Extended Reality Flight Simulation and Control Laboratory

UNIVERSITY OF MARYLAND

UMBERTO SAETTI

Assistant Professor

Department of Aerospace Engineering

- **Research Overview**
  - Bio
  - Overview of Research Topics
- **Experimental Capabilities**
  - Approach to Flight Simulation
  - Laboratory Setup
- **Computational Capabilities**
  - Simulation Models
  - State-Space Free-Vortex Wake
  - Aeroacoustic Solver
- **Sponsored Research**

Presenter's Bio

Education

- **Penn State**
  - Ph.D. Aerospace Engineering (2019)
  - M.Sc. Electrical Engineering (2017)
  - M.Sc. Aerospace Engineering (2016)
- **Politecnico di Milano** (Italy)
  - B.Sc. Aerospace Engineering (2014)

Research Experience

- Assistant Professor (**University of Maryland**) 2022-Present
- Assistant Professor (**Auburn University**) 2021-2022
- Postdoctoral Fellow (**Georgia Tech**) 2019-2021
- Graduate Research Assistant (**Penn State**) 2015-2019
- Visiting Scholar (U.S. Army ADD, **NASA** Ames) 2018

Research Field

- Flight Dynamics & Control, System ID, Handling Qualities
- Coupled Flight Dynamics, Aeromechanics, and Acoustics
- Time-Periodic Systems

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Research Overview

Coupled Flight Dynamics, Aeromechanics, and Aeroacoustics Simulations

- Linearization, stability, order reduction, control
- Rotary-Wing Vehicles (helicopter, tiltrotors, etc.)
- Flapping-Wing MAVs (insects, birds)

Advanced Flight Control Systems

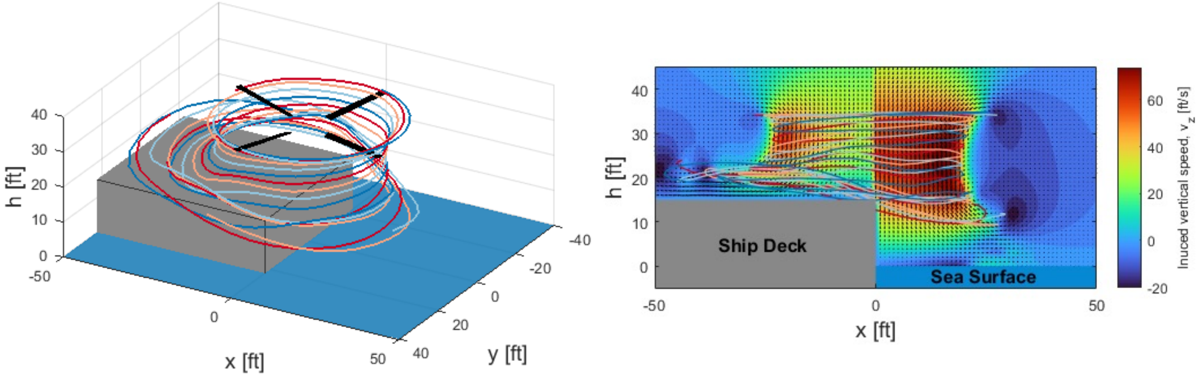
- Rotorcraft flight control systems
- Active noise-abatement flight control laws
- Active rotor vibration flight control laws

Perception Modeling and Pilot Cueing Methods

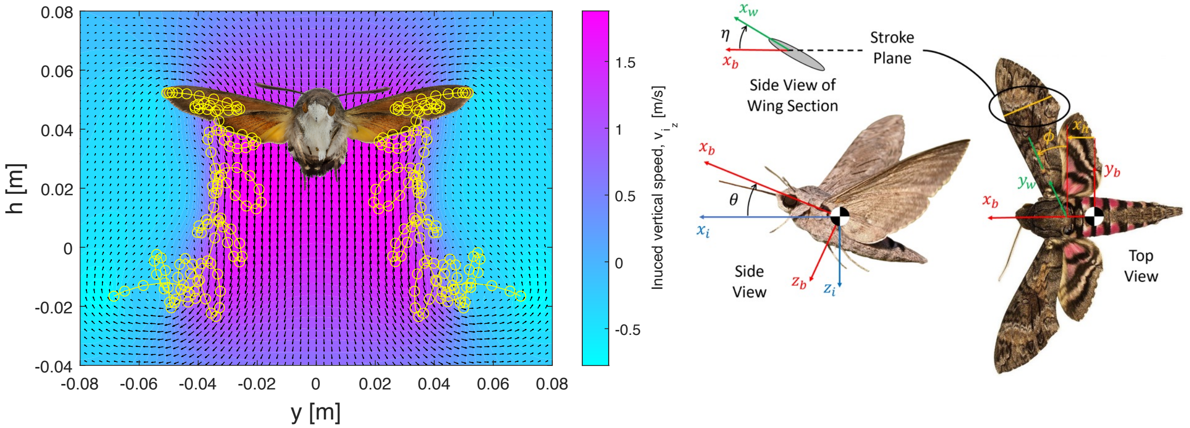
- Full-body haptic feedback
- Cueing algorithms for autorotation/shipboard landing

