AFRL-RB-WP-TM-2011-3043

RISK-BASED COMPUTATIONAL PROTOTYPING (BRIEFING CHARTS)

Philip Beran, José Camberos, Ned Lindsley, and Bret Stanford

Multi-Disciplinary Technologies Branch
Structures Division

OCTOBER 2010
Interim Report

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14. ABSTRACT
We are developing computational methods that will enable the computational design of air vehicles accounting for inherently nonlinear dynamic behaviors. These behaviors fall into two categories: behaviors that are beneficial for vehicle operation, such as could be observed for micro air vehicles propelled by wing flapping (e.g., a productive energy transfer between the unsteady vortical flow produced by a flapping wing and the associated nonlinear deformation of the wing), and behaviors that constrain vehicle operation, such as in the dangerous limit-cycle oscillation of large aircraft. In either case, the design space is large and the analysis multi-disciplinary. We have investigated different ways of computing sensitivities of vehicle dynamics to a large number of design variables, compressing the computation using model reduction, and assessing the impact of variability on the reliability of the system.

15. SUBJECT TERMS
computational design, sensitivity analysis, limit-cycle oscillation, flapping

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Prescribed by ANSI Std. Z39-18

Risk-Based Computational Prototyping

Dr. Philip Beran, Principal Research Aerospace Engineer, PI
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Dr. Ned Lindsley, Aerospace Engineer, Co-PI
Dr. Bret Stanford, Post-Doctoral Research Associate
Multidisciplinary Science & Technology Center (MSTC)
Air Vehicles Directorate

September, 2010

MSTC Organization & Activity

Mission: ***Integrate multiple disciplines to discover and exploit new phenomena for system optimization and assessment of revolutionary aerospace vehicles***

Center Director

Branch Chief
- Tech Advisor

Prototype Representation & Design Exploration Methods
- Parametric Geometry & Mesh
- Subsystem Representation
- Design Space Exploration & Optimization
- Risk-based Design

Analysis Methods for Prototypes
- Multidisciplinary Analysis
- Appropriate-fidelity Solutions and Sensitivities
- Nondeterministic Models

Prototype Validation & Assessment
- HiFi QTA
- Prototype Experimental Validation
- TRL Assessment

Shared Activity - Utilize a Unified Framework (SORCER, MODEL Center)

Some Significant Collaborations

MSTC Collaborative Center with
VPI & SU, WSU, and University of Maryland
(Formed March 2009)

Prof Kapania, Director
Dr. Kolonay, PM

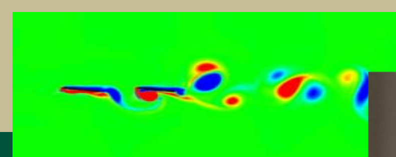
WRIGHT STATE UNIVERSITY

VirginiaTech
Invent the Future

AFRL/RB and WSU Center for Micro Air Vehicle Studies (Formed June 2010)

Prof Huang, Director
Dr. Beran, PM

WRIGHT STATE UNIVERSITY



- Prof Missoum, Mr. Basudhar (UA, Tucson) and Dr. Lambe (MSSRC) – RBDO with LCO
- Prof Dong and Mr. Gaston (WSU) – ROM and Simulation of falling bodies
- Prof McFarland and Mr. Hubbard (UIUC) – Transmission design with nonlinearity

Internal Collaborations in MAVs

Math (6.1)

Risk-Based Computational Prototyping

Beran (PI), Camberos, Lindsley

Physics (6.1)

Physics-Based Design Analysis of MAVs

Snyder (PI), Beran, Kolonay

NRC: Chabalko, Kurdi, McClung, Stanford

Basic Research in Computational Design (2009-2011)

Flapping Sciences Integration (2009-2011): **6.2**

- ***Service-oriented framework***
- ***In-house computer scientists***
- ***Design tools (Transition)***
- ***Funded follow-on design program (MPP, FY12+)***

AFRL/RB MAV Team

Basic and Applied Research in MAVs

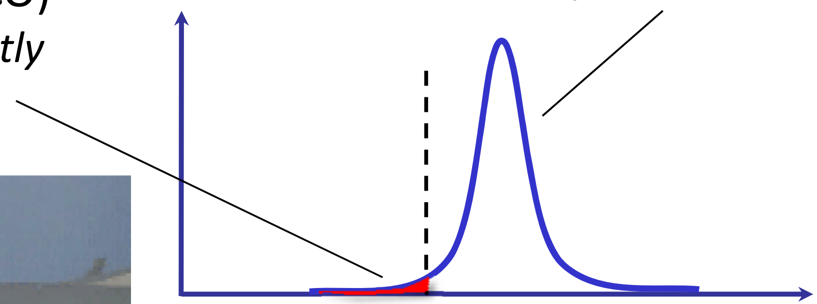
- ***Structural and Flight Testing*** **(Parker) – validation of structural and system models**
- ***CFD*** **(Visbal) – verification of aero models**
- ***Controls Science*** **(Doman) – integration of controls models**
- ***Unsteady Aerodynamics*** **(OL) – validation of aero models**
- ***Perching Technologies*** **(Reich) – application of aero models**

Role of Computational Mathematics

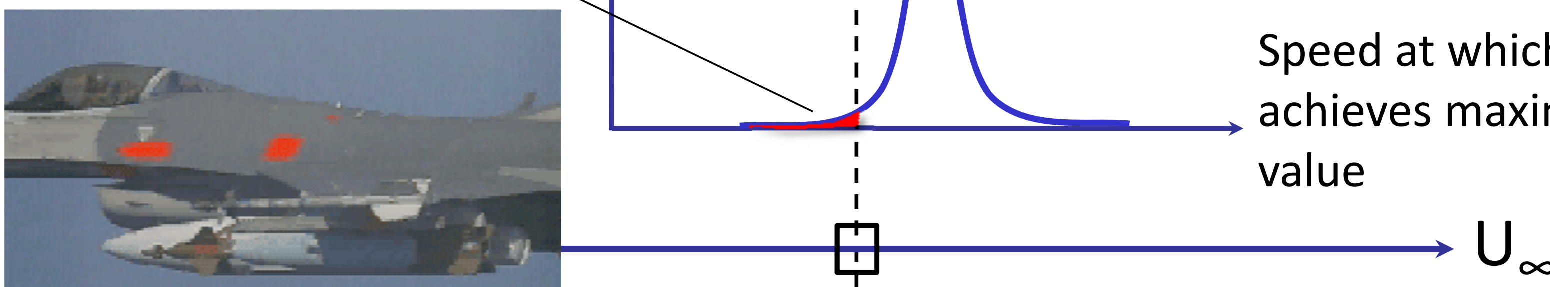
P_F = Probability of Failure (large LCO)
Must be sufficiently small

PDF

Distribution of critical speeds arises via variability in air vehicle or environment

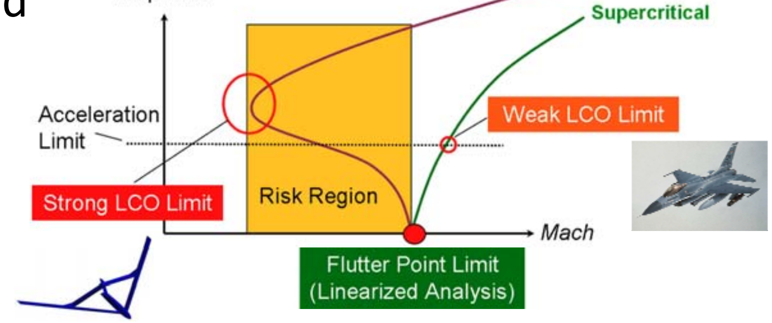


Speed at which LCO achieves maximum value



Large Vehicles

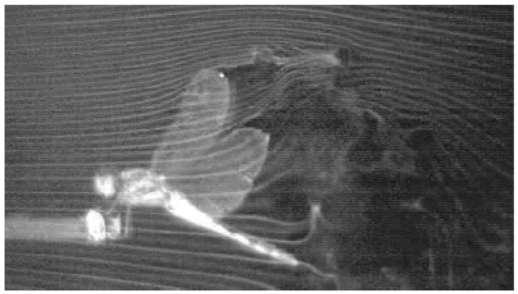
Target Flight Speed



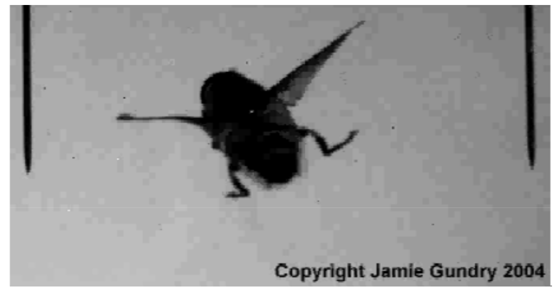
Computational mathematics needed for physics-based design of reliable vehicles

Role of Computational Mathematics (cont.)

