BIO-INSPIRED INTELLIGENT AND GREEN FLYING VEHICLES (IGFVs)

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Supervisor: Dr. Rajeev Jaiman

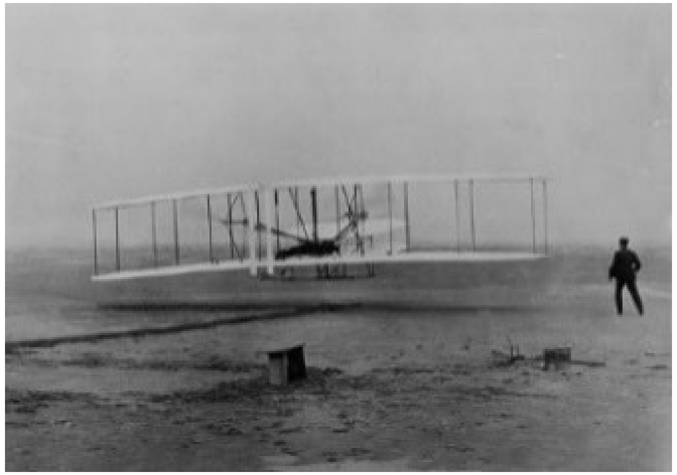
Presented by: Shayan Heydari
Aarshana Parekh
Rachit Gupta
Amir Chizfahm

Department of Mechanical Engineering
The University of British Columbia, Vancouver, CA

Inspired but not copy (mimic) nature

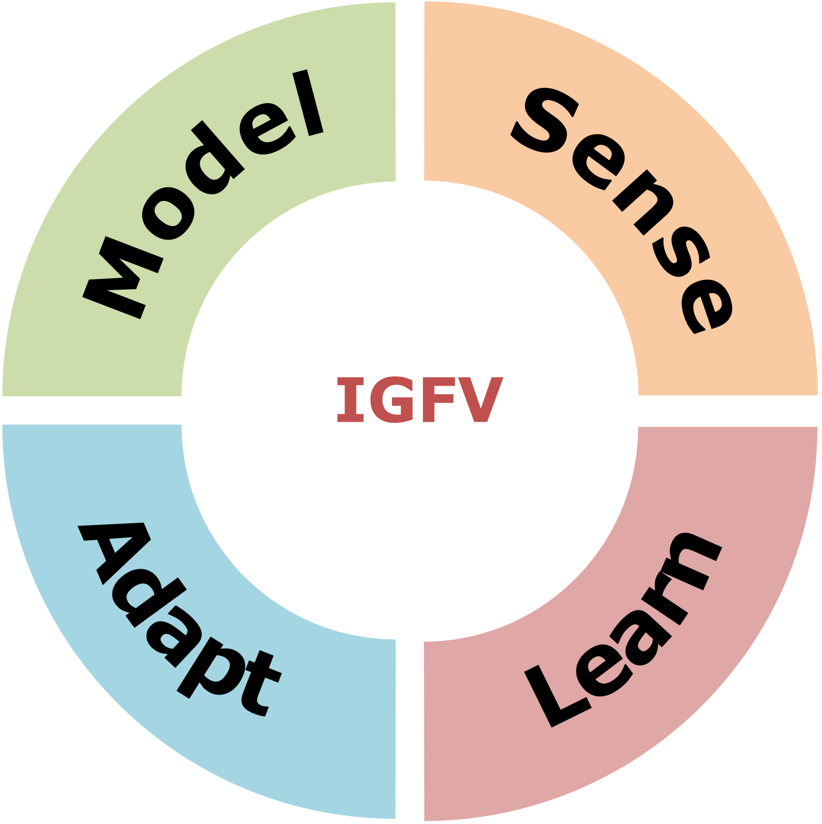
- ❑ Prior to 1903, human flight was

  - ▶ In 1903, the Wright brothers achieved the first powered flight and laid the foundation for the present days' aerodynamics
- ❑ Next generation of flying vehicles and brain-inspired machine learning should be engineered with scientific understanding
  - ▶ Breaking barriers of impossible?



What do we mean by Intelligent and Green?

- ❑ Intelligent; ability to model the environment and to act accordingly
- ❑ Green; low emissions in environment
- ❑ Can human-engineered aircraft operate like flying animals?
  - ► Biological systems perceive the world by simultaneously processing inputs from sensory cues as diverse as vision, auditory, haptic, etc.
    - ◇ Brain-inspired computation
    - ◇ <u>Model, sense, learn and adapt</u>



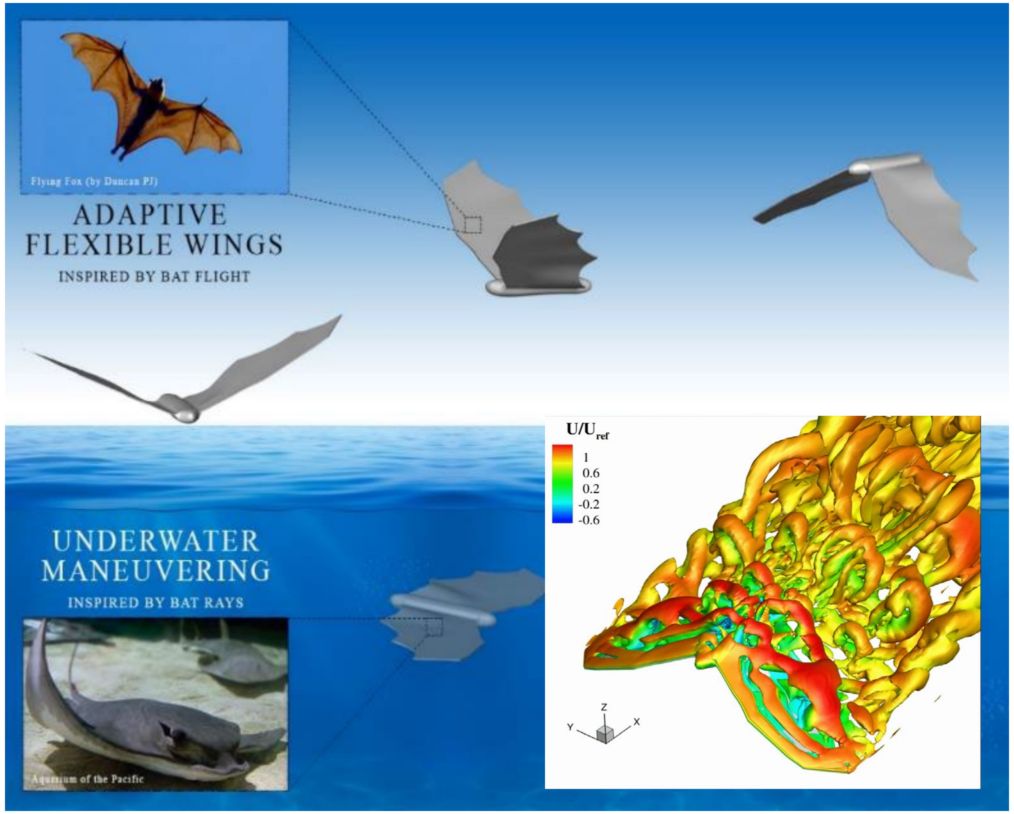
Flying Vehicles vs Natural Flyers

- ❑ Maneuverability and agility
  - ▶ Gust handling
  - ▶ Hovering
  - ▶ Reconfiguration
- ❑ Swarming and coordinated flight
  - ▶ Complex wake interactions
  - ▶ Distributed sensing and control
- ❑ Endurance and silencing
  - ▶ High energy efficiency
  - ▶ Noise reduction

Bar-tailed godwits flies 7,500 miles nonstop, breaking the world record (2020)

Scientific Challenges of Bio-Inspired Flight Dynamics

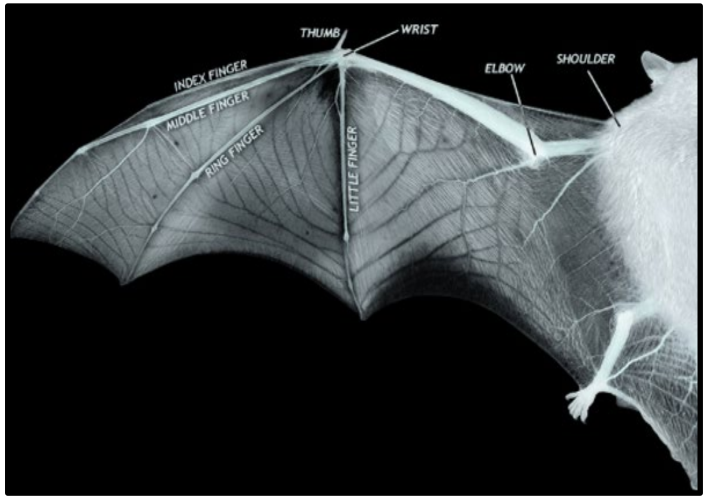
- ❑ Complex Fluid-Structure Interactions
  - ► Highly deformable structures interacting with fluid flow
- ❑ Unsteady Aero/Hydrodynamics
  - ► Massively separated flow
  - ► Low Reynolds numbers to transitional/turbulent flows
- ❑ Flow Control
  - ► Adaptive feedback control
  - ► Sensing and multifunctional materials
  - ► Reduced order modeling
    - ◇ Computational intelligence
    - ◇ Neuroscience

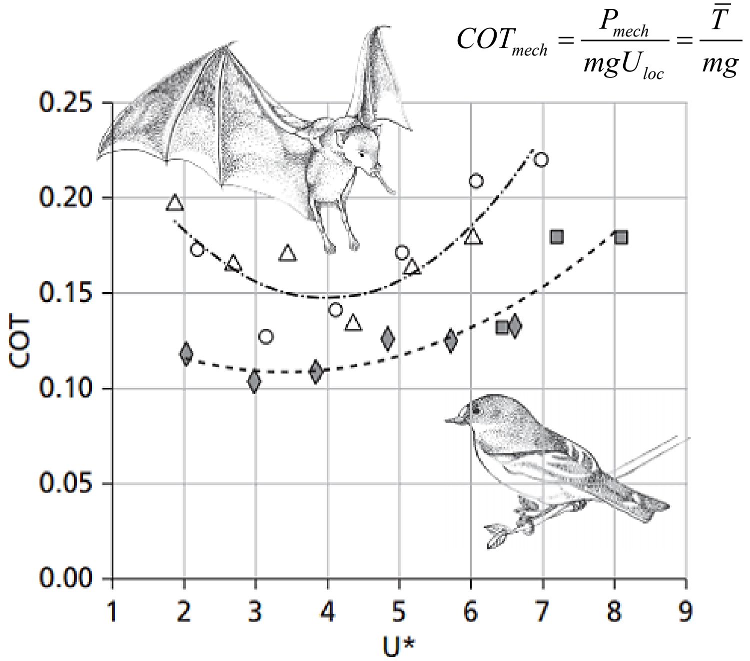


Concept of hybrid avian-aquatic vehicles and drones

Why Bat-Inspired Designs?