Dynamic Systems Approach to Fluids/Aeroacoustics

- Time-periodic fluid flows
- Linearization Methods



State-space free-vortex wake for shipboard interactions



State-space free-vortex wake for bioinspired flight

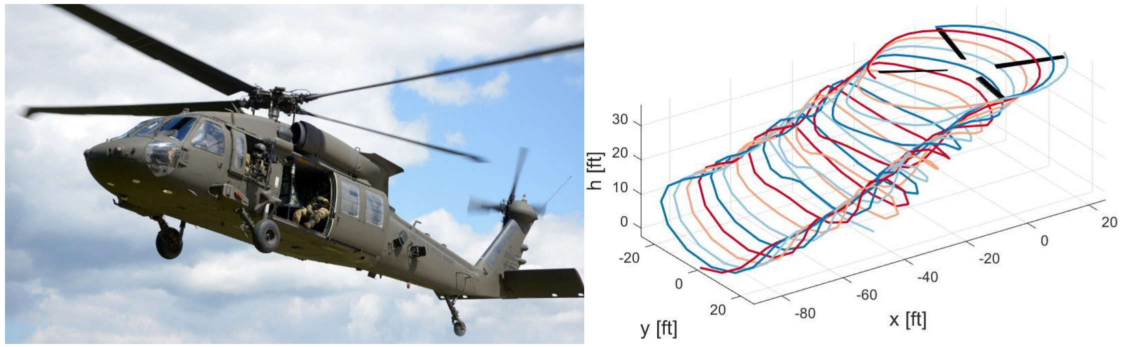
Modeling, Order Reduction, and Control of the Coupled Flight Dynamics, Free-Vortex Wake, and Aeroacoustics

Current Work

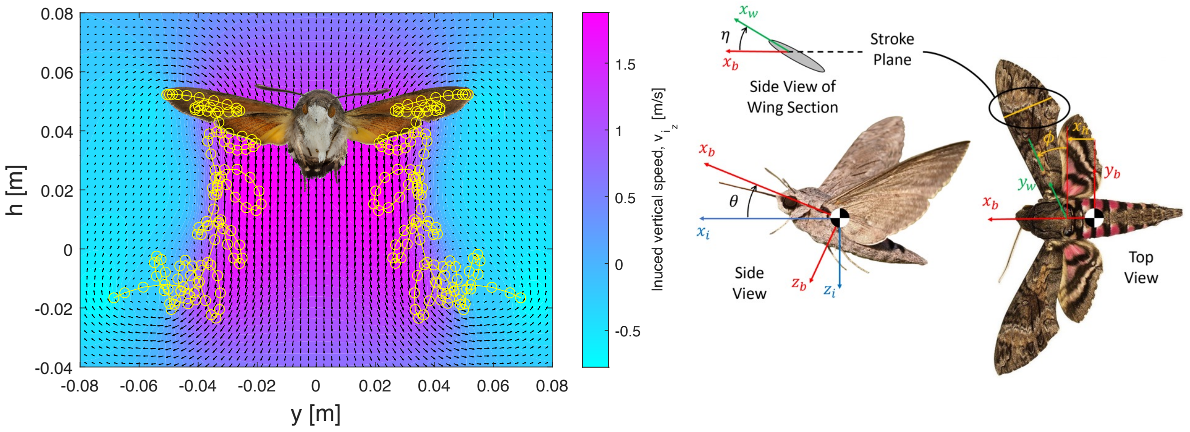
- ❑ **Development of coupled simulations of time-periodic systems**
  - Flight dynamics
  - State-space free-vortex wake
  - Aeroacoustics
- ❑ **Stability and Real-time Aeroacoustics**
  - Linearization methods
  - Approximation with higher-order linear time-invariant systems
  - Real-time linear predictions

Broader Impact

- ❑ Stability of flapping-wing flight
- ❑ Complete description of aerodynamic noise in generalized maneuvering flight
- ❑ Real-time prediction of rotary/flapping-wing acoustics



State-space free-vortex wake of a UH-60 helicopter



State-space free-vortex wake for bioinspired flight

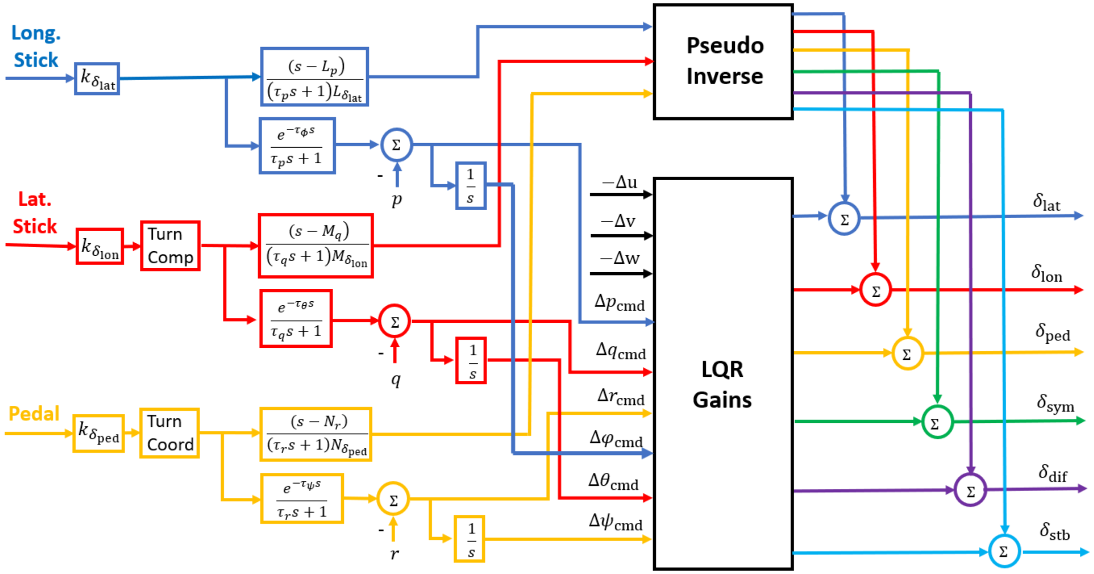
Advanced Flight Control Systems

Current and Past Work

- ❑ Flight control laws
  - ▪ Load alleviation control (LAC)
  - ▪ Noise abating control
  - ▪ Higher-harmonic control (HHC)
  - ▪ Carefree maneuvering
  - ▪ Redundant control allocation
- ❑ Integrated flight control design
  - ▪ Primary flight controls
  - ▪ Vibration/noise control laws