- Exploit nonlinear aeroelastic interactions for small aircraft



Unsteady Flow, Iida (2004)



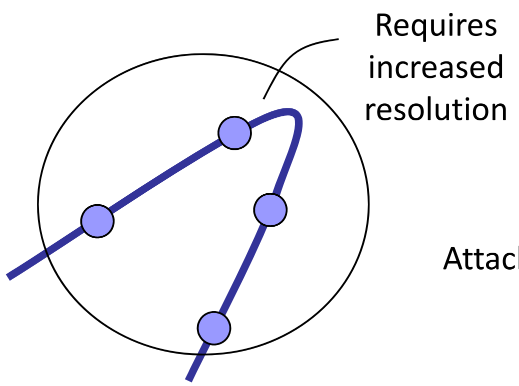
Unsteady Deformations

- Numerous challenges for design of Micro air vehicles (MAVs)
  - Physics Rich (must be a physics-based approach)
  - Complex and time-dependent actuations (unsteady)
  - Non-conventional geometries and structural topologies
  - Power-based integration of propulsion, structure, control components

Computational mathematics needed for physics-based design of MAVs

Akiyoshi Iida (2004) – Kogakuiu Univ, http://www.nagare.or.jp/mm/2004/gallery/iida/dragonfly.html

Spectral Formulation for Time-Periodic Systems

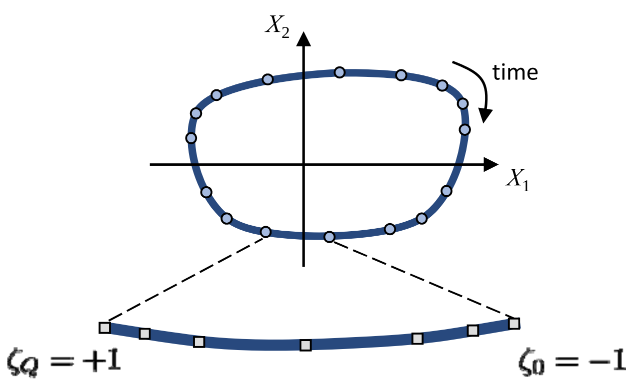


Monolithic-time collocation

Attack high-frequency content with *hp*-refinement

Attack Large # of space DOFs with ROM

Dimensionality of **X** $\times$ Number of DOFs in time (elements x order+1) $=$ $\mathbf{X}_{\text{mon}}$ Total DOFs



- Uses a local basis instead of global basis

$$X_e(\zeta) = \sum_{q=0}^{m} X_e(\zeta_q)\Psi_q(\zeta)$$

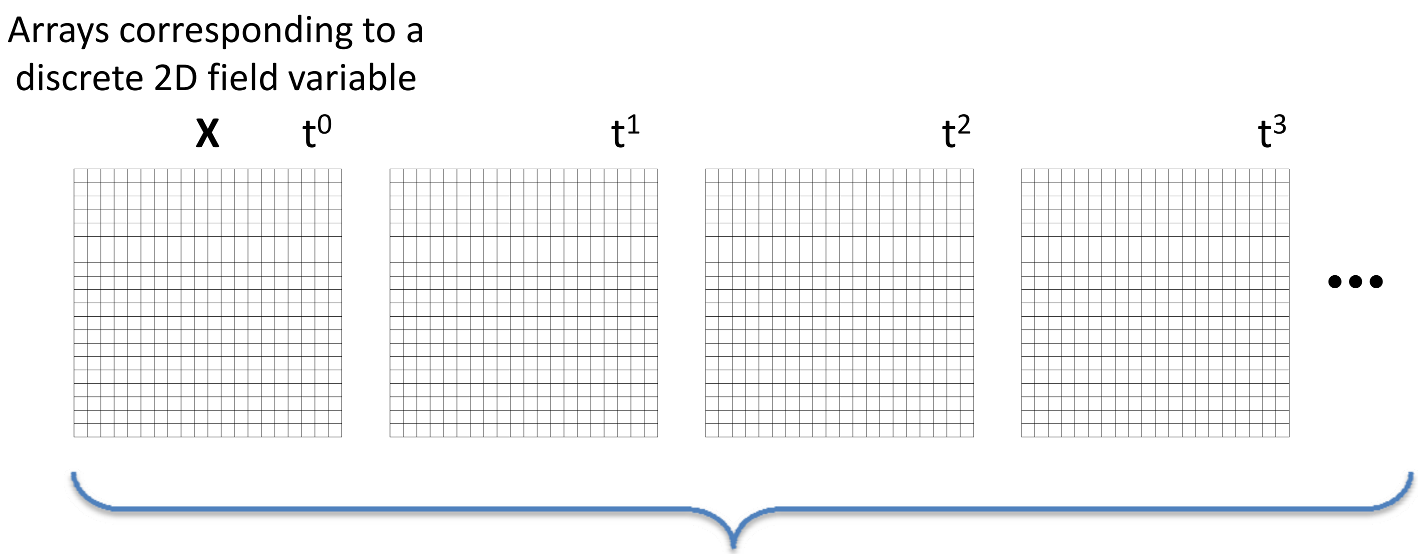
m – Order of the spectral element

ζ_q – Zeroes of the Lobatto-Legendre polynomials

$\Psi_q(\zeta)$ – Lagrange polynomial of order *m*

Kurdi and Beran, "Spectral Element Method in Time for Rapidly Actuated Systems," *JCP*, Vol. 227, No. 3, 2008, pp. 1809-1835.

Monolithic-Time Collocation



$$\mathbf{X}_{mon} = [X^0, X^1, X^2, X^3, \ldots]$$

Context for time-periodic *and* transient solutions

Adjoint-Variable Approach

1

Solve $\mathbf{F}_{mon}(\mathbf{X}_{mon},\lambda) = 0$

$H(\mathbf{X}_{mon})$ = objective

$\mathbf{F}_{mon}$ = equation residual

Sensitivity:
$$\frac{dH}{d\lambda} = -\overbrace{\frac{\partial H}{\partial \mathbf{X}_{mon}}\left(\frac{\partial \mathbf{F}_{mon}}{\partial \mathbf{X}_{mon}}\right)^{-1}}^{\text{adjoint}}\;\underbrace{\!\!\!\!\!\!\!\!\!\!\phantom{\left(\frac{\partial \mathbf{F}_{mon}}{\partial \mathbf{X}_{mon}}\right)^{-1}}\frac{\partial \mathbf{F}_{mon}}{\partial \lambda}}_{\text{direct}}$$

2

$$\left(\frac{\partial \mathbf{F}_{mon}}{\partial \mathbf{X}_{mon}}\right)^{T} \mathbf{C}_{mon} = \left(\frac{\partial H}{\partial \mathbf{X}_{mon}}\right)^{T}$$

High cost:
computed once

3

$$\frac{dH}{d\lambda} = -\mathbf{C}_{mon}^{T} \frac{\partial \mathbf{F}_{mon}}{\partial \lambda}$$

Inexpensive:
analytic or finite-difference (repeat for each variable) about monolithic solution

Goal: Examine challenge of storing $\mathbf{X}_{mon}$ between step 1 and 2

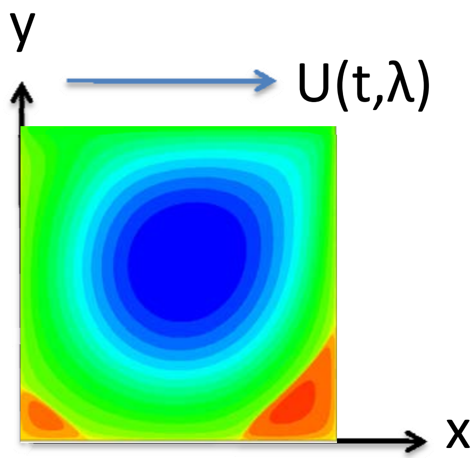
Adjoint Computation for Transient Sensitivity Analysis

Goal: Develop a sensitivity analysis process that scales well with total # DOFs

- Interested in the adjoint-variable approach in anticipation of:
  - many design variables (not true of direct and sampling based approaches)
  - use of gradient-based optimization (trade global effectiveness for efficiency)
- Some relevant literature
  - Nadarajah and Jameson, "Optimum Shape Design for Unsteady Flows with Time-Accurate Continuous and Discrete Adjoint Methods," AIAA Journal Vol. 45, No. 7, 2007
  - Thomas, Hall, and Dowell, "A Discrete Adjoint Approach for Modeling Unsteady Aerodynamic Design Sensitivities," AIAA 2003-0041, 2003
  - Mani and Mavriplis, "An Unsteady Discrete Adjoint Formulation for Two-Dimensional Flow Problems with Deforming Meshes," AIAA 2007-60, 2007
- Create a sample problem to explore a POD-based approach to eliminate challenge of storing the forward solution

Problem Description

Transient analysis of incompressible flow in a square cavity with unsteady lid



Flow at rest initially

- Steady: U = 1 (impulsive)
  - verify; assess accuracy
- Transient: U = ½(1-cos(f t))
  - define H, a function of the transient solution
  - compute sensitivity of H to frequency, f
- Streamfunction-vorticity form

$$\frac{\partial \omega}{\partial t} + u\frac{\partial \omega}{\partial x} + v\frac{\partial \omega}{\partial y} = \frac{1}{Re}\nabla^2\omega \qquad \nabla^2\Psi = -\omega \qquad u = \frac{\partial \Psi}{\partial y}, \quad v = -\frac{\partial \Psi}{\partial x}$$

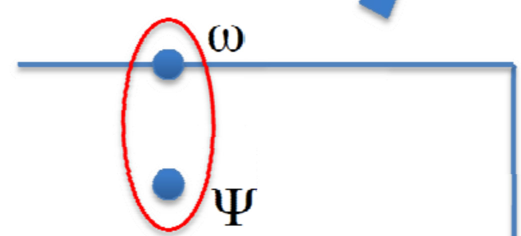
Discretization and Time Integration

Explicit/implicit formulation

1. $$\frac{\omega^{n+1}-\omega^{n}}{dt}+\left(u\delta_x\omega+v\delta_y\omega\right)^{n}=\frac{1}{Re}\left(\delta_{xx}+\delta_{yy}\right)\omega^{n+1}$$

2nd-order-accurate, central-difference operators

2. $$\left(\delta_{xx}+\delta_{yy}\right)\Psi^{n+1}=-\omega^{n+1}$$



3. Repeat for next time step

$$\omega(x,1)=-\frac{2}{\Delta_y^2}\left(\Psi(x,1-\Delta_y)+U(t)\Delta_y\right)+O(\Delta_y)$$

Adjoint-Variable Approach

Linear, time invariant

$$
\begin{array}{l}
n = 1 \\[3em] n = 2 \\[3em] n = 3
\end{array}
\quad
\begin{bmatrix}
\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} & \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} & \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \\
\begin{bmatrix} -\mathbf{I}_i + \mathbf{G}_W^{n=1} & -\mathbf{S} + \mathbf{G}_P^{n=1} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} & \begin{bmatrix} \mathbf{L}_\omega & \mathbf{0} \\ \mathbf{I}_i & \mathbf{L}_\Psi \end{bmatrix} & \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \\
\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} & \begin{bmatrix} -\mathbf{I}_i + \mathbf{G}_W^{n=2} & -\mathbf{S} + \mathbf{G}_P^{n=2} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} & \begin{bmatrix} \mathbf{L}_\omega & \mathbf{0} \\ \mathbf{I}_i & \mathbf{L}_\Psi \end{bmatrix}
\end{bmatrix}
\Delta\mathbf{X}_{mon} = -\mathbf{F}_{mon}
$$