- ❑ Unique flight dynamics
  - ▶ Multifunctional adaptive wing
  - ▶ Membrane-like wing instead feathered: elastic fibers, muscles, blood vessels etc.
  - ▶ Articulated kinematics: flexible bones and joints
- ❑ Aerodynamic performance
  - ▶ Adaptive to wind gusts
  - ▶ Comparable cost of transport
  - ▶ Favorable lift-to-drag ratio
  - ▶ Low flight noise
- ❑ Maneuverability
  - ▶ Active control for wing shape by muscles
  - ▶ Complex kinematic behaviors



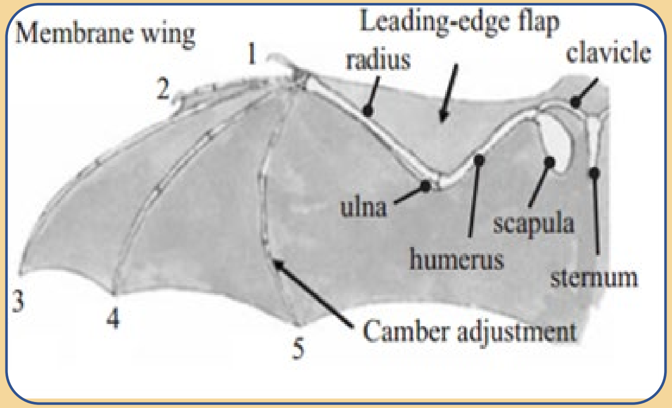


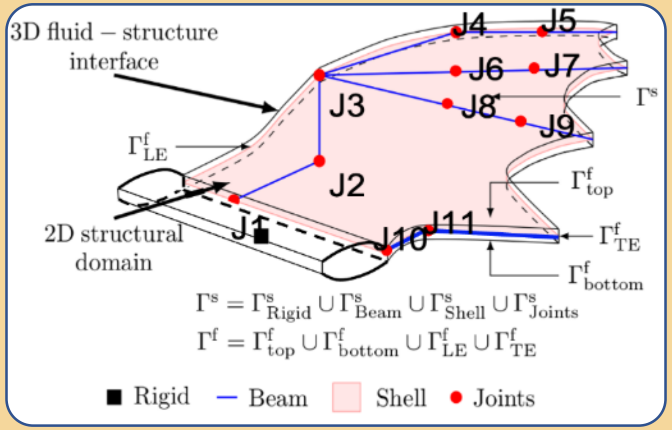
The cost-of-transport COT_{mech} VS. normalized flight speed
(Hansson, L. A. Animal movement across scales. 2014.)

Modeling of a Bat-Inspired Wing

Complex Flexible Multibody Structure

- ❑ <u>Wing Flexibility</u>
  - ► Benefit of delayed stall and attached leading edge vortex
- ❑ <u>Adaptive Wing-Span</u>
  - ► Induced drag reduction and increased agility
- ❑ <u>Articulated Kinematics</u>
  - ► Dynamic wing conformations with 40+ active and passive joints





Displacement, Motion

Fluid

(Aerodynamics)

Flow structures

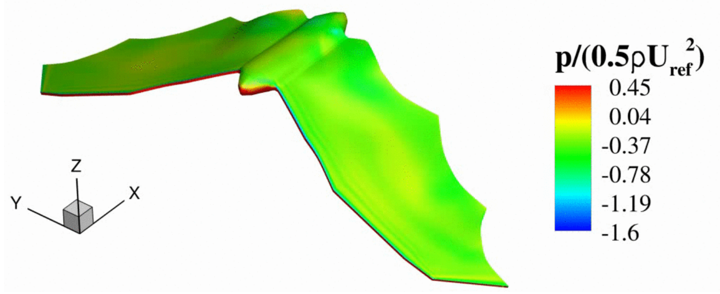
Vorticity and pressure distributions

Traction

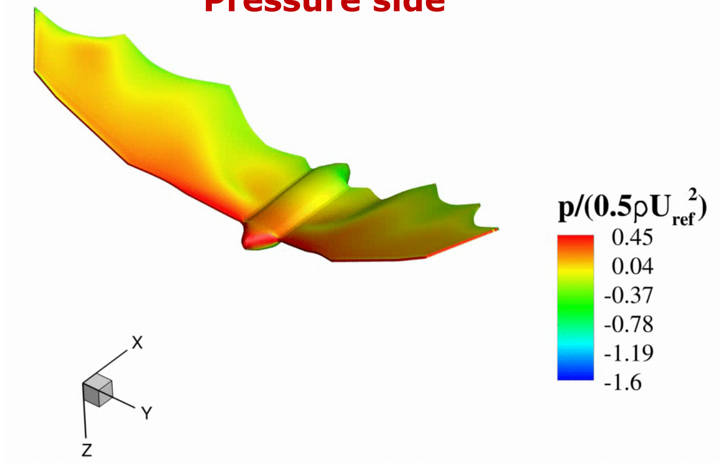
Forward Flight: Full-Scale Bat Model

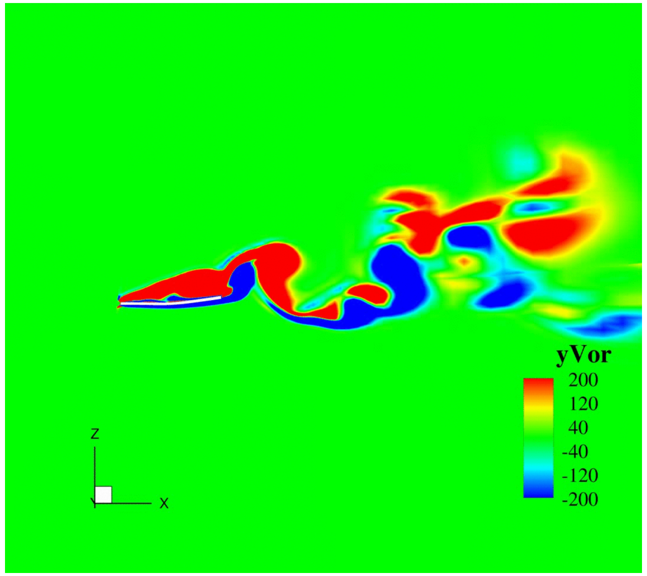
- ❑ 15% increase in mean lift compared to the stationary wing
- ❑ More freedom of movement due to the multibody system
- ❑ Large deformation leads to high unsteady lift

