Aerodynamic Forces on a Wing Surfing in a Two-dimensional Vortex Wake

Siyang Hao*, Pedro Costa Ormonde, Kenneth. Breuer
School of Engineering, Center for Fluid Mechanics
Brown University

BROWN — Breuer Lab — NSF

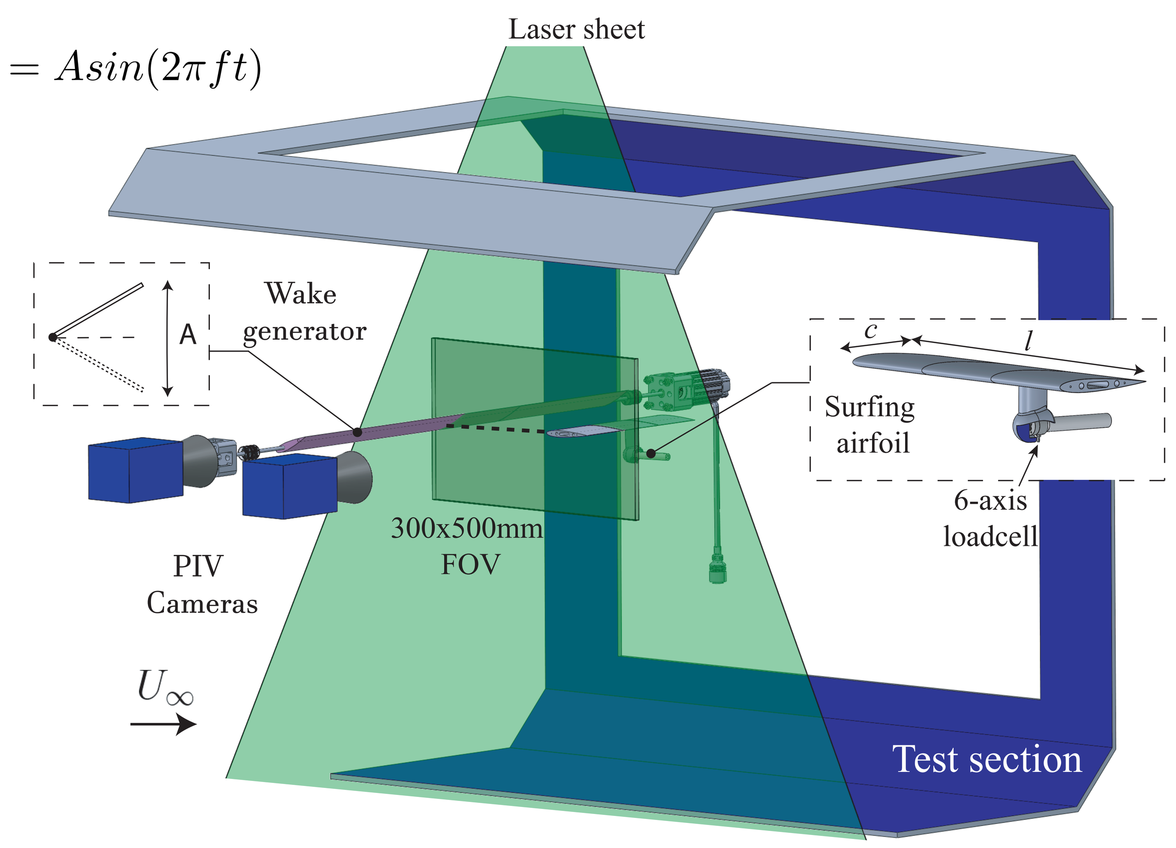
MOTIVATION

- Understand the aerodynamic force variation on a wing surfing in an unsteady 2-D wake
- Determine dependence of the overall lift fluctuations on the up-stream flapping kinematics
- Provide further interpretation of the dynamics in animal flocking