Vorticity BC coupling terms

Jacobians arising from convective terms [apply data compression]

Reverse-time

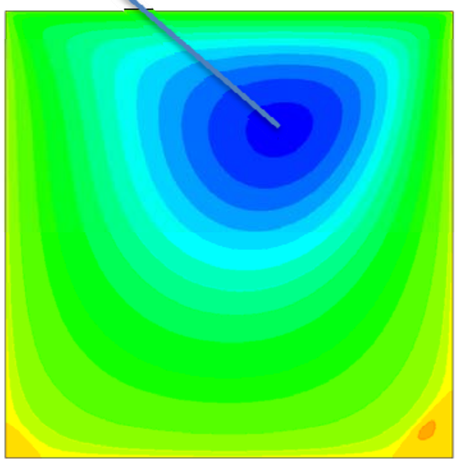
$$
\left[
\begin{matrix}
\begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} \end{bmatrix} & \begin{bmatrix} -\mathbf{I}_i + \mathbf{G}_W^{n=1} & -\mathbf{S} + \mathbf{G}_P^{n=1} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}^T & \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \\
\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} & \begin{bmatrix} \mathbf{L}_\omega & \mathbf{0} \\ \mathbf{I}_i & \mathbf{L}_\Psi \end{bmatrix}^T & \begin{bmatrix} -\mathbf{I}_i + \mathbf{G}_W^{n=2} & -\mathbf{S} + \mathbf{G}_P^{n=2} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}^T \\
\begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} & \begin{bmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} & \begin{bmatrix} \mathbf{L}_\omega & \mathbf{0} \\ \mathbf{I}_i & \mathbf{L}_\Psi \end{bmatrix}^T
\end{matrix}
\right|_{\mathbf{X}^*_{mon}}
\mathbf{C}_{mon} = \left(\frac{\partial H}{\partial \mathbf{X}_{mon}} \right)^T
$$

Linearization

Verification (Steady State)

Ψ_{min}

[-.1026, -.1035]	Collected*
-.1035	Current

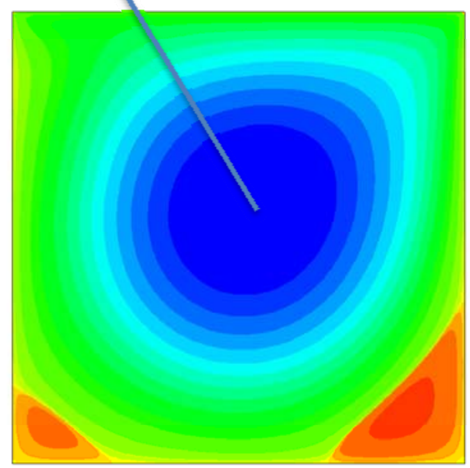


t_{final} = 20, time step = 0.001

Re = 100

Ψ_{min}

[-.1163, -.1188]	Collected*
-.1180	Current

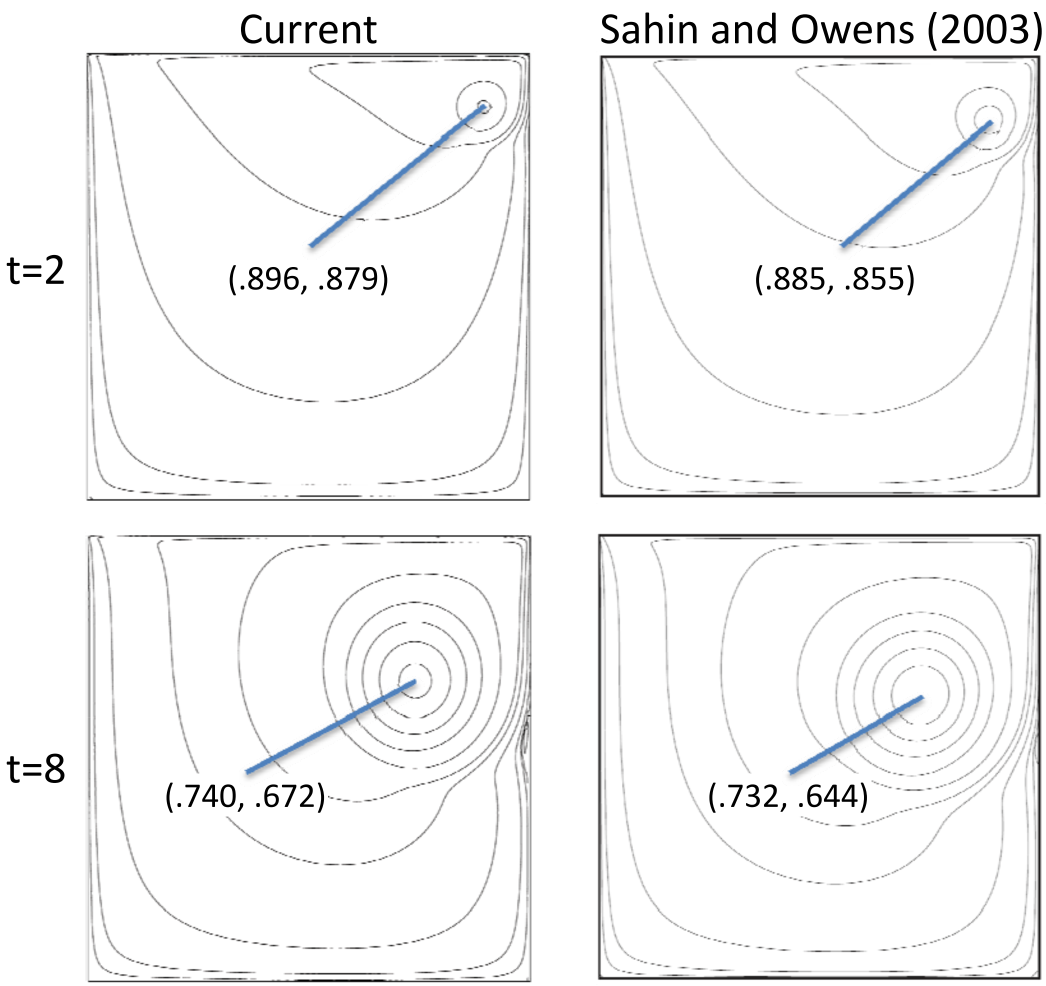


t_{final} = 50, time step = 0.001

Re = 1000

*Sahin and Owens, “A Novel Fully Implicit Finite Volume Method Applied to the Driven Cavity Problem – Part I: High Reynolds Number Flow Calculations,” *Int J Num Methods Fluids*, Vol. 42, Issue 1, May 2003, pp. 79-88

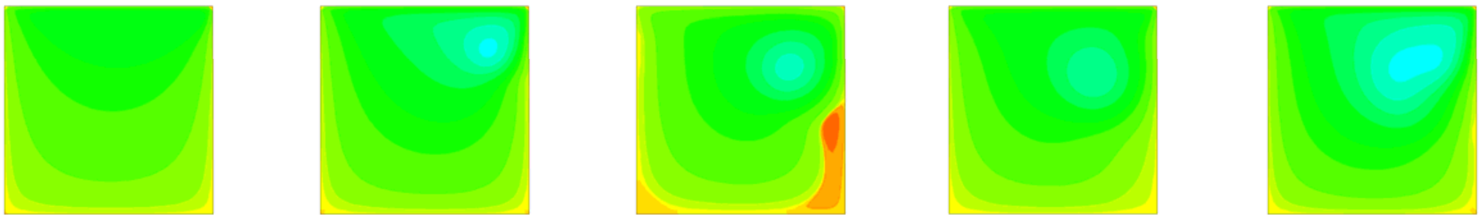
Verification (Transient)



- Re=10000
- U(t) = 1
- Contour plots of Ψ
- *t=2: agree within 2.8%*
- *t=8: agree within 4.4%*
- Need to explore mesh and time step refinements

Verification (Sensitivity)

t=2 | t=4 | t=6 | t=8 | t=10



U=0.71 | U=0.83 | U=0.02 | U=0.57 | U=0.92

- Re=1000 with baseline mesh (101 × 101)
- U varies in time
- Determine sensitivity of H_2 about f = 1
- H_2 evaluated at t = 10
- Finite-difference sensitivity: δf = 0.0001
- *Sensitivities match to 6 significant digits*

