Modeling and linearization of longitudinal dynamics for a flapping wing micro aerial vehicle dragonfly-like with active rigid tail

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ABSTRACT

The main purpose of this paper is to model and simulate flight dynamics for a flapping wing micro aerial vehicle dragonfly-like with two pair clap and fling mechanism and active rigid tail. This article simulates the flight dynamics of a micro aerial vehicle dragonfly-like that can also use tail movements for longitudinal stability. Initially, using kane's method, the equations of motion of the longitudinal mode are obtained. Then aerodynamics forces of Delfly II micro aerial vehicle and gearbox simulation are added to the equations of motion. Also, a novel design for a flapping wing micro aerial vehicle dragonfly-like is presented, in which tail movement is similar to the movement of insect tails in longitudinal mode. In this work, the tail movement is not used as an elevator, but the rigid tail movement is used as a control torque. The difference in brush motor rpm leads to differential thrust and pitch moment generation, similar to a quadrotor. Finally the dynamic equations and aerodynamics and gearbox are all linearized and presented as state space equations. Also, the response of the open loop linearized model is compared with the nonlinear response by creating suitable initial conditions for the brush motor rpm.

KEYWORDS

Micro Aerial Vehicle Dragonfly-like, Clap and Fling Mechanism, Flapping wing, Hover, Kane's method

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1. Introduction

The amazing flight of insects and birds has always been of interest to researchers. Birds and insects have specific mechanism for guidance, control and producing lift and thrust. Among the maneuvers of insects and birds, hover with high stability shows the quality of flight and the complexity of their creation. Hover is an unstable flight mode and is very important in micro aerial vehicles (MAV). In this paper, two pairs of Delfly II mechanism are used in series (one pair as the front wings and one pair as rear wings). It also uses a rigid tail that can rotate with a servo mechanism (Fig.1). The Dragonfly-like Micro Aerial Vehicle designed in this paper has a length of 40cm and a wing span of 27.4cm. Mr. De Croon has done valuable research on aerodynamics and its coefficients and extracted exact equation for lift and drag forces, which are simulated in this paper.

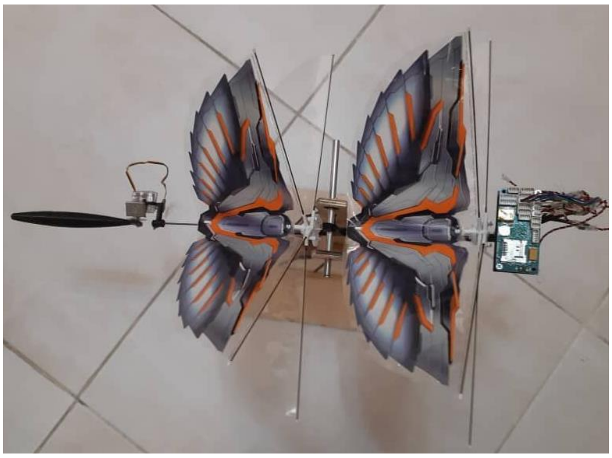

Figure 1. The proposed dragonfly-like MAV with a new structure

2. Methodology

After obtaining the kinematics of tail and body (linear velocities and rotational velocities of tail and body and linear acceleration and rotational acceleration of tail body) using the free body diagram (Fig.2), these velocities and accelerations are substituted in Kane's equations. The equations of motion for the longitudinal mode are obtained using Kane's method as follows [1]:

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{3} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} \dot{U} \\ \dot{W} \\ \dot{Q} \end{bmatrix} + \begin{bmatrix} -(m_t+m_b)QW - m_t l_b Q^2 - m_t l_t \cos\Theta_T (Q+Q_T)^2 \ldots \\ -m_t l_t \sin\Theta_T \dot{Q}_T \\ (m_t+m_b)QU + m_t l_t \sin\Theta_T (Q+Q_T)^2 \ldots \\ -m_t l_t \cos\Theta_T \dot{Q}_T \\ m_t QU(l_b + l_t\cos\Theta_T) - m_t l_t l_b \sin\Theta_T Q_T (Q_T+2Q) \ldots \\ -m_t l_t \sin\Theta_T QW \ldots \\ +(-I_{Tyy} - m_t(l_t^2 + l_t l_b \cos\Theta_T) - m_t l_t^2)\dot{Q}_T \end{bmatrix} + \begin{bmatrix} -(m_b+m_t) g \sin\theta \\ (m_b+m_t) g\cos\theta \\ m_t g l_b \cos\theta + m_t g l_t \cos(\theta+\Theta_T) \end{bmatrix} + \begin{bmatrix} -D_F - D_B \\ -L_F - L_B \\ L_F b_{FW} - L_B b_{BW} \end{bmatrix} = 0 \quad (1)$$

Where m_{ij} is the inertia matrix and given by:

$$m_{11} = m_{22} = -(m_t + m_b)$$
$$m_{12} = m_{21} = 0$$
$$m_{13} = m_{31} = -m_t l_t \sin\Theta_T$$
$$m_{23} = m_{32} = -m_t (l_b + l_t \cos\Theta_T)$$
$$m_{33} = -I_{Tyy} - I_{Byy} - m_t (l_b^2 + 2l_t^2 + 2l_t l_b \cos\Theta_T)$$

where D_F is the front wing drag force, D_B is the rear wing drag force, L_F is the front wing lift force, L_F is the front wing lift force and Q_T is angular velocity of tail. The lift and drag forces are shown in fig.2:

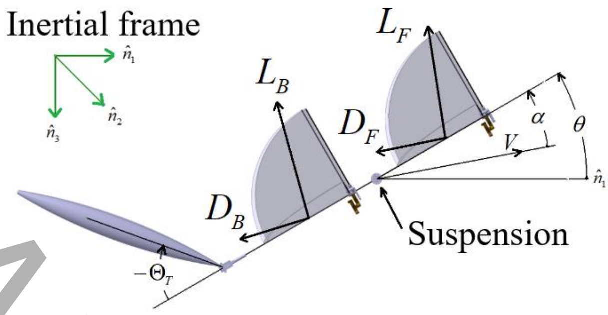

Figure 2. dragonfly- like free body diagram

where b_{FW} is the moment arm of the lift force and is equal to the distance between the effective point of the lift force of the front wing and the center of suspension of the dragonfly-like MAV. Similarly, b_{BW} is equal to the distance between the effective point of the lift force of the rear wing and the center of suspension. Therefore $L_F b_{FW}$ and $L_B b_{BW}$ are the moments due to the lift force of the front and rear wings. The difference between these two torques $L_F b_{FW}$ and $L_B b_{BW}$ is equal to the differential thrust that causes a pitch moment. Equation(2) shows the angular velocity of the flapping wing in terms of gearbox motor speed $\dot{\Theta}_i$ and the length of the links of the four-link mechanism a,b,k.

$$\dot{\zeta} = \dot{\Theta}_i (a/b)(\cos\Theta_i (k\cos\delta - a\sin\Theta_i + b\sin\zeta)...$$
$$+\sin\Theta_i (a\cos\Theta_i + k\sin\delta - b\cos\zeta))...$$
$$/(\cos\zeta (k\cos\delta - a\sin\Theta_i + b\sin\zeta)...$$
$$+\sin\zeta (a\cos\Theta_i + k\sin\delta - b\cos\zeta)) \quad (2)$$

3. Aerodynamic model to derive lift and drag forces

In this section, relations from reference [2] are used. Reference [2] has calculated the relationships for the lift force and drag in the body coordinate for the flapping wing (clap and fling) and has also obtained aerodynamic coefficients in the wind tunnel. In this section, the resultant of the quasi-steady aerodynamic forces for a wing element (rectangular element from the leading edge to the trailing edge) in reference [2] is obtained from the following equation:

$$d\vec{F} = d\vec{F}_{inertial} + d\vec{F}_{circ} + d\vec{F}_{added\,mass} - d\vec{F}_{visc} \quad (3)$$