Broader Impact

- ❑ Advance state of the art of fly-by-wire systems
- ❑ Increase safety and comfort of future aerial platforms



Load alleviation control (LAC) law using redundant control effectors on a compound helicopter

Multimodal Perception Modeling for Full-Body Haptic Cueing

Problem

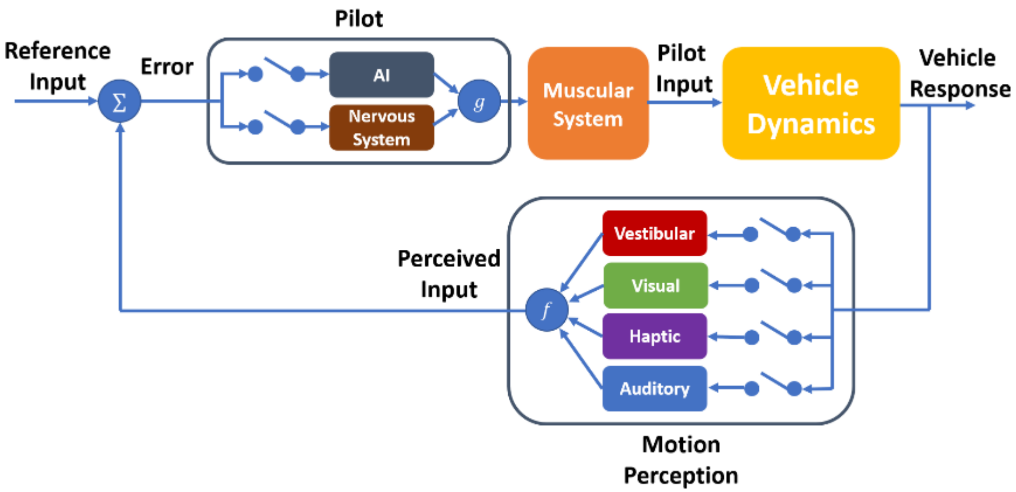
- Pilot models limited to **visual** and **vestibular** cues
- Currently no modeling of **haptic** or **auditory** cues
- How to optimize cueing strategy for guidance, control, and navigation (GNC)?

Solution

- Multimodal perception modeling
- Full-body haptics + spatial audio cueing
- Use secondary cues in case of primary cue impairment/denial
- Real-time cross-diagnostics of human/AI pilot performance

Applications

- Manned lunar landing
- Extra vehicular activities
- Flight in degraded/denied visual environments



Symbiotic pilot-vehicle system

Use of full-body haptics for manned lunar landing

Dynamic Systems Approach to Time-Periodic Fluid Flows

Application Examples

- Rotary- and flapping-wing aerodynamics/aeroacoustics
- Pitching and plunging airfoils
- Plasma flows in Tokamak (nuclear fusion)
- Flow past an oscillating cylinder

Problem

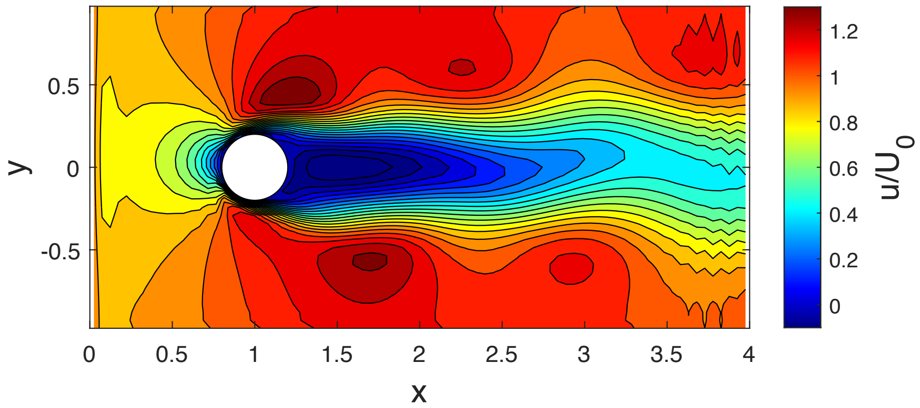
- Expensive simulations (especially if viscous)
- Cannot be linearized with standard methods
- Need linearized model for **active flow control**

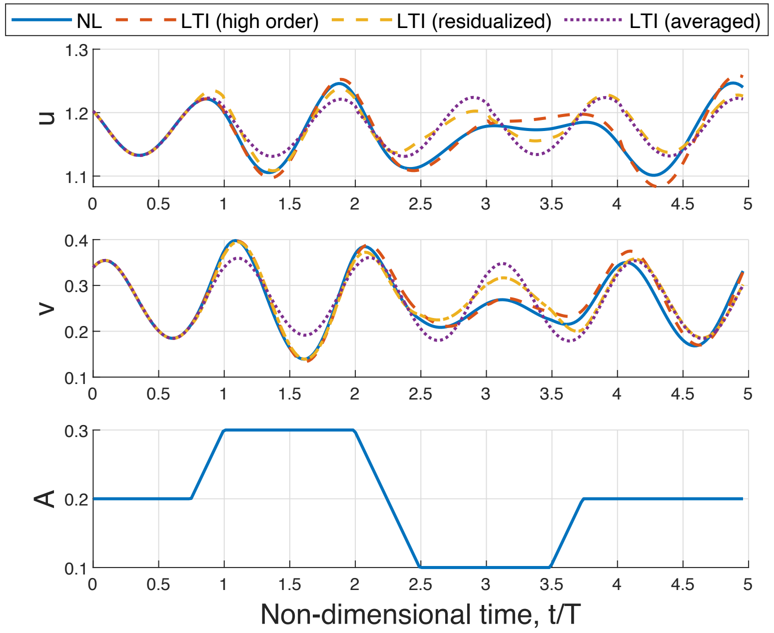
Solution

- Dynamic system approach to periodic fluid flows
- Harmonic decomposition and order reduction
- Open- and closed-loop control design