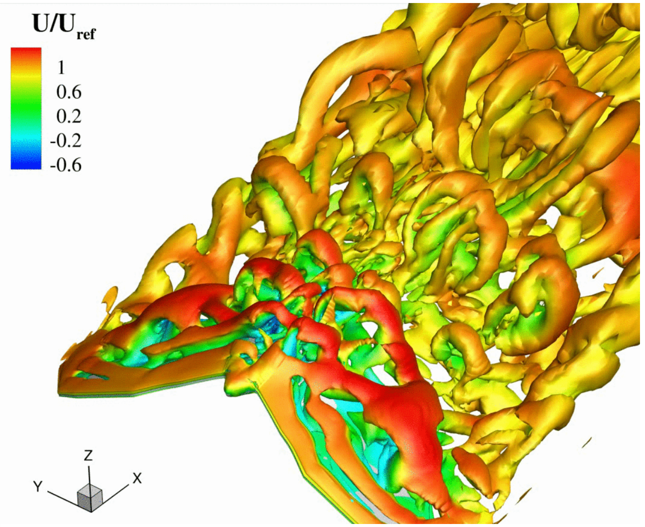
Suction side



Pressure side



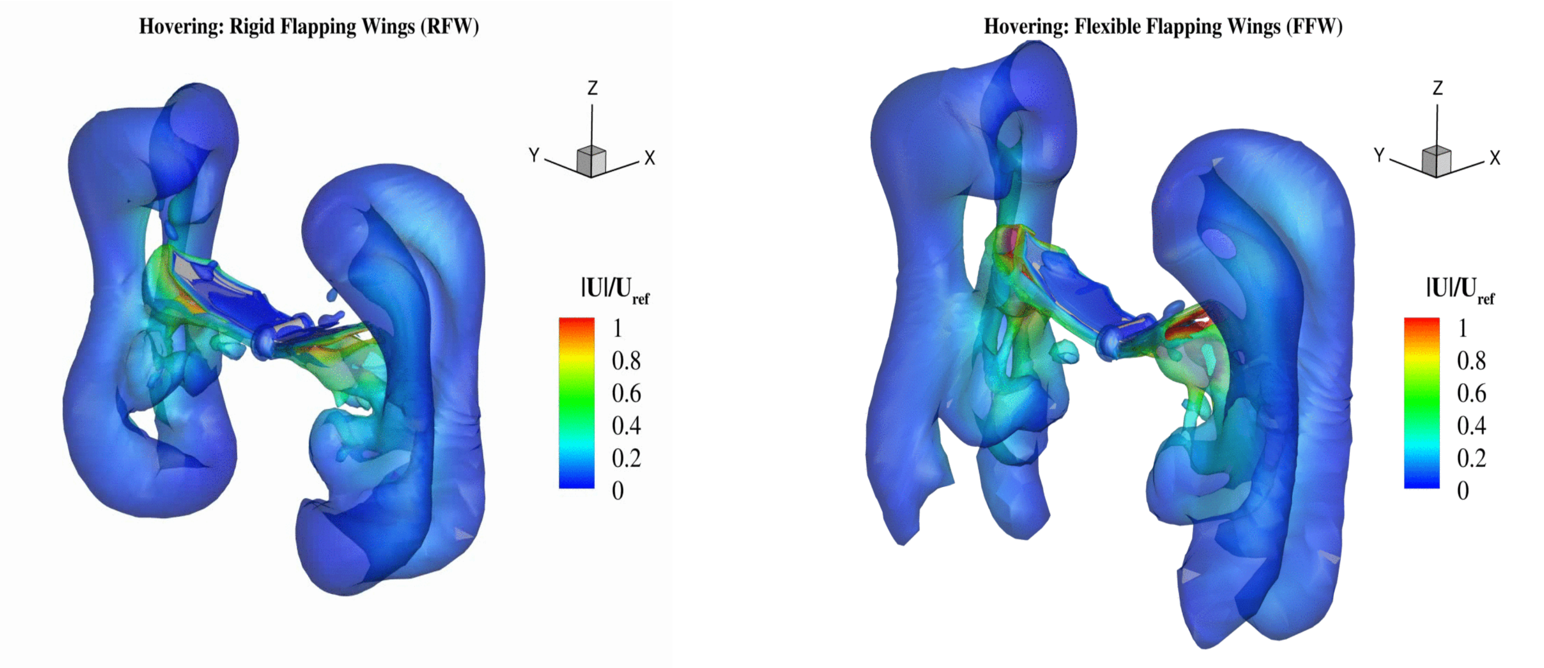


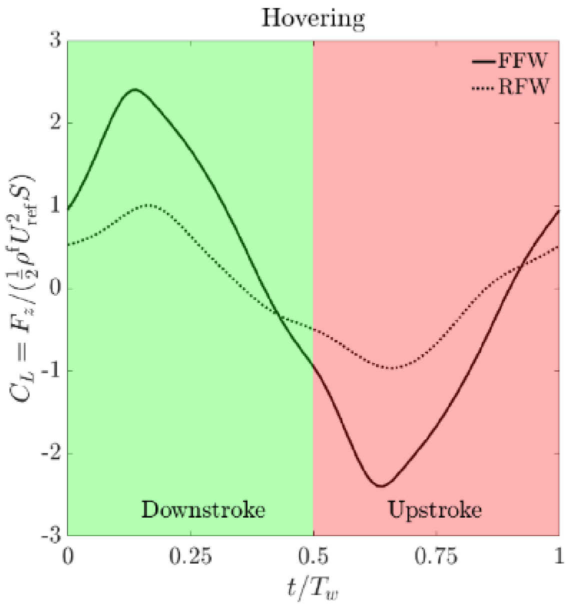


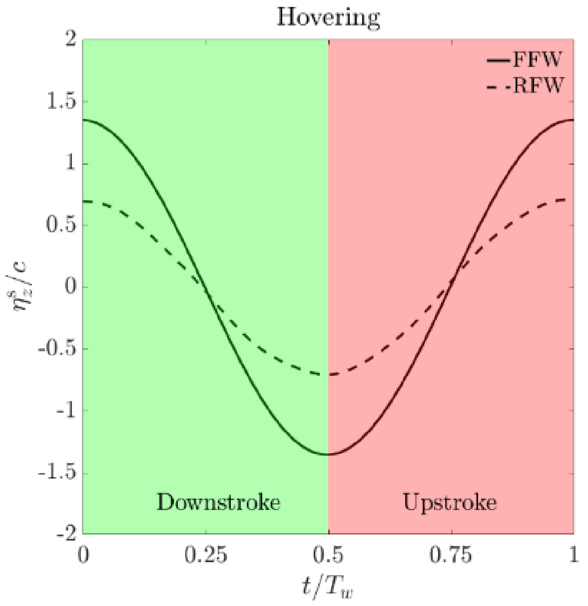
Vortex structures represented by Q-criterion colored by normalized streamwise velocity

Hovering Bat: Vortex dynamics

- Maximum unsteady lift increased by about <u>137%</u> for the flexible wing during downstroke
  - Increasing flexibility of the wing improves aerodynamic performance



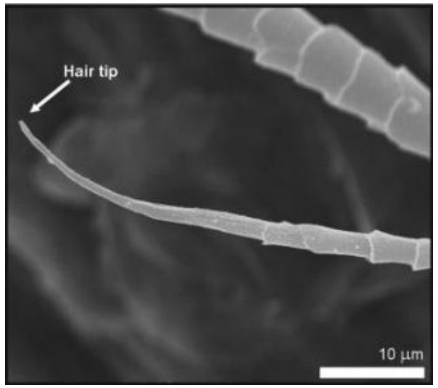




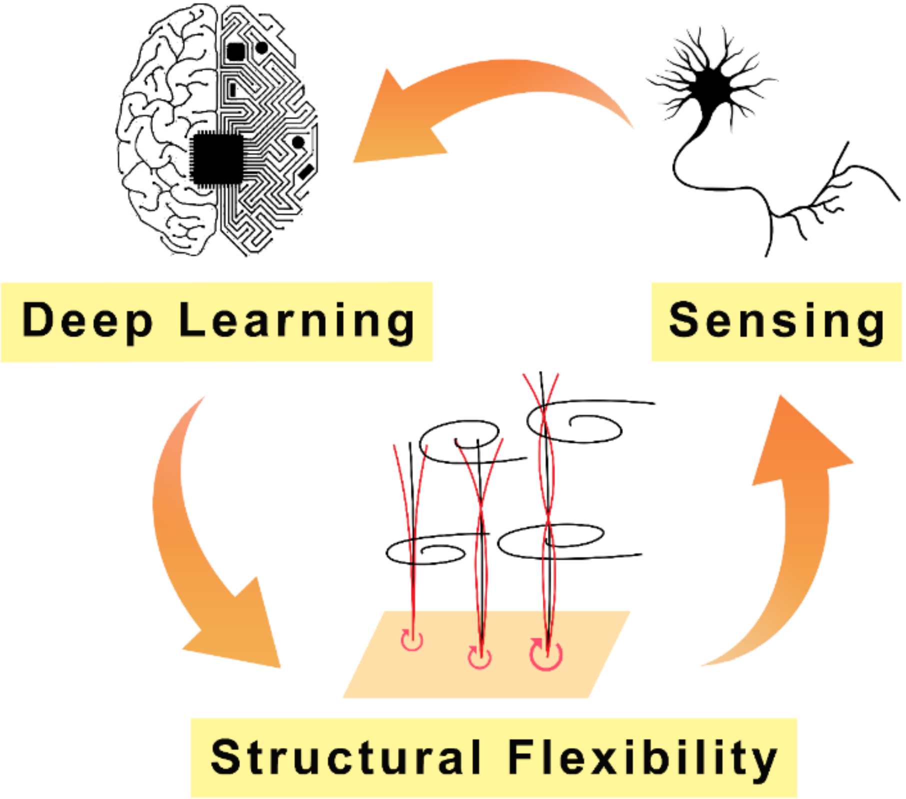
Joshi & Jaiman, AIAA 2020

Powered Flight in Bats: Role of Sensory Receptors in Wings

- ❑ Rapid integration of sensory inputs enable bats to make split-second flight control adjustments
  - ▶ Hairy-like sensory receptors in bat wings send information about airflow to neurons in in the brain
- ❑ A physics-based digital twin
  - ▶ Emulate the biomechanical behavior of hairy-like structures in bat wings during flight
  - ▶ Importance in design of agile aircraft that maneuver through complex environments

