

TRIMMED FLIGHT OF FLAPPING-WING MICRO-AIR VEHICLES

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MOTIVATION

Why MAV?

There has been a **growing interest** in the last decade to develop Micro-Air Vehicles (MAV) due to the **wide range of applications** envisioned for them:

- ✓ Remote monitoring
- ✓ Aid in Agriculture activities
- ✓ Search and Rescue
- ✓ Communication support
- ✓ Extraterrestrial exploration

Why Flapping Wings?

Small scale MAVs work on **low Reynolds regimes**, where $Re \sim O(10^2 - 10^3)$

Low-speed operation of MAVs lead to **unsteady aerodynamics**, with similar convective and flapping characteristic times

$$t_{flapping} \sim t_{convective}$$

Solution in nature are flapping-wings due to **maneuverability** and **energy efficiency**

What is the research gap?

There exists **no complete model** for the FSI problem of flapping-wing MAVs due to the complex **aero-structural-dynamics coupling**

Reference	Aerodynamic Model	Dynamical Model	Wing inertia
[1]	BEM	Multibody	Negligible
[2]	~DNS	Central rigid body	~Included
[3]	BEM	Central rigid body	~Included
[4]	BEM	Central rigid body	~Included
Present	DNS	Multibody	Included



OBJECTIVES

- ✓ Develop a numerical tool to compute **trimmed flight solutions** of FWMVs, coupling **fluid DNS** with **rigid-body** solvers
- ⌚ Analyze aerodynamic **performance and stability** of trimmed flight solutions
- ⌚ Extend the solver to **flexible** bodies, assessing the full **aero-structural-dynamic problem**
- ⌚ Generate Reduced Order Models (**ROM**) of flight dynamics **for control**



METHODOLOGY

FWMV model

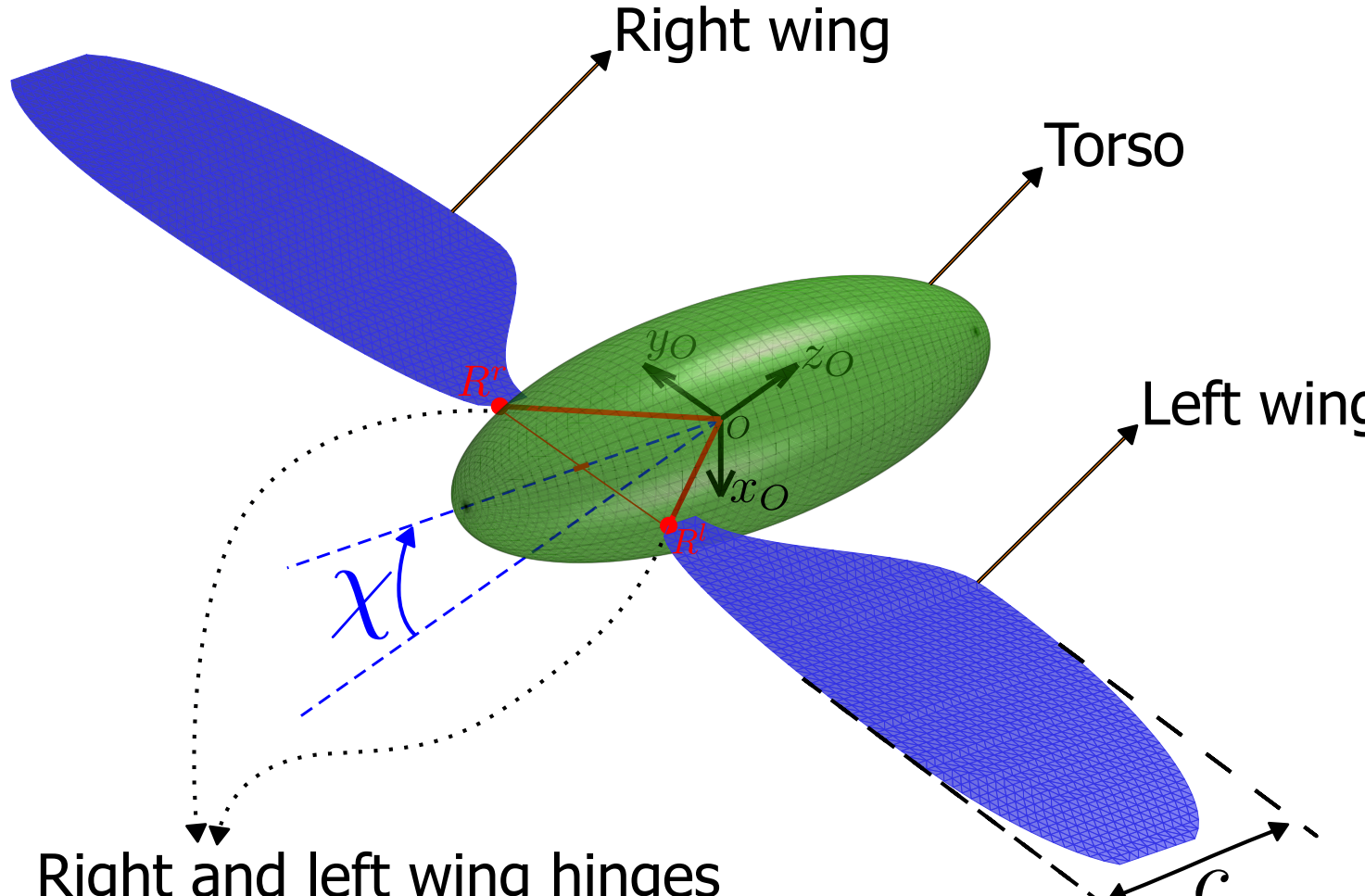
System of rigid bodies inspired on **fruit fly**

