle of the simulation of the above model, and Figure 6 shows the trend of the height and speed of the result solved by the solver of Simulink ODE 45. However, simulation of raised and lowered is only once because it was too fast.

![Fig.5 Trend of Wing Angle (\( \theta_1, \theta_2 \)) [deg]

![Fig.6 Height H[m] v.s Velocity V[m/s] & Position[m]

In the real machine, it seems that it is probably going up and down with flapping pitch (frequency control) using segroon gull as a model. When it is modeled here as a model, it is raised by flapping and the descent amount by gravity is adjusted by the glide time.

3. Simple elevation - forward model expression with twist angle of 2-link hinge wing and fluttering gliding simulation

3.1 Simple elevation-forward model

A simple model of elevating / advancing with a twist as shown in Fig. 4, is shown below, and simulation results (fluttering wing angle and \( H - X \) curve) of the leader / follower after a fixed time start by the EXCELL Euler method were shown from Fig. 7 to 10.
$\alpha_h(t) = -g + \frac{1}{M} D_h(t)$

$v_h(t) = v_o + \frac{1}{s} \alpha_h(t)$

$H(t) = H_o + \frac{1}{s} v_h(t)$

$D_h(t) = (D_1(t) + D_2(t)) \cos \theta_3(t)$

$D_1(t) = 0.5 \rho C_d v_1^2(t) S_1 \cos \theta_1(t)$

$+ 0.5 \rho C_l v_1^2(t) S_1$

$D_2(t) = 0.5 \rho C_d v_2^2(t) S_2 \cos[\theta_1(t) + \theta_2(t)]$

$+ 0.5 \rho C_l v_2^2(t) S_2$

$v_1(t) = 0.5 l_1 \omega_1(t) + v_h(t)$

$v_2(t) = 0.5 l_2 \omega_2(t) + v_h(t)$

$\alpha_s(t) = \frac{1}{M} D_s(t)$

$v_s(t) = v_o + \frac{1}{s} \alpha_s(t)$

$X(t) = X_o + \frac{1}{s} v_s(t)$

$D_1(t) = (D_1(t) + D_2(t)) \sin \theta_1(t) - 0.5 \rho C_d v_1^2(t) S_x$

$v_{1x}(t) = 0.5 l_1 \omega_1(t) + v_h(t)$

$v_{2x}(t) = 0.5 l_2 \omega_2(t) + v_h(t)$

$\omega_1(t) = \dot{\theta}_1(t)$

$\omega_2(t) = \dot{\theta}_2(t)$

where the suffix $h$ is variables for elevation direction, and the suffix $x$ is variables for forward direction. It is assumed that the body was a thin plate and the cross section area for forward drag was omitted.

### 3.2 Simulation results

Figure 7 shows the trend of the flapping angle and twist angle of the simulation of the leader by the above model, and Figure 8 shows the trend of the height and position (H-X curve) for forward on the leader solved by the Excell (Euler method; fixed sampling time $h$).
Figure 9 shows the trend of the flapping angle and twist angle of the simulation of the leader by the above model, and Figure 10 shows the trend of the height and position ($H$-$X$ curve) for forward on the follower which started and followed behind the leader.
Where $\theta_1$ is the flapping angle of link1, $\theta_2$ is the angle of link2, and $\theta_3$ is the twist angle of link 1. It is understood from the figure that the link 2 is bent downward when swinging up the link 1 of the wing and that the link 2 extends straight and link 1 is twisted (tilt) down for sending air behind when swinging down the link 1.

The parameters list in Excell simulation (Euler method) were shown in Table 1.

### Table 1 Parameters list (in EXCELL simulation)

| Parameter | Value | Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|-----------|-------|
| $\rho$    | 1.293 [kg/m$^3$] | $C_d$ | 0.53 [Ns$^2$/kg] | $C_L$ | 0.83 [Ns$^2$/kg] |
| $S_1$     | 0.07 [m$^2$] | $S_2$ | 0.07 [m$^2$] | $S_x$ | 0.01 [m] |
| $l_1$     | 0.4 [m] | $l_2$ | 0.6 [m] | $d$ | 0.3 [m] |
| $M$       | 0.4 [kg] | $h$ | 0.001 [s] | |

4. Conclusion

The author investigated German smart birds, American robot birds, Korean papers etc and modeled up and down flapping machines using the same specifications as smart birds with two link hinge wing and simulated lifting and advancement of fluttering with two kinds of solvers. Then, as a result of difficult parameter adjustment, he was able to make the model fly well.

Furthermore, twisting was added to the base of the wing of the first link, and the ascent, the descent and the forward motion by the flapping were simulated with two different solvers. Fast responses such as servo characteristics are neglected, and only aerodynamic characteristics are considered. It is assumed that the flight was done indoors and it was not disturbed by the wind.

This model has high parameter sensitivity even if solved in either solver, the range of parameters that can succeed is narrow, and the balance value is different depending on the solver used. However, in the case where a flightable parameter area was found, the state of ascending, descending and advancing was generally good.

In order to simplify the flight model, the active method was to fold and stretch the wing for lifting and the wings were chosen to be twisted from the root by the servo for forward movement, but as passive way, forward and upward servos were ignored. This made the modeling advantageous in terms of weight, but the model error increased.
Furthermore, it will be possible to realize left and right turning by rotating operation of the tail wing or asymmetric operation of the left and right independent wings.

Even in passive forward, there are many problems such as considering the weight of batteries, servo, controllers, radio receivers and servo arms for flapping.

Although increasing the width of the flapping machine increases the danger level, if it can be made into a flexible material without rotating parts, the risk of collision is considered to be low. However, making it a full-fledged mechanism model is difficult because it is a rather large mechanism structure.

Since products that are similar to this model and are flying already exist, qualitative verification of simulation results will not be necessary. Quantitative verification is a future task, but as a general view, if it is possible to increase the accuracy of identifying shape dependent parameters such as drag coefficient and lift coefficient, verification of numerical experimental results will be possible.

The value of such modeling is to be able to upgrade the actual machine structure and control system developed based on the experience and trial and error of the craftsman to the model base. Therefore, further trial and error in such a theoretical model and the future development of the result will be expected in the future.

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