Interactions

- Nek Sharan (Auburn)





Prediction of velocity fluctuations for an oscillating cylinder using harmonic decomposition models

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Extended Reality Flight Simulation and Control Lab

VR/AR Headset

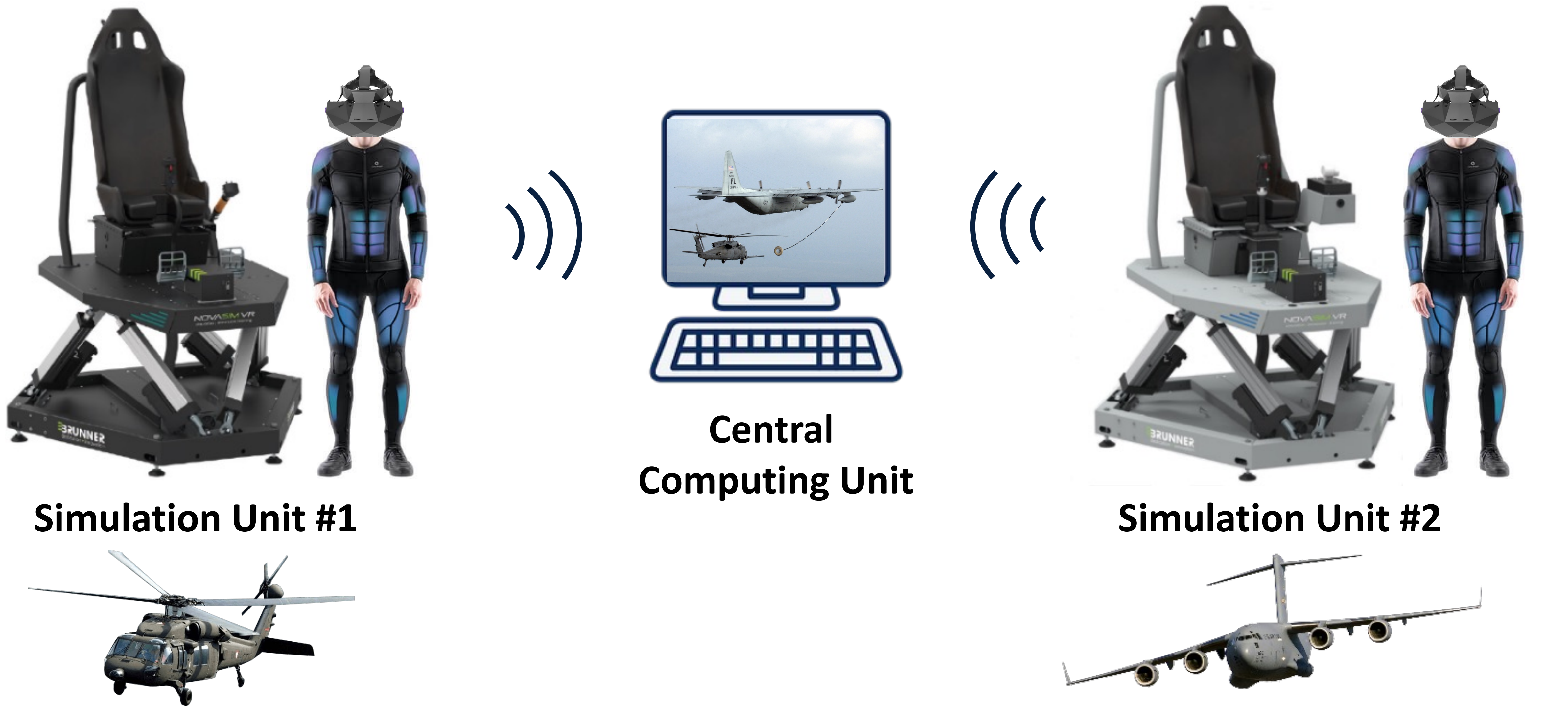
+

Haptic Feedback
Pilot Suit

+

Motion-Base
Simulator

Extended Reality Flight Simulation and Control Lab



Extended Reality Flight Simulation and Control Lab

Multi-Purpose
- Can interface w/ MATLAB, Flightlab, Julia, etc.
- Can simulate different cockpit graphics

Reconfigurable
- Fixed-wing (GA + jet) + rotorcraft controls
- Can implement motion cueing algorithms

Modular
- Can link multiple units together

Enhanced Motion Cueing
- Low mass/inertia → Increased motion bandwidth and range

Immersive
- VR provides 360° visual environment
- Look-down capability
- Pilot can see its hands and interact with cockpit
- Haptic feedback (force-feel controls + suit + gloves)

VR motion-base simulator at
Extended Reality Flight Simulation and Control Lab

Extended Reality Flight Simulation and Control Lab

6-DoF Motion Platform

- Max payload: 660 lb (300 kg)
- Displacement and velocity
  - **Heave**: $\pm$185 mm, $\pm$600 mm/s
  - **Surge**: $\pm$240 mm, $\pm$600 mm/s
  - **Sway**: $\pm$240 mm, $\pm$600 mm/s
  - **Roll, Pitch, Yaw**: $\pm$30 deg, $\pm$120 deg/s

Visual System

- XTAL 8k
- Display
  - Resolution: 3840x2160 (4K) per eye
  - 180 deg field of view
  - Refresh rate: 75 hz @ 4K per eye
- Hand Tracking
  - Ultraleap Motion Rigel
  - 170 deg circular viewing angle
- Eye tracking @ 100 Hz

Motion-Base Flight Simulator

VR/AR Headset (XTAL 8K)