$$f = 200[\text{Hz}] \quad Re_{tip} = 275 \rightarrow Re_0$$

Body kinematics with 2-1-2 wing Euler angles

Stroke plane: $\beta = \beta_m + \beta_0 \cdot \sin(2 \cdot \pi \cdot f \cdot t)$
Flapping: $\phi = \phi_0 \cdot \sin(2 \cdot \pi \cdot f \cdot t)$
Pitching: $\alpha = \alpha_0 \cdot \sin(2 \cdot \pi \cdot f \cdot t + \Delta\alpha)$

$x, \dot{x}$: vertical position and velocity
 $z, \dot{z}$: horizontal position and velocity
 $\chi, \dot{\chi}$: torso pitching and angular rate



Trimmed-flight solver - Hover

Flapping-wing vehicles show **time-periodic trimmed flight** solutions

Solution is sought in a flapping period $T = 1/f$ for a state vector q

$$G(q) \begin{cases} x(t=T) - x(t=0) \\ z(t=T) - z(t=0) \\ \chi(t=T) - \chi(t=0) \\ \dot{x}(t=T) - \dot{x}(t=0) \\ \dot{z}(t=T) - \dot{z}(t=0) \\ \dot{\chi}(t=T) - \dot{\chi}(t=0) \\ F_i(t=T) - F_i(t=0) \end{cases} = 0$$

$$q = [\dot{x}(t=0), \dot{z}(t=0), \chi(t=0), \dot{\chi}(t=0), \phi_0, \beta_m, F_i(t=0)]$$

Vehicle kinematics Fluid flow

Fluid-Structure Interaction model

Fluid flow solved using the Incompressible Navier-Stokes equations

→ **TUCAN:** In-house GPU-accelerated **DNS solver** [6], using Immersed Boundary Method [7]