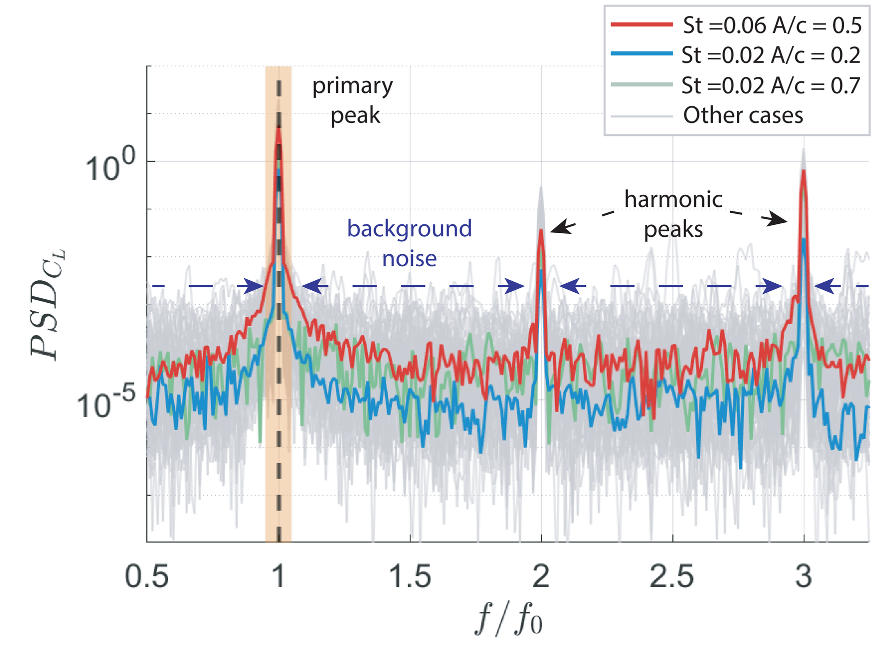
EXPERIMENTAL SETUP

- A servo-driven wake generator with a flat plate pitching sinusoidally upstream.
- A NACA 0012 wing, placed 350 mm downstream, was mounted on a load cell to measure forces at 5000 Hz over 100 cycles.
- Vortex dynamics were captured via 2D2C PIV.
- The entire setup was automated by Matlab, with synchronized data acquisition.