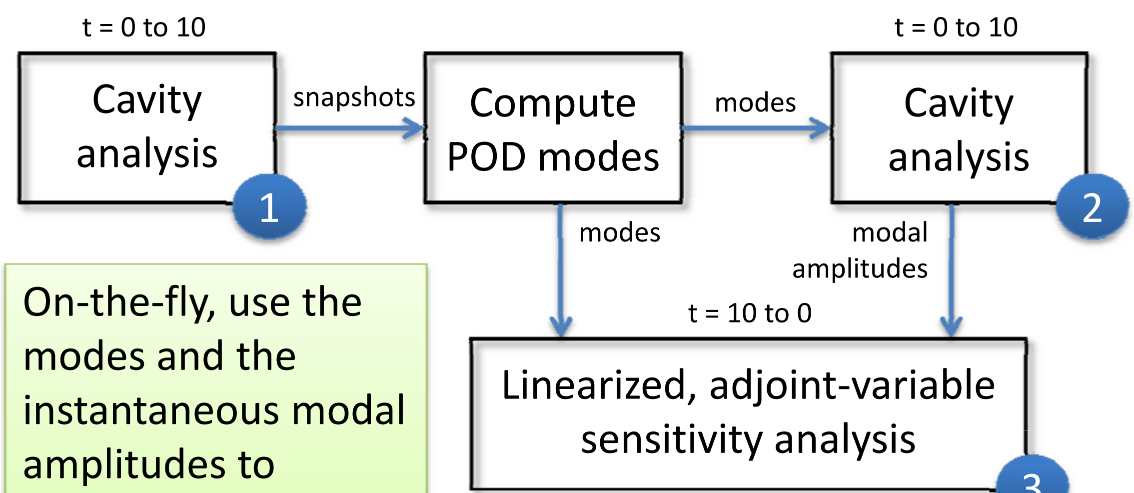
$$U(t) = \frac{1}{2}\left(1 - \cos(ft)\right)$$

$$H_2\left(\mathbf{X}_{mon}\right) = \sum_k \left(\Psi_k^n\right)^2$$

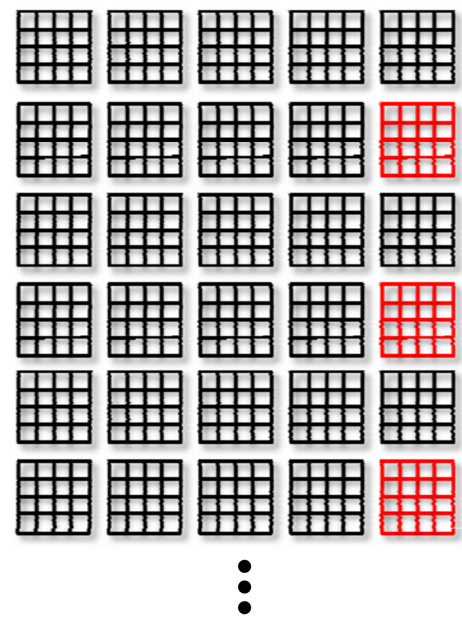
$\partial H_2/\partial f$ (Adjoint)	$\partial H_2/\partial f$ (Finite Difference)
4.70771958780	4.7077182309

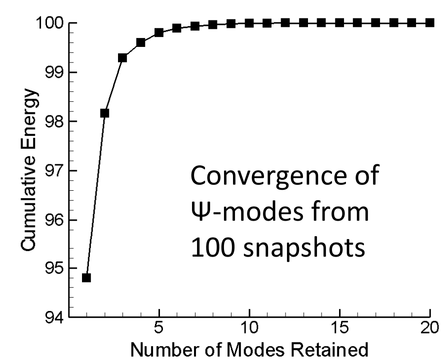
POD Data Compression for Sensitivity Analysis

- Same conditions as verification case
- Integration time of 10; 1000 time steps
- Collect snapshots once every 10 time steps
- Decimate snapshot set to coarsen
- Evaluate efficiency and accuracy of POD-based adjoint sensitivity analysis as function of number of snapshots and modes



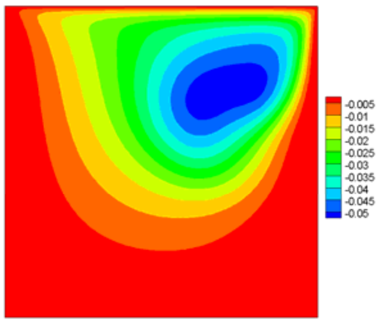
On-the-fly, use the modes and the instantaneous modal amplitudes to reconstruct the flow solution



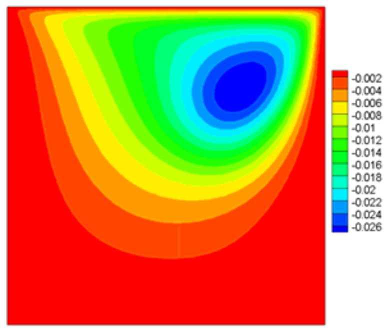


Solution and POD Modes (Streamfunction)

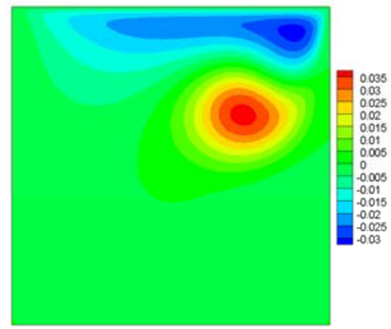
Solution



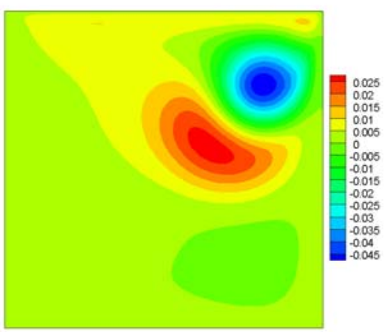
Mode 1



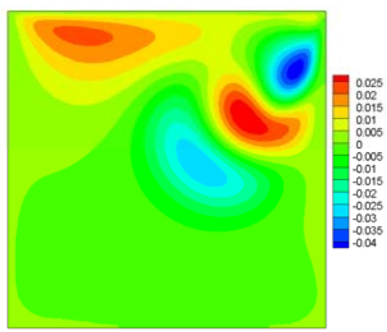
Mode 2



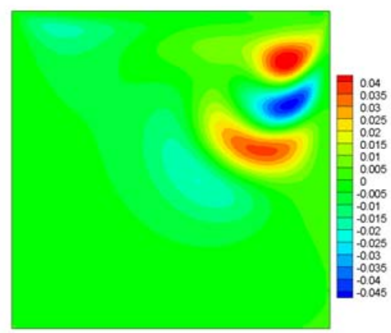
Mode 3

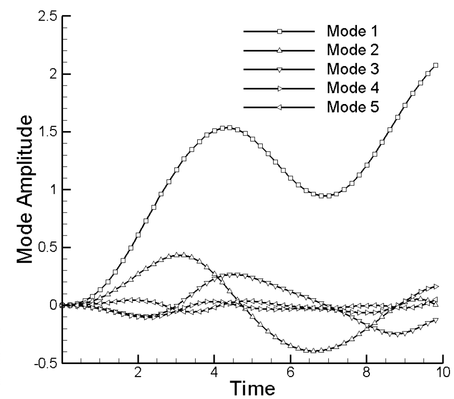


Mode 4



Mode 5





Efficiency and Accuracy

$\partial H_2/\partial f$ using 100 snapshots

Full order	50 modes	20 modes	10 modes	5 modes
4.707719587	4.707725353	4.711403732	4.724862963	3.121007234

% Error in $\partial H_2/\partial f$

	50 modes	20 modes	10 modes	5 modes
100 snapshots	0.00012	0.078	0.36	-34
20 snapshots	–	1.4	3.2	-31
10 snapshots	–	–	1.6	2.8

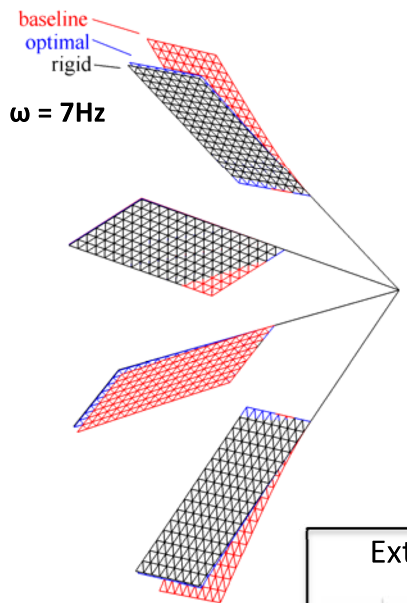
20 snapshots = 2% of time-history data
10 modes = 1% of time-history data

High efficiency
Good accuracy

Greatly decrease memory requirement at 2× cost: explore other POD uses

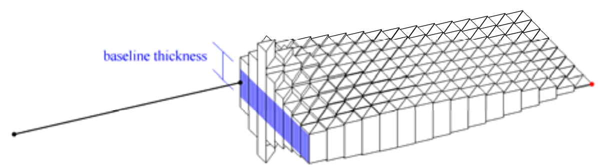
Structural Design (Inertial Loads Only)

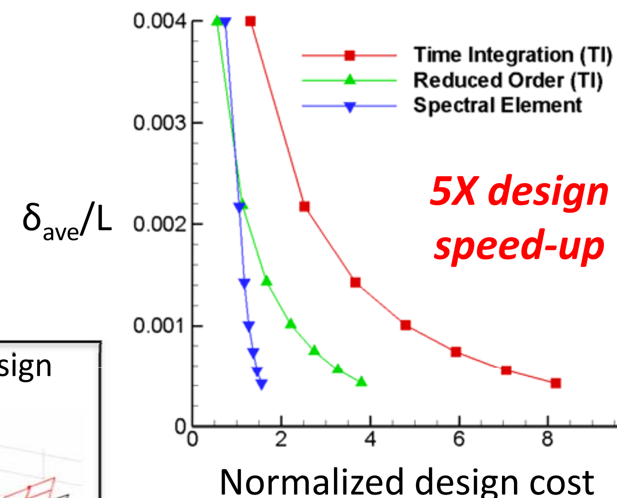
Goal: study transient sensitivity analysis in context of DOF reduction



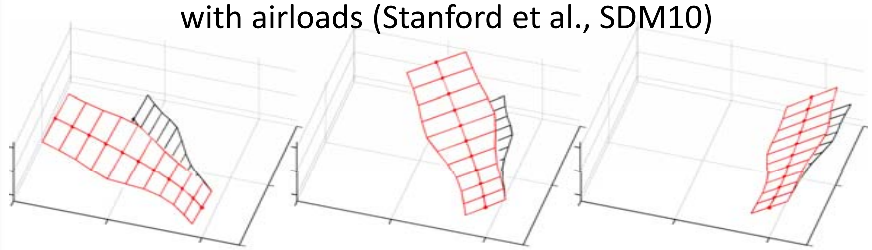
- Identify best thickness distribution for rapidly actuated plate
- Nonlinear modeling of a flapping plate
- Minimize δ_{ave} = time-averaged δ
- 256 variables (element thicknesses w/ constraints)
- GBO via MATLAB (*fmincon*)

Resultant thickness distribution





Extension: Kinematic/Structural design for wing design with airloads (Stanford et al., SDM10)