Body Dynamics: Solved through the Rigid Body Dynamics Library [8]

$$\nabla \cdot u = 0$$

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\nabla p + \frac{1}{Re} \nabla^2 u + \underbrace{f}_{\text{Immersed-Boundary forcing to ensure no-slip at the body surfaces}}$$

$$\bar{H} \cdot \bar{g} + c = \xi + \underbrace{\xi_h}_{\text{coupling}}$$

$$g = [x, z, \chi, \beta^r, \phi^r, \alpha^r, \beta^l, \phi^l, \alpha^l]$$

Generalized position vector

Solver Jacobian-Free Newton-Krylov

An **iterative-based** solver integrating body dynamics and fluid variables, leveraging on the **GMRES** algorithm to solve the resulting linear system of equations.

$$G(q^*) = G(q_0 + \Delta q) = 0$$

Problem linearization

$$J \cdot \Delta q = -G(q_0)$$

Create an orthogonal basis using Krylov subspaces

$$K_r = [G(q_0), J \cdot G(q_0), \dots, J^{r-1} \cdot G(q_0)]$$

Solution spanned by K_r

$$\Delta q = \underset{||J \cdot \Delta q + G(q_0)||}{\text{argmin}}$$

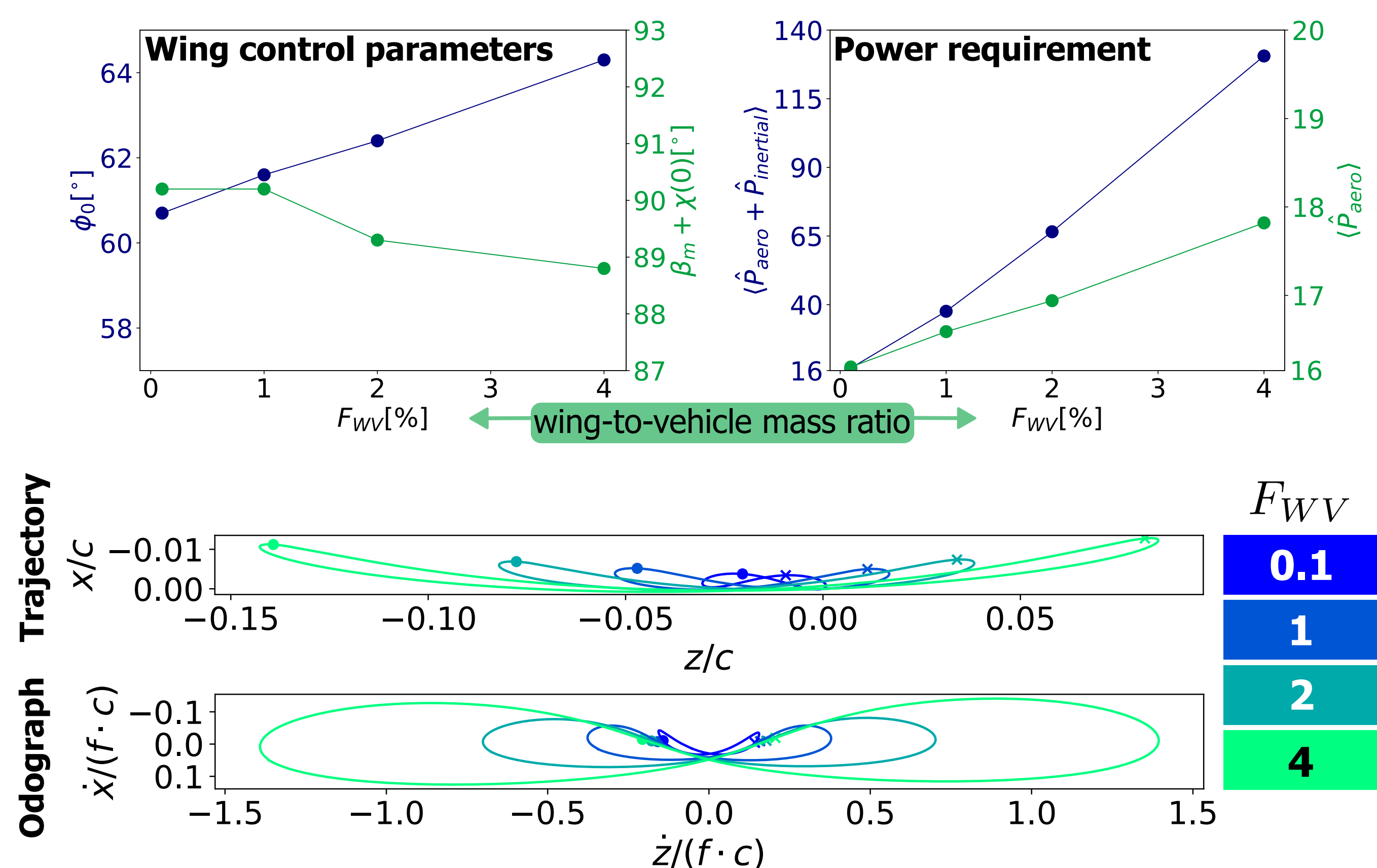
Update state vector guess

$$q_0^* = q_0 + \Delta q$$

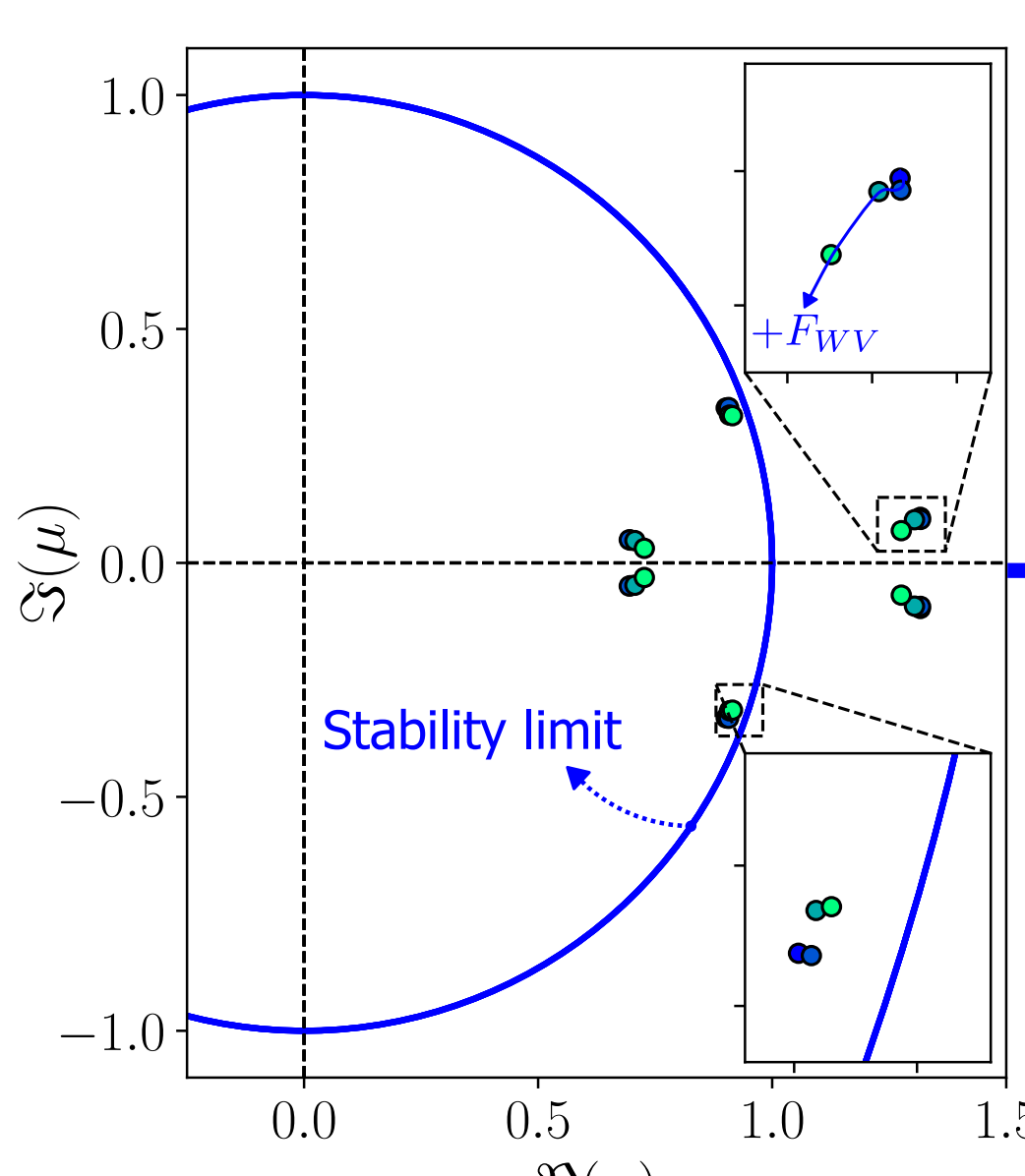
RESULTS

Initial hypothesis: Solutions are achievable neglecting the fluid degrees of freedom in the trimmed-flight solver $\Rightarrow$ ✗

