FUN3D v12.7 Training

Session 15:
Adjoint-Based Design for Unsteady Flows

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Learning Goals

- The challenges of unsteady adjoint-based design
- Additional inputs for unsteady design
- Example problem: Maximize L/D for a pitching wing
- Application examples

What we will *not* cover

- Extensive details on setting up the most general problems

The Challenges of Unsteady Adjoint-Based Design

Sheer Expense

- The adjoint approach still provides all of the sensitivities at the same cost as analysis, and the 20x estimate still applies for the expense of an optimization
- But every simulation is now an unsteady problem
- Where the steady adjoint solver linearized about a single solution (the steady-state), the unsteady adjoint solver must essentially do this at every physical time step

The Challenges of Unsteady Adjoint-Based Design

Big Data

- Since the adjoint must be integrated backwards in time, this implies that we have the forward solution available at every time plane
  - Brute force it: Store the entire forward solution
  - Recompute it: Store the forward solution periodically and recompute intermediate time steps as needed
  - Approximate it: Store the forward solution periodically and interpolate intermediate time planes somehow

The Challenges of Unsteady Adjoint-Based Design

Big Data

In FUN3D, we store all of the forward data to disk

- The amount of data adds up fast – consider an example:
  - 50,000,000 grid points and 10,000 physical time steps
  - Using a 1-equation turbulence model (6 unknowns per grid point)
  - Dynamic grids (3 additional unknowns per grid point)

    → 50,000,000 x 10,000 x (6+3) x 8 bytes = 36 Terabytes
- So far, this amount of data has not been prohibitively large for our resources, but it is a lot (and we need to go bigger)
  - Will need to tackle this in the long-term
- So far, the challenge has been efficiently getting the data to/from the disk at every single time step

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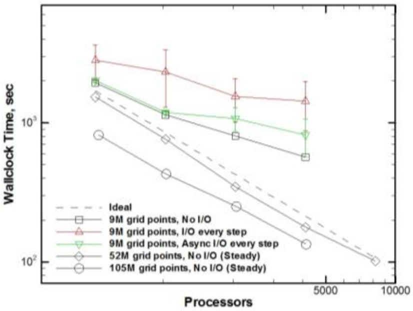
The Challenges of Unsteady Adjoint-Based Design

Big Data

- Conventional approaches used to write restart files are prohibitively expensive
- System should have a parallel file system
- FUN3D uses parallel, asynchronous, unformatted direct access read/writes from every rank
  - Flow solver is writing the previous time plane while the current time step is computing
  - Adjoint solver is pre-fetching earlier time planes while the current time step is computing
- This strategy performs well for the problems we have run, but is not infinitely scalable



The Challenges of Unsteady Adjoint-Based Design

Extensive Linearizations

- If dynamic grids are involved, all of the unsteady metrics and mesh motion/deformations must be differentiated at each time step
- If overset dynamic grids are involved, the relationship between the component grids must also be differentiated at each time step – both motion and interpolants
- If another disciplinary model impacts the CFD model, then that other discipline must also be differentiated, as well as the coupling procedure between the two

The Challenges of Unsteady Adjoint-Based Design

The Chaos Problem

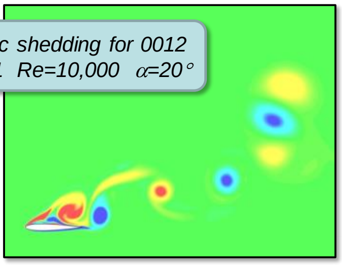
Wish to compute sensitivities of infinite time averages for chaotic flows (DES, HRLES, LES…)

- Theory exists that states these sensitivities are well-defined and bounded

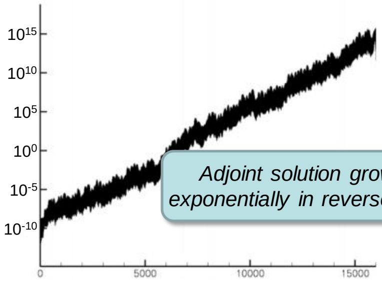
Why does conventional approach not work?

For chaotic flows:

- The finite time average approaches the infinite time average
- The sensitivity for a finite time average does not approach the sensitivity for the infinite time average



Chaotic shedding for 0012
M_∞=0.1 Re=10,000 α=20°



Adjoint solution grows exponentially in reverse time

The Challenges of Unsteady Adjoint-Based Design

The Chaos Problem

- Least-Squares Shadowing (LSS) method proposed by Wang (MIT) and Blonigan (MIT; former LaRC student)
  - Key assumption is ergodicity of the simulation: long time averages are essentially independent of the initial conditions
  - Also assumes existence of a shadowing trajectory
- The LSS formulation involves a linearly-constrained least squares optimization problem which results in a set of optimality equations
- **The LSS adjoint equations are a globally coupled system in space-time**
- To date, work at MIT has focused on solutions of this system for academic dynamical systems containing O(1) state variables
- Close collaboration between LaRC and MIT is exploring the extension to CFD systems: *enormous* computational challenge for even the smallest of problems

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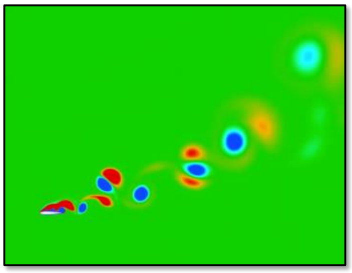
The Challenges of Unsteady Adjoint-Based Design

