LCTR2 Design Study and Aeromechanics Analyses

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Background

- NASA Heavy Lift Rotorcraft Systems Investigation produced the Large Civil Tiltrotor (LCTR) advanced conceptual design in 2005.
- Goal was to identify research requirements for large rotorcraft.
- New design, LCTR2, is sized to be representative of regional jets (90 passengers), convenient for technology investigations.
- Focus for near-term research is more realistic assessment of technology requirements.
- Use LCTR2 to explore fundamental aeromechanics issues.
- Here present examples of performance optimization.

Impact

Technology Limitations

- **No *successful* precedent for very large, high-speed rotorcraft**
- **High risk technical issues:**
  - **high torque, multi-speed, lightweight drive system**
  - **low noise, hover and cruise, exterior and interior**
  - **super-integrated vehicle management system**
  - **large, high performance rotor/wing system**

Research Products

- **Requirements for new/improved design and analytical tools, including tool integration**
- **Definition of needed experimental database**

Outline of Design Study

1. Define mission requirements and generate baseline design.

2. Examine basic performance (hover & cruise efficiency, turns) with aeromechanics code.

3. Optimize rotor and wing: taper, solidity, twist, rotor/wing interference.

4. Update aircraft design with results of optimizations.

5. Examine effects of cruise tip speed in detail.

6. Summarize implications for rotorcraft research.

Use AFDD RC sizing code for aircraft design synthesis and CAMRAD II for rotor and wing aeromechanics analyses.

Methodology Levels

Design code:

mission analysis, aircraft sizing and geometry

seconds to minutes

Aeromechanics code:

beam model for rotor structure, airfoil tables and wake models for aerodynamics

minutes to hours

CFD/CSD:

detailed physical analyses

hours to days

Hardware tests (ground and flight tests):

definitive results

days to months

Increasing

realism,

detail,

time,

cost

Methodology for LCTR2 to Date

RC* design synthesis code:

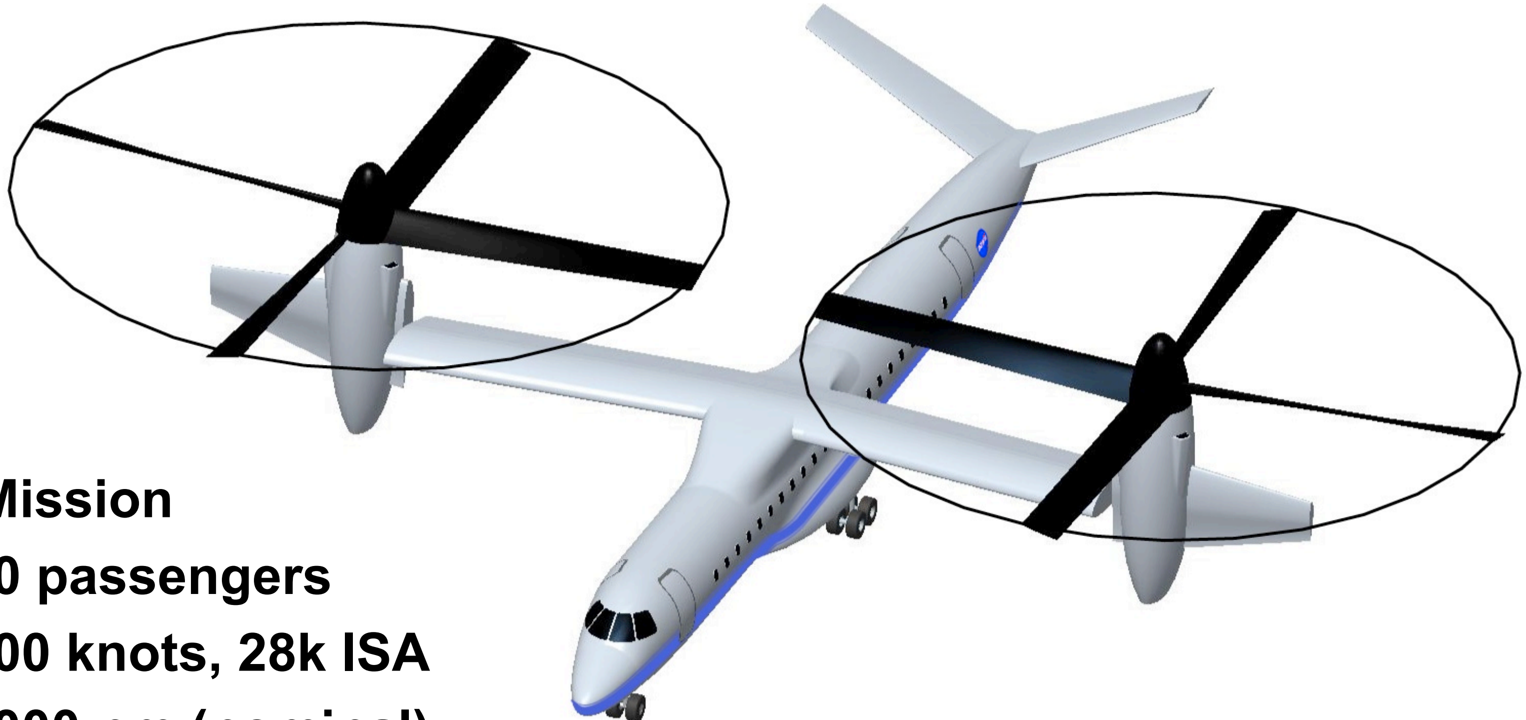
mission analysis
airframe and rotor sizing and geometry
technology factors derived from large rotorcraft database