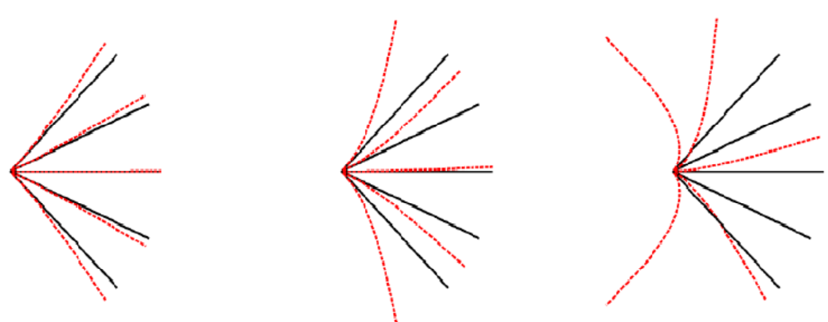


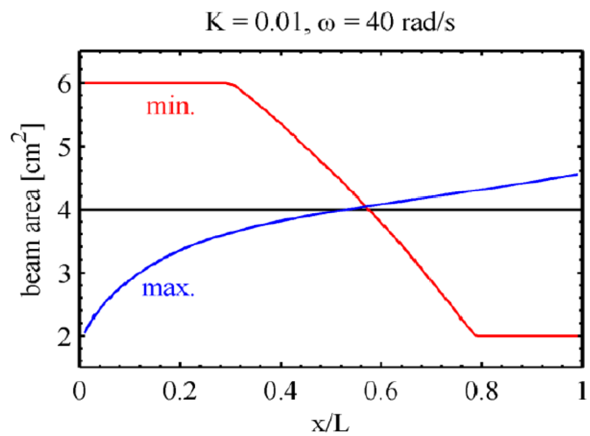
ROM Adjoints ≈ Free

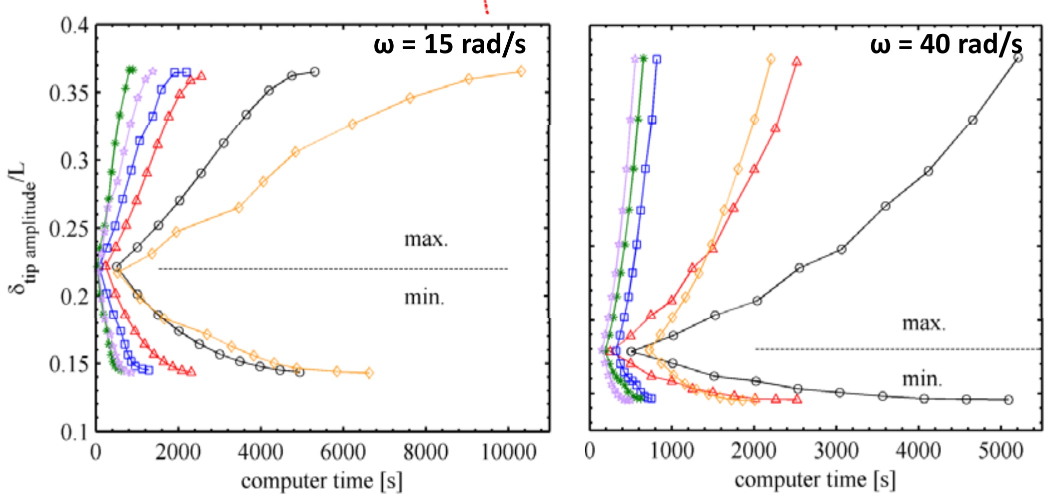
Stanford, Beran, and Kurdi, "Adjoint Sensitivities of Time-Periodic Nonlinear Structural Dynamics via Model Reduction," *Computers and Structures* (to appear), 2010.

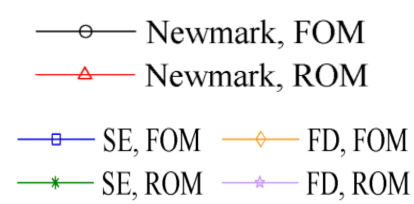
Beam Design (Inertial Loads Only)

- Identify best area distributions for minimum and maximum time-averaged tip displaced
- Co-rotational FEA formulation; 50 beam elements, each with a different sectional area
- Side constraints on area; GBO via MATLAB (*fmincon*)
- Compute sensitivities with the adjoint formulation







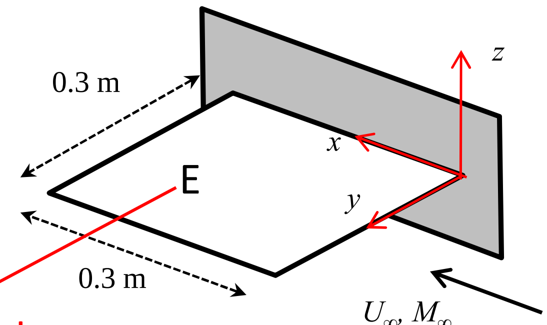


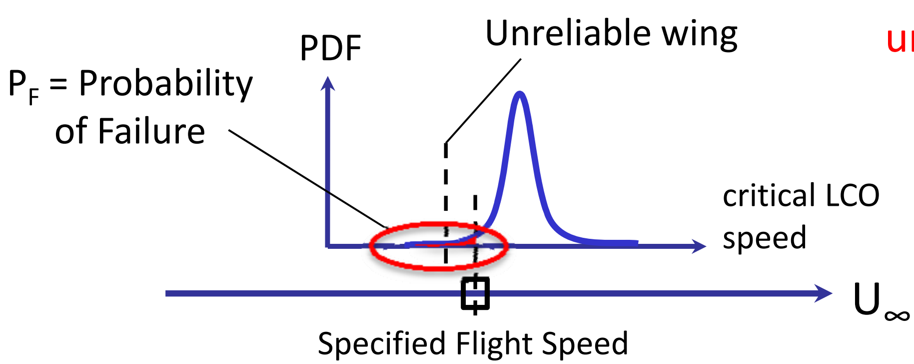
Some benefits of combining SE and ROM in time-periodic formulation

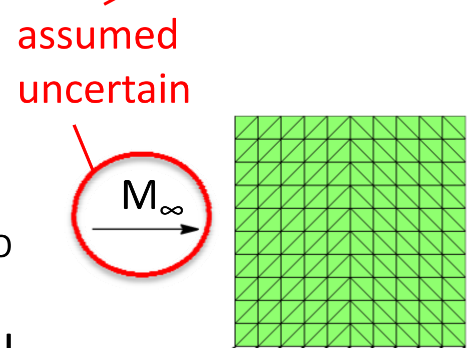
Reliability-Based Design Optimization (RBDO)

Goal: Examine use of transient sensitivity analysis to design a plate wing that is both light and reliable

- Reliable: wing does not exhibit too severe a limit-cycle oscillation
- $U_\infty > U_{flutter} \rightarrow$ limit cycle oscillation
- Piston theory aerodynamics ($M_\infty > 1$)
- Nonlinear von Kármán plate FEA





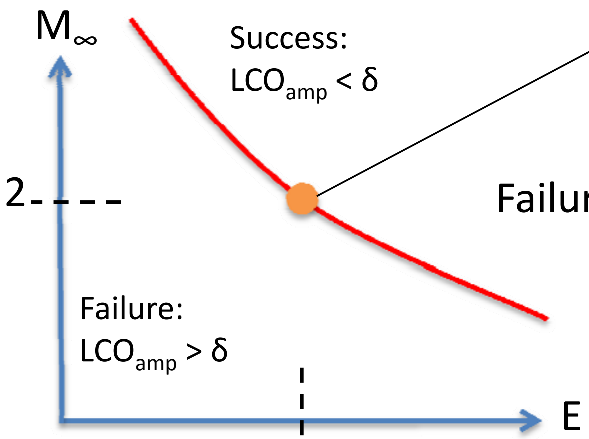


Vary thickness of each triangular element (200 design variables total)

Minimize mass of plate; constrain the probability that $LCO_{amp} > \delta$ ($P_F \leq \sigma$)

Contrasting Approaches

Deterministic Optimization



Generally, the designed plate "moves" to the constraint boundary ($P_F \approx ½$)

Failure surface:

$$g = g(\, \mathbf{x}(\mathbf{d}, E, M_\infty)\,) = \delta - LCO_{amp} = 0$$

$\mathbf{x}$ = response variables

$\mathbf{d}$ = design variables

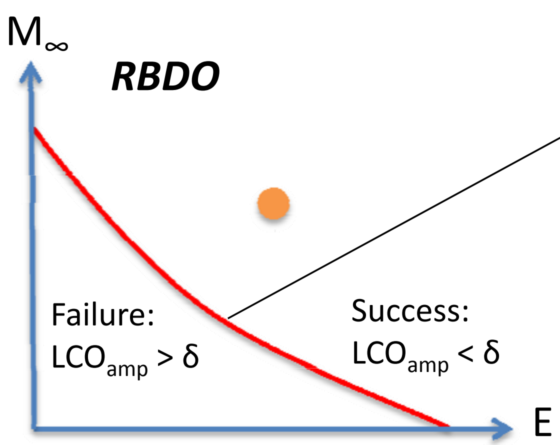
$$\min_{\mathbf{d}} \ \text{weight} = f(\mathbf{d})$$

subject to:

$g(\mathbf{x}(\mathbf{d}, E, M_\infty)) > 0$;

side constraints on **d**

RBDO



Generally, the designed plate "moves" away from the constraint boundary a "safe" distance ($P_F = \sigma$)

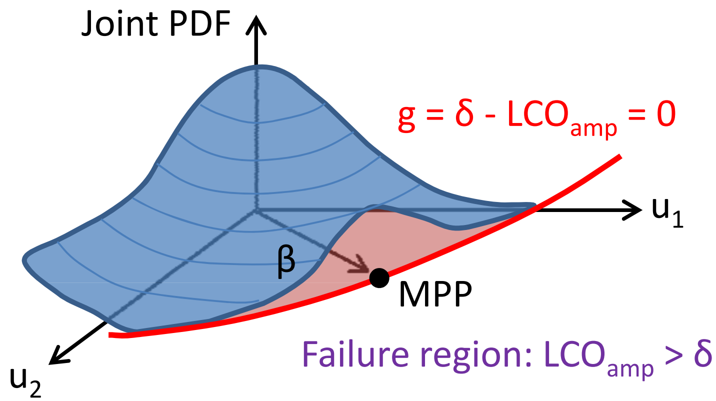
$$\min_{\mathbf{d}} \ \text{weight} = f(\mathbf{d})$$

subject to:

$1 - \mathit{Prob}(g < 0\,)/\sigma \geq 0$; side constraints on **d**

Allen and Maute, "Reliability-based design optimization of aeroelastic structures," *Structural and Multidisciplinary Optimization,* Vol. 27, 2004, pp. 228-242. *(Static Aeroelasticity)*

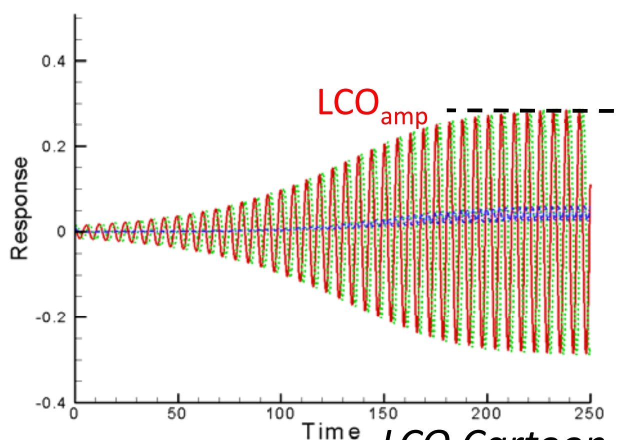
RBDO Formulation



AIAA Short Course: Introduction to Non-Determinstic Approaches

- M_∞ and E are chosen to be uncertain (normal)
- Map to uncorrelated random variables u_1 and u_2 in standard normal space
- Compute Most Probable Point (MPP) and reliability index β
- Approximate failure surface as linear: First Order Reliability Method (FORM)
- Compute probability of failure, $P_F = P_F(\beta)$
- Meet P_F constraint using analytical gradients

1. <u>For a given structure</u>, compute MPP using gradient based optimization: require sensitivities of g to u_1 and u_2
2. Reduce weight while meeting P_F constraint using gradient based optimization: require sensitivities of P_F to d_i (found from sensitivities of g to d_i)

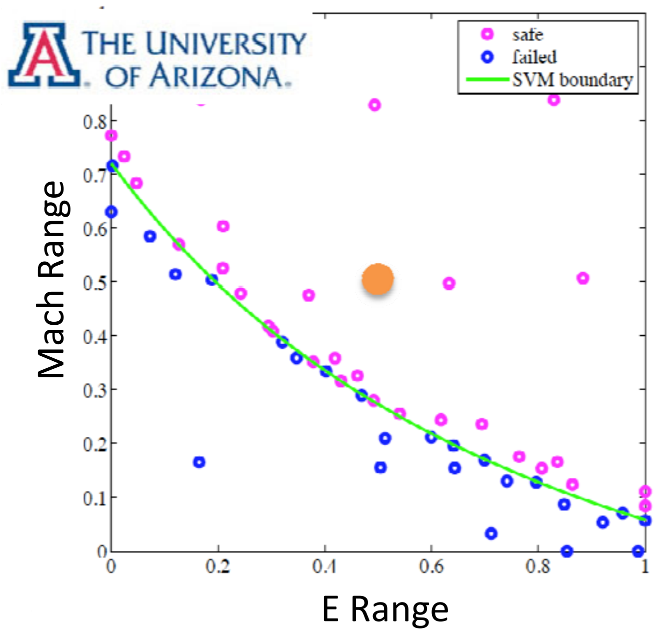


LCO Cartoon

Adjoints of transient solutions used to compute sensitivities of g to d_i

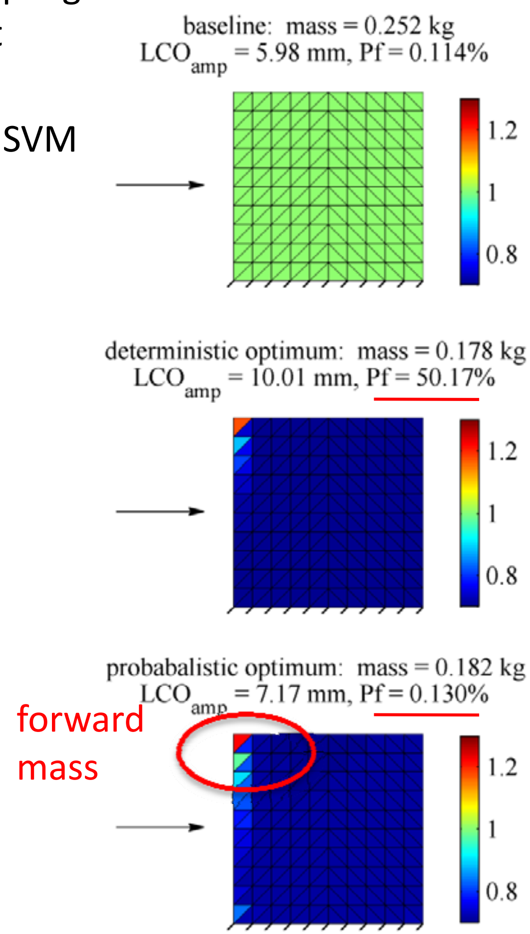
RBDO and SVM Results

Uniform (baseline) panel



1. Basudhar used Support Vector Machine and adaptive sampling to approximately construct failure surface
2. Computed P_F with MCS on SVM boundary (55 samples)
3. Computed P_F with QMCS (Lambe, MSSRC)

Method	**PF**
FORM	0.0197
MCS (10^6)	0.0248
QMCS (10^4)	0.0244



Basudhar and Missoum, "Update of explicit limit state functions constructed using Support Vector Machines," AIAA 2007-1872, April 2007.

RBDO Step	**Cost (MATLAB, single CPU)**
Simulation	10 minutes
Adjoint	5 minutes
MPP	1 hour
Optimization	4 hours (deterministic), 12 hours (probabilistic)

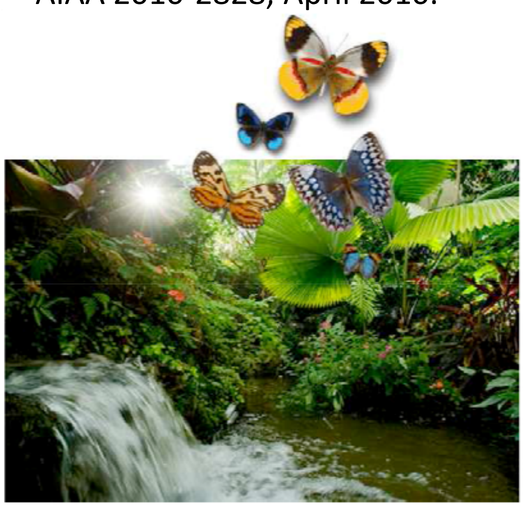
Recent Activities: Rigid-Body MAV Motions

- Start to investigate impact of rigid-body motion on MAV performance
- Prof. Haibo Dong (WSU), Mr. Zachary Gaston (WSU)
- Mr. Tim Broering (UL)

UNIVERSITY OF LOUISVILLE

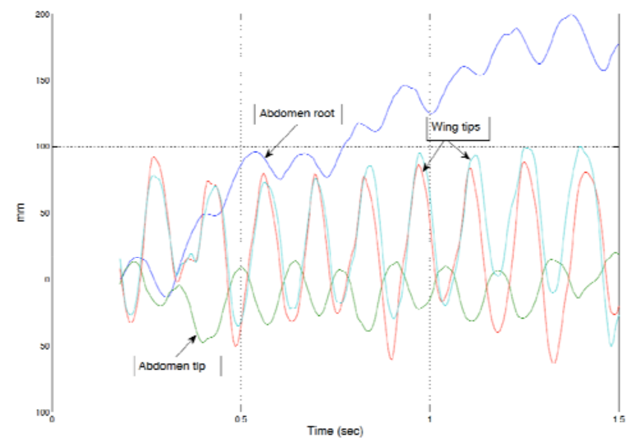
WRIGHT STATE UNIVERSITY

Chakravarthy, Albertani, Evers, "In-Flight Dynamically Adaptive Configurations: Lessons from Live Lepidoptera," AIAA 2010-2828, April 2010.



Digital Image Correlation by Prof. Albertani using live specimens of *Lepidoptera*

McGuire Center for Lepidoptera and Biodiversity, Gainesville, FL



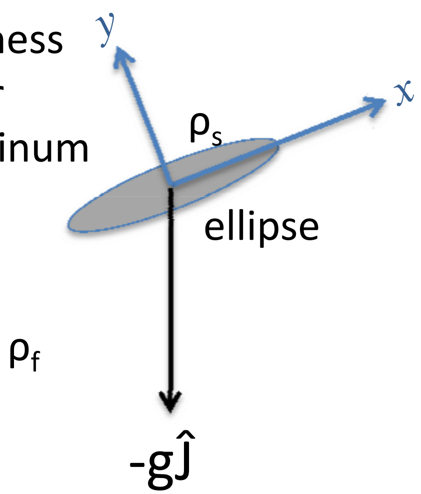
Need to include rigid-body motions and body flexibility in bio-inspired MAV models

