Multi-point Adjoint-Based Design of Tilt-Rotors in a Noninertial Reference Frame

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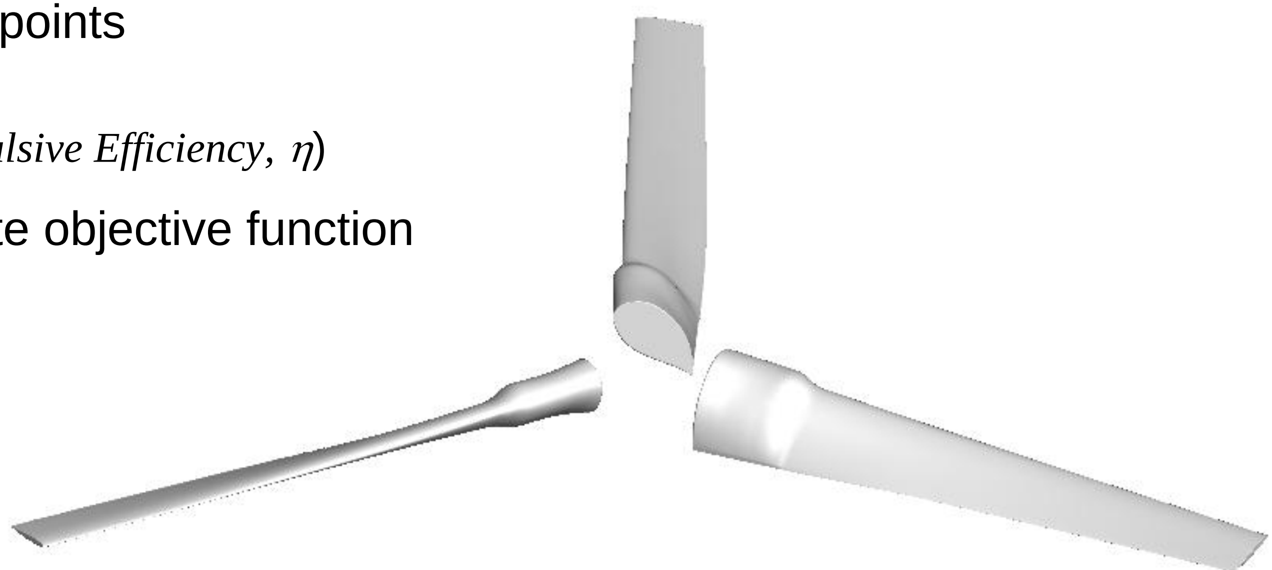
http://fun3d.larc.nasa.gov

FUN3D
Fully Unstructured Navier-Stokes

Geometry Model

- Isolated rotor for Tilt-Rotor Aeroacoustics Model (TRAM)
  - Represents an optimized system designed with traditional tools
  - ¼ scale model of the V-22
    - Modified cuff for structural reasons
    - Resized to match full scale conditions
- Multiple design points
  - Hover (*FM*)
  - Cruise (*Propulsive Efficiency*, η)
- Single composite objective function