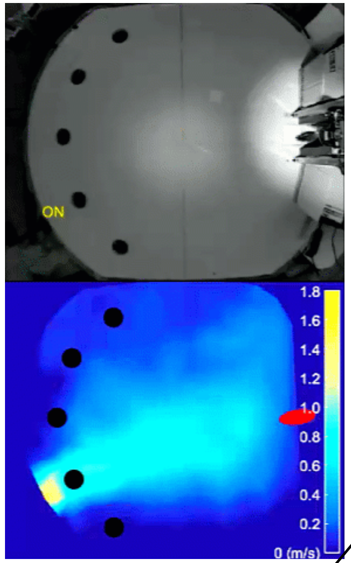


Sterbing-D'Angelo et al., J Neurophysiol. 2017

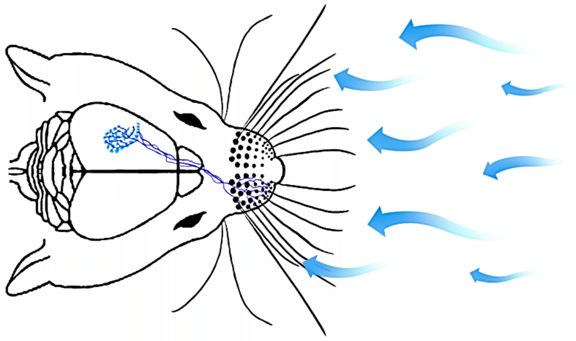


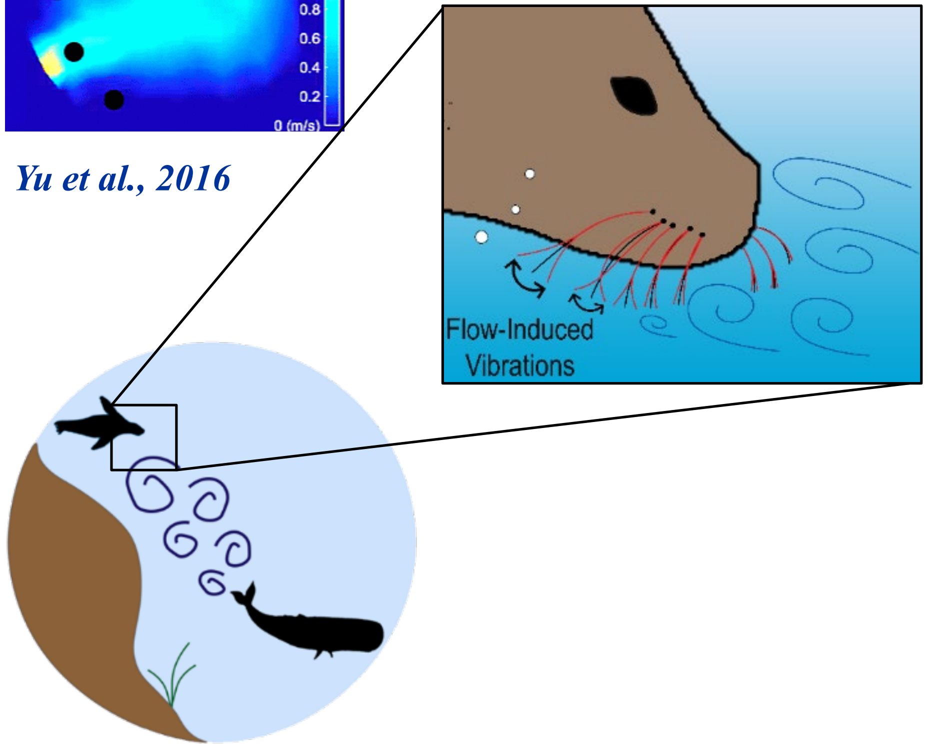
Aerodynamic Perception and Sensing in mammals

- ❑ Whiskers facilitate wind-sensing and prey detection in some mammals such as rats and seals
  - ► Flow detection and localization through flow-induced vibrations
- ❑ Fluid-structure interaction of whiskers in fluid flow
  - ► Large-amplitude vibrations at laminar flows
- ❑ Flow-sensing devices inspired by whiskers
  - ► Application in robotics, flying vehicles, etc.

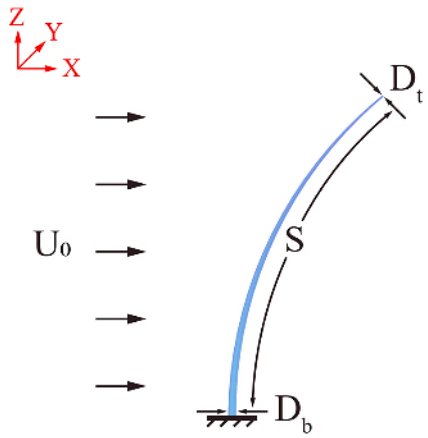


Yu et al., 2016



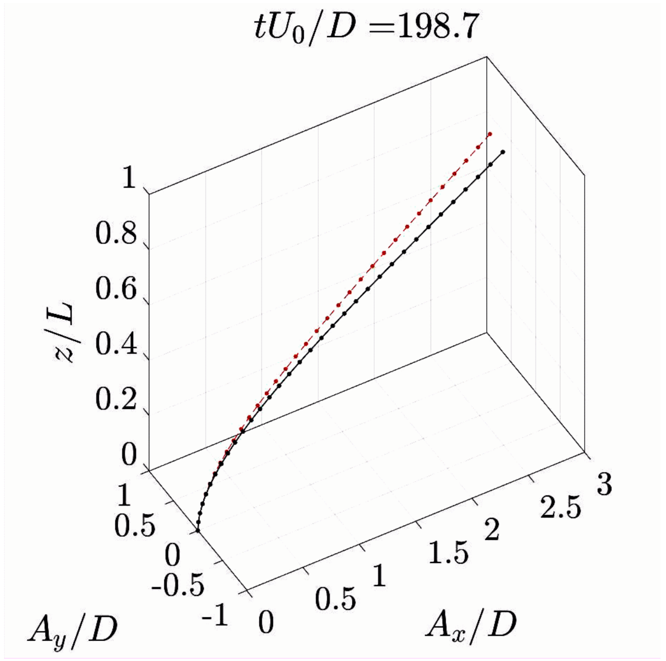


Dynamics of Whiskers in Fluid Flow

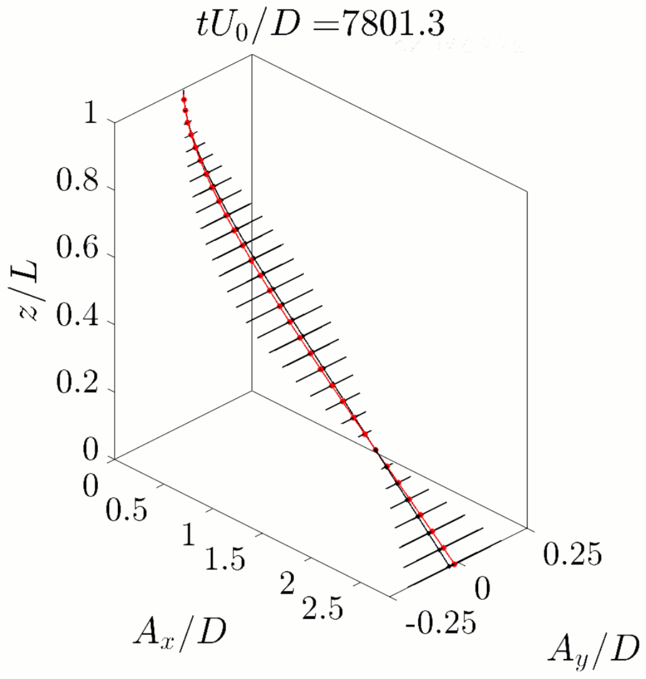


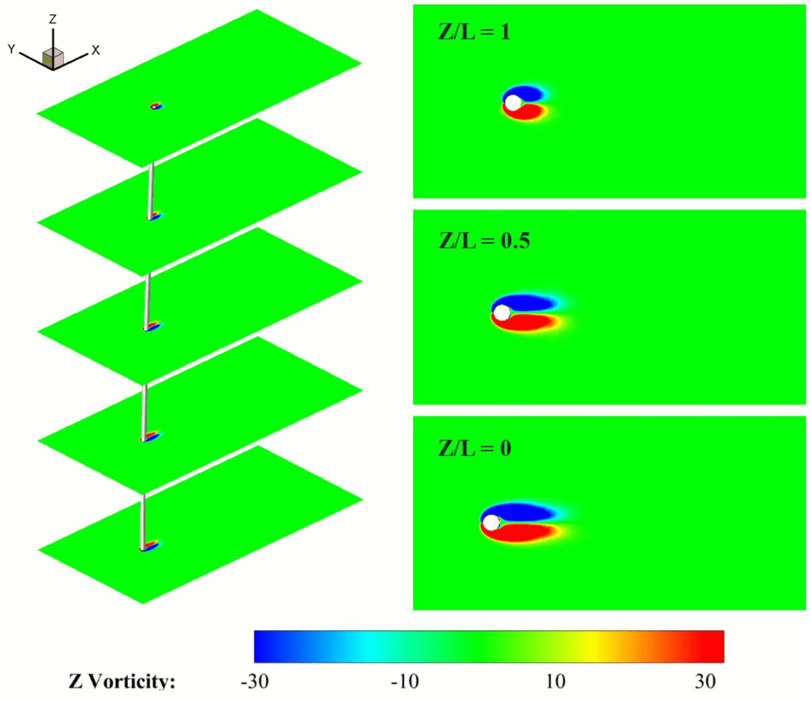
- ❑ Whiskers have a tapered conical geometry
  - ▶ Aspect ratio $50 < S/D_b < 500$
- ❑ Resonance in natural modes of vibrations

