Nonlinear Fluid-Structure Interaction Dynamics of an Elastically Mounted Airfoil in an Inviscid Fluid

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Motivation

- Development of futuristic flapping-wing Micro Air Vehicles (MAVs) are primarily inspired from insect flights comprising of complex interactions between flexible flapping wings and unsteady flow-field augmenting the generation of aerodynamic loads.
- The coupling between the unsteady flow and the flexible wing is essential to take into consideration for very light-weight flapping wing MAVs resulting in a nonlinear FSI system in the presence of structural nonlinearities.
- The coupled dynamics shows a rich bifurcation behaviour including quasi periodicity and chaos in the presence of an actuation force which would require specialized control algorithms for MAVs.

Highlights of the Study

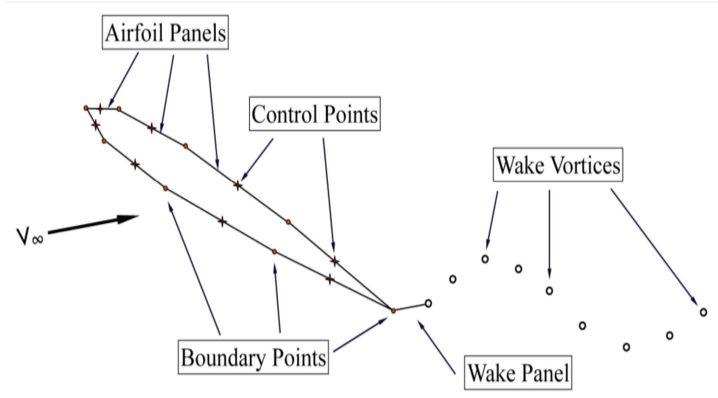
- A span-wise flexible wing has been modelled as an elastically mounted airfoil having pitching-plunging dof in 2D with cubic stiffness attributing to large deformations.
- The nonlinear structural model is weakly coupled with a linear potential flow solver to investigate the fluid-structure interaction effect.
- In the absence of an actuating force, the nonlinear FSI system shows a supercritical Hopf bifurcation route considering the non-dimensional upstream velocity as the control parameter.
- In the presence of a periodic actuating force, the bifurcation analysis considering the actuating force amplitude as the control parameter in the post flutter regime reveals an interesting interplay between periodic and quasi-periodic dynamic leading to a chaotic transition.

