Emergent wing-stroke in asynchronous insects and robots is governed by time-delayed strain rate feedback

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Background

The wing motion of many flying insects is generated by pairs of antagonistic power muscles that pull on the elastic exoskeleton which transmits motion to rotational wing hinges (Fig. 1). Insect flight muscle is typically characterized as either **synchronous** or **asynchronous.** Asynchronous muscle is a specialized type that experiences a **delayed increase in tension** (Fig. 2) in response to a step strain increase, a phenomenon known as **delayed stretch-activation (dSA).**

When arranged antagonistically, asynchronous muscles **self-oscillate**, enabling high-frequency wingbeats in flies, bees, and other insects [1]. While the physiology of dSA muscle in isolation has been studied extensively, **the interaction of body elasticity, asynchronous muscle, and aerodynamic loading in a complete "spring-wing" mechanical system has not been examined.**

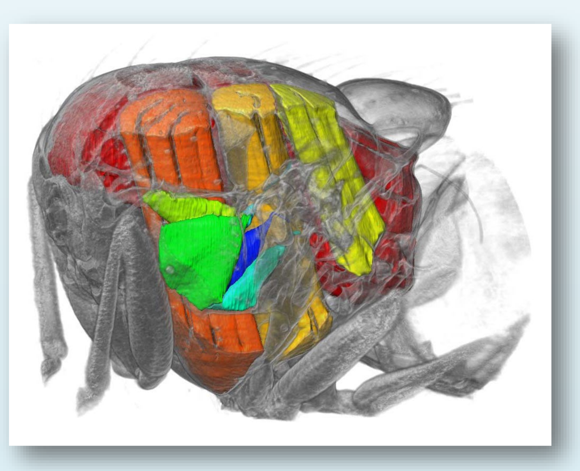


Figure 1. Cutaway visualization of a blowfly thorax with antagonistic power muscles shown in red and yellow [2]

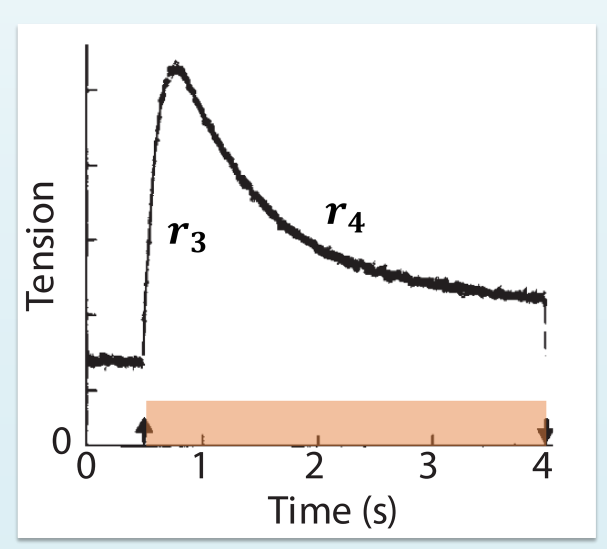


Figure 2. Transient dSA tension response from the giant waterbug *L. indicus* [3].

A Feedback-Based Model of dSA

The transient dSA response, taken as a sum of exponents – a slow rise with **rate r_3** and slower decay with **rate r_4** (Fig 2.) – and a constant may be expressed as