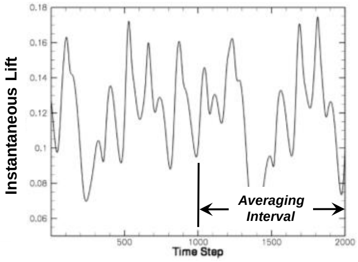
The Chaos Problem

Shedding NACA 0012
M_∞=0.1 Re=10,000 α=20°
102,940 grid points

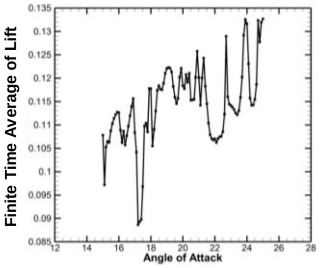


- Goal is to compute an AOA sensitivity that would allow us to maximize the time-averaged lift over final 1,000 time steps

Instantaneous Lift vs Time



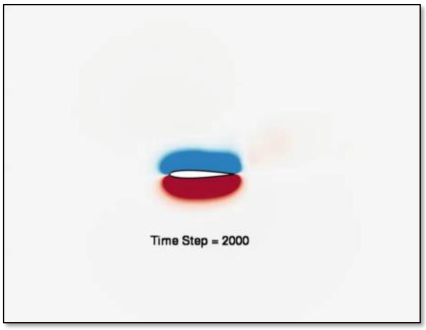
Finite Time Average of Lift vs Alpha



The Challenges of Unsteady Adjoint-Based Design

The Chaos Problem

- FUN3D used to output data for use in LSS solver
  - Nonlinear residual vectors; Jacobians of residual, objective function
  - For this tiny problem, this is 1.1 TB of raw data
- Dimension of the resulting LSS matrix problem:
  102,940 grid points x 5 DOFs
  x 2,000 time planes = 1.03 billion
- Stand-alone LSS solver has been developed where decomposition is performed in time with a single time plane per core
- Global GMRES solver used with a local ILU(0) preconditioner for each time plane

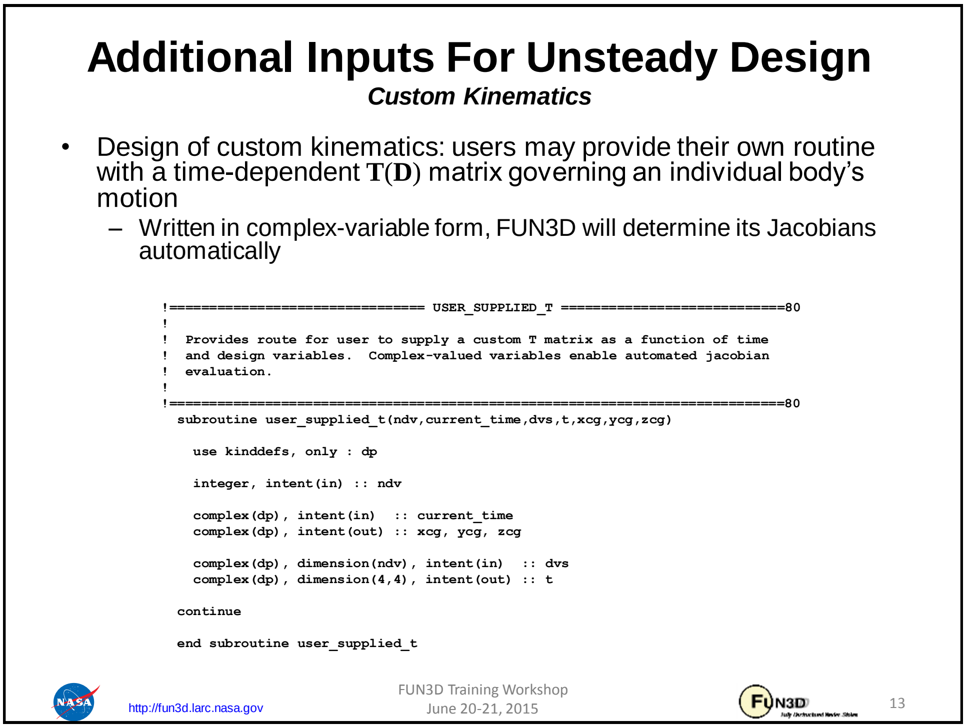


Just tip of the iceberg – desired simulations are 10^6 larger!
Desired matrix dimension = 10^9 x 10^6 = 10^{15}

Additional Inputs For Unsteady Design

Design Variables

- All design variables available for steady flows are also available for unsteady flows
- Design variables for a body may now also include FUN3D's rigid motion parameters
- Also have infrastructure for other variables such as boundary condition parameters (e.g., blowing/suction rates), pilot inputs (collective, cyclics) for rotor trimming, etc



Additional Inputs For Unsteady Design

Custom Kinematics

- Design of custom kinematics: users may provide their own routine with a time-dependent $\mathbf{T}(\mathbf{D})$ matrix governing an individual body's motion
  - Written in complex-variable form, FUN3D will determine its Jacobians automatically

```
!================================ USER_SUPPLIED_T ============================80
!
!  Provides route for user to supply a custom T matrix as a function of time
!  and design variables.  Complex-valued variables enable automated jacobian
!  evaluation.
!
!=============================================================================80
  subroutine user_supplied_t(ndv,current_time,dvs,t,xcg,ycg,zcg)

    use kinddefs, only : dp

    integer, intent(in) :: ndv

    complex(dp), intent(in)  :: current_time
    complex(dp), intent(out) :: xcg, ycg, zcg

    complex(dp), dimension(ndv), intent(in)  :: dvs
    complex(dp), dimension(4,4), intent(out) :: t

  continue

  end subroutine user_supplied_t
```