Resonance in First Mode



Resonance in Second Mode

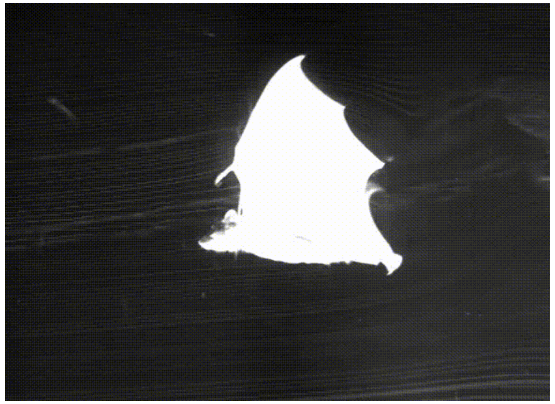




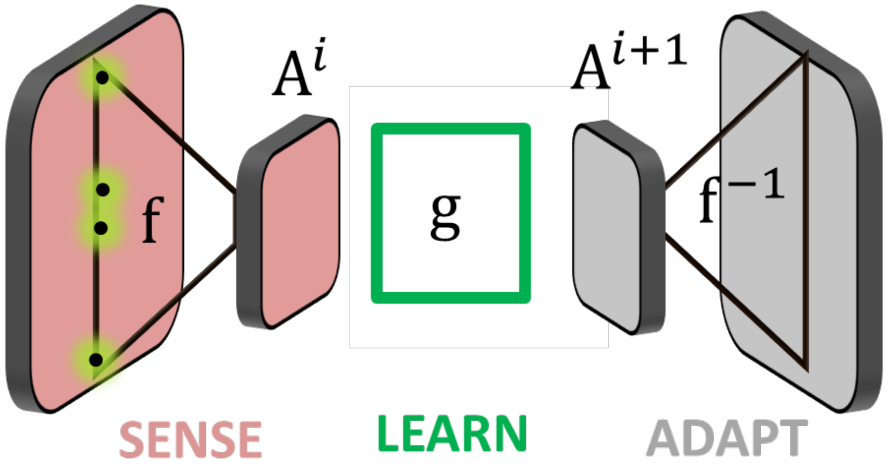
Enhancing Aeromechanics via AI/Machine Learning

- ❑ Data-driven computing for real-time predictions of multiphysics and multiphase systems for flying vehicles

- ❑ Can we find useful features or embedding functions in low-dimension, then make inference and predictions from datasets?
  - ▶ Separation of spatial-temporal scales
  - ▶ Composition of feature maps with hierarchical importance



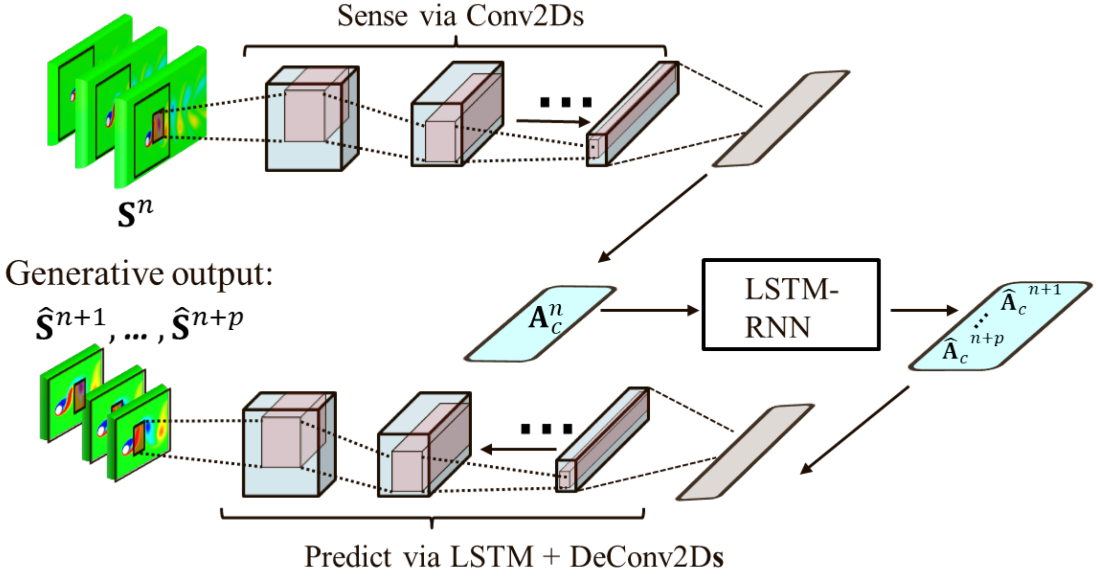
Breuer & Swartz (Brown University)



f = Reduced model
g = Deep Learning

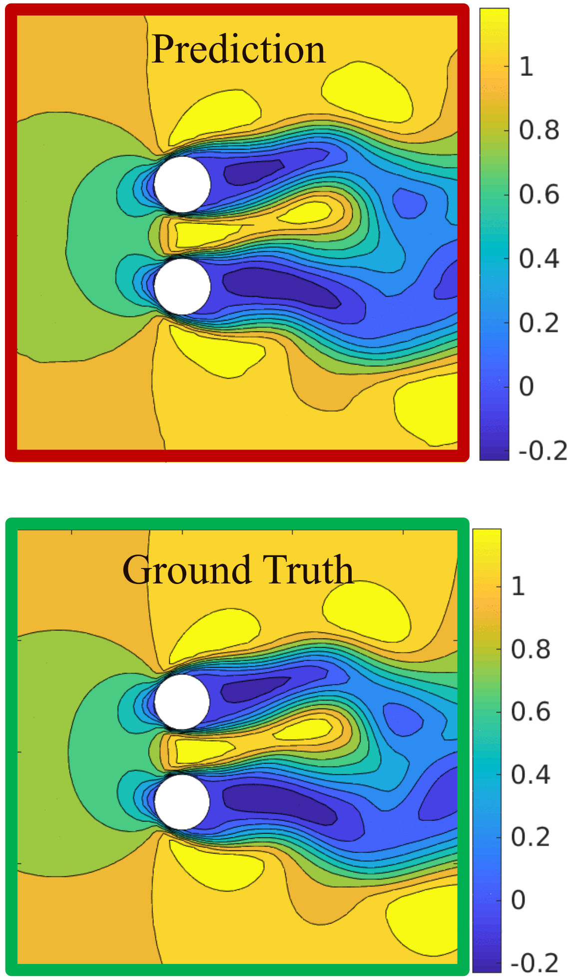
Deep Learning-based Reduced Order Model (DL-ROM) for Aerodynamic Predictions

- DL-ROM: Convolution Recurrent Autoencoder Net (CRAN)
  - Automatic ROM/feature detection using autoencoders
  - Nonlinear generalization of Galerkin-ROMs