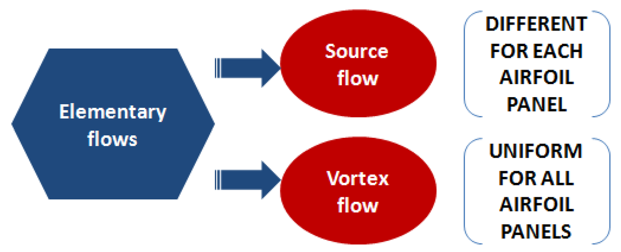
Formulation of the FSI solver

Unsteady Vortex Lattice Method

Weak coupling

2-dof Nonlinear Aeroelastic Model

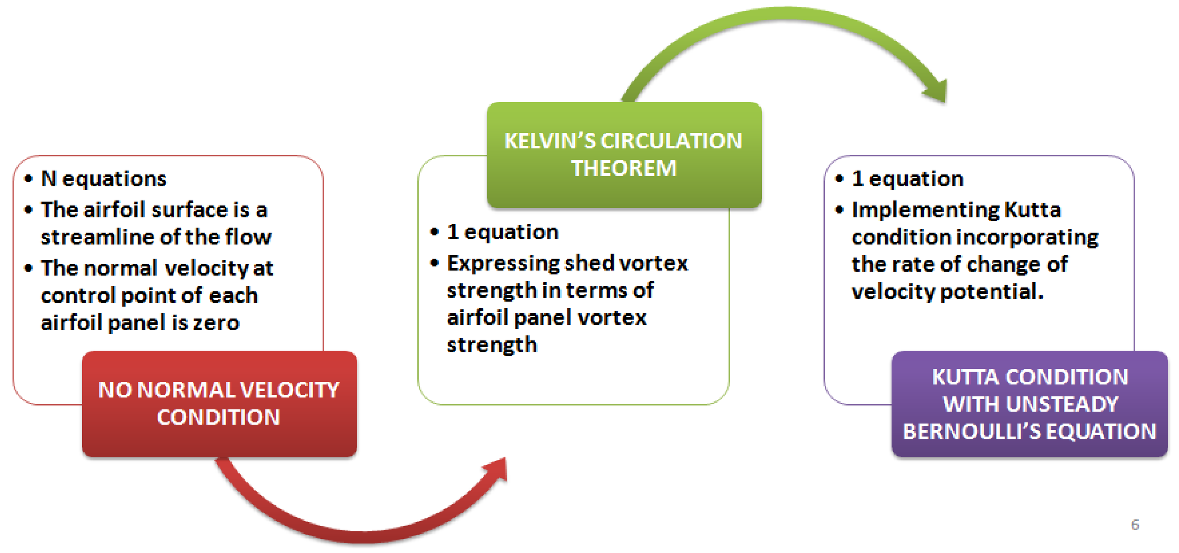


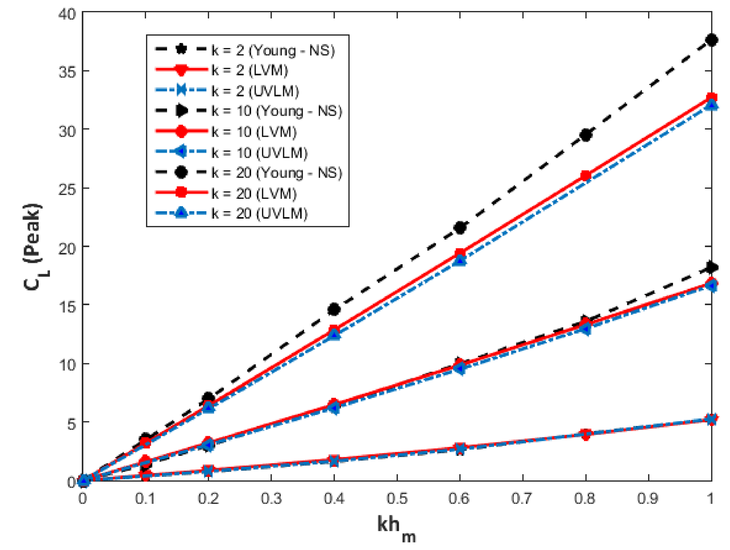


N Airfoil panel source strengths

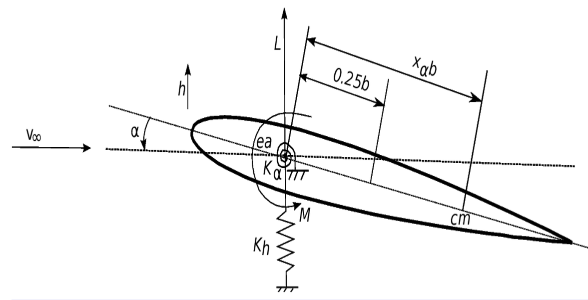
1 Airfoil panel vortex strength

1 Shed vortex strength





Flow solver validation



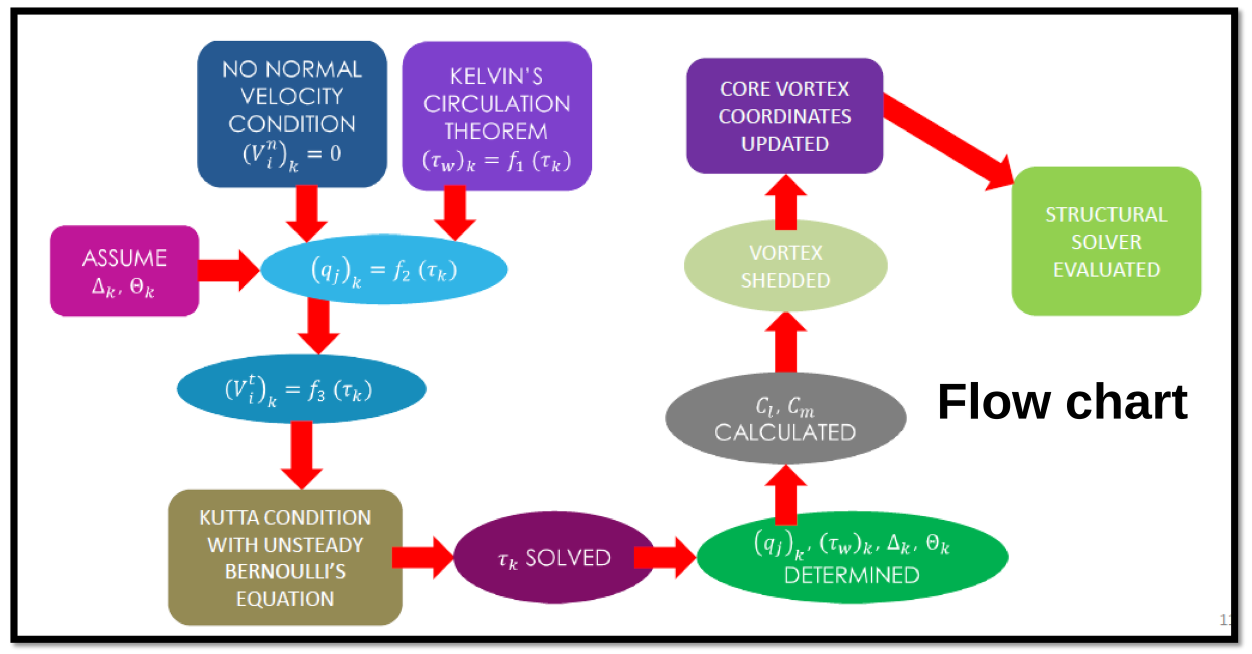
Schematic of the structural model

$$\ddot{\xi} + x_\alpha \ddot{\alpha} + 2\zeta_\xi\left(\frac{\bar{\omega}}{U^*}\right)\dot{\xi} + \left(\frac{\bar{\omega}}{U^*}\right)^2 \xi = -\frac{1}{\pi\mu}C_l(\tau) + F^*$$

$$\frac{x_\alpha}{r_\alpha^2}\ddot{\xi} + \ddot{\alpha} + 2\left(\frac{\zeta_\alpha}{U^*}\right)\dot{\alpha} + \left(\frac{1}{U^*}\right)^2(\alpha + \beta_\alpha \alpha^3) = \frac{2}{\pi\mu r_\alpha^2}C_m(\tau)$$