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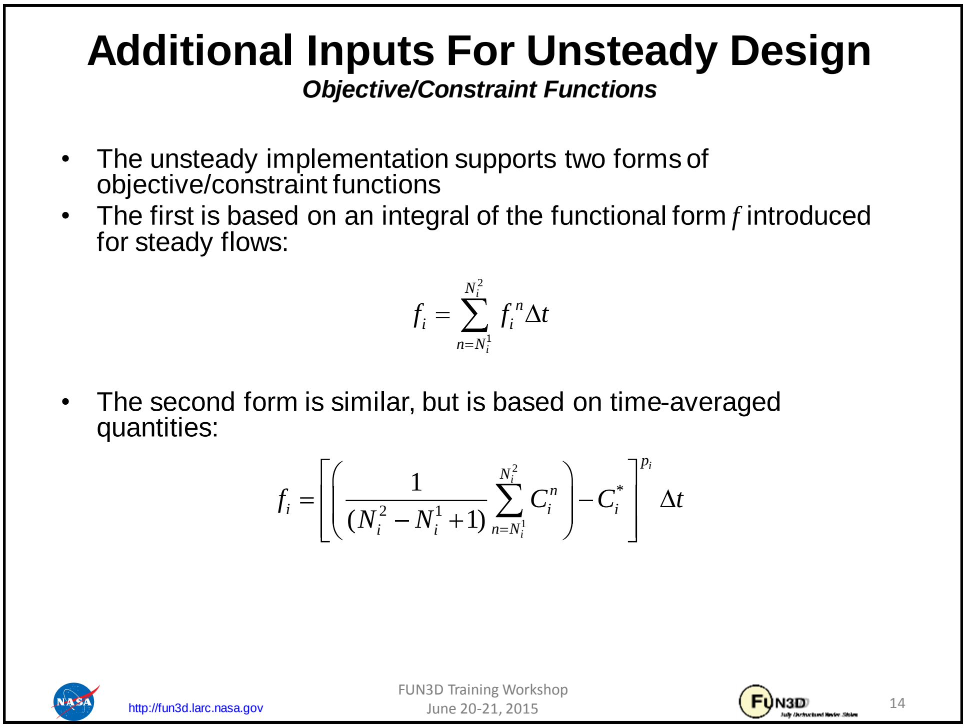

Additional Inputs For Unsteady Design

Objective/Constraint Functions

- The unsteady implementation supports two forms of objective/constraint functions
- The first is based on an integral of the functional form *f* introduced for steady flows:

$$f_i = \sum_{n=N_i^1}^{N_i^2} f_i^{\,n} \Delta t$$

- The second form is similar, but is based on time-averaged quantities:

$$f_i = \left[\left(\frac{1}{(N_i^2 - N_i^1 + 1)} \sum_{n=N_i^1}^{N_i^2} C_i^n \right) - C_i^* \right]^{p_i} \Delta t$$

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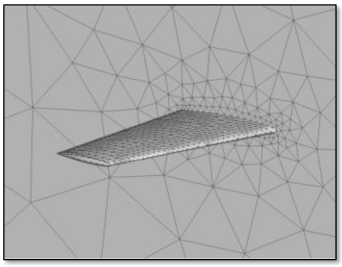
Additional Inputs For Unsteady Design

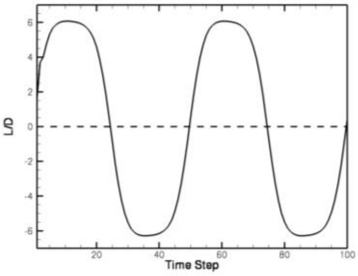
Objective/Constraint Functions

- The sign of the cost function/constraint input toggles between the two unsteady function forms
  - Positive sign indicates form #1, negative sign indicates form #2
- In addition to the inputs required for steady simulations, the user must now also provide the time interval over which to accumulate the cost function

```
##############################################################################
############################ Function Information ############################
##############################################################################
Number of composite functions for design problem statement
    1
##############################################################################
Cost function (1) or constraint (2)
    1
If constraint, lower and upper bounds
    0.0 0.0
Number of components for function   1
    1
Physical timestep interval where function is defined
    1 1
Composite function weight, target, and power
1.0 0.0 1.0
Components of function   1: boundary id (0=all)/name/value/weight/target/power
    0 clcd          0.000000000000000           1.000   20.00000 2.000
```

Maximize Time-Averaged L/D for a Pitching Wing





- FUN3D's design driver and the optimization packages themselves don't distinguish between steady and unsteady CFD problems – they just see f and ∇f
- The problem setup is very similar to steady design cases; will only highlight the differences here

Maximize Time-Averaged L/D for a Pitching Wing

command_line.options

```
2
2 flow
‘--moving_grid’
‘--timedep_adj_frozen’
2 adjoint
‘--moving_grid’
‘--timedep_adj_frozen’
```