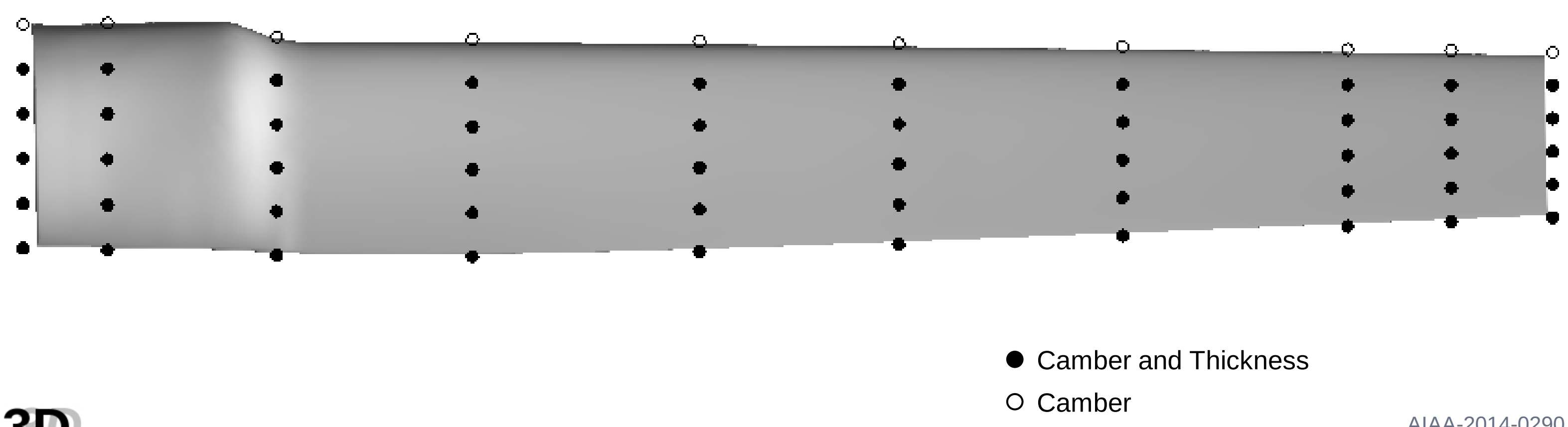


Flow and Sensitivity

- Solve as a steady problem relative to rotating reference frame
  - Constant angular velocity
  - Additional source term to represent Coriolis effect
  - Single mesh zone
  - Applicable to rigid tilt-rotor in helicopter or airplane mode
    - Freestream velocity vector is parallel to angular velocity vector
      - Helicopter: hover, ascending, descending
      - Airplane: cruise
  - Spalart-Almaras turbulence model
- Functions and gradients provided to SNOPT 7.2 (Stanford)
  - http://www.sbsi-sol-optimize.com/asp/sol_product_snopt.htm
- Gradient evaluation requires sensitivity analysis
  - Perturbation of design each design variable prohibitively expensive
    - 100 DVs X 2 Points X 50 Cycles X 2 Central Difference = 20,000 flow solutions
    - 0.5 hour / solution => 1.1 years
  - Adjoint gives Gradients at the cost of 1 flow solution + 1 adjoint solution (for all DVs)
    - 2 Points X 50 Cycles = 100 flow solutions => 50 hours

