Vibrational Control: Mysterious Stabilization Mechanism in Bioinspired Flying Robots

Haithem Taha*

Department of Mechanical and Aerospace Engineering, University of California, Irvine, CA, USA

Abstract. Over the past two decades, there has been consensus among the biology and engineering communities that insects are unstable at hover. Here, we discuss a hidden passive stabilization mechanism that insects exploit through their natural wing oscillations: vibrational stabilization. This stabilization technique cannot be captured using the common averaging approach in literature. In contrast, it is discovered using a special type of calculus: the chronological calculus. This result is supported via experiments on a real hawkmoth subjected to pitch disturbance from hovering and also demonstrated on a flapping robot. This finding is particularly useful to biologists from one hand as the vibrational stabilization mechanism may also be exploited by many other creatures: Nature is teeming with oscillatory species. From the other hand, the obtained results will enable the engineering community to develop more optimal designs for bio-inspired flying robots by relaxing the stability requirements.

Introduction

Flapping flight dynamics may be represented by the exact same set of equations that govern the flight dynamics of conventional airplanes, which can be written in an abstract form as

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{F}(\boldsymbol{x}, t) = \boldsymbol{f}(\boldsymbol{x}(t)) + \boldsymbol{g}_a(\boldsymbol{x}(t), \tau) \tag{1}$$

where the vector $\boldsymbol{f}$ represents inertial and gravitational loads and the vector $\boldsymbol{g}_a$ represents aerodynamic loads. A major distinction between flapping and conventional flight dynamics is that the former has a time-varying aerodynamic loads $\boldsymbol{g}_a$. Two symbols t and τ are used in Eq. (1) to denote the slow and fast time scales, respectively. The ratio between these two time scales is deceptively large; for the slowest flapping insect (the Hawkmoth), the ratio between the flapping frequency and the flight dynamics natural frequency is around 30 [1, 2], which naturally invokes averaging. That is, the aerodynamic loads oscillates with a too high frequency to affect the body. In other words, the body only feels the average values of the time-periodic aerodynamic loads. This assumption is found in most of flapping flight dynamics and control efforts.

Adopting the direct averaging assumption yields a nonlinear time-invariant (NLTI) system whose stability analysis is considerably easier than that of the nonlinear, time-periodic (NLTP) system (1). First of all, a periodic orbit representing equilibrium of the NLTP system (1) reduces to a fixed point (equilibrium point) of the NLTI system. Moreover, the averaging theorem guarantees exponential stability of a periodic orbit of the original NLTP (1) based on exponential stability of the corresponding fixed point of the NLTI system, provided that the flapping frequency is *high-enough*. Using this direct averaging approach, it has been known for a long time that insects are unstable at hover.

Results and discussion

Sarychev [3] developed higher-order averaging techniques for time-periodic systems, generalizing the classical averaging theorem to cases where the excitation frequency is not high-enough. In particular, Sarychev [3] introduced the notion of *complete averaging* for the nonlinear, time-periodic (NLTP) system as (1):

$$\dot{\overline{\boldsymbol{x}}}(t) = \epsilon\overline{\boldsymbol{F}}(\overline{\boldsymbol{x}}(t)) = \epsilon\boldsymbol{\Lambda}_1(\overline{\boldsymbol{x}}(t)) + \epsilon^2\boldsymbol{\Lambda}_2(\overline{\boldsymbol{x}}(t)) + ..., \tag{2}$$

where $\boldsymbol{\Lambda}_1(\boldsymbol{x}) = \frac{1}{T}\int_0^T \boldsymbol{F}(\boldsymbol{x}, t)\, dt$, and $\boldsymbol{\Lambda}_2(\boldsymbol{x}) = \frac{1}{2T}\int_0^T \left[\int_0^T \boldsymbol{F}(\boldsymbol{x}, \tau)\, d\tau, \boldsymbol{F}(\boldsymbol{x}, t)\right] dt$. That is, $\boldsymbol{\Lambda}_1$ simply represents the direct averaging contribution.

We used second-order averaging as discussed above to rigorously assess the flight dynamic stability of hovering insects. It is shown that the interaction between the periodic aerodynamic loads and the body motion induce stabilizing actions. In particular, it is found that $\boldsymbol{\Lambda}_2$ induces a pitch stiffness mechanism to the hovering flight dynamics, which is instrumental to static and dynamic stability of flying vehicles [4]. Therefore, the lack of pitch stiffness in $\boldsymbol{\Lambda}_1$ as predicted by direct averaging ultimately results in an unstable hovering flight dynamics of insects and FWMAVs. However, the adopted higher-order averaging techniques revealed a vibrational stabilization mechanism in insect flight dynamics at hover that is similar to the Stephenson-Kapitza pendulum.

References

[1] M. Sun, J. Wang, and Y. Xiong. Dynamic flight stability of hovering insects. *Acta Mechanica Sinica*, 23(3):231–246, 2007.

[2] H. Taha, M. R. Hajj, and A. H. Nayfeh. On the longitudinal flight dynamics of hovering mavs/insects. *Journal of Guidance Control and Dynamics*, 37(3):970–978, 2014.

[3] A. Sarychev. Stability criteria for time-periodic systems via high-order averaging techniques. In *Nonlinear Control in the Year 2000*, volume 2 of *Lecture Notes in Control and Information Sciences*, pages 365–377. Springer-Verlag, 2001.

[4] R. C. Nelson. *Flight stability and automatic control*, volume 2. WCB/McGraw Hill New York, 1998.