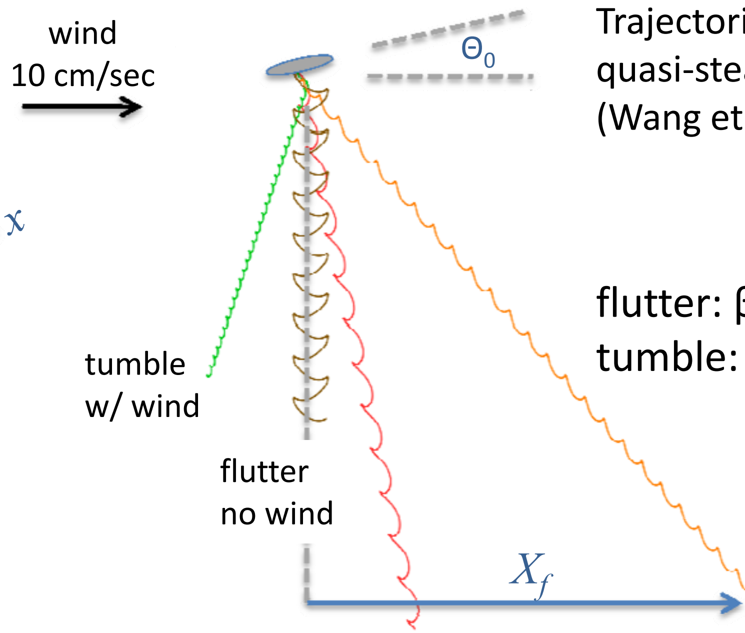
Plan for Rigid-Body Coupling

- Emphasize passive motions first: falling bodies in quiescent flow
  - Pesavento and Wang, "Falling Paper: Navier-Stokes Solutions, Model of Fluid Forces, and Center of Mass Elevation", *PRL*, Vol. 93, No. 14, 2004
  - Modify high-fidelity tools to repeat 2D simulations and extend in 3D; validate at WSU with high-speed photography (want comparisons)
  - Calibrate quasi-steady models (like those used in flapping)
- Examine influences of gust and variability on falling motions
  - Introduce variability into quasi-steady models (e.g., how is seed dispersal impacted by winds?)
- Re-examine design procedures that have been developed so far: want MAVs that are robust to gust

Some Typical Motions

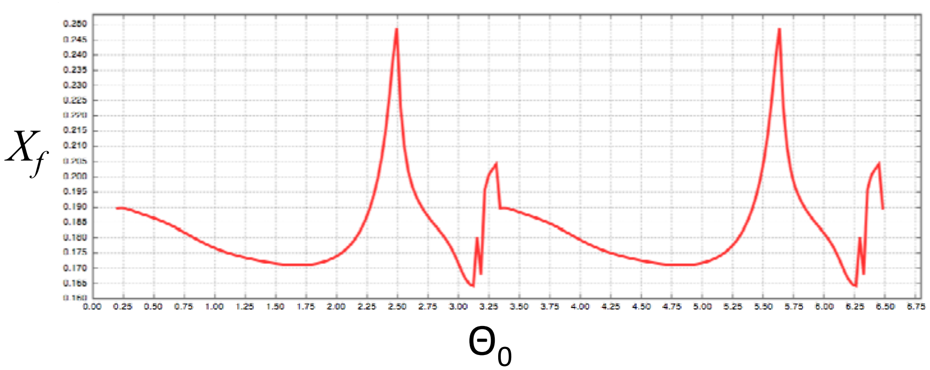
c = chord
h = thickness
ρ_f = water
ρ_s = aluminum





Trajectories computed with quasi-steady aerodynamics (Wang et al.)

flutter: $\beta = h/c = 1/14$
tumble: $\beta = h/c = 1/5$



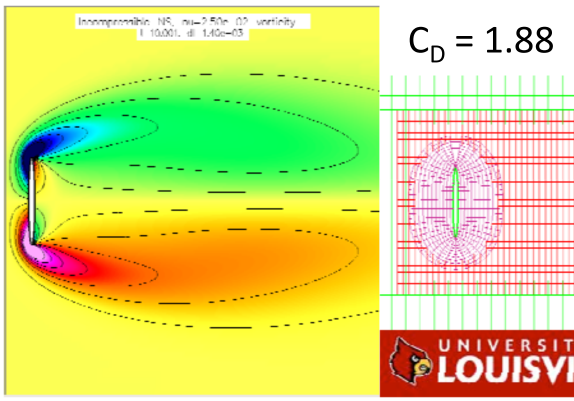
- Will explore impact of variability (physical and model) on distribution of landing locations
- Developed transient sensitivities (direct): role in selecting bodies with more desirable falling characteristics?

High-Fidelity Results

Re = 40 (Stationary)

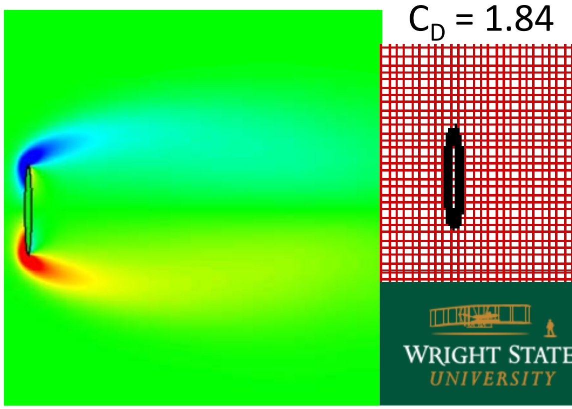
Overture

$C_D = 1.88$



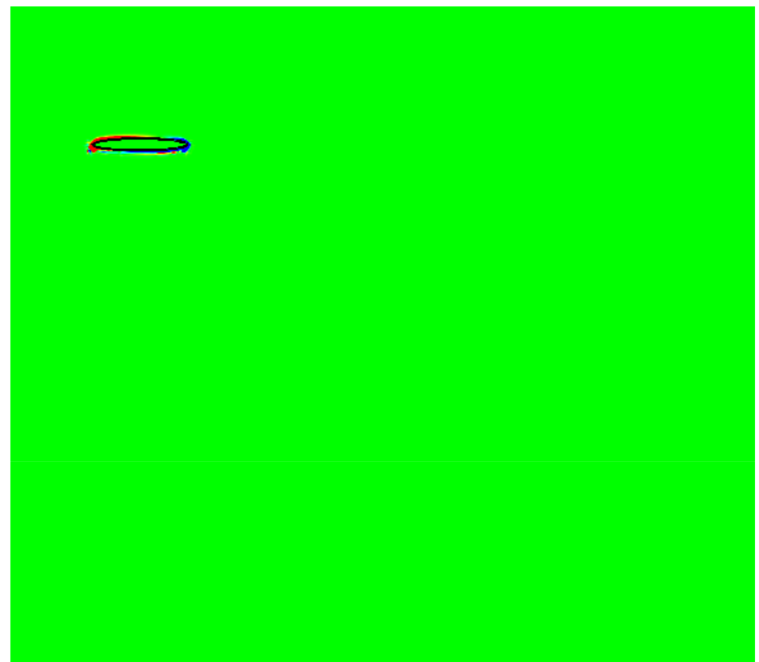
VICAR3D

$C_D = 1.84$



Re = O[10^3] (Falling)

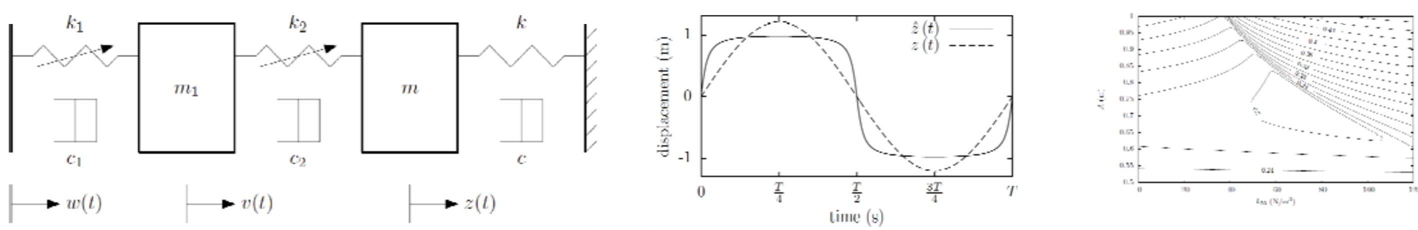
Preliminary VICAR3D result



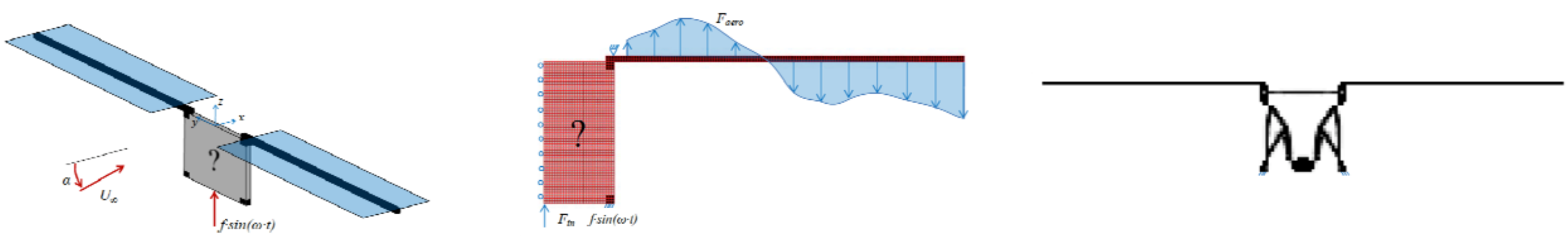
Recent Activities (cont.)