Analysis of wing-inertia effects



Stability analysis: Linear stability assessed via Floquet multipliers μ



Time-to-double a initial perturbation

$F_{WV} [\%]$	t_2/T
0.1	2.5
1	2.5
2	2.58
4	2.83

Flow video



$$\uparrow ||G||_2 \sim O(10^{-3})$$

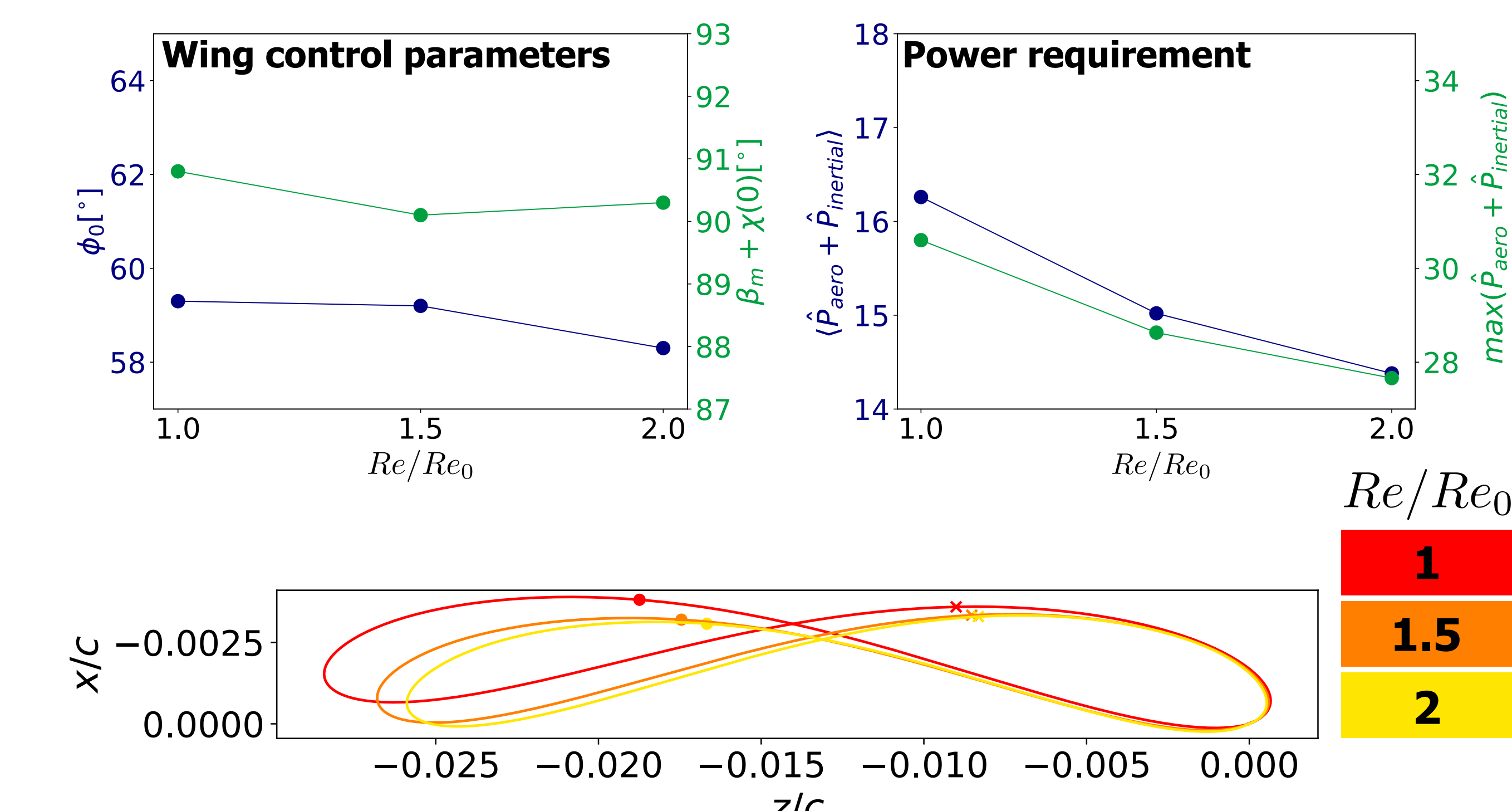
$$\downarrow ||G||_2 \sim O(10^{-4})$$

Refined hypothesis: More accurate solutions are achievable including a latent space of fluid degrees of freedom in the solver $\Rightarrow$ ✓