Extended Reality Flight Simulation and Control Lab

Pilot Suit

- Haptic system / NMES
  - ❑ 80 electrostimulation channels
  - ❑ 114 electrodes
- Biometry
  - ❑ Electrocardiography
- Motion tracking
  - IMU 9 axes and 6 axes modes
  - 10 internal motion capture sensors
- Connectivity
  - ❑ Wi-Fi 2.4 ghz

Haptic Gloves

- Sensoryx Haptic Gloves

TESLASUIT

Sensoryx Haptic Gloves

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Flight Simulation Models

Versions Available

- ❑ MATLAB
- ❑ julia

Rotorcraft Models

- ❑ **SimpleHel** (UH-60, AH-1, Bell 430)
  - Minimum fidelity
  - Quasi-static rotor dynamics
- ❑ **GenHel** (UH-60)
  - Higher fidelity
  - Rotor + inflow dynamics

Fixed-Wing Aircraft Models

- ❑ F-16

In Development

- ❑ Tiltrotor (V-22 Osprey)
- ❑ Co-axial rotorcraft (SB>1 Defiant)

UH-60 Black Hawk

AH-1 Cobra

Bell 430

F-16 Fighting Falcon

V-22 Osprey

State-Space Free-Vortex Wake

Free-Vortex Wake Code Highlights

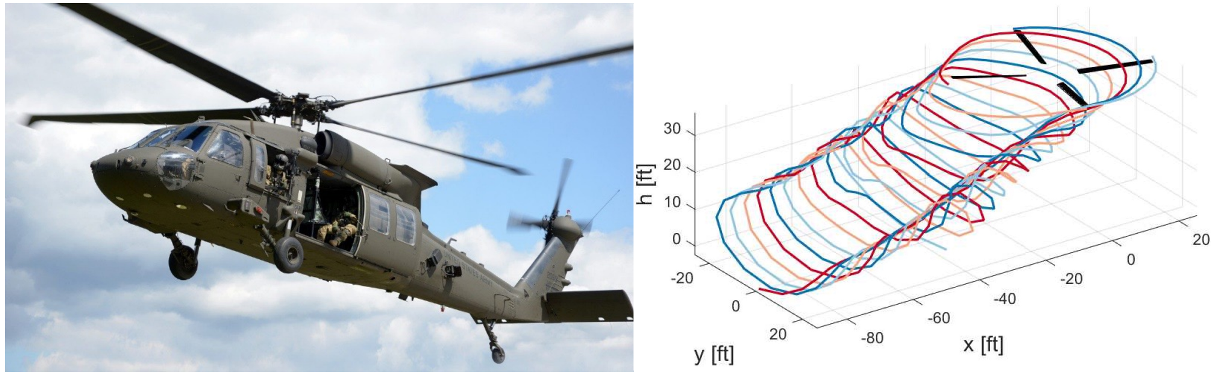
- ❑ Implemented in MATLAB
- ❑ Models dynamics of tip-vortex filaments
- ❑ **State-space free-vortex wake**

$$\frac{\partial \boldsymbol{r}(\psi,\zeta)}{\partial \psi} + \frac{\partial \boldsymbol{r}(\psi,\zeta)}{\partial \zeta} = \frac{1}{\Omega}\boldsymbol{V}(\boldsymbol{r}(\psi,\zeta))$$

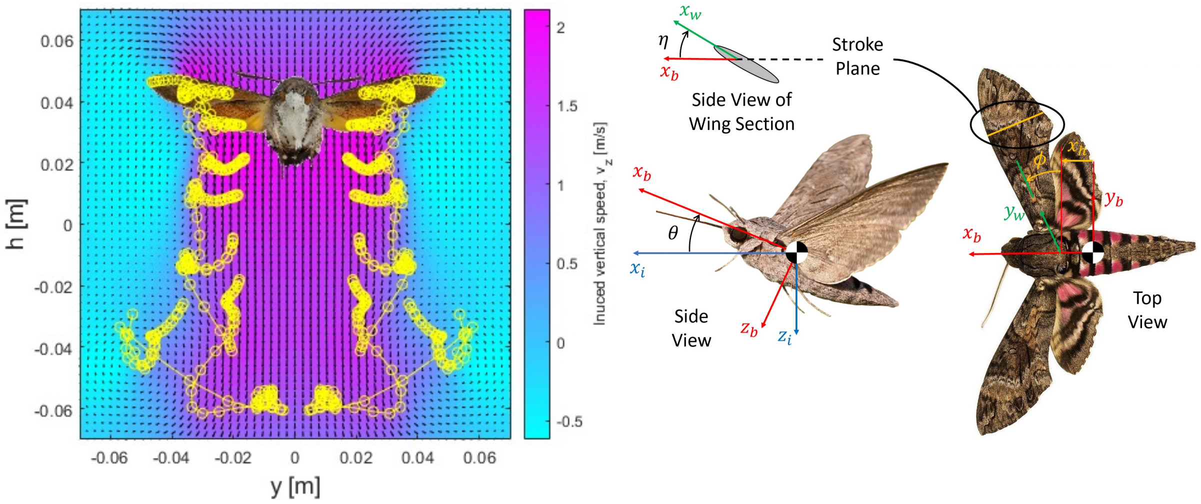
$$\frac{\partial \boldsymbol{\Gamma}(\psi,\zeta)}{\partial \psi} + \frac{\partial \boldsymbol{\Gamma}(\psi,\zeta)}{\partial \zeta} = 0$$

$$\dot{\boldsymbol{v}}_i = \frac{1}{\tau_{v_i}}\left[\boldsymbol{V}\big(r_B(t,\zeta)\big) - \boldsymbol{v}_i\right]$$

- ❑ Can be linearized to yield <u>real-time</u> flow-field computations
- ❑ Stability of coupled flight dynamics and aeromechanics
- ❑ High-fidelity wing/rotor loads