McFarland and Hubbard

- Start to explore role of actuation mechanism in MAV design
  - Investigate physical interactions between a flapping wing and the mechanism that flaps the wing (e.g., transmission of inertial loads)



- Developing compliant mechanisms via topological optimization
  - Link mechanism with generated inertial/aero loads (MAO 2010)



Understanding/modeling energy transfers between mechanism and wing critical

Concluding Remarks

- Sensitivity analysis of transient/time-periodic systems serves an important role for design of both large and small aircraft
  - Constraint boundaries often nonlinear (LCO and aeroelastic response in gust); strive for physics-based approaches not reliant on safety factors
  - Essential for design of flapping wing MAVs; strive for physics-based approaches that account for gust
- Lessons learned through unsteady sample problems
  - POD is a straightforward means for data compression in sensitivity analysis for large systems; extensions using POD ripe for study
  - Adjoint vectors in ROM formulation computed virtually for free (tailoring of structure for nonlinear response during rotary actuation)
  - Adjoint-based sensitivities work well in an RBDO context; want to extend (e.g., transonic, SVM, SORM) based on lessons learned
- Interesting departure points for further study: variability in motion subject to gust, mechanism design

Recent Publications

- Stanford, B., and Beran, P., “Adjoint Sensitivities of Time-Periodic Nonlinear Structural Dynamics via Model Reduction,” *Computers and Structures* (to appear), 2010.
- Stanford, B., and Beran, P., “Analytical Sensitivity Analysis of an Unsteady Vortex Lattice Method for Flapping Wing Optimization,” *Journal of Aircraft*, Vol. 47, No. 2, Mar.-Apr. 2010, pp. 647-662.
- Ghommem, M., Hajj, M.R., Pettit, C.L., and Beran, P.S., “Stochastic Modeling of Incident Gust Effects on Aerodynamic Lift,” *Journal of Aircraft* (to appear), 2010.
- Missoum, S., Dribusch, C., and Beran, P., “Reliability-Based Design Optimization of Nonlinear Aeroelasticity Problems,” *Journal of Aircraft*, Vol. 47, No. 3, May-June, 2010, pp. 992-998.
- Kurdi, M., Beran, P., Stanford, B., and Snyder R., “Optimal actuation of nonlinear resonant systems,” *Structural and Multidisciplinary Optimization*, Vol. 41, No. 1, Feb. 2010, pp 65-86.
- Pettit, C.L., Hajj, M.R., and Beran, P.S., “A Stochastic Approach for Modeling Incident Gust Effects on Flow Quantities,” *Probabilistic Engineering Mechanics*, Vol. 25, Issue 1, Jan. 2010, pp. 153-162.
- Stanford, B., Beran, P., and Kurdi, M., “Model Reduction Strategies for Nonlinear Beams Subjected to Large Rotary Actuations,” *Aeronautical Journal*, Vol. 113, No. 1150, Dec. 2009, pp. 751-762.

Questions?

AMP Team Composition (WPAFB)

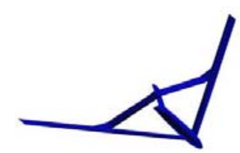
Mission: ***Integrate multiple disciplines to discover and exploit new phenomena for system optimization and assessment of revolutionary aerospace vehicles***

Center Director

Branch Chief
- Tech Advisor

Analysis Methods for Prototypes

- Dr. José Camberos – On detail as RB Deputy Chief Scientist
- *Dr. Chris Chabalko – Postdoc (NRC, UTC)*
- Dr. Ned Lindsley – Supporting prototype validation/assessment
- *Dr. Aaron McClung – Civil Servant, formerly NRC*
- Mr. John Moore – Undergraduate Co-op (University Florida)
- Mr. Michael Robbeloth – Computer Scientist, DSA
- Dr. Rich Snyder
- *Dr. Bret Stanford – Postdoc (NRC)*
- Dr. Phil Beran - Lead



Methods Development Strategy

Develop methods: start with low-dimensional formulations and move towards high-dimensional

Goal: *Multifidelity framework built on new methods*

Development of New Methods

- Time-Periodic Analysis
- Sensitivity Analysis
- Reduced Order Modeling
- Uncertainty Characterization

Application and Extension of High-Fidelity Methods

- Navier-Stokes (OVERFLOW)
- Beams, Plates, Shells models
- Aeroelasticity
- Vortex methods (medium fidelity)

Validation through physical experiment

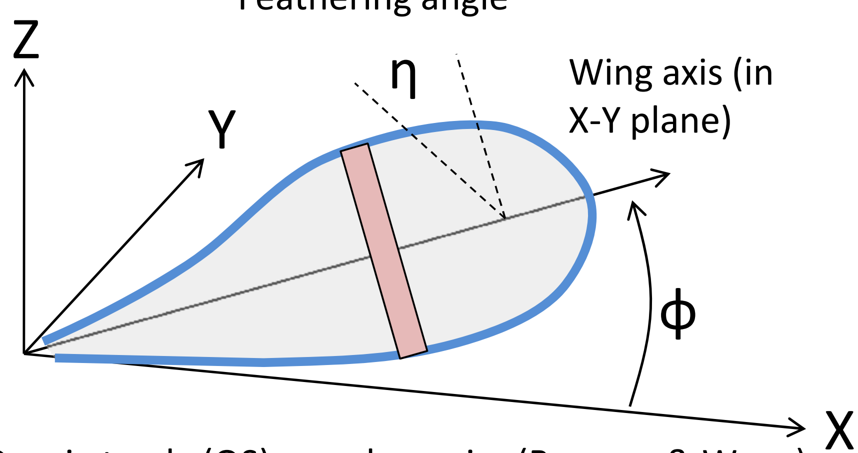
- Water channel (OL, AVT-149)
- Free flight (TU Delft, AVT-184)
- Aeroelastic ground-test facility (Parker)

Characterize physical limitations of lower fidelity approaches

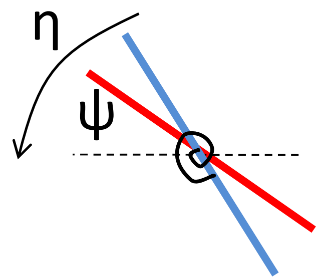
Assess validity of all methods

Application to Insect Wing

Berman and Wang, "Energy-Minimizing Kinematics in Hovering Insect Flight," *JFM*, Vol. 582, 2007 (Rigid wing with stroke-plane deviations)

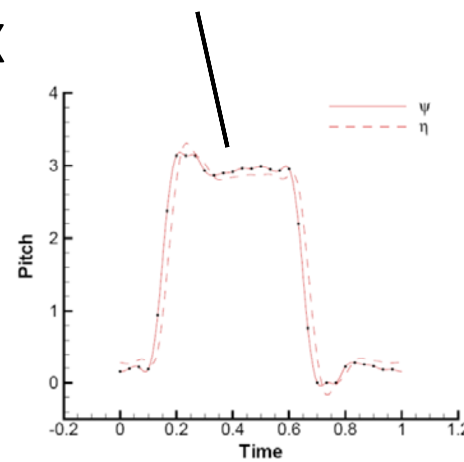


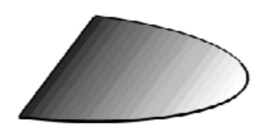
Quasi-steady (QS) aerodynamics (Berman & Wang)



Prescribed (ψ) and realized (η) angles
- mass-spring-damper
- inertial & aero loads

Large snap rotations favored





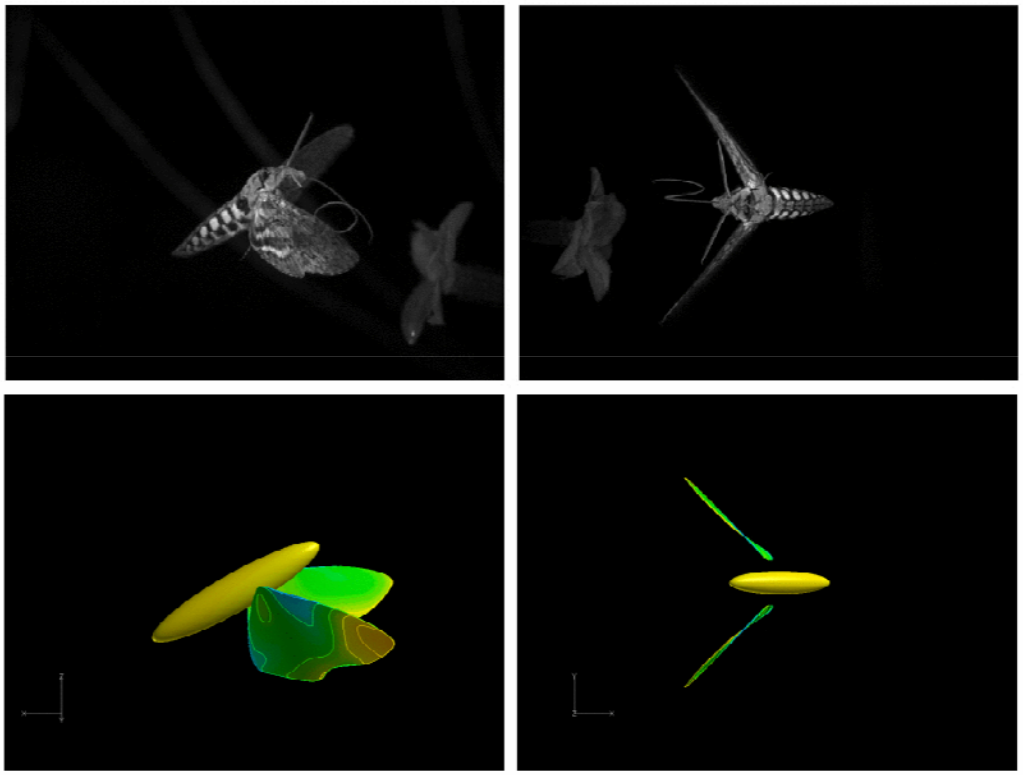
Optimized fruitfly wing kinematics (235 Hz)

Power reduction from initial design:
- 55% for unconstrained acceleration
- 40% for constrained acceleration

Looking at inertial power contribution

Kurdi, Beran, Stanford, and Snyder, "Optimal Actuation of Nonlinear Resonant Systems," *Structural and Multidisciplinary Optimization*, Published online June 2009.

High-Fidelity Analysis



Planform	Study	Fx (N)	Fy (N)	Fz (N)
Rectangular	Current Work	7.24e-04	-1.46e-03	7.26e-03
Manduca sexta	Current Work	8.42e-04	-1.65e-03	6.16e-03
Agrius convolvuli	Aono and Liu [1]	1.20e-03	-1.20e-03	8.48e-03

Understanding Complex Physics

- Study Hawkmoth physics using Navier-Stokes (NS) simulation
- Collaboration with AFIT
- Hawkmoth kinematics (hover)
- What's new?
    - OVERFLOW 2.1 Elastic ($5^{th}/2^{nd}$-order in space/time)
    - Prescribed wing deformations
    - Variations in kinematics
- *Moderate flexibility increases hover efficiency*

McClung, "Influence of Structural Flexibility on Flapping Wing Propulsion," AFIT Dissertation, April 2009