$$\tilde{F}_a(t) = (1 - e^{r_3 t}) + e^{-r_4 t} - 1$$

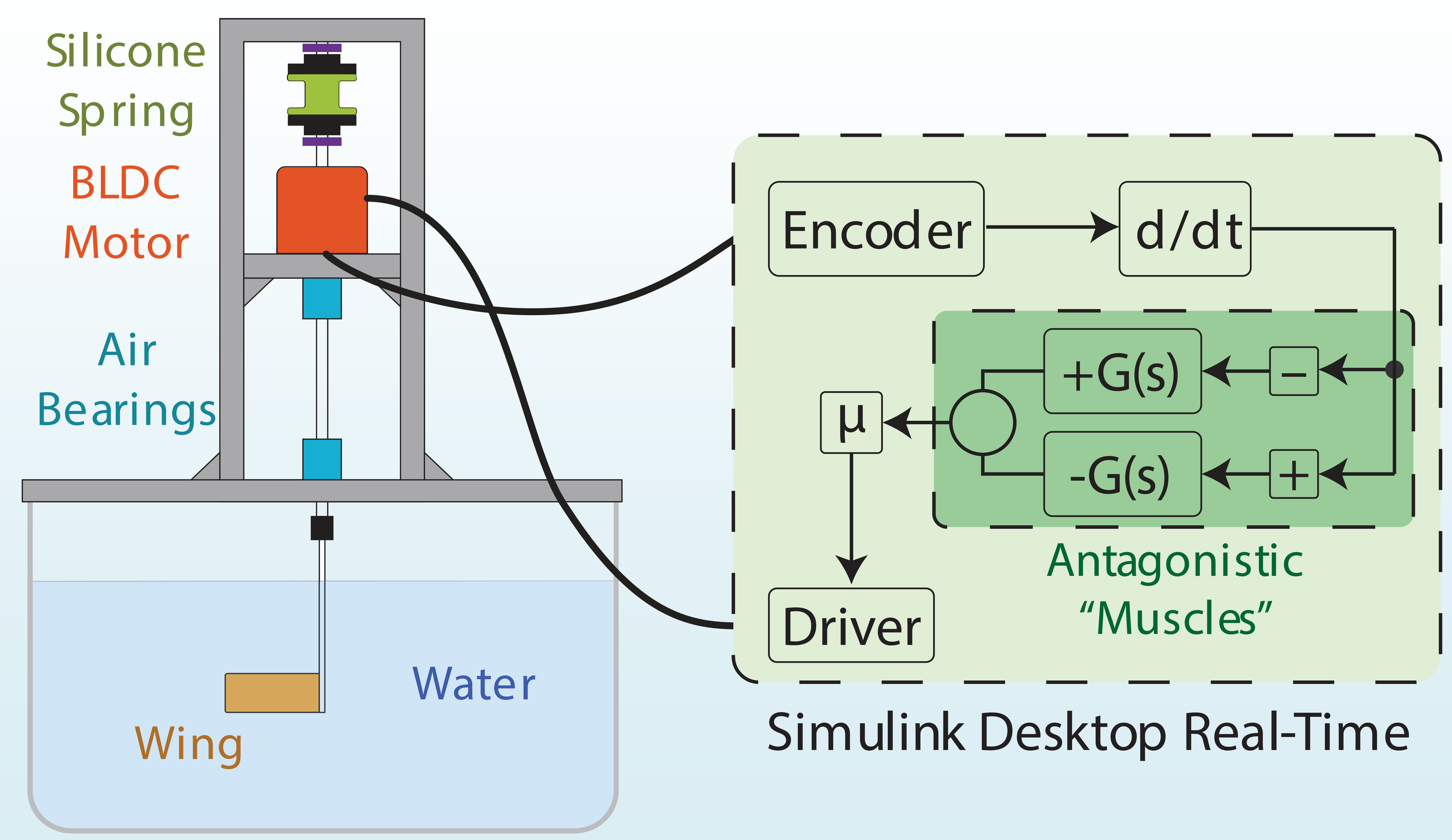
Since $\tilde{F}_a(t)$ is the response of the muscle to a **strain-rate impulse (strain step),** the Laplace transform of the response yields the **transfer function** from strain rate to muscle force:

$$G(s) = \frac{\tilde{F}_a(s)}{V(s)} = \frac{r_3 - r_4}{s^2 + (r_3 + r_4)s + r_3 r_4}$$

The impulse response of this transfer function is qualitatively similar to insect muscle response data and the transfer function has a form that

1. Is easily integrated into a feedback control system
2. Can be parameterized by 2 rates, r_3 and r_4, and a strength term, μ

Experimental Methods



We built a **dynamically-scaled spring-wing system** (detailed in [4]) of a flapping insect consisting of