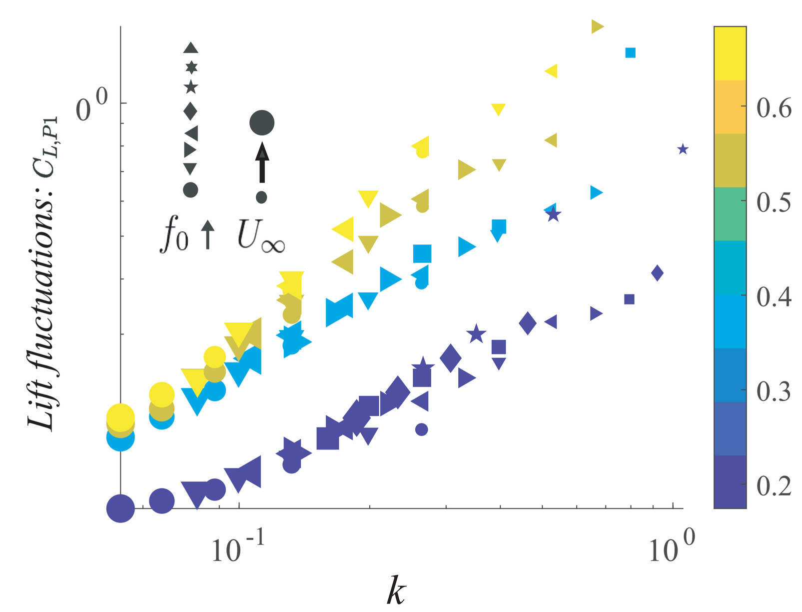
$\theta(t) = A sin(2\pi f t)$

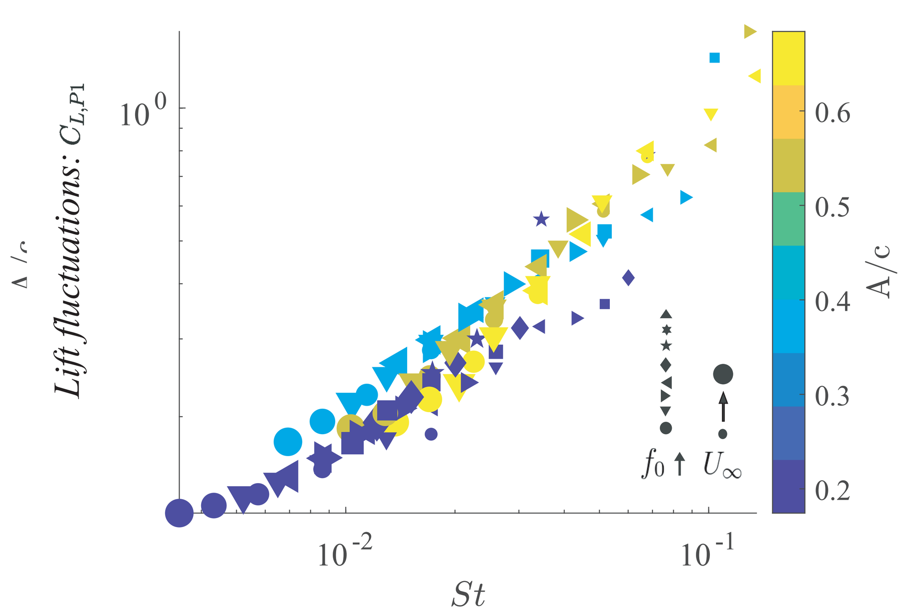


CYCLE-LEVEL LIFT FLUCTUATIONS



A. Power spectral density (PSD_{C_L}) of the lift coefficient for all measurements, with the example cases highlighted. The majority of the spectral energy (58%-99%) are distributed in the primary peak (highlighted in orange).





B. Narrow band integral

$$C_{L,P1} = \sqrt{\int_{0.95}^{1.05} PSD_{C_L}\, d\frac{f}{f_0}}$$

is used to quantify the cycle-level lift fluctuation.

C. To account for this A/c and k deviation, is plotted as a function of the Strouhal number, $St = fA/U_\infty$

PHASE-RESOLVED LIFT PREDICTION WITH UNSTEADY AERODYNAMICS

$C_{L,QS,2D} = 2\pi\alpha_{ins}$ — Duhamel's integral

Time-domain approach $C_{L,W}(t) = \left[C_{L,QS,2D}(0)\Phi(\tau) + \int_0^\tau \Phi(\tau - \tau_0)\frac{dC_{L,QS,2D}}{d\tau_0}d\tau_0\right]\frac{AR}{AR+2}$

