On Control of Flapping Flight of Butterfly with Experimental Observation

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Abstract: This study discusses controls of flapping flights of butterflies. Free-flying motions of butterflies are measured in a low-speed wind tunnel of an experimental system. A numerical model realizes a free flight by repeating of a joint motion, whereas the flapping flight is unstable. A feedback control is designed and it successfully stabilizes the free-flying motion of the butterfly model. The control of a living butterfly is analyzed by comparison between an experimental observation and a numerical simulation.

Keywords: Flapping flight, Butterfly, Control, Experimental observation

1. INTRODUCTION

Flapping flights of butterflies seem unstable, but in reality they are stable. Butterflies can maintain stable flapping flights robustly against environmental uncertainties and variations. References [1,2] have shown that free vortices in wakes generated by flapping provide a type of passive stabilization effects, but they cannot make butterflies' flights sufficiently stable. Therefore, the objective of this study is to clarify active controls of butterflies. The approach is as follows. At first, motions of living butterflies are experimentally observed in order to understand their controls. Secondly, an artificial feedback control is designed and implemented to an existing numerical simulator [1,2]. Finally, similarities and differences of two controls are analyzed by comparison between an experimental observation and a numerical simulation.

2. EXPERIMENTAL OBSERVATION

An experimental system with a low-speed wind tunnel (Fig. 1) has been constructed. A free-flying butterfly is put into the wind tunnel, and the flapping-of-wings motion in the flow is captured by three high-speed cameras. The joint angles of the butterfly are calculated from the measured positions of typical points on the body in video images. The variables that represent kinematics are defined in Fig. 2. The states of the thorax are represented by$[x, z, \theta_t]^T$ and the joint angles of the abdomen and wings are represented by $[\theta_a, \beta, \eta, \theta]^T$.

3. ARTIFICIAL FEEDBACK CONTROL

Eq. (1) is the perturbation equation that is a linear sampled-data system where sampling is taken every flapping period T [s] from the numerical simulator and linearized:

$$\delta \boldsymbol{x}(t_{k+1}) = \boldsymbol{A}\delta \boldsymbol{x}(t_k) + \boldsymbol{B}\delta \boldsymbol{u}(t_k), \qquad (1)$$

where $t_{k+1} = t_k + T$, $\boldsymbol{x} = [x, z, \theta_t, \dot{x}, \dot{z}, \dot{\theta}_t]^T$ the controlled-variable vector, $\boldsymbol{u}$ the manipulated-variable vector, and δ perturbation. Based on the optimal regu-

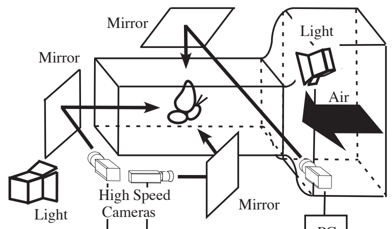

Fig. 1 Experimental setup.

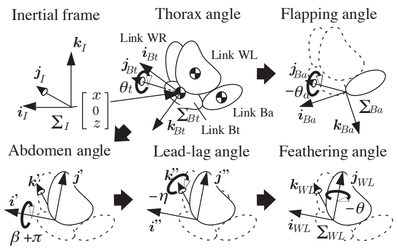

Fig. 2 Definition of the parameters on kinematics.

lator theory, a feedback-controller is designed as:

$$\delta \boldsymbol{u}(t_k) = -\boldsymbol{K}\delta \boldsymbol{x}(t_k), \qquad (2)$$

where $\boldsymbol{K}$ is a feedback gain.

The poles of the autonomous system are

$$\begin{gathered} 0.891,\ 0.597,\ 0.520,\ -0.0559, \\ -2.60 \times 10^{-5},\ 1.27 \times 10^{-4}, \end{gathered} \qquad (3)$$

where the controller is implemented to the nominal plant. On the other hand, the corresponding values of the original nonlinear simulator implemented by the controller are

$$0.957,\ 0.934,\ 0.915,\ 0.881,\ 0.797,\ 0.751. \qquad (4)$$

The magnitude of the value is the expansion rate of the corresponding mode. Each controlled system is stable because the all values are less than one and any perturbation reduces. However, the control performance is decreased because the controller is designed for the reduced-order and linearized plant and implemented to the original nonlinear model.