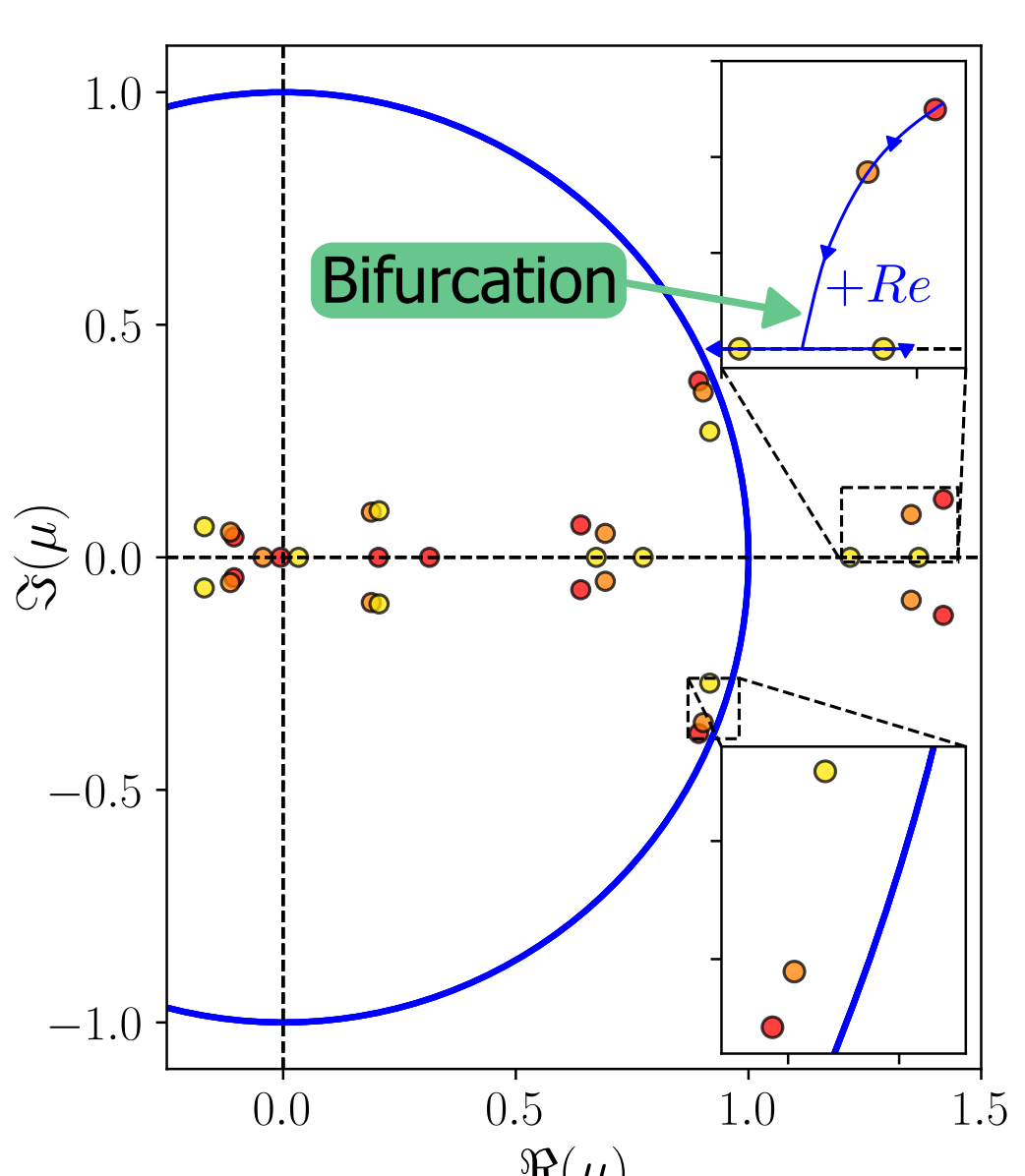
$$u(x, t) \xrightarrow{\text{POD: } n \text{ modes}} u(x, t=0) = \sum_{i=1}^r \Phi_i \cdot F_i(t=0) + \sum_{i=r+1}^n \Phi_i \cdot W_i(t=0)$$