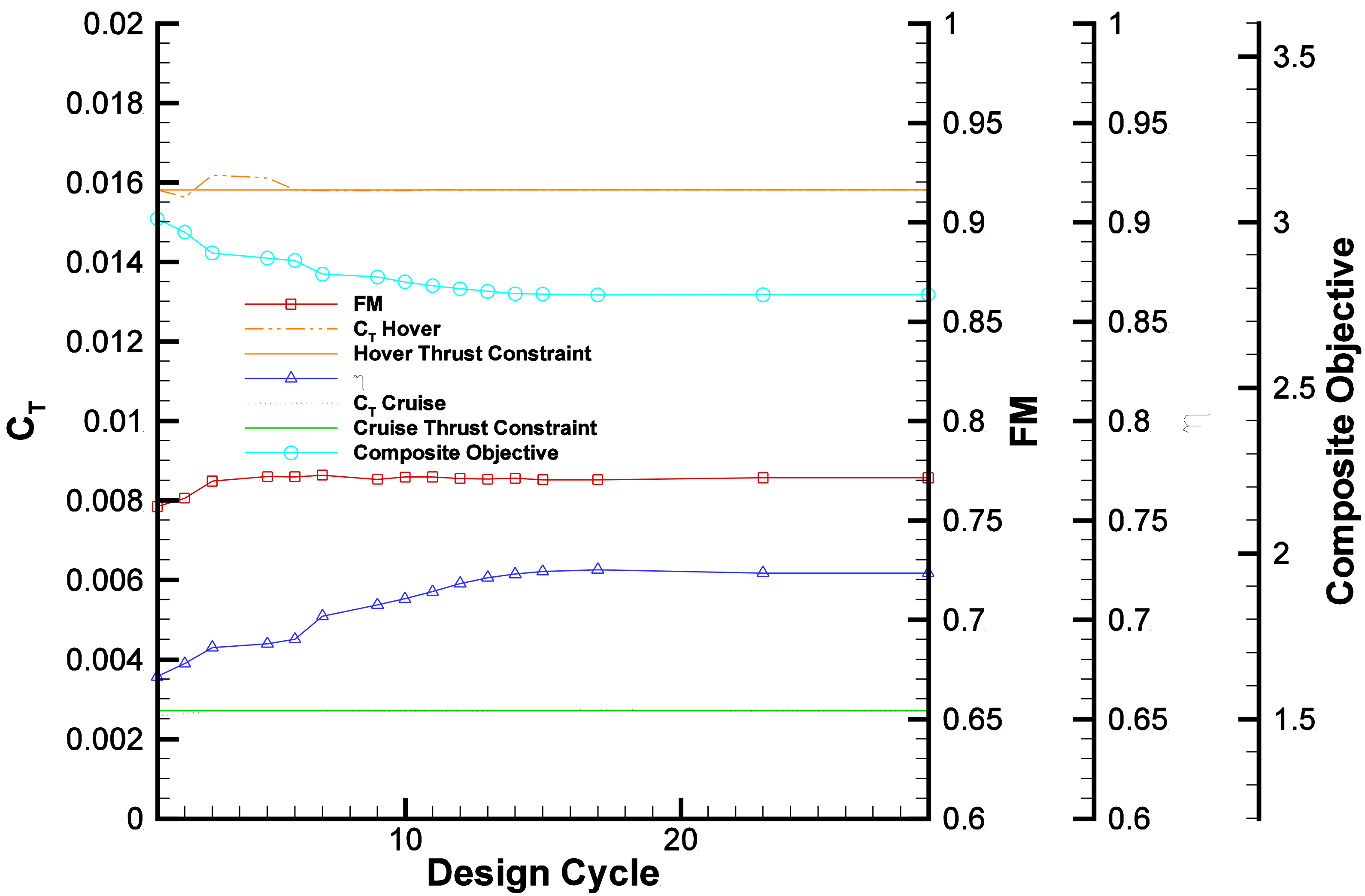
Geometric Parameterization

- MASSOUD
- 123 active design variables
  - 60 camber
  - 50 thickness
  - 10 twist
  - 1 taper
  - 1 collective for each of two design points
- Collective variable formed by linking twist variables
- Taper variable formed by linking in-plane components of planform at tip
  - ¼ chord invariant to design changes
- Variables bounded to prevent non-physical surface
- Boundary grouping used to maintain same shape for all blades



Results: Design Convergence

Convergence History for Step C (Constraint on minimum Thrust)



Results: Hover and Cruise Points

Hover Figure of Merit function (Constant Thrust constraint)

Step	C_T	C_T/σ	FM	ΔFM	$\%Change$
Baseline	0.0158	0.151	0.756	-	-
C	0.0158	0.137	0.771	0.015	1.98

$$FM^2 = \frac{C_T^3}{2C_Q^2}$$

Cruise Propulsive Efficiency (Constant Thrust constraint)

Step	C_T	C_T/σ	η	$\Delta\eta$	$\%Change$
Baseline	0.0027	0.0257	0.671	-	-
C	0.0027	0.0233	0.723	0.052	7.75

$$\eta = \frac{C_T U_\infty}{C_Q U_{tip}}$$

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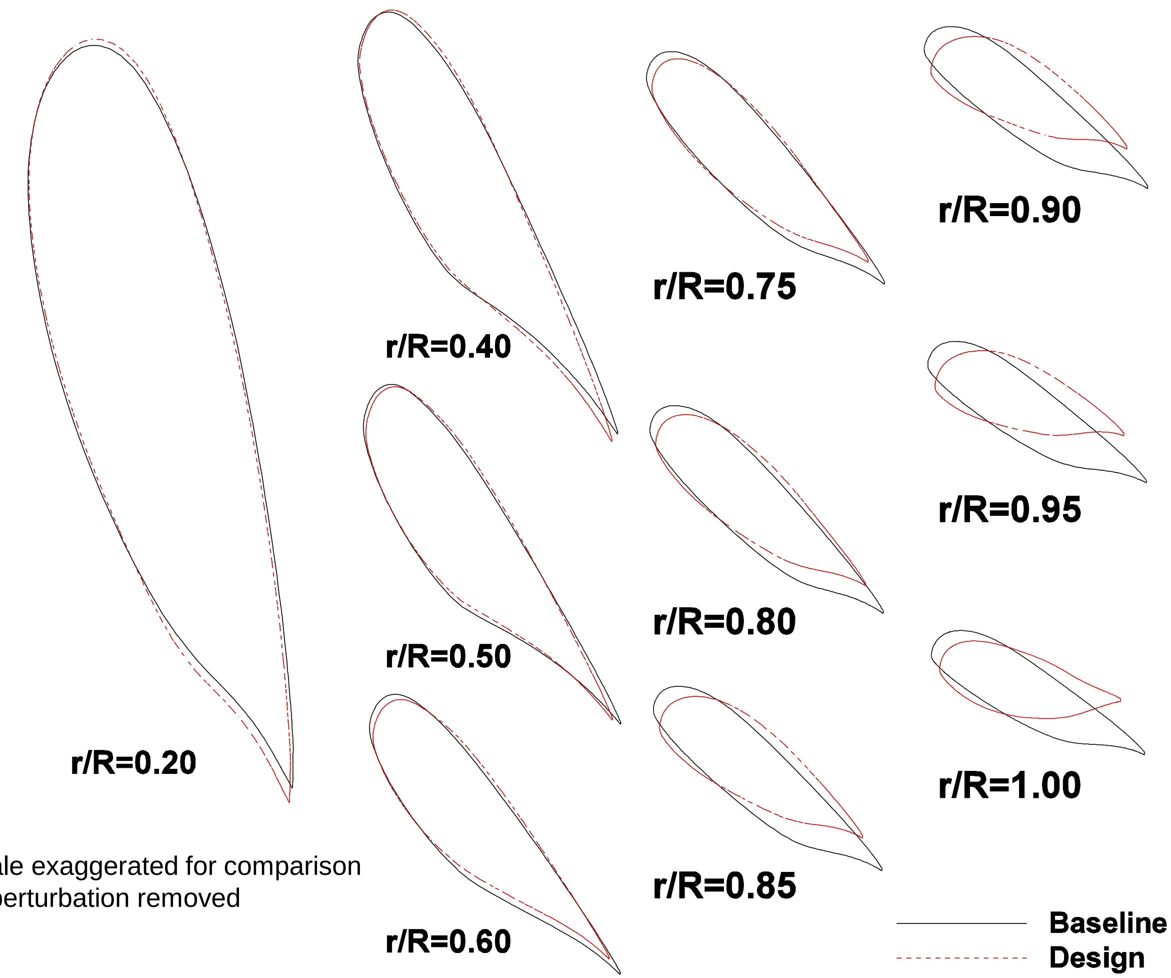
Results (cont.)