* To be replaced by NDARC

CAMRAD II aeromechanics code:

multi-element beam model for rotor blade structure
airfoil tables synthesized from CFD analyses
3-D stall delay model for hover aerodynamics
free-wake model for hover and cruise (isolated rotor)
calibrated against JVX test data
add wing wake model for turns and rotor/wing interference

LCTR2 Baseline Design



Mission

Payload: **90 passengers**

Cruise: **300 knots, 28k ISA**

Range: **1000 nm (nominal)**

Operational Requirements

One engine inoperative: **Category A at 5k ISA+20°C**

All-weather operations: **CAT IIIC SNI, Free Flight**

Maneuver capability: **45-deg turn at 80 knots, 5k ISA+20°C**

LCTR2 Design Constraints and Results

Design Constraint	Value
Installed power, hp	4x7500
Rotor radius, ft	32.5
V_{tip}, hover, ft/sec	650
V_{tip}, cruise, ft/sec	350
Hover C_W/σ	0.133

Baseline Design	Result
Gross weight, lb	107,500
Rotor solidity σ	0.13
Rotor taper (tip/root chord)	0.7
Hover C_T/σ	0.166
Cruise C_T/σ	0.0867
Disk loading, lb/ft^2	16.2
Wing area, ft^2	1001
Hover FM	0.787
Cruise η	0.870
Cruise L/D_e	10.1

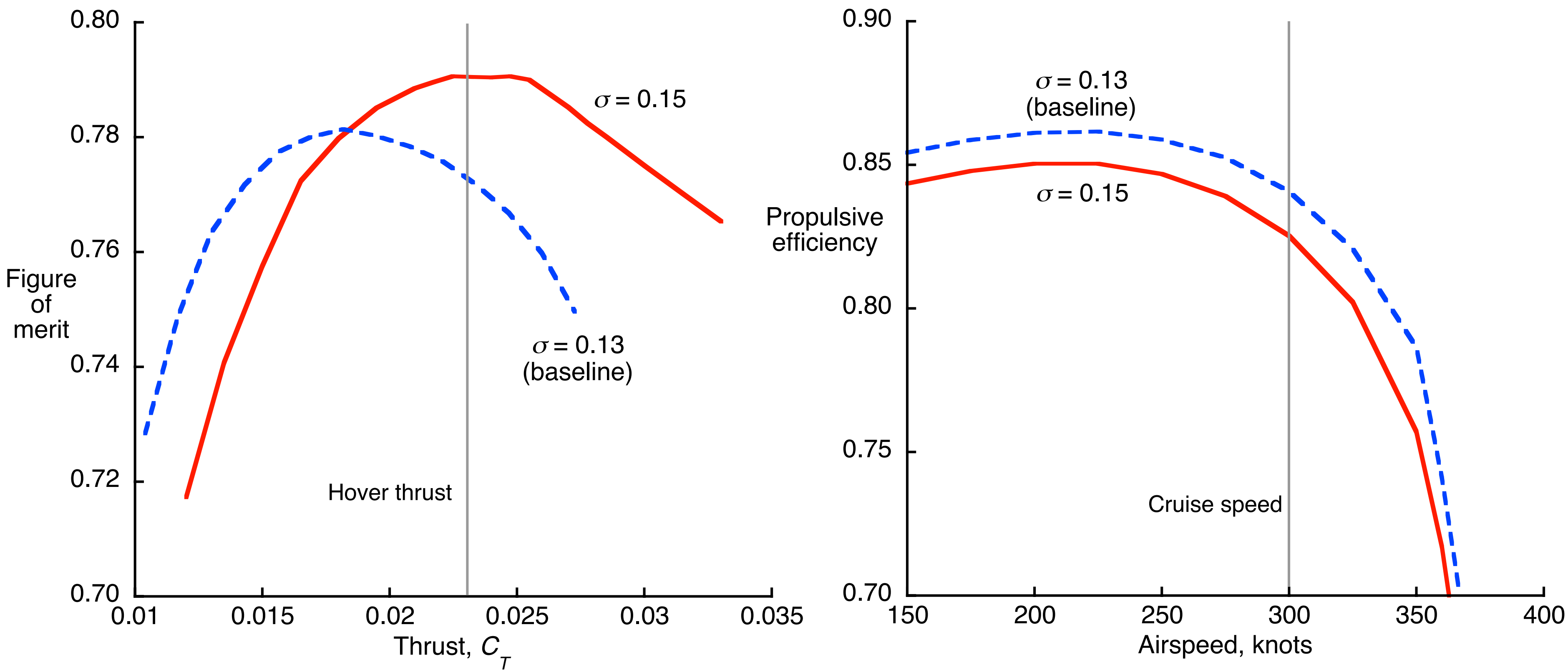
LCTR2 design assumes active load/vibration control, assumes no active stability augmentation.