- Tell the solvers that it is a moving grid case
- Also specify that we want to do a time-dependent adjoint
  - This kicks in the I/O mechanisms, among other things

Maximize Time-Averaged L/D for a Pitching Wing

moving_body.input

```
&body_definitions
  n_moving_bodies = 1,          ! number of bodies in motion
  body_name(1) = 'domain',      ! name must be in quotes
  parent_name(1) = '',          ! '' means motion relative to inertial ref frame
  n_defining_bndry(1) = -1,     ! shortcut to specify all solid surfaces
  defining_bndry(1,1) =  1,     ! index 1: boundary number 2: body number; use any number for shortcut
  motion_driver(1) = 'forced', ! 'forced', '6dof', 'file', 'aeroelastic'
  mesh_movement(1) = 'rigid',  ! 'rigid', 'deform'
  x_mc(1) = 0.25,               ! x-coordinate of moment_center
  y_mc(1) = 0.0,                ! y-coordinate of moment_center
  z_mc(1) = 0.0,                ! z-coordinate of moment_center
  move_mc(1) = 1                ! move mom. cntr with body/grid: 0=no, 1=yes
/
&forced_motion
  rotate(1) = 2,                   ! rotation type: 1=constant rate 2=sinusoidal
  rotation_freq(1) = 0.009000,     ! reduced rotation frequency
  rotation_amplitude(1) = 5.00,    ! max rotational displacement
  rotation_origin_x(1) = 0.25,     ! x-coordinate of rotation origin
  rotation_origin_y(1) = 0.0,      ! y-coordinate of rotation origin
  rotation_origin_z(1) = 0.0,      ! z-coordinate of rotation origin
  rotation_vector_x(1) = 0.0,      ! unit vector x-component along rotation axis
  rotation_vector_y(1) = 1.0,      ! unit vector y-component along rotation axis
  rotation_vector_z(1) = 0.0,      ! unit vector z-component along rotation axis
/
```

- Body names must match those specified in rubber.data

Maximize Time-Averaged L/D for a Pitching Wing

rubber.data

```
################################################################################
######################## Design Variable Information ###########################
################################################################################
Global design variables (Mach number / angle of attack)
Index Active          Value                  Lower Bound              Upper Bound
 Mach     0    0.000000000000000E+00  0.000000000000000E+00  0.000000000000000E+01
  AOA     0    0.000000000000000E+00  0.000000000000000E+00  0.000000000000000E+01
Number of bodies
    1
Rigid motion design variables for 'domain'
  Var Active          Value                  Lower Bound              Upper Bound
RotRate  0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
RotFreq  0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
.
.
TrnVecy  0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
TrnVecz  0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
Parameterization Scheme (Massoud=1 Bandaids=2 Sculptor=4)
    1
Number of shape variables for 'domain'
  166
Index Active          Value                  Lower Bound              Upper Bound
    1     0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
    2     0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
.
.
  164     0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
  165     0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
  166     0    0.000000000000000E+00  0.000000000000000E+00  0.500000000000000E+01
```

- Body names must match those specified in moving_body.data

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Maximize Time-Averaged L/D for a Pitching Wing

rubber.data

```
################################################################################
############################ Function Information ##############################
################################################################################
Number of composite functions for design problem statement
    1
################################################################################
Cost function (1) or constraint (2)
    -1
If constraint, lower and upper bounds
    0.0 0.0
Number of components for function   1
    1
Physical timestep interval where function is defined
   51    100
Composite function weight, target, and power
1.0 0.0 1.0
Components of function   1: boundary id (0=all)/name/value/weight/target/power
    0 clcd                   0.000000000000000           1.000   20.00000 2.000
```

- Negative sign on function/constraint selection indicates time-averaging form is to be used
- Time step interval for function is also specified

$$f = \left[\left(\frac{1}{50} \sum_{n=51}^{100} (L/D)^n \right) - 20 \right]^2 \Delta t$$