Wagner (or Küssner) function — Aspect Ratio Correction

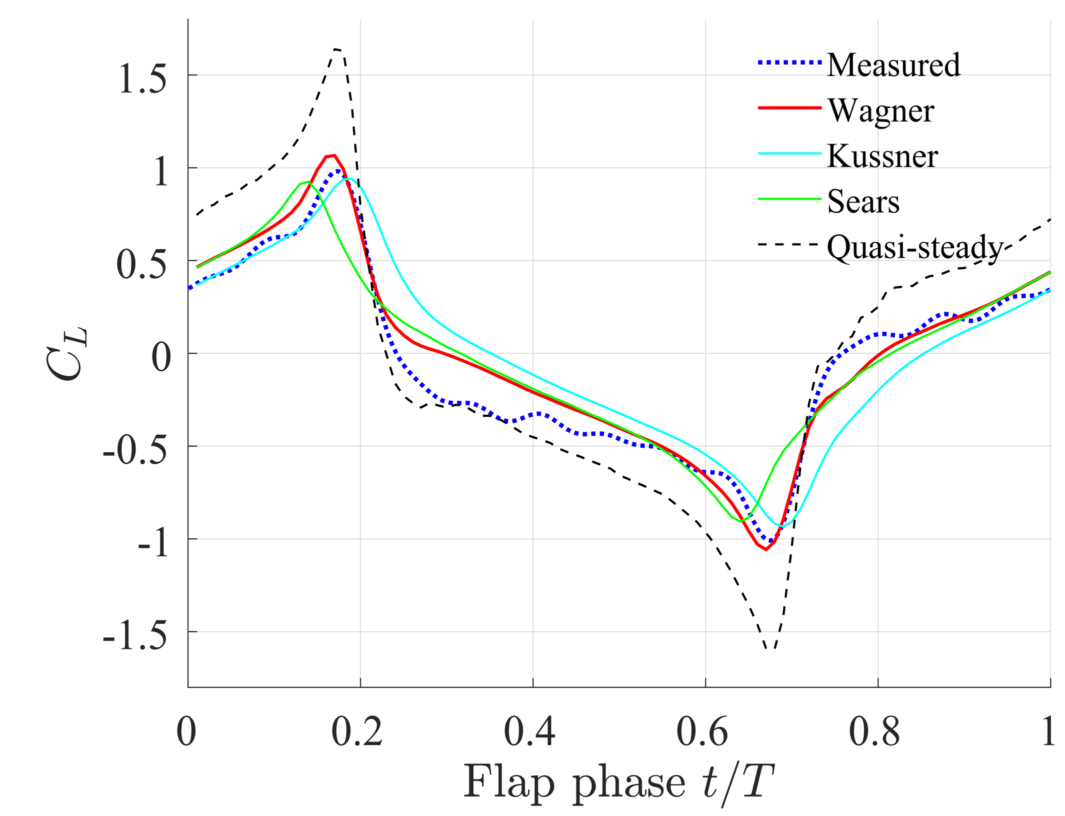
Sears function

Frequency-domain approach $C_{L,S}(t) = \mathcal{F}^{-1}\{\mathcal{F}\{C_{L,QS,2D}(t)\}\cdot S(k)\}\frac{AR}{AR+2}$

$\tau = \frac{2tu}{c}$

$k = \frac{\pi c f}{U_\infty}$

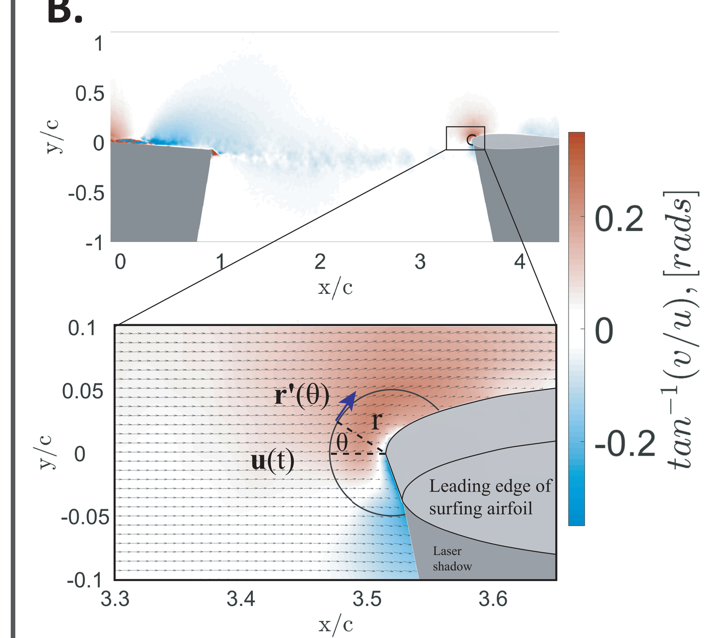
A.



A. Comparison of unsteady approaches

- Quasi-steady approach shows a massive over prediction.
- The Wagner function with Duhamel's integral has the closest prediction compared to the directly measured data
- The Küssner function with Duhamel's integral exhibits a greater phase delay
- Sear's function applied with Fourier synthesis has good estimation of amplitude but lacks phase-wise accuracy in this case

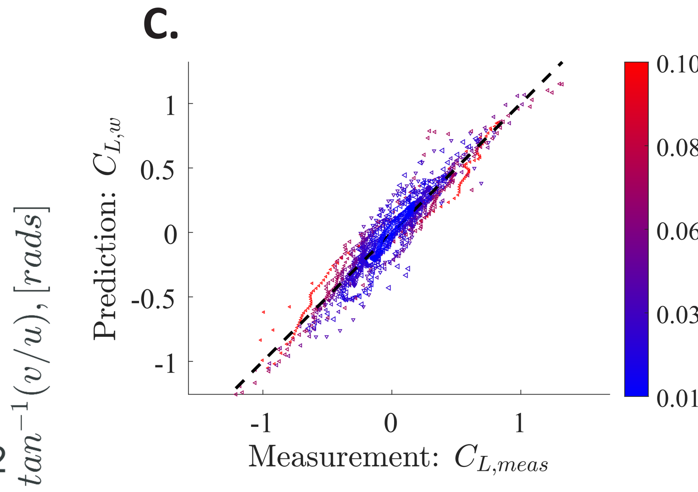
B.