Actuation Force

$$F^* = f^*\sin(\bar{\omega}_f \tau)$$

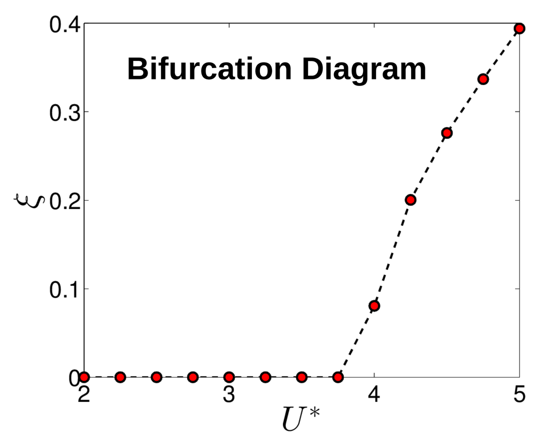


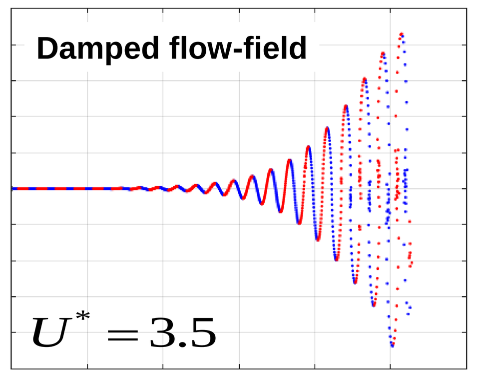
Flow chart

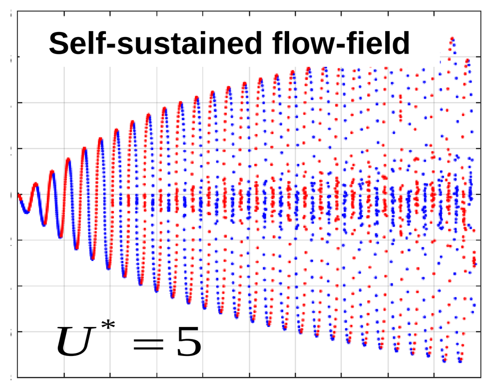
Bifurcation Analysis in the Absence of Wing Actuation Force

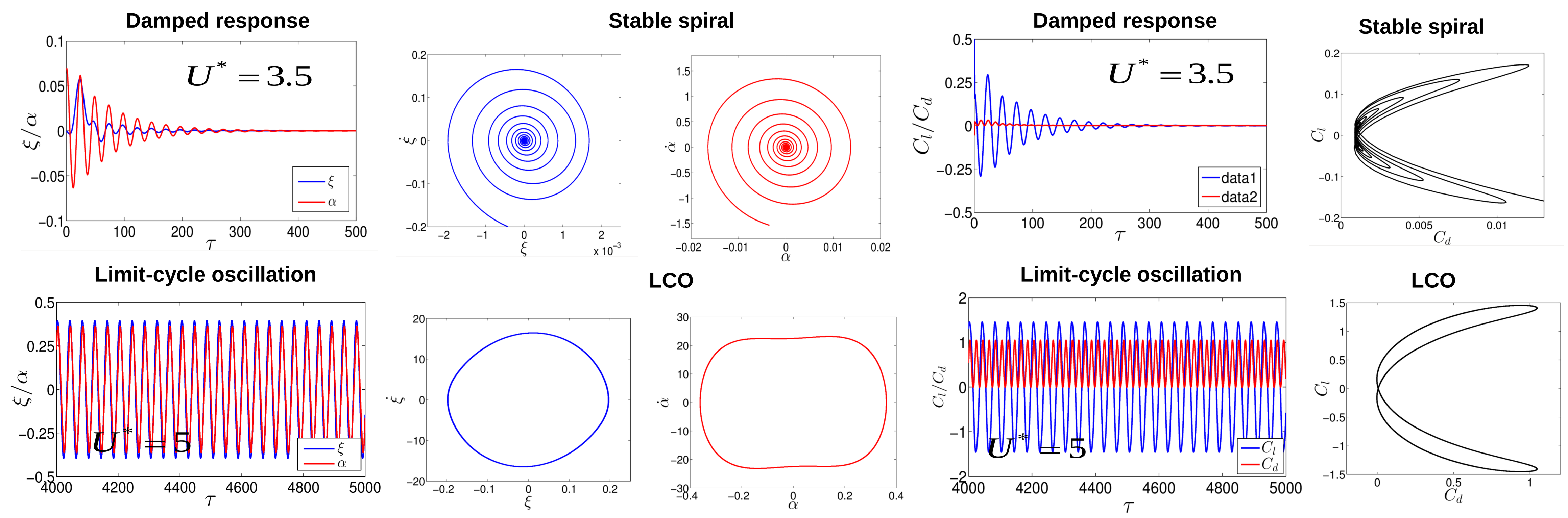
A Supercritical Hopf Bifurcation Route: Fixed Point → LCO

Parameter	Value (S.I.)
$\bar{\omega}$	0.2
$\bar{\omega}_f$	0.1
μ	40
r_α	0.58
x_α	0.34
c	1