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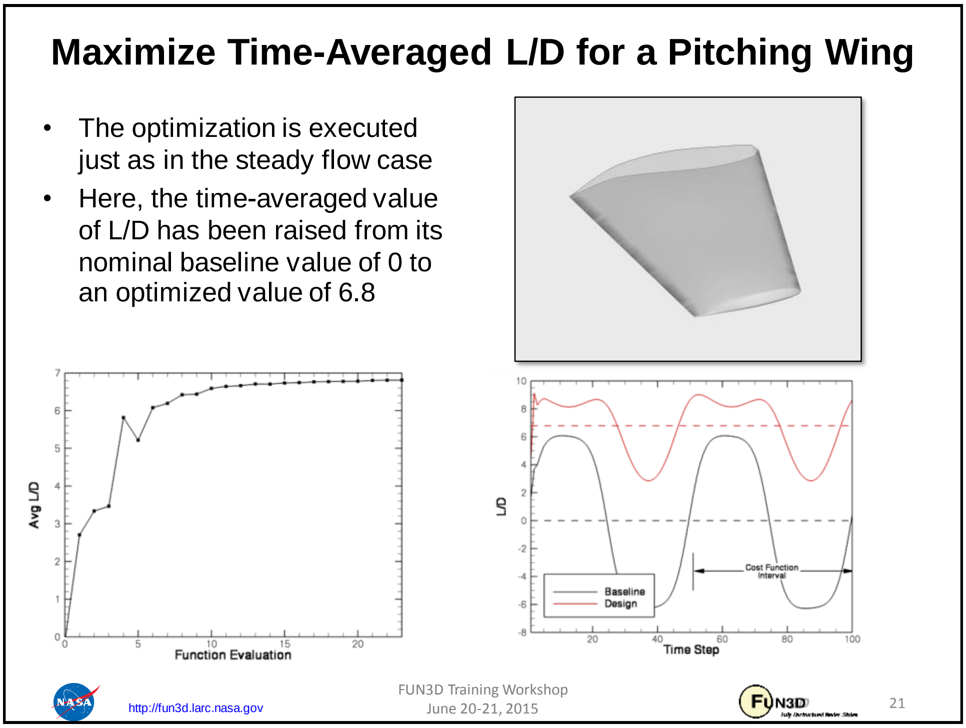
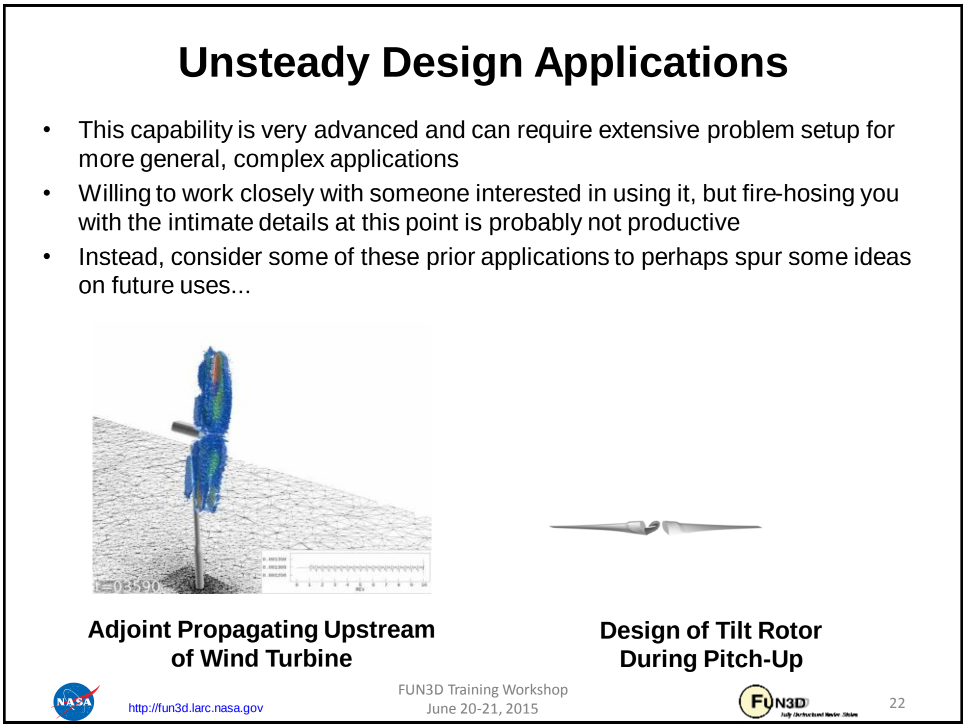


Maximize Time-Averaged L/D for a Pitching Wing

- The optimization is executed just as in the steady flow case
- Here, the time-averaged value of L/D has been raised from its nominal baseline value of 0 to an optimized value of 6.8

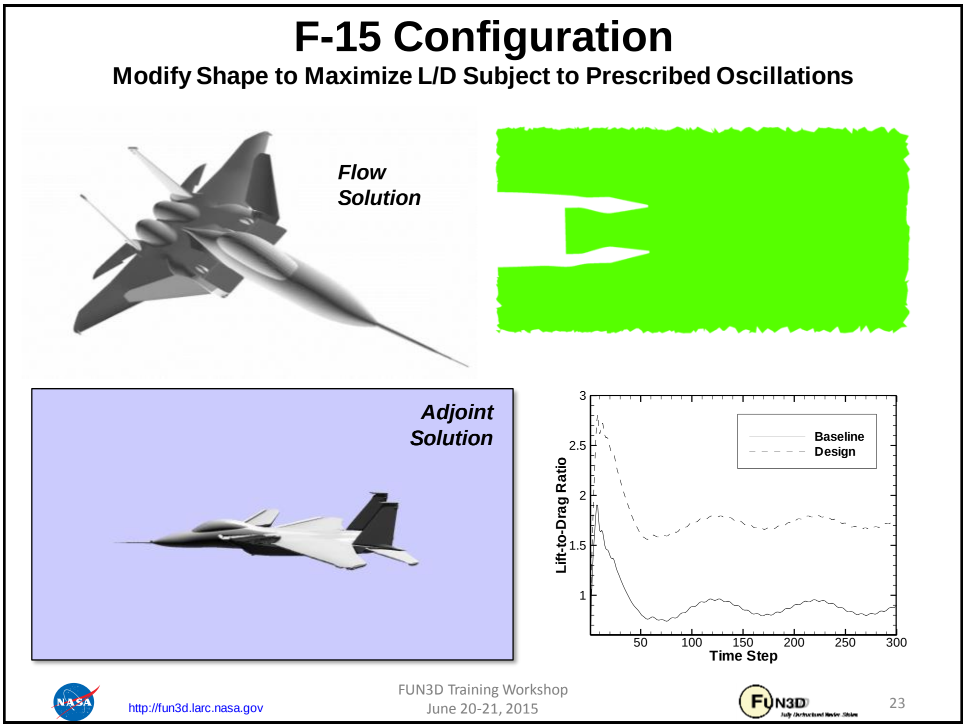


Unsteady Design Applications

- This capability is very advanced and can require extensive problem setup for more general, complex applications
- Willing to work closely with someone interested in using it, but fire-hosing you with the intimate details at this point is probably not productive
- Instead, consider some of these prior applications to perhaps spur some ideas on future uses…

