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Matěj Karásek

Studies of insect flight reveal how flapping-induced vibrations augment flight stability of tailless flapping-wing flyers.

The field of aerial robots is currently dominated by propeller-based designs. Recent developments in bioinspired flyers, however, suggest that flapping-wing propulsion is becoming a promising alternative (*1*, *2*). This is particularly true at small scales, where flapping-wing drones could offer better flight performance (high agility and power efficiency in hover as well as in forward/sideways flight) combined with inherent safety (low weight, no fast spinning sharp blades, tolerance of obstacles) and greater societal acceptance (natural sound and appearance) (*3*). For now, though, the performance of flapping-wing robots remains inferior to conventional drone designs predominantly due to technological constraints (lack of powerful and lightweight muscle-like actuators needed for wing actuation) and, to some extent, an incomplete understanding of the underlying physics of these complex systems.

The time-varying, nonlinear, and unsteady nature of flapping-wing aerodynamics poses great challenges in mathematical modeling and, consequently, in stability analysis and control design (*4*). To overcome these challenges, most studies employ analytical methods such as rigid body assumption, cycle averaging, and linearization. These techniques allow traditional (control-) engineering tools, which have been developed for conventional systems, to be used (*4*, *5*). However, such an approach may not always be appropriate. Writing in *Science Robotics*, Taha *et al.* (*6*) show that employing classical direct averaging methods to a time-varying model of hovering flapping-wing flight can lead to the omission of a major part of the system dynamics. In fact, including the omitted dynamics could, in some cases, even lead to inherent, passive stability of otherwise unstable systems. The authors term this newly discovered mechanism in insect flight "vibrational stabilization," because this stability augmentation originates from the body oscillations induced by wing flapping.

Stabilization through vibration is not a new phenomenon. The Kapitza pendulum is a classic example (*7*)—an inverted pendulum whose pivot point can vibrate in the vertical direction. The pendulum will remain stable in its inverted position if the pivot point is driven at a correct (high) frequency and (small) amplitude. Motivated by this phenomenon, Taha and co-workers analyzed the longitudinal flight stability of hovering tail-less fliers while including also (part of) the flapping-wing dynamics. To reduce the model complexity, they employed higher-order averaging techniques for time-periodic systems (*8*). With only the first-order averaging terms included (equivalent to classical, direct averaging), their linearized model predicted an unstable system, with dynamic behavior that was consistent with what has been reported in the literature: a diverging, coupled oscillation of forward and pitching motion (*4*, *5*). However, when the second-order terms were also included, an additional pitch stiffness term, representing a stabilizing spring action, was revealed. This stiffness originates from horizontal body oscillations at double the flapping frequency, which the previous models, averaging over the entire wingbeat, ignored.

The new theory further suggests that the contribution of the vibrational stabilization increases as the flapping frequency decreases (Fig. 1). For small insects with high flapping frequency, such as fruit flies and parasitic wasps, the vibrational stabilization contribution is negligible, and a conventional, direct averaging approach remains sufficient to model these. Conversely, for larger flyers with low flapping frequency, such as hawkmoths and hummingbirds, this contribution becomes substantial, and the model even predicts inherent, passive stability. This finding is new and, in the context of the general consensus about insect flight being unstable (*4*, *5*), certainly surprising. Nevertheless, it had previously been known that averaging the flapping effects is a valid approach only in smaller fliers, where the time scales of wing flapping and of the dynamics of the flyer are sufficiently far apart (*4*), and should only be applied to larger systems with caution.

To further support their theory, the authors analyzed hawkmoth flight data in the recovery phase just after a pitch disturbance. The predicted vibrational stabilization contributions are, in comparison to the pitch damping predicted by the existing models, dominant especially in the case of a large pitch disturbance, showing that the new mechanism could indeed play an important role in disturbance rejection. The theory could also explain why hawkmoths can fly even when their antennae (serving as inertial sensors) are clipped off (*9*).

To date, tail-less flapping-wing flight has only been achieved with robots equipped with active stabilization (*2*, *3*). It remains to be seen whether inherently stable robots can be designed, as predicted by the theory, or whether the real stability augmentation will be less effective due to the simplifying assumptions made. Nevertheless, vibrational stability augmentation could become one of the factors driving the choice of design parameters, especially in larger robotic flappers.

This newly introduced theory shows that modeling of flapping flight remains complex and that applicability of commonly employed techniques such as cycle averaging needs to be revisited. It is also exciting to see that vibrations can play yet another surprising role in flapping flight and its stability. Insects such as flies exploit resonance of their thorax to flap their wings (*10*), and oscillations of body appendages (halteres and antennas) are used by many insect species to sense their body rotations through Coriolis effect (*9*, *10*). Correspondingly, resonance is being exploited also by artificial

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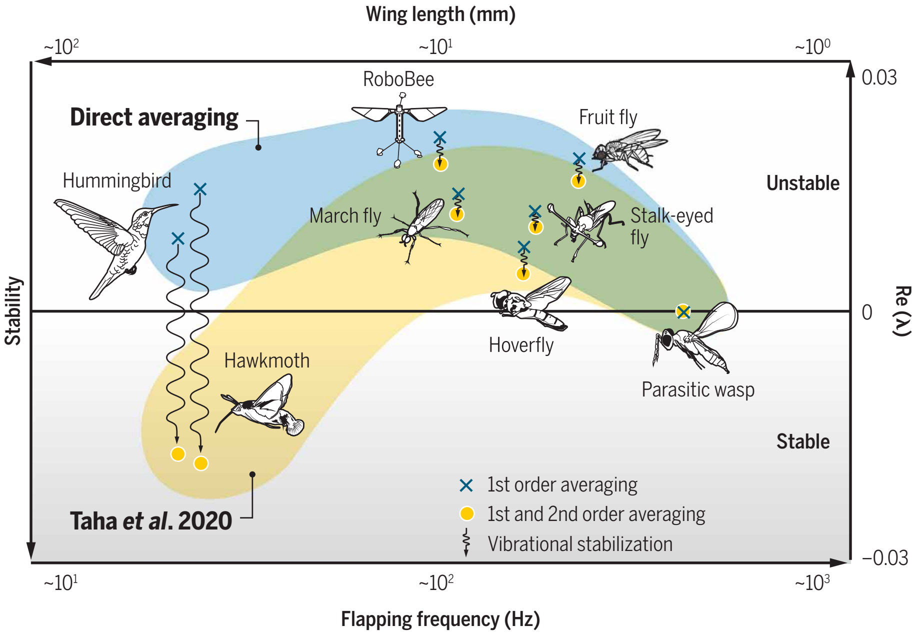

Fig. 1. Flight stability of several flapping-wing flyers. Stability is predicted by direct (first order) averaging (used in all previous stability models) and by the new model by Taha *et al*. that also includes vibrational stabilization (second order averaging). The stability of the system is characterized by the real part of its most unstable eigenvalue; the contribution of the newly discovered vibrational stabilization is represented by the black arrows. For small flyers (short wing lengths, high flapping frequencies), this contribution is negligible; however, the role of vibrational stabilization becomes notable in larger flyers and could even lead to inherent stability in hawkmoths and hummingbirds according to the new theory.

flapping-wing robots, for power-efficient propulsion (*1*) as well as in the MEMS sensors (gyroscopes and accelerometers) needed for active flight stabilization (*2*). Vibrational stabilization is thus another piece of the puzzle, which could bring flapping-wing robots a step closer to their biological counterparts.

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Competing interests: M.K. is CEO of Flapper Drones B.V., which develops flapping-wing drones for the entertainment industry.

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