- Airfoil sections, Step C, constant C_T constraint



- Vertical scale exaggerated for comparison
- Collective perturbation removed

Conclusions

- Demonstrated gradient-based aerodynamic optimization methods for tilt-rotor
  - High-fidelity CFD
  - Non-inertial reference frame for efficient steady state solution
  - Gradients supplied by flow adjoint solution
    - 123 aerodynamic design variables
  - Multi-point objective function
- Optimization sought to maximize rotorcraft FM in Hover and cruise η
- Multiple designs of increasing degrees of freedom examined impact of design variables
- Designs subject to thrust constraint
  - Constant thrust
  - Maintain minimum thrust
  - Unable to impose a blade loading constraint
    - Results indicated such a constraint is needed
- Process modestly improved hover FM and cruise η for all designs
  - Improved physics with many design variables
  - Designs validate process

Motivation

- Develop and demonstrate aerodynamic optimization methods for tilt-rotor application
  - Enhance the current process
    - Improved physics
    - Larger design space
- High-fidelity CFD is commonplace in steady aerodynamic analysis
  - Application to full rotorcraft configurations is still challenging
    - Unsteady flows
    - Wide range of velocities
    - Complex aerodynamic and structural interaction
- Adjoint methods provide sensitivity information for gradient-based optimization
  - Cost independent of number of design variables
  - Rotorcraft application requires time dependent adjoint implementation
    - Can cast isolated rotor as a steady problem in non-inertial frame
- Multi-point design at hover and cruise conditions

Design Methodology : Design Points

- Multiple design points supported by FUN3D implementation
  - Each point defined by a variation of basic flowfield quantities
  - Points may also represent more general characteristic changes
- Two design points for tilt-rotor optimization
  - Hover
    - $C = FM^2$
    - $f_{hover} = 1.0\left(FM^2 - 2.0\right)^2$
    - $C_T = 0.0158$

$$FM^2 = \frac{C_T^3}{2C_Q^2}$$

  - Cruise
    - $C = \eta$
    - $f_{cruise} = 1.0\left(\eta - 2.0\right)^2$
    - $C_T = 0.0027$

$$\eta = \frac{C_T U_\infty}{C_Q U_{tip}}$$

  - Separate meshes used for each condition due to collective pitch differences
- Single composite objective function, f_{mp}
  - $f_{mp} = \alpha_{hover} f_{hover} + \alpha_{cruise} f_{cruise}$ — α – *Weight factor for each design point*

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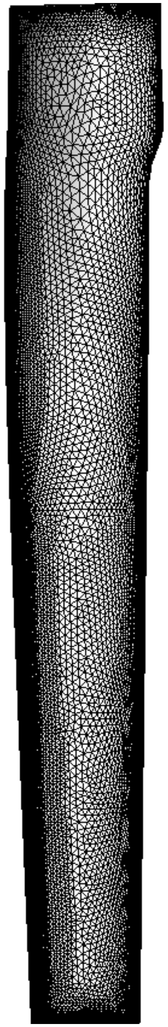
Design Methodology : Design Conditions

- Open literature cruise conditions of V-22
  - Hover

M_{tip}	0.707
R_e	9.2M
C_{ref}	22 inches
Θ	41º
T_∞	519º Rankine
Mesh	8M nodes (48M tetrahedra)

  - Cruise

Altitude	3,000 feet
M_{tip}	0.650
R_e	6.1M
c_{ref}	22 inches
Θ	14º
T_∞	551.5º Rankine
Mesh	8M nodes (48M tetrahedra)



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