State-space free-vortex wake of a UH-60 helicopter



State-space free-vortex wake for bioinspired flight

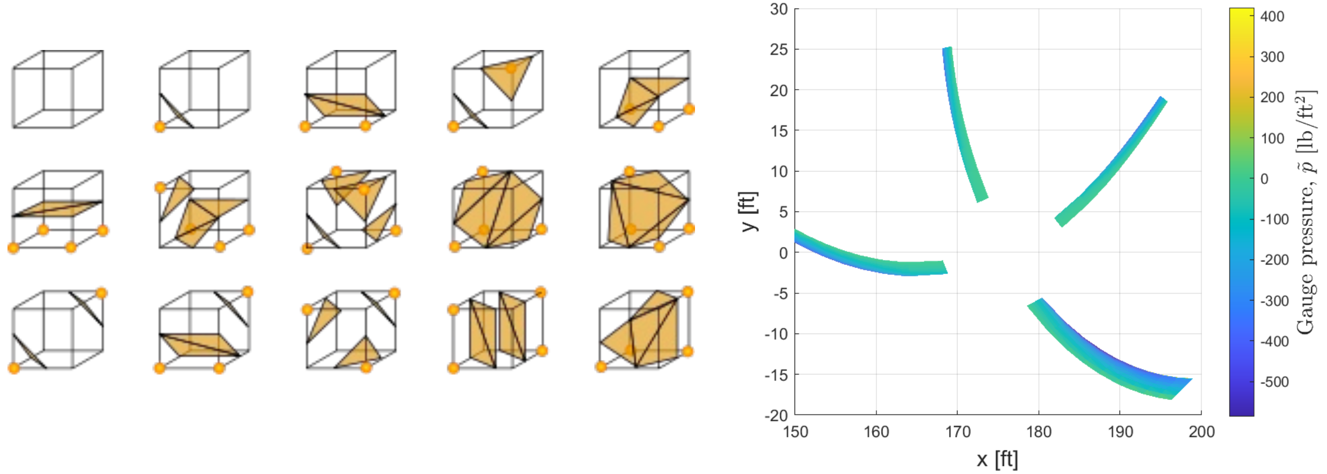
Aeroacoustic Solver

Solver Highlights

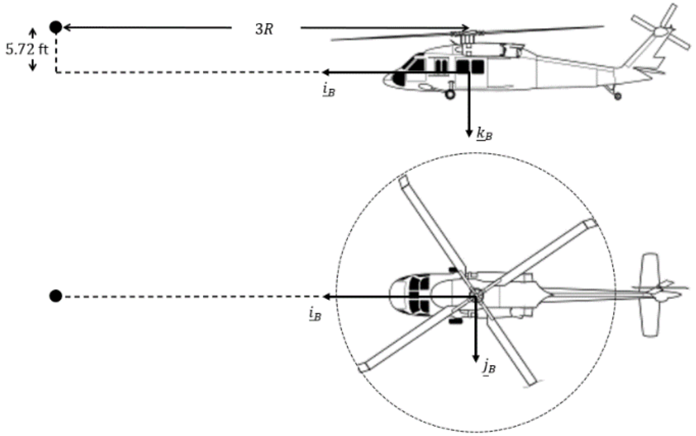
- ❑ Implemented in MATLAB
- ❑ Impermeable Ffowcs Williams-Hawkings surface formulation

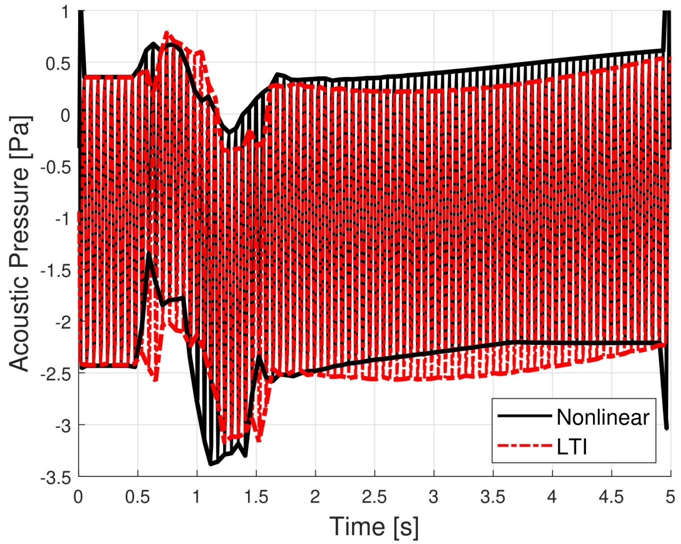
$$4\pi p'(x,t) = \frac{1}{c_0}\frac{\partial}{\partial t}\int_{\Sigma}\left[\frac{\rho_0 c_0 u_n + \tilde{p}\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{r}}}{r\Lambda}\right]_{\text{ret}} d\Sigma + \int_{\Sigma}\left[\frac{\tilde{p}\hat{\boldsymbol{n}}\cdot\hat{\boldsymbol{r}}}{r^2\Lambda}\right]_{\text{ret}} d\Sigma$$

- ❑ Marching-cubes algorithm to solve for iso-surface



Iso-surface computed with marching cubes approach





Acoustic pressure for generalized maneuvering flight of a H-60-like helicopter

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AUBURN
ENGINEERING

Linearized High-Fidelity Aeromechanics for Extended Reality Simulation and Control of Shipboard Interactions

Problem

- Rotor wake interaction w/ ship deck affects
  - ❑ Performance
  - ❑ Handling qualities
- Fatal MV-22 Osprey crashes (2015, 2017)