Adjoint Propagating Upstream of Wind Turbine

Design of Tilt Rotor During Pitch-Up

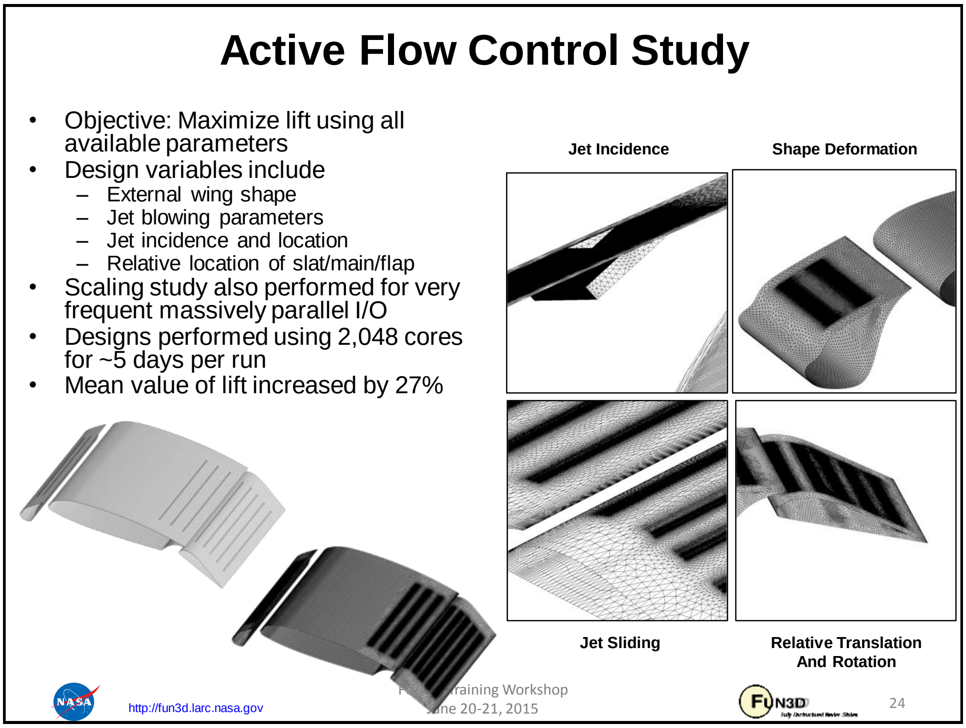


F-15 Configuration

Modify Shape to Maximize L/D Subject to Prescribed Oscillations

Flow Solution

Adjoint Solution



Active Flow Control Study

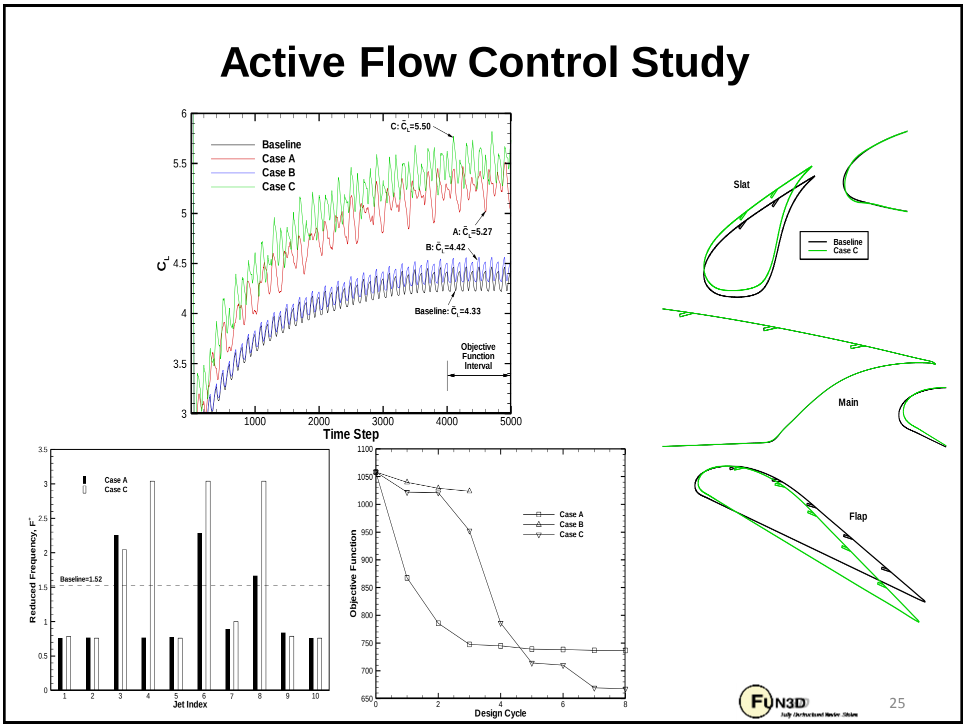
- Objective: Maximize lift using all available parameters
- Design variables include
  - External wing shape
  - Jet blowing parameters
  - Jet incidence and location
  - Relative location of slat/main/flap
- Scaling study also performed for very frequent massively parallel I/O
- Designs performed using 2,048 cores for ~5 days per run
- Mean value of lift increased by 27%