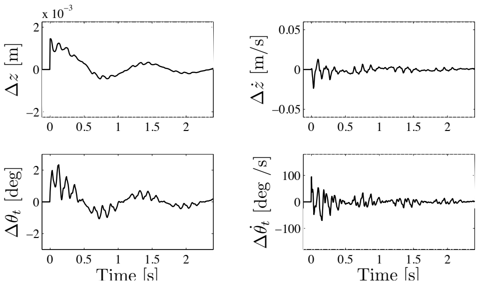

Fig. 3 Response of perturbations for 20 periods of simulator.

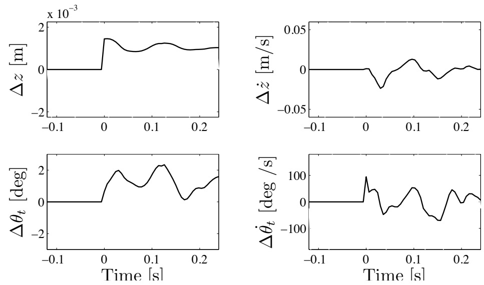

Fig. 4 Response of perturbations for 3 periods of simulator.

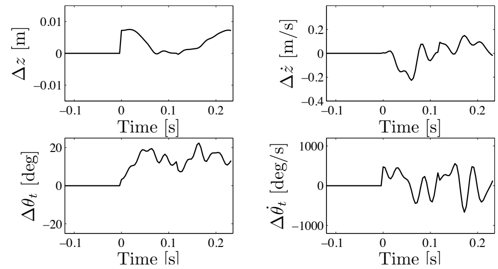

Fig. 5 Response of perturbations for 20 periods of living butterfly.

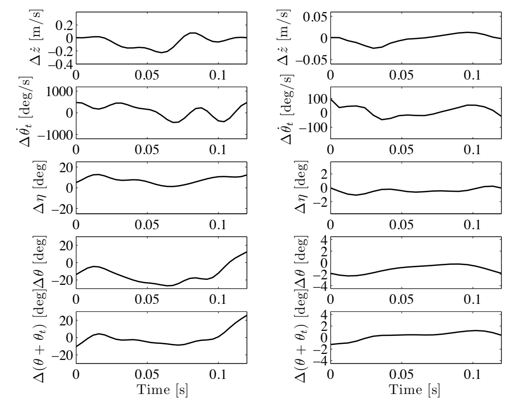

Fig. 6 Response of perturbations, left: experiment, right: simulator.

4. COMPARISON

A living butterfly repeats almost same periodic motion when it maintains steady flapping flight. But, each motion is slightly different from others. The standard trajectory is the most typical trajectory that is selected from the experimental data of an individual under the same condition. A perturbed trajectory is in a slightly different state at the beginning of downstroke, but it tends to approach the standard trajectory. For the simulator, the standard trajectory is when it maintains steady flapping flight, and a perturbed trajectory has one fifth of the initial perturbation of the experimental perturbed trajectory.

The response of a perturbation for 20 periods is shown in Fig. 3, where the initial perturbation is applied at the beginning of downstroke, time $t = 0$ [s]. The perturbation is reducing, and the control is stable.

Fig. 4 shows the first 3 periods of Fig. 3. Fig. 5 shows the response to the same initial perturbation observed in experiments that corresponds to the simulator. In this case, there are relatively large initial perturbations in $\dot{z}$ and $\dot{\theta}_t$. The former is negative and the latter is positive. Both controllers in the living butterfly and the simulator tend to suppresses increasing of the thorax angle and the descending speed. They are regarded as corresponding controllers because their transient response of the controlled variables are similar to each other.

Between the living butterfly and the simulator, their transient responses of the manipulated variables are compared. In case of the living butterfly, $\Delta(\theta + \theta_t)$ is kept almost 0 whereas $\Delta\theta$ is almost always negative value. If positive perturbation of $\Delta\theta_t$ is generated by an initial perturbation, the leading edge is twisted down, i.e. $\Delta\theta$ becomes negative, and $\Delta(\theta + \theta_t)$ is kept 0. Negative moment of force is applied to the thorax because of this wing torsion. The similar behavior is observed in the simulator.

On the other hand, there are differences to realize the $\Delta\theta$. The θ may be indirectly controlled by manipulating η because the butterfly seems difficult to drive θ directly. On the other hand, the simulator is modeled such that it can directly manipulate both η and θ independently. Therefore, the way to manipulate η is different from the living butterfly.

5. CONCLUSION

Comparison between the living butterfly and simulator has provided following results. Both control systems have been stabilized. Their transient responses of the controlled variables against the same perturbations have been similar, but those of the manipulated variables different. It might be because the simulator has not modeled some mechanical structures of living butterflies. Therefore, to design controllers considering the properties of living butterflies will help us to understand their control.

REFERENCES

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