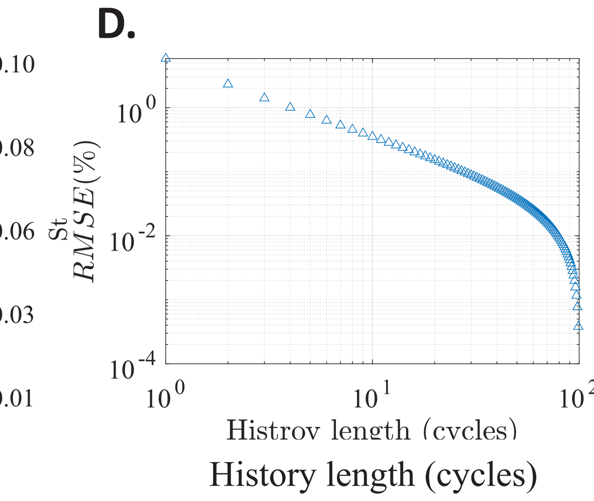
$\alpha_{ins}(t) = \arg\min_\theta (|\mathbf{u}(t)\cdot \mathbf{r}'(\theta)|)$

B. Instantaneous angle of attack sampling from PIV data

C.



D.

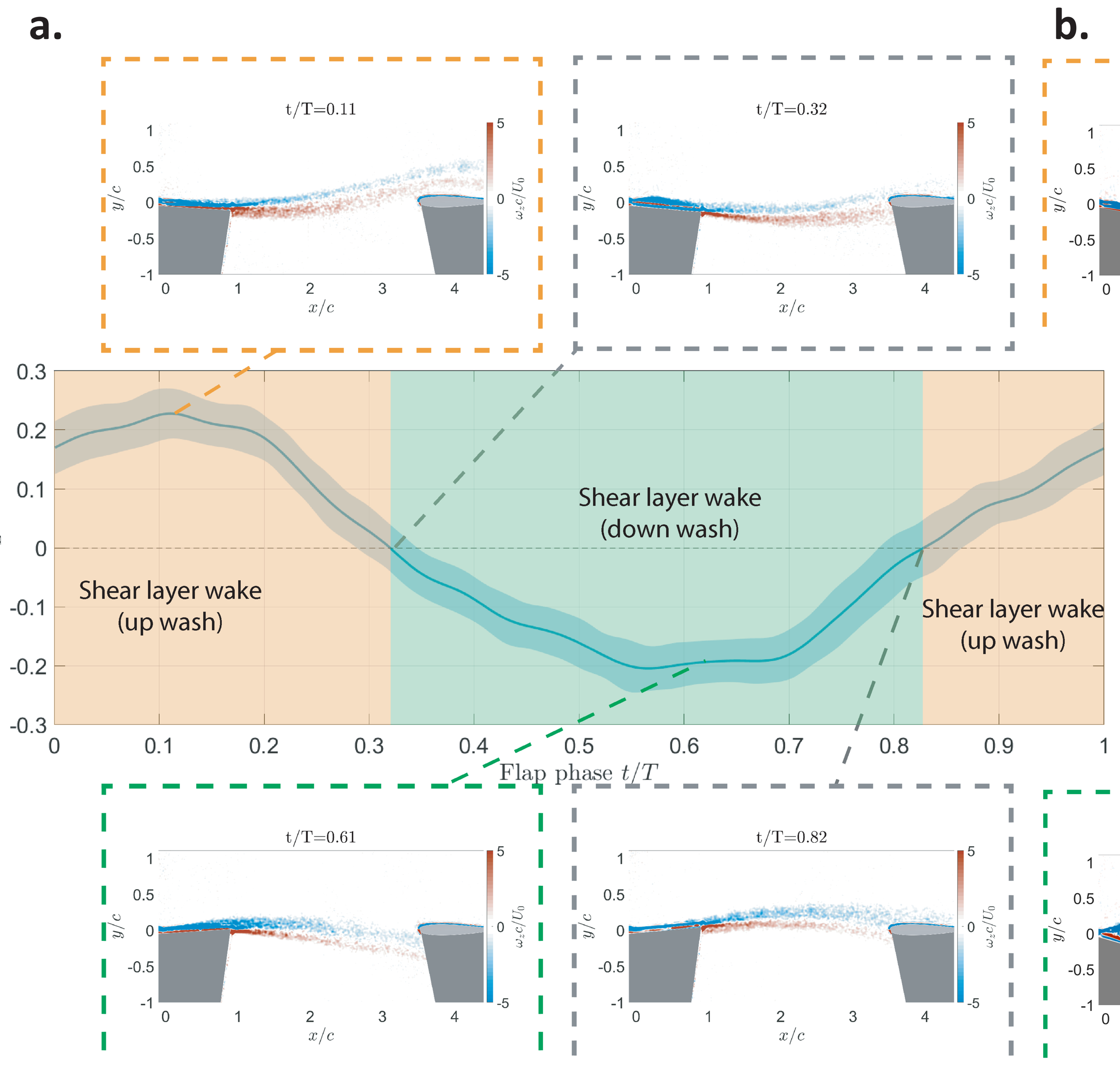


C. Frame-by-frame comparison of calculated vs. measured lift coefficient for various St numbers (14 cases, 1400 frames) by Wagner approach.

D. Convergence of the predictions: $RMSE = RMS(C_{L,w,cycn} - C_{L,w,cyc100})/C_{L,max}$ of the Wagner approach as a function of time history length included in the calculation comparing with the final result with 100 cycles