CRAN-based solvers scalable to moving boundaries and 3D flows

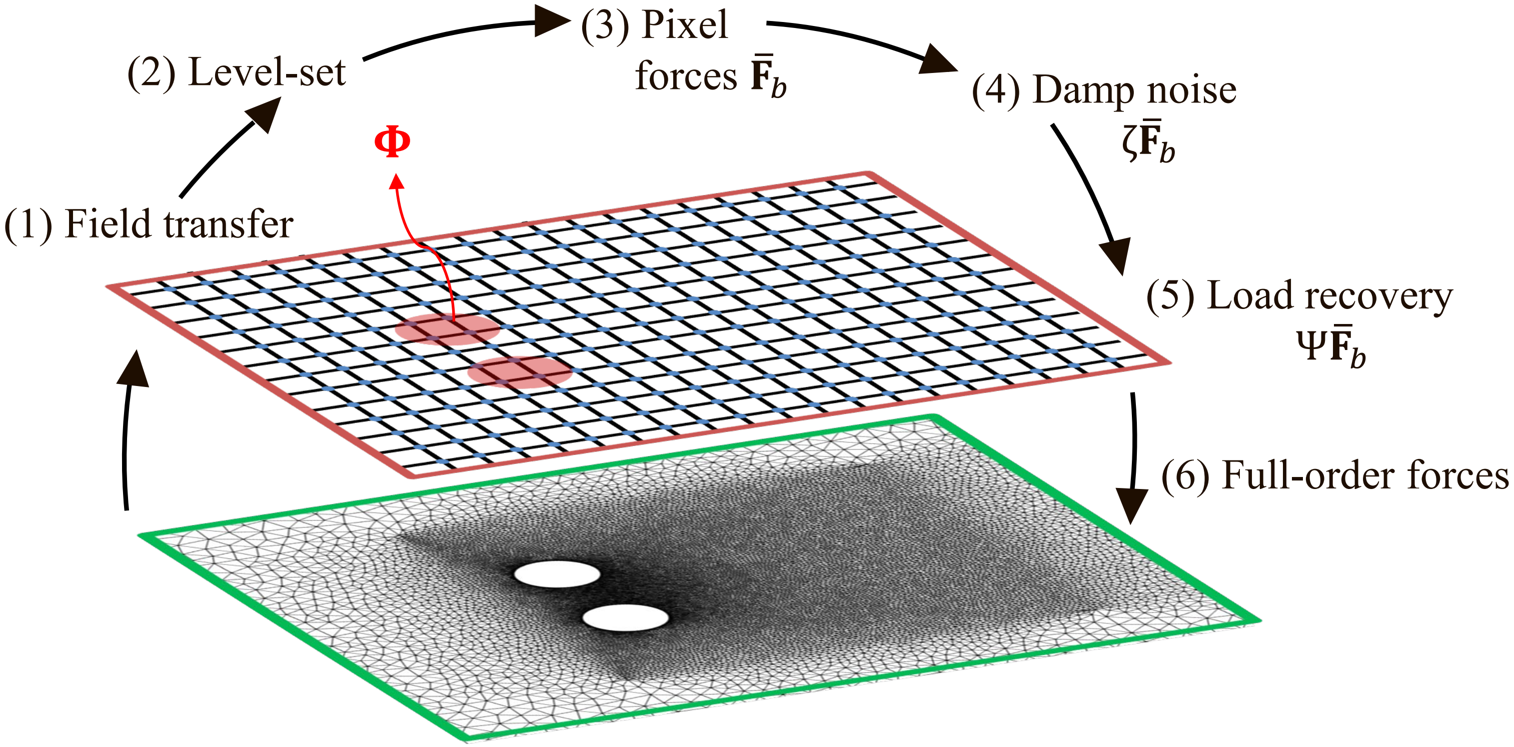
Bistable flows

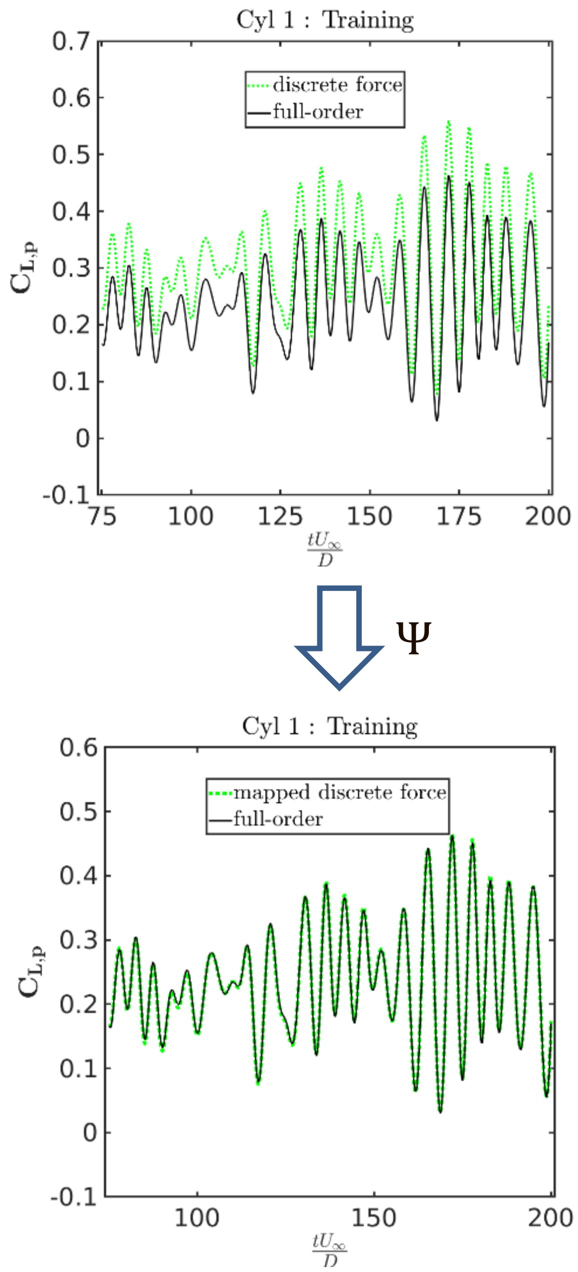


Bukka, Gupta & Jaiman, POF 2021

Unstructured to Structured Grids

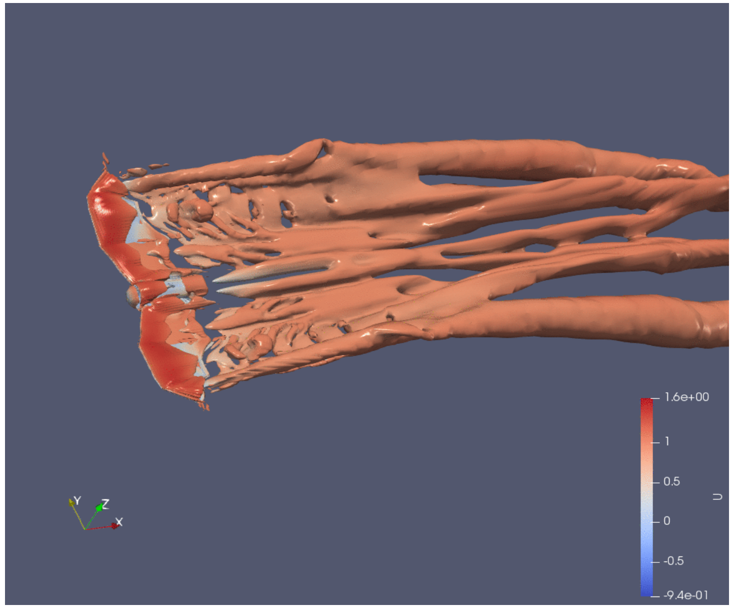
- ❑ Mesh-to-mesh field transfer & interface force recovery
  - ▶ CFD unstructured mesh complexities is overcome in neural networks
  - ▶ Preserving interface description from sensor data for arbitrary geometry and boundary conditions



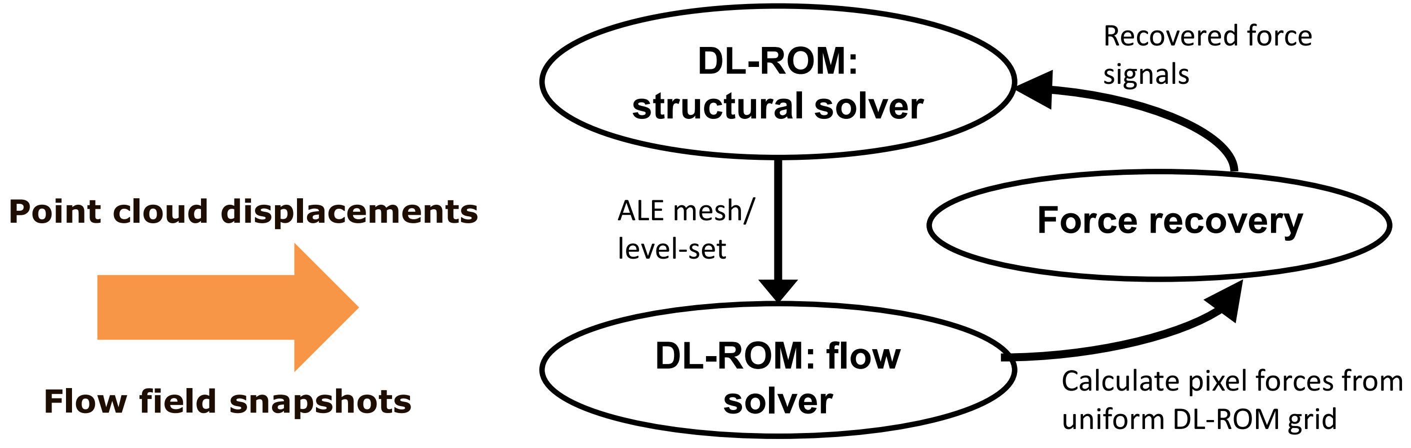


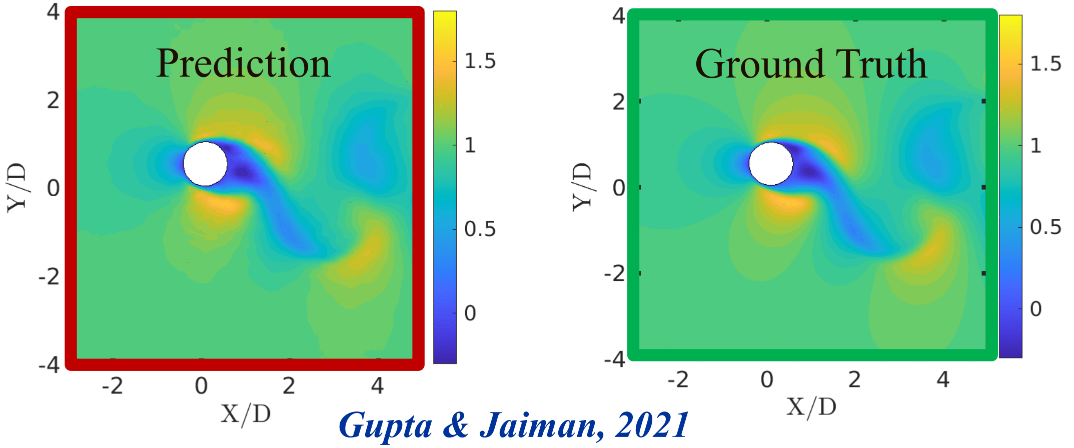
Generalized Deep Learning for Fluid-Structure Coupling

❑ Partitioned full-order FSI solver



❑ Partitioned DL FSI solver





Gupta & Jaiman, 2021

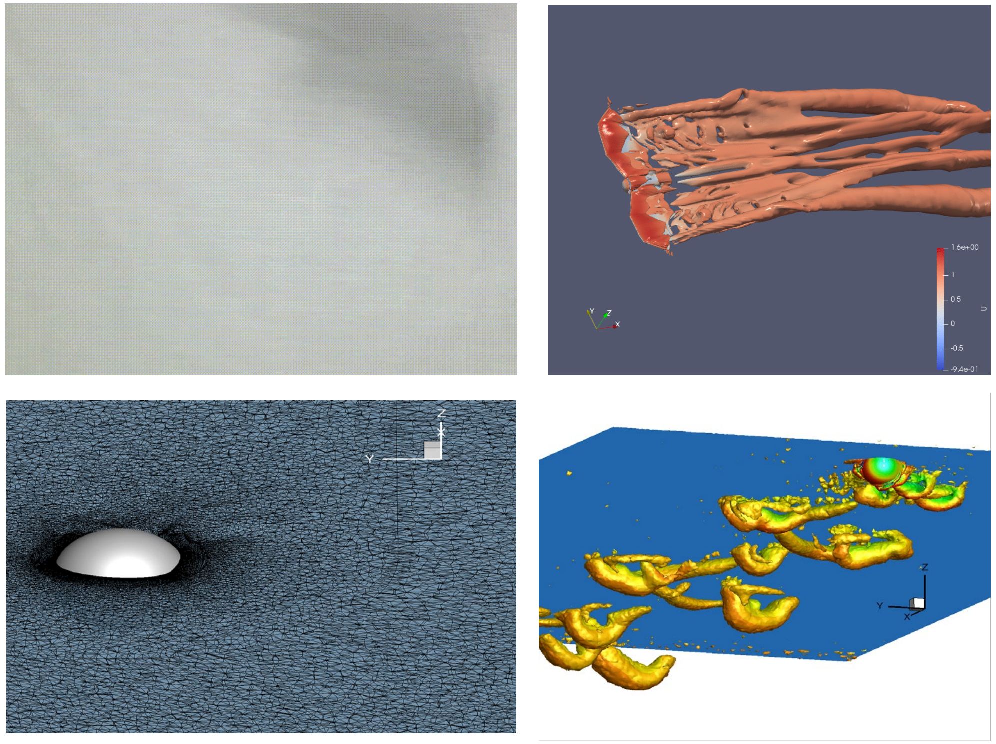
❑ Partitioned DL-ROMs for FSI

- ▶ Decouple structural and fluid flow representations
- ▶ Modular learning of two physical fields