Solution

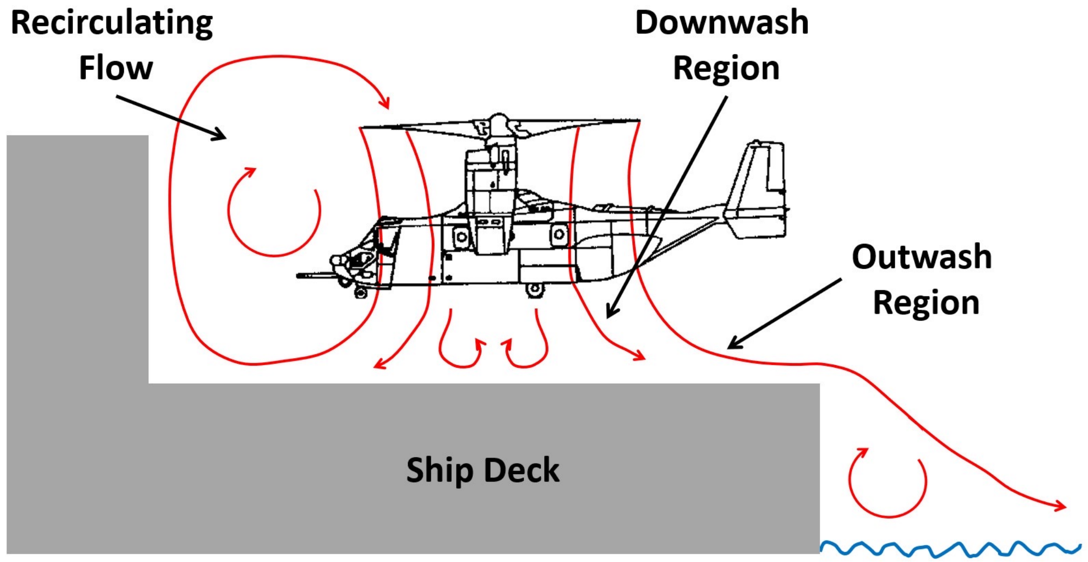
- Real-time prediction of adverse shipboard interactions
- Control laws to compensate for adverse interactions
- Innovative cueing methods (**full-body haptics**) for increased pilot awareness

Funding

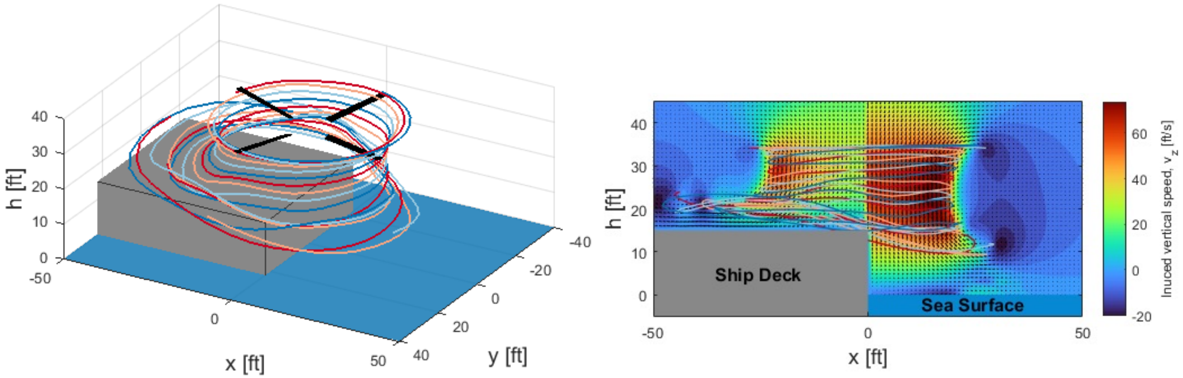
- **ONR YIP $ 510,000** (B. Holm-Hansen) – **Awarded**

Interactions

- John Tritschler (USNTPS)
- Sven Schmitz (Penn State)



Adverse shipboard interactions



State-space free-vortex wake for prediction of shipboard interactions

State-Space Implementation and Linearization of Simulations with High-Fidelity Aeromechanics

Problem

- Rotor noise expressed with PDE's
  - ❑ Much slower than real-time
  - ❑ No linear model to base control system upon
- Complex to cue rotor noise visually

Solution

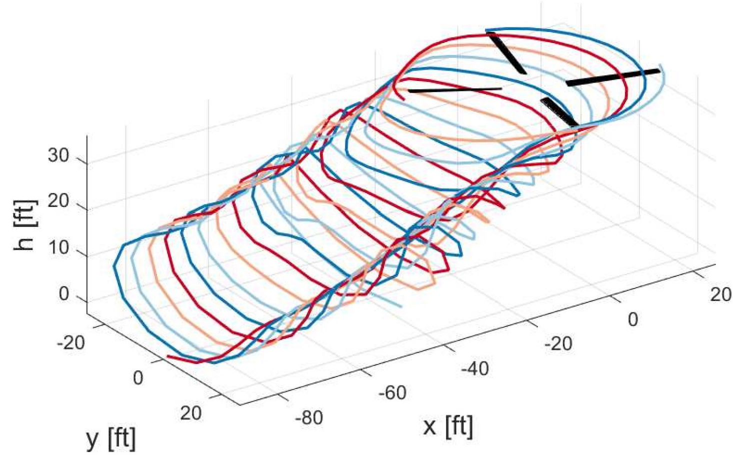
- State-variable implementation of aeromechanics
- Linearize dynamics with noise as output
- Active noise-abating flight control laws
- Cueing through full-body haptics (feel noise)