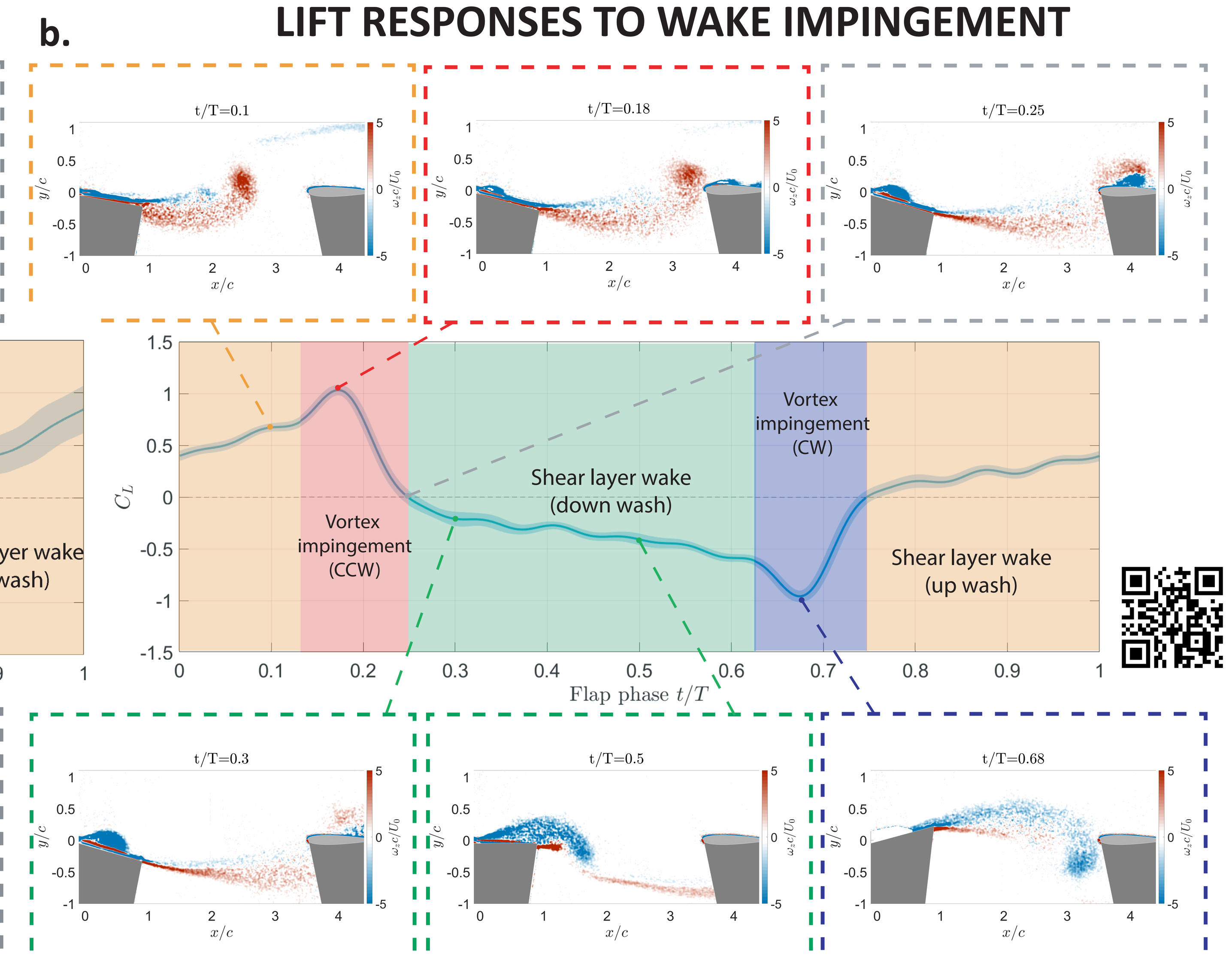
LIFT RESPONSES TO WAKE IMPINGEMENT

a.



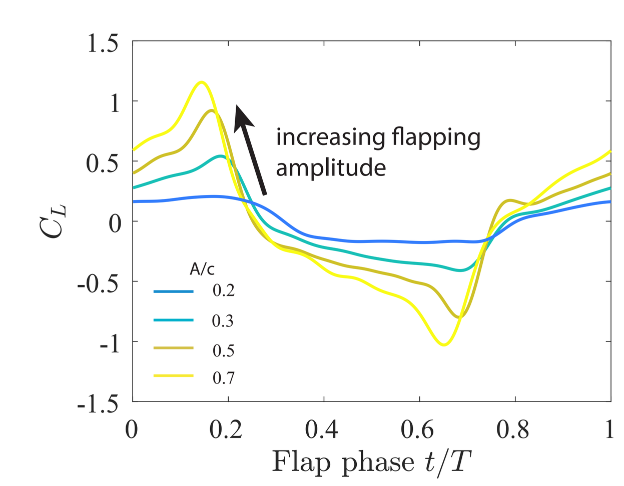
Re = 42k, St = 0.02, A/c = 0.2

b.

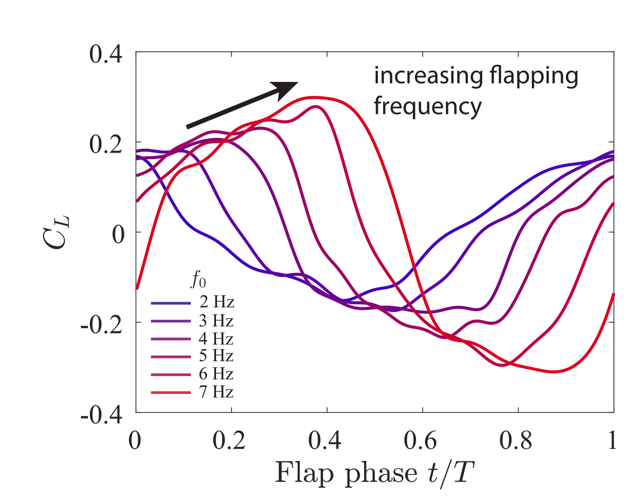


Re = 42k, St = 0.06, A/c = 0.5

c.



Lift vs. flapping amplitude at fixed flapping frequency



d. Lift vs. flapping frequency at fixed flapping amplitude

a. In low St case, **down wash** and **up wash** are induced from strokes

b. In high St case, a primary **CCW** vortex shed in the first half-stroke, as it approaching, the surfing airfoil sees an increment in lift coefficient. The lift coefficient reach the peak on the impingement (t/T =0.18) with a separation bubble initiated on LE. As the separation growing, the lift coefficient falls back to neutral (t/T = 0.25). The **symmetric** process repeat in the other half-stroke.

CONCLUSIONS

- The force response of the surfing wing is aligned with the impingement of flow structures
- The wing's lift response frequency locks to the wake-generating frequency, with cycle-level fluctuations scaling with Strouhal number.
- A predictive model leveraging classic unsteady aerodynamics to account for structured wake interactions, with theoretical predictions closely aligning with force sensor data—particularly when using the Wagner approach in the time domain.

*Correspondence:
siyang_hao@brown.edu

This work was supported by the National Science Foundation Grant number: IOS-1930924