Jet Incidence

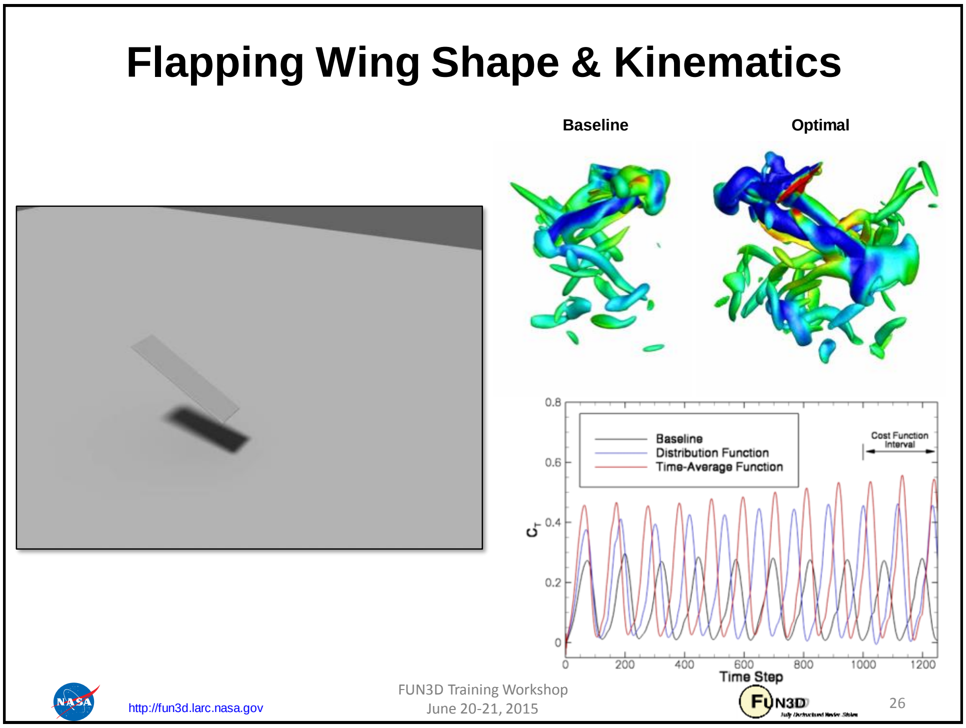
Shape Deformation

Jet Sliding

Relative Translation And Rotation



Active Flow Control Study



Flapping Wing Shape & Kinematics

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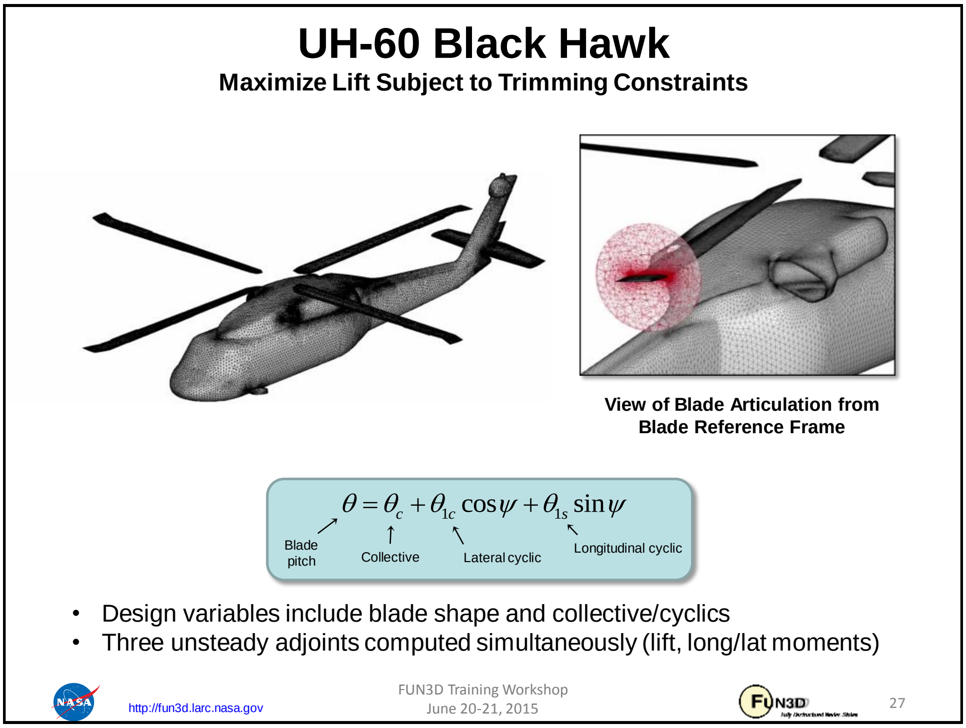