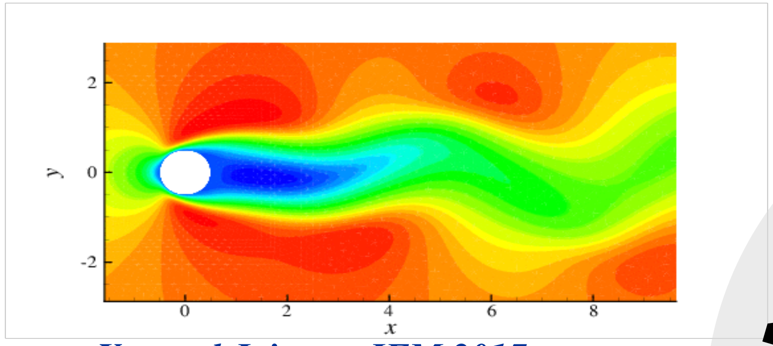
Bio-inspired Designs and Feedback Control

- ❑ High-fidelity model
  - ▶ Validation study
  - ▶ Physical understanding
  - ▶ Ground truth data

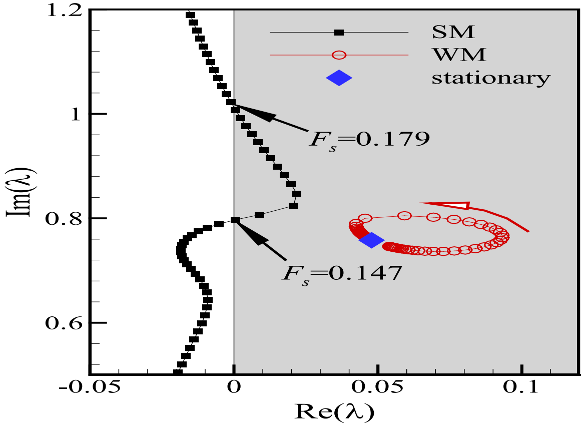
- ❑ Reduced-order model
  - ▶ Stability analysis
  - ▶ Online control strategies
  - ▶ Parameter space exploration

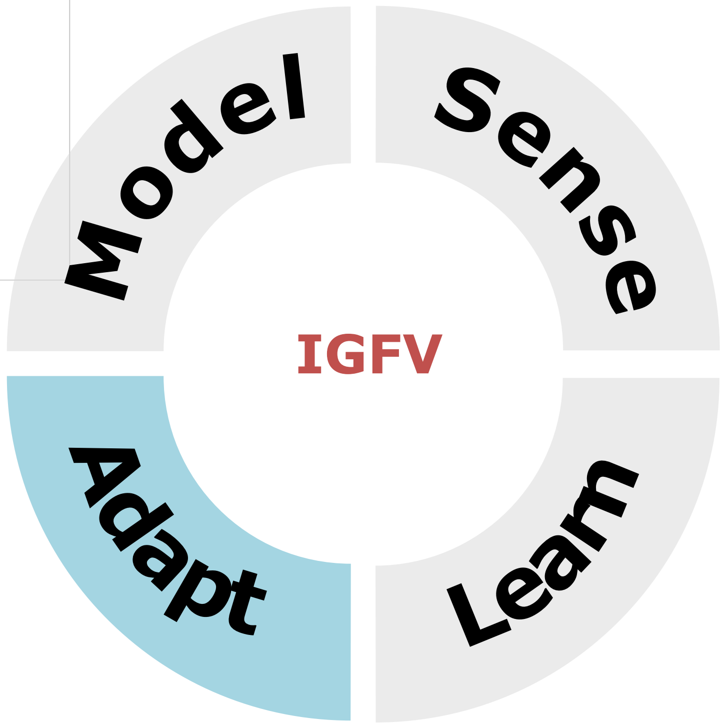


Chizfahm & Jaiman, JFS 2021



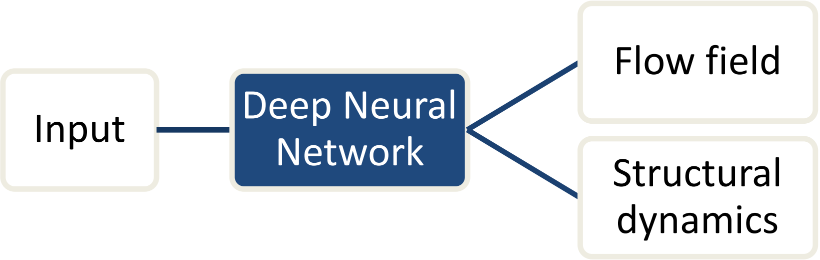
Yao and Jaiman, JFM 2017



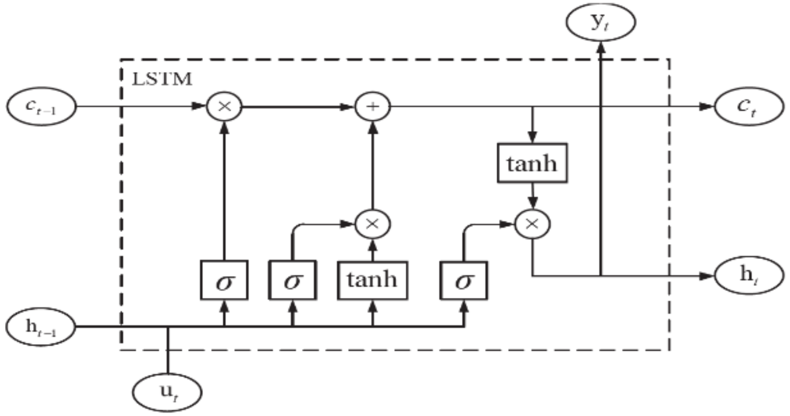


Deep Learning for Control

- ❑ Data-driven approximations via deep learning
  - ▶ Describing and modeling nonlinear systems

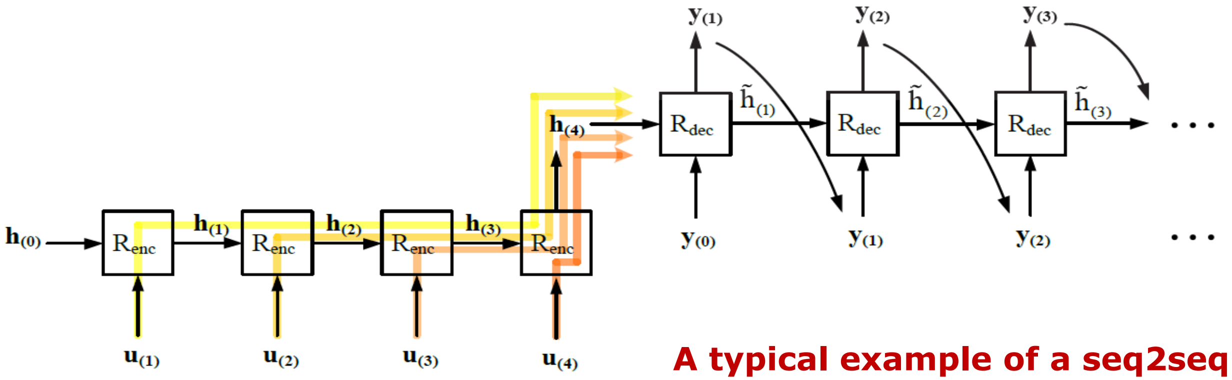


- ❑ RNN-LSTM can be easily adapted for a time series forecast problem and suitable for control systems.



Cell structure of long short-term memory network (LSTM)

- ❑ Encoder-Decoder (ENC-DEC) networks are a particular variant of RNN



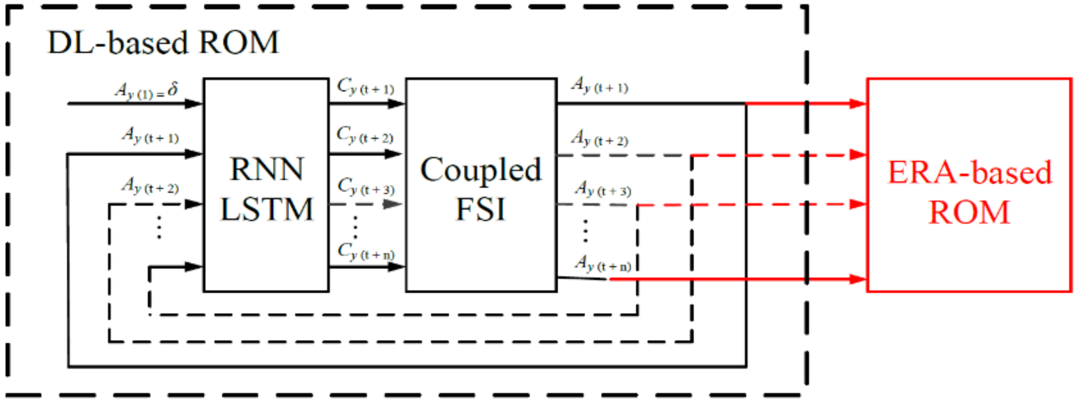
A typical example of a seq2seq architecture with an RNN encoder-decoder