We define the state vector as $x = [x_1 \quad x_2]^T$, where $x_1 = \theta$ and $x_2 = \dot{\theta}$. Also we define $u = [\dot{Q}_T \quad f_{F\_motor} \quad f_{B\_motor}]^T$. Thus, the linearized equations of the dragonfly-like MAV with active rigid tail and clap and fling mechanism for the hover are obtained at a pitch angle of 80°.

$$\dot{x} = \begin{bmatrix} 0 & 1 \\ -11.5128 & 0 \end{bmatrix} \begin{bmatrix} x_1 - \frac{80\pi}{180} \\ x_2 \end{bmatrix} ...$$
$$+ \begin{bmatrix} 0 & 0 & 0 \\ -0.8444 & -17.02417 & 17.02417 \end{bmatrix} \begin{bmatrix} \dot{Q}_T \\ f_{F-motor} \\ f_{B-motor} \end{bmatrix} \quad (4)$$

In figure 3 the simulated linear and nonlinear responses are compared.

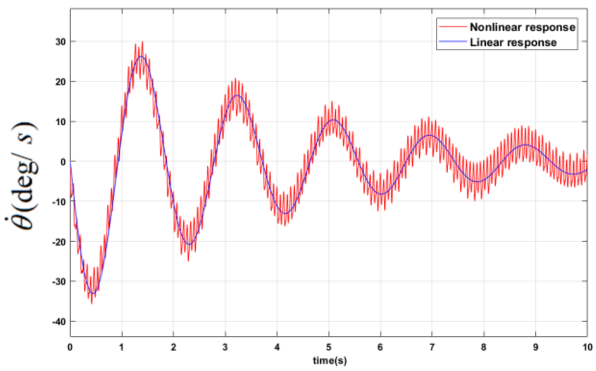

Figure 3. Comparison of linear and nonlinear responses for pitch rate

4. Analysis of the tail movement role in open loop

To show the effect of tail movement in the open loop, a torsional spring was placed between the tail and the body in the Simulink simulation. The oscillatory response of the body around the hover equilibrium at a pitch angle of 80° with the response for the case that the tail without torsional spring is freely connected to the body only with a torsional constraint was compared in fig.4. As shown in fig.4, the oscillatory motion of the tail acts as a vibration absorber for the body, and in this case the body has a lower oscillation amplitude around the hover equilibrium at a pitch angle of 80°. The open loop poles of the system were also obtained using the linearized equations. When there is no torsional spring between the tail and the body, open loop poles are on the imaginary axis. The tail angle and the velocity of the tail movement angle make the poles of the open loop model move slightly to the left of the imaginary axis, thus the system is marginally stable.

5. Conclusions

In this paper a new structure is presented for the dragonfly-like MAV with an active rigid tail. The tail of dragonfly-like MAV thus does not play the role of control surface in flight. Modeling of two-body nonlinear dynamics by Kane's method was performed for a dragonfly-like MAV with an active rigid tail in the presence of aerodynamic forces and flapping wing gearbox parameters. In the modeling section in the following works, similar to the longitudinal mode done in this paper, equations of 6-dof model can be obtained. It is possible to build a dragonfly-like MAV with the new structure that was presented.

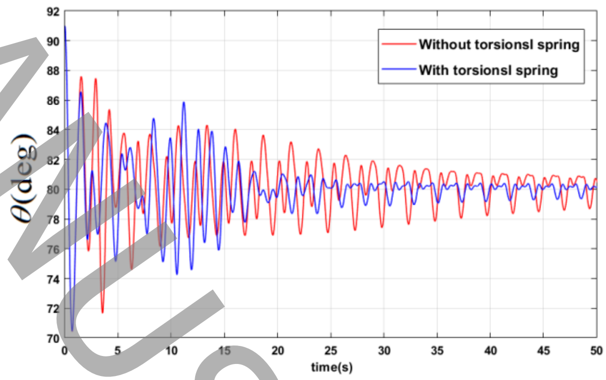

Figure 4. The role of tail movement as a vibration absorber

6. References

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