Funding

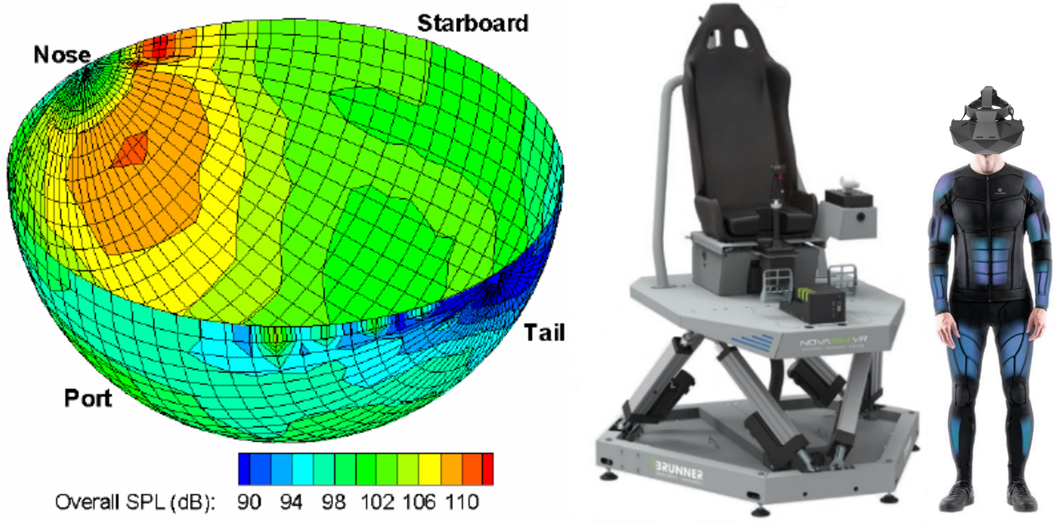
- Penn State **VLRCOE $380,000** – **Awarded**

Interactions

- Joe Horn, Ken Brentner (Penn State)



Time-periodic state-space free vortex wake model



Real-time prediction and cueing of rotorcraft noise via full-body haptics

Interactional Aerodynamics Modeling and Flight Control Design of Multi-Rotor Unmanned Aircraft Systems

Problem

- Rotor-on-rotor interactions predicted with very high-order models
- Simulations far slower than real-time
- Linearized models non tractable for control design

Solution

- Implementation of low-order dynamic inflow model for predicting rotor-on-rotor interactions
- Linearization and model-order reduction
- Flight control laws based on linear models that account for rotor-on-rotor interactions

Funding

- **U.S. Army $ 133,000** (Tom Berger) – **Awarded**

Interactions

- Roberto Celi (UMD)
- Tom Berger, Mark Lopez, Emily Glover (US Army CCDC)

Malloy TRV-80 Coaxial Quadcopter

State-Variable High-Fidelity Aeromechanics for Stability Analysis, Control, and Noise Prediction of Bio-Inspired Flight

Problem

- Interactional wing-body-wake aerodynamics
- Stability analysis including higher harmonics
- HHC design
- Acoustics in generalized maneuvering flight

Solution

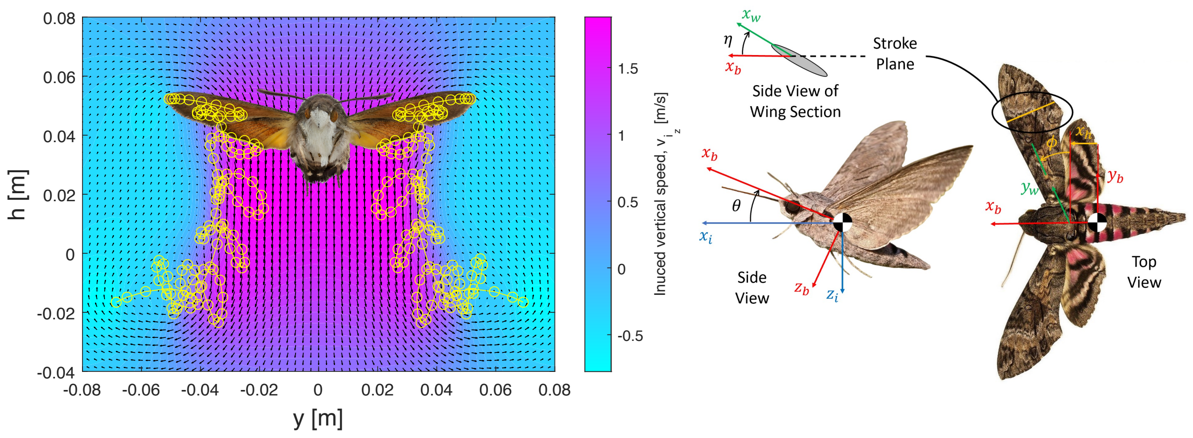
- State-variable aeromechanics models
- Time-periodic linearization methods
- Dynamic system approach to acoustics

Funding

- **NSF JGCD $ 320,000** (Jordan Berg) – **Pending**

Interactions

- Haithem Taha (UC Irvine)



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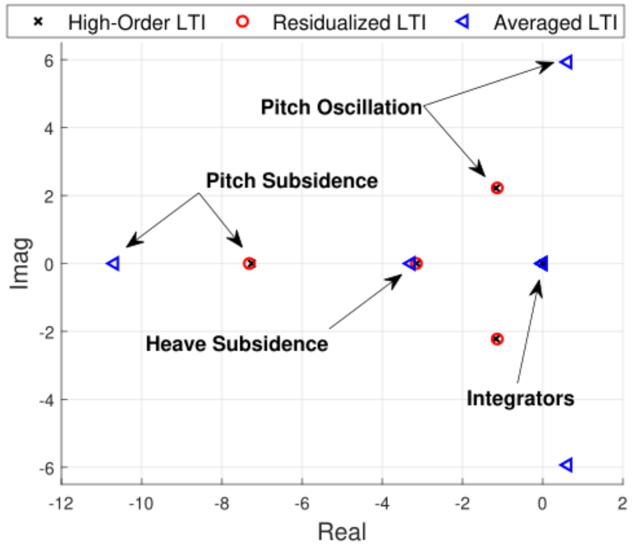

Hawkmoth's eigenvalues at hover