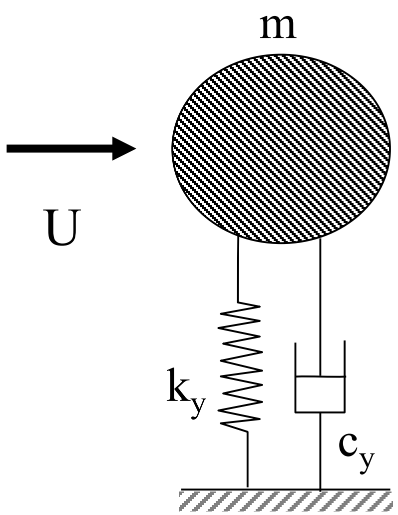
Deep Learning for Stability Prediction and Adaptation

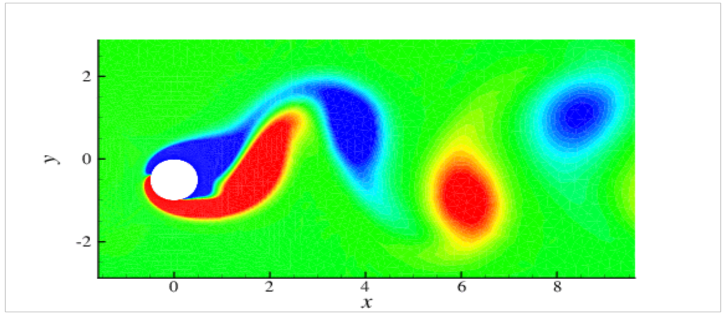
- ❑ LSTM network is applied to construct nonlinear DL-based ROM
  - ▶ Coupled nonlinear state-space model (NLSS)

$$\mathbf{x}_{\mathrm{fs}(t+1)} = \mathcal{A}_{\mathrm{fs}}\mathbf{x}_{\mathrm{fs}(t)}$$

  - ▶ Stability predictions
  - ▶ Parameter space exploration
  - ▶ Online adaptation and control







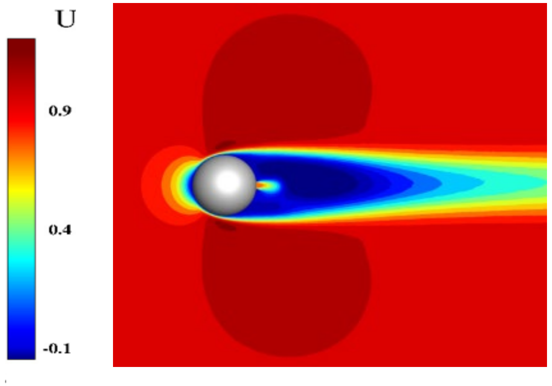
$$\lambda = \log(\mathrm{eig}(A_{sf}))/\Delta t$$

$$\textit{Reduced velocity}: \; U^* = \frac{U}{f_N D} = \frac{1}{F_s}$$

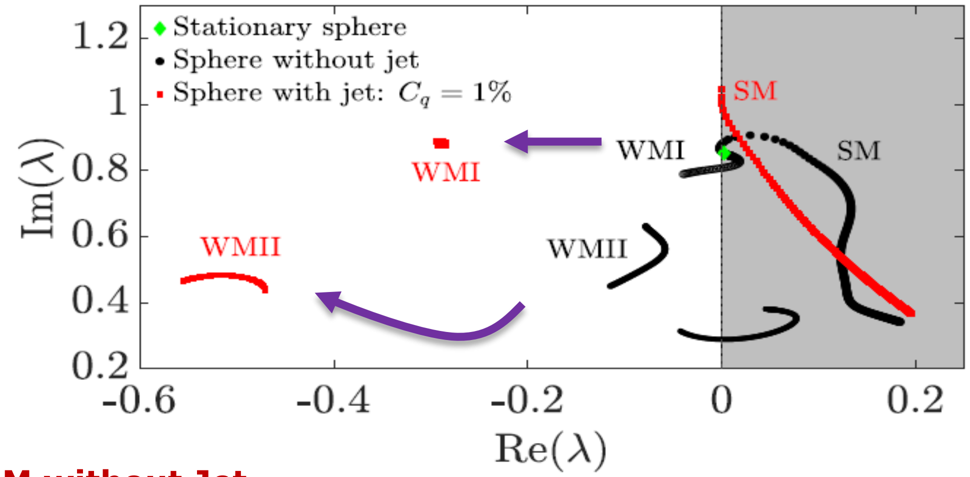
$$\textit{Mass ratio}: \; m^* = \frac{m}{\rho\pi D^2}$$

Reduced-Order Models for Active Near-Wake Jet Control

- ❑ Active control strategy to attenuate unsteady aerodynamics

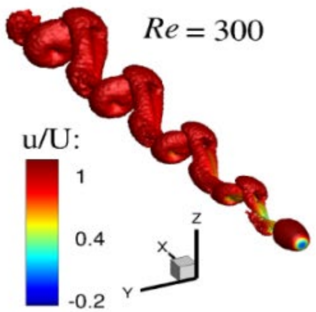


Reduced Model: Eigenvalue distribution

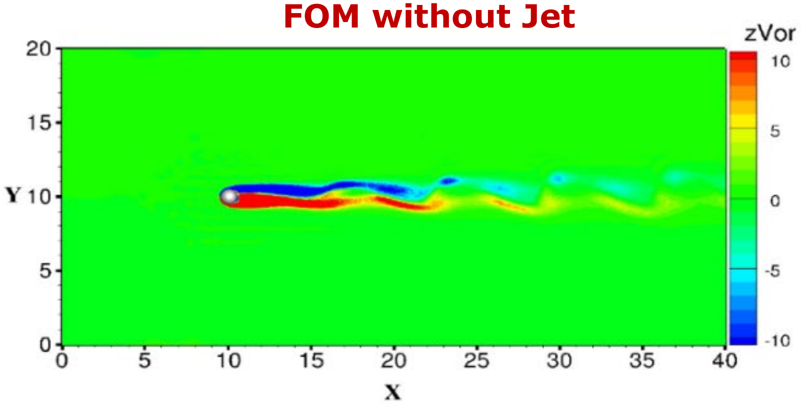


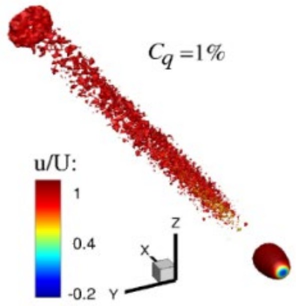
Just a tiny jet flow (C_q=1%) can suppress unsteady aerodynamics completely!

Chizfahm & Jaiman, POF 2021

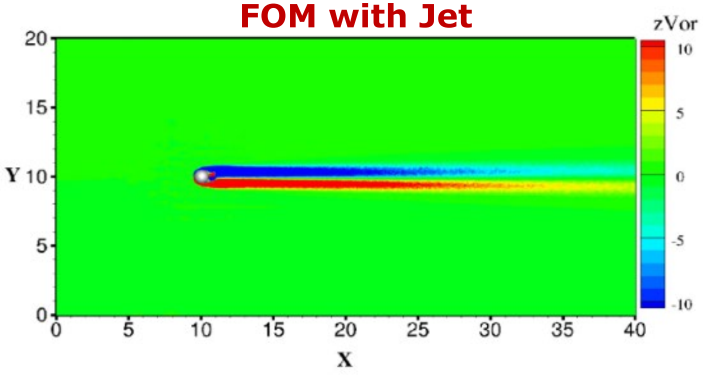


FOM without Jet



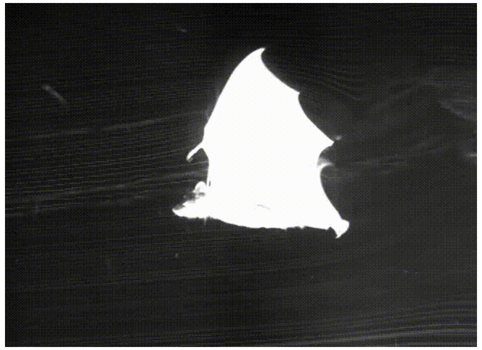


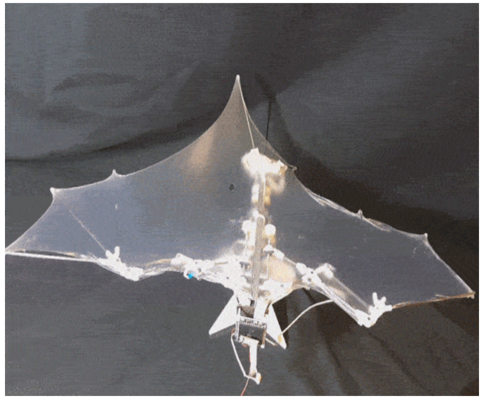
FOM with Jet



Summary and Barriers

- ❑ Flexible multibody fluid-structure interaction
  - ▶ Flexibility of structures (i.e., wing morphing) can drive a new revolution in aerospace engineering
  - ▶ Natural flyers (birds and bats) can offer design solutions to engineers
- ❑ Automation and control
  - ▶ Reduced order modeling
  - ▶ Sensing and control of aeroelastic modes of interest
  - ▶ Physics-based articulatory motion synthesizer
- ❑ Manufacturing and fabrication
  - ▶ Complex muscular hydrostats and tissue structures
  - ▶ Material characterization and biomechanics





Ramezani A. et al. SCI 2017

Thank you for your attention!