LCTR2 Baseline Performance

Baseline rotor sized by synthesis code RC.

Isolated rotor performance analyzed with CAMRAD II.

CAMRAD II calibrated against JVX test data.



LCTR2 Turn Performance

Require performance margin for maneuvers during approach and departure.

- **Original design met specification, but rotor was stalled.**
- **Solidity was increased to 0.15 for better margin.**

<u>Specified maneuver</u>

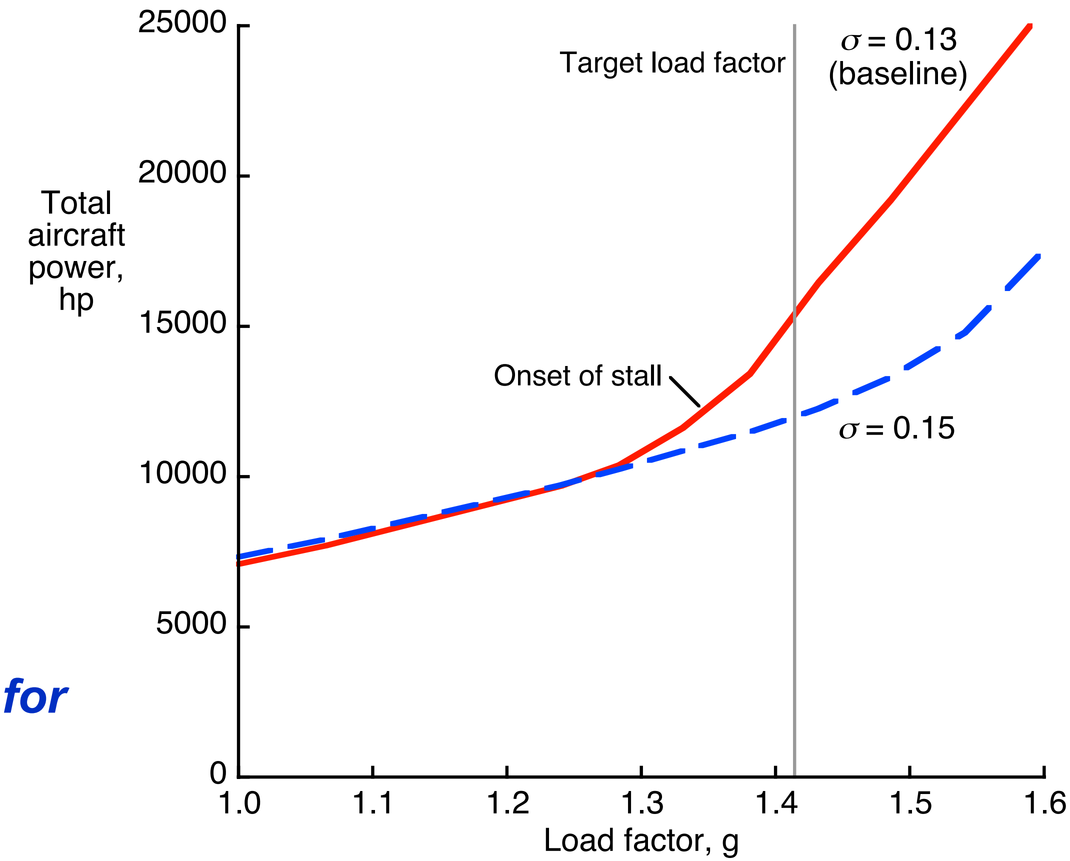
45-deg banked turn

60-deg nacelles

80 knots

5k ISA+20°C

90% MCP



Need different criteria for rotor performance.