$u(x, t) = \Phi(x) \cdot W(t)$ Latent space

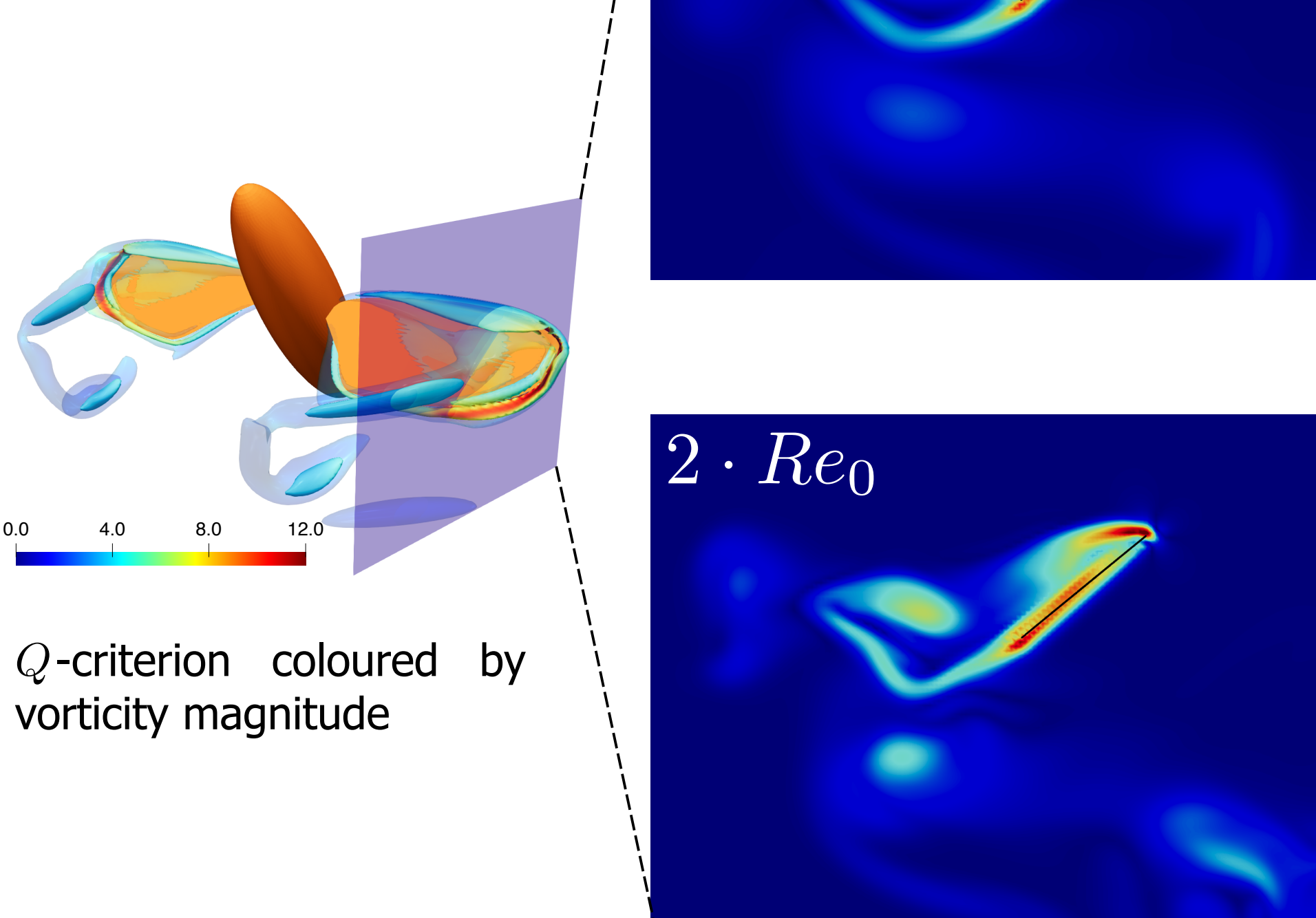
Analysis of Re



Stability analysis:



Flow visualization:



References

- [1] Bhatti, M. Y., & Addo-Akoto, R. (2022). Influence of Wing Kinematics on Lateral Dynamic Stability of Bioinspired Flapping Wing
- [2] Dietl, J. M., & Garcia, E. (2012). Stability in Ornithopter Longitudinal Flight Dynamics.
- [3] Orlowski, C. T., & Girard, A. R. (2011). Modeling and Simulation of Nonlinear Dynamics of Flapping Wing Micro Air Vehicles.
- [4] Sun, M., Wang, J., & Xiong, Y. (2007). Dynamic flight stability of hovering insects. Acta Mech. Sin.
- [5] Roy Eglhoff, CC BY-SA 4.0
- [6] Guerrero-Hurtado et al. (2024). A Python-based flow solver for numerical simulations using an IBM. Arxiv.
- [7] Uhlmann, M. (2005). An Immersed Boundary Method with Direct Forcing for the Simulation of Particulate Flows. J.Comput.Phys.
- [8] Felis, M.L. (2017). RBDL: An efficient rigid-body dynamics library. Auton. Robots

CONCLUSIONS

- ✓ Periodic orbits achieved for the FSI problem of FWMVs
- ✓ Stability analysis depict unstable periodic orbit solutions
- ✓ Increasing wing inertia produces larger vehicle motion and power consumption
- ✓ Increasing Re produces a bifurcation of the most unstable Floquet multiplier