UH-60 Black Hawk

Maximize Lift Subject to Trimming Constraints

View of Blade Articulation from Blade Reference Frame

$$\theta = \theta_c + \theta_{1c} \cos\psi + \theta_{1s} \sin\psi$$

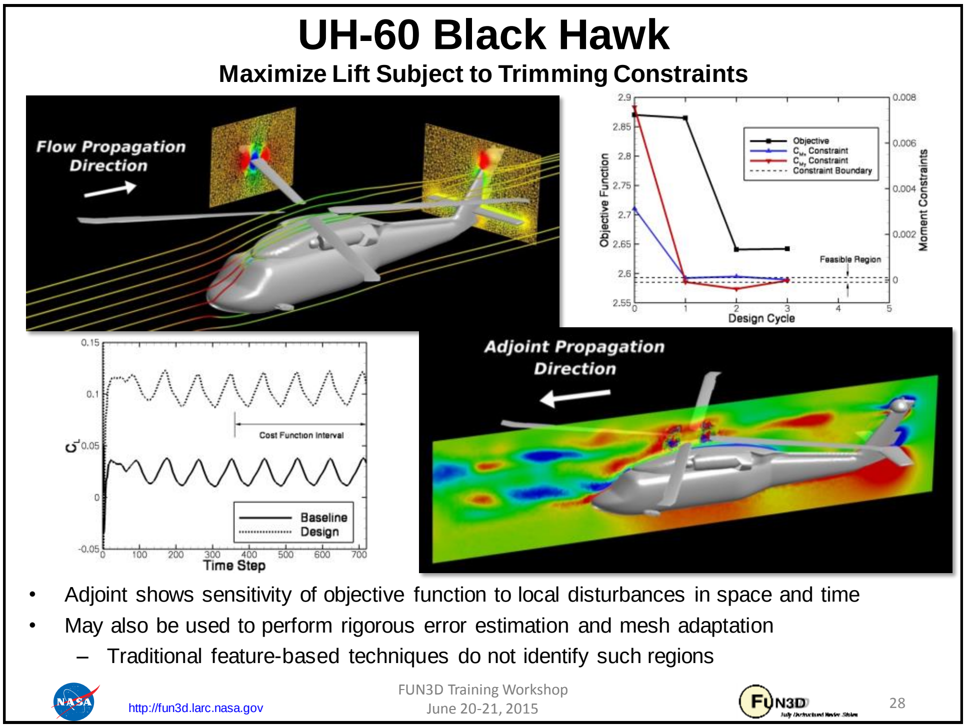
Blade pitch

Collective

Lateral cyclic

Longitudinal cyclic

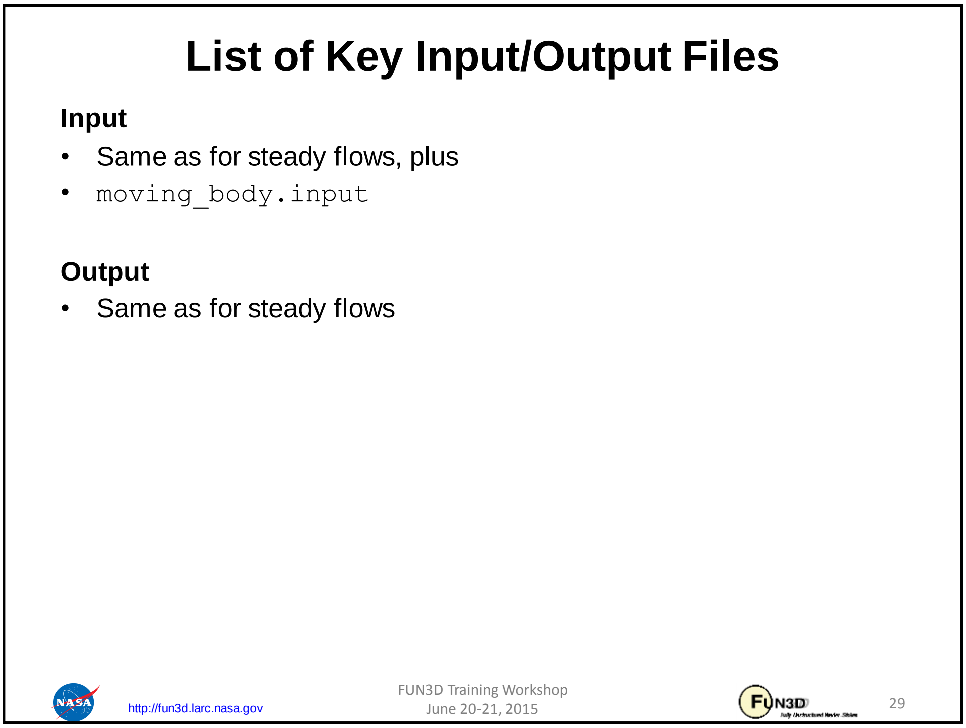
- Design variables include blade shape and collective/cyclics
- Three unsteady adjoints computed simultaneously (lift, long/lat moments)



UH-60 Black Hawk

Maximize Lift Subject to Trimming Constraints

- Adjoint shows sensitivity of objective function to local disturbances in space and time
- May also be used to perform rigorous error estimation and mesh adaptation
  - Traditional feature-based techniques do not identify such regions



List of Key Input/Output Files

Input

- Same as for steady flows, plus
- `moving_body.input`

Output

- Same as for steady flows

What We Learned

- Challenges involved with adjoint-based unsteady design
- Additional inputs required for unsteady design
- Simple design example for pitching wing
- Previous applications

Many aspects of this capability are "researchy" and applications of it would benefit from close collaboration