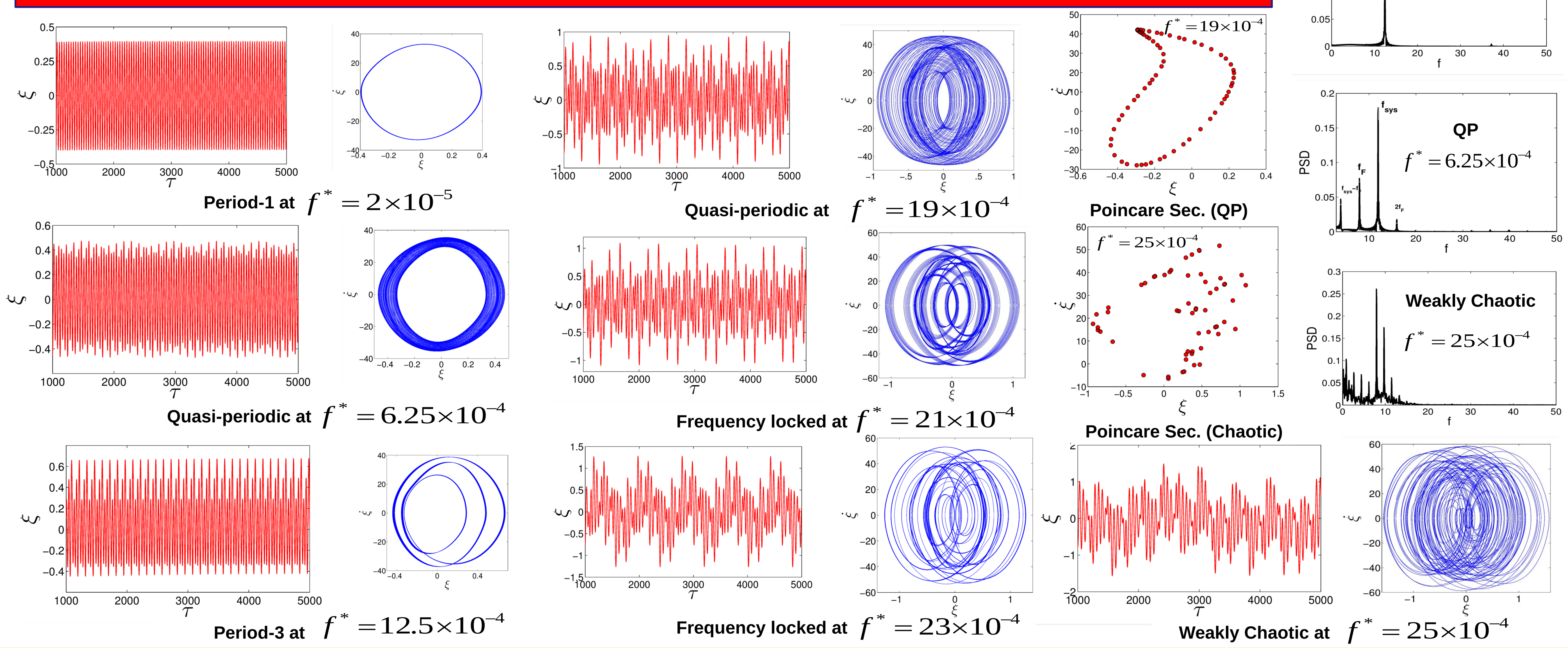






Dynamics in the Presence of Wing Actuation Force at $U^* = 5$

Interplay between Periodic and Quasi-Periodic Dynamics → Chaos?!



Conclusion

1. Different dynamical transitions have been observed in the FSI dynamics in the presence and absence of the actuating force.
2. In the absence of actuation force, a self-sustained LCO emerges from a fixed point response beyond the Hopf bifurcation point.
3. The dynamical system undergoes an interplay between periodic and quasi-periodic dynamics with the increase in the forcing amplitude through frequency locking and finally the system transitions into a weakly chaotic dynamics.

References

1. Lee, B.H.K., Jiang, L.Y., Wong, Y.S., Flutter of an airfoil with a cubic restoring force. *Journal of Fluids and Structures* 13 (1), 75–101 (1999).
2. Ramesh, K., Murua, J., & Gopalarathnam, A., Limit-cycle oscillations in unsteady flows dominated by intermittent leading-edge vortex shedding. *Journal of Fluids and Structures*, *55*, 84-105 (2015).
3. Cebeci, T., Platzer, M., Chen, H., Chang, K. C., Shao, J.P., Analysis of low speed unsteady airfoil flows. *Springer Berlin Heidelberg* (2005).