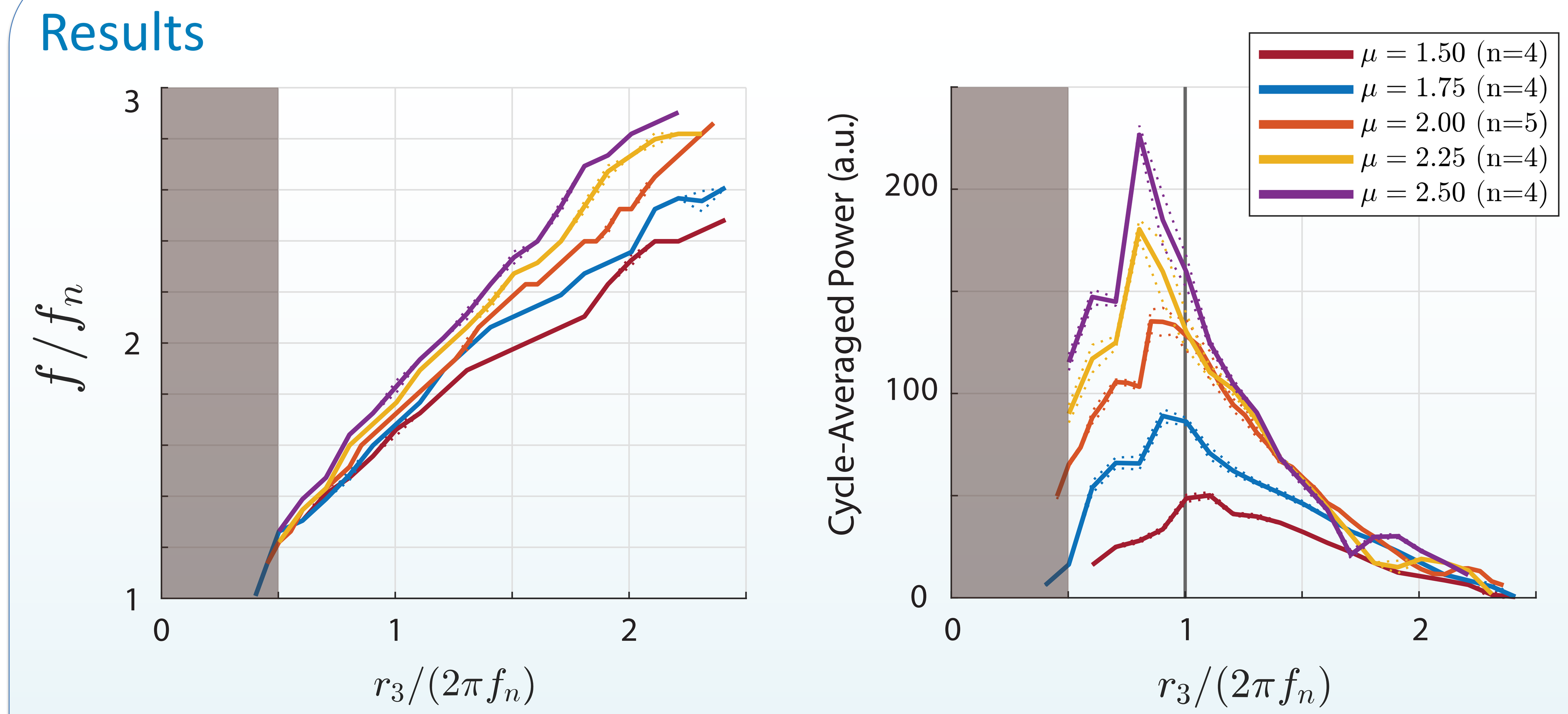
- A fixed-pitch rigid wing in water, driven by a torque-controlled BLDC motor
- A silicone torsion spring approximating elastic elements in the insect thorax
- A control system in Simulink Desktop Real-Time that measures wing angle (strain), computes the forces from antagonistic "muscle" blocks, and sends torque commands to the motor driver

Oscillations were induced by providing a torque "kick" to overcome friction.

We measured how **frequency** and **cycle-averaged power** varied when we varied:

- **The rate parameter r_3** (holding $r_4 = 0.8r_3$) from $\sim 0.5(2\pi f_n)$ to $\sim 2.5(2\pi f_n)$, where $f_n = 2.4\ Hz$ is the natural frequency of the system
- **The strength parameter μ** from 1.5 to 2.5 (constrained by hardware limits)

Results



The above plots show the resulting frequencies and cycle-averaged power, respectively, of the emergent oscillations at each value of r_3. Different colors represent values of μ, and the dotted lines indicate the upper and lower 95% confidence bounds.

- **No oscillations at low values of r_3,** though the exact value at which they begin varies with μ
- Oscillation frequency **increases with r_3**, and oscillation frequencies are **consistently higher than the system's natural frequency**
- Despite higher frequencies, decreasing oscillation amplitudes lead to a **peak in cycle-averaged power around $r_3 = 2\pi f_n$ (gray line),** followed by a drop-off at higher values of r_3

Discussion & Conclusions

1. Our results corroborate observations from muscle physiology literature, suggesting that **our model captures important features of asynchronous muscle dynamics.**
   - Molloy showed that w.b.f. is proportional to r_3 [3].
   - Pringle [5] suggested that peak power should correspond to $r_3 = 2\pi f_n$
2. We show that **emergent asynchronous oscillations depend on muscle parameters AND mechanical system parameters**
   - Peak power changes with muscle strength
   - Internal friction must be overcome to induce oscillations
   - Oscillation frequencies will always be near, *but not equal to* the natural frequency of the system
3. This simple formulation allows us to learn **how insects and robots may achieve control by modulating the material properties (stiffness, inertia, etc.) of their flight anatomy** rather than the muscle/actuator input

References

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[5] Pringle, J. W. S. (1978).