(see H. Yeo paper)

Optimize Rotor and Wing

Have performance of baseline design, so now optimize with aeromechanics code.

1. Vary taper and solidity:

compare tradeoff between hover and cruise efficiency

2. Vary twist (bilinear) at chosen solidity:

compare performance tradeoffs for optimized twist

3. Analyze rotor/wing interference:

analyze effect on total aircraft efficiency

optimize tip-extension incidence angle

LCTR2 Twist Variations

Bilinear twist optimization recovered a small amount of the cruise performance lost when solidity was increased (≤0.005 FM and η).

Hover trim

V_{tip} = 650 ft/sec

C_T = 0.0215

Cruise trim

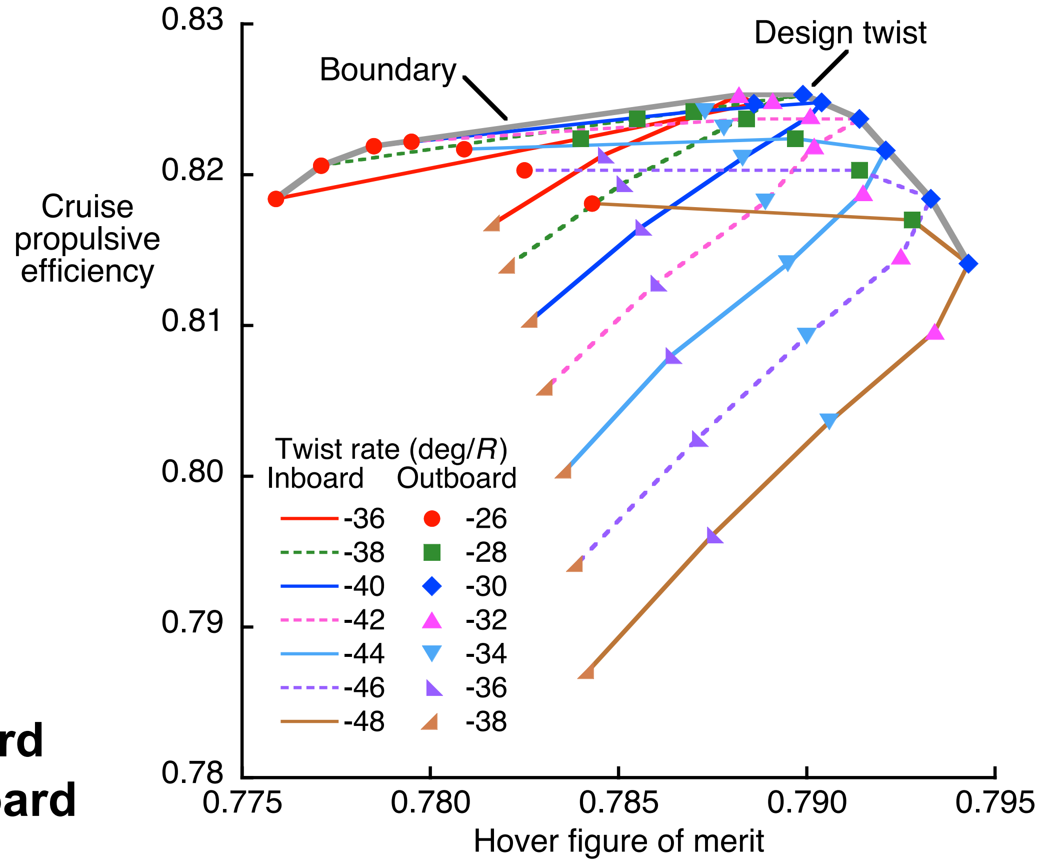
300 knots

V_{tip} = 350 ft/sec

C_T = 0.0113

Design twist = –38 deg/R inboard
–30 deg/R outboard

Optimize twist at σ = 0.15:



Effects of Solidity on Performance

Twist map boundaries show approximately linear tradeoff between hover and cruise performance as solidity is increased.

Hover trim

V_{tip} = 650 ft/sec

C_T = 0.0215

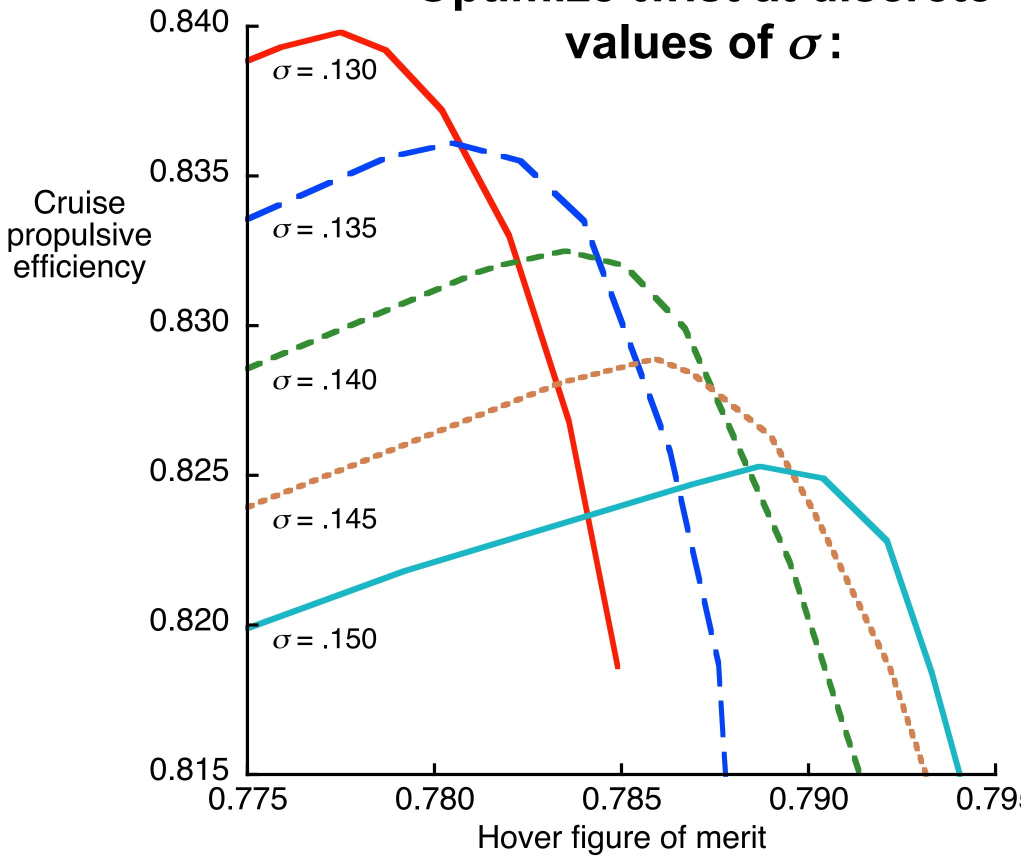
Cruise trim

300 knots

V_{tip} = 350 ft/sec

C_T = 0.0113

Optimize twist at discrete values of σ:



Goal is to feed back aeromechanics results to synthesis code.

Vehicle Design Update

Vehicle synthesis code (RC) sizing strategy:

- **Fix rotor radius and power available (same engines).**
- **Adjust hover and cruise performance to match results of aeromechanics analyses.**
- **Increase solidity for turn performance.**
- **Increase wing span as necessary to achieve range.**

More recent results suggest lower solidity is acceptable, but need different rotor/wing lift sharing in turns.

Impact of Rotor Performance and Solidity

1. Rotor Update = resize with higher solidity

	Baseline	Rotor Update
Rotor solidity	0.13	0.15
Hover FM	0.787	0.790
Cruise η	0.870	0.825
Gross weight, lb	107,500	107,700
Rotor weight, lb	8,756	9,803
Wing weight, lb	6,505	6,641
Mission fuel, lb	20,408	18,154
Cruise L/D_e	10.1	9.3
Wing span, ft	107	107
Wing area, ft^2	1,001	1,001
Drag D/q, ft^2	33.9	34.2
Range w/ 90 pax, nm	1,246	972

Impact of Rotor Performance and Solidity

1. Rotor Update = resize with higher solidity
2. Wing Mod = resize with longer wing

	Baseline	Rotor Update	Wing Mod
Rotor solidity	0.13	0.15	0.15
Hover FM	0.787	0.790	0.790
Cruise η	0.870	0.825	0.825
Gross weight, lb	107,500	107,700	107,725
Rotor weight, lb	8,756	9,803	9,805
Wing weight, lb	6,505	6,641	7,010
Mission fuel, lb	20,408	18,154	17,790
Cruise L/D_e	10.1	9.3	9.9
Wing span, ft	107	107	117
Wing area, ft^2	1,001	1,001	1,061
Drag D/q, ft^2	33.9	34.2	34.7
Range w/ 90 pax, nm	1,246	972	1,038

Effects of Cruise Tip Speed

Optimize twist at discrete values of tip speed.

Optimum V_{tip} = 400 ft/sec

Hover trim:

V_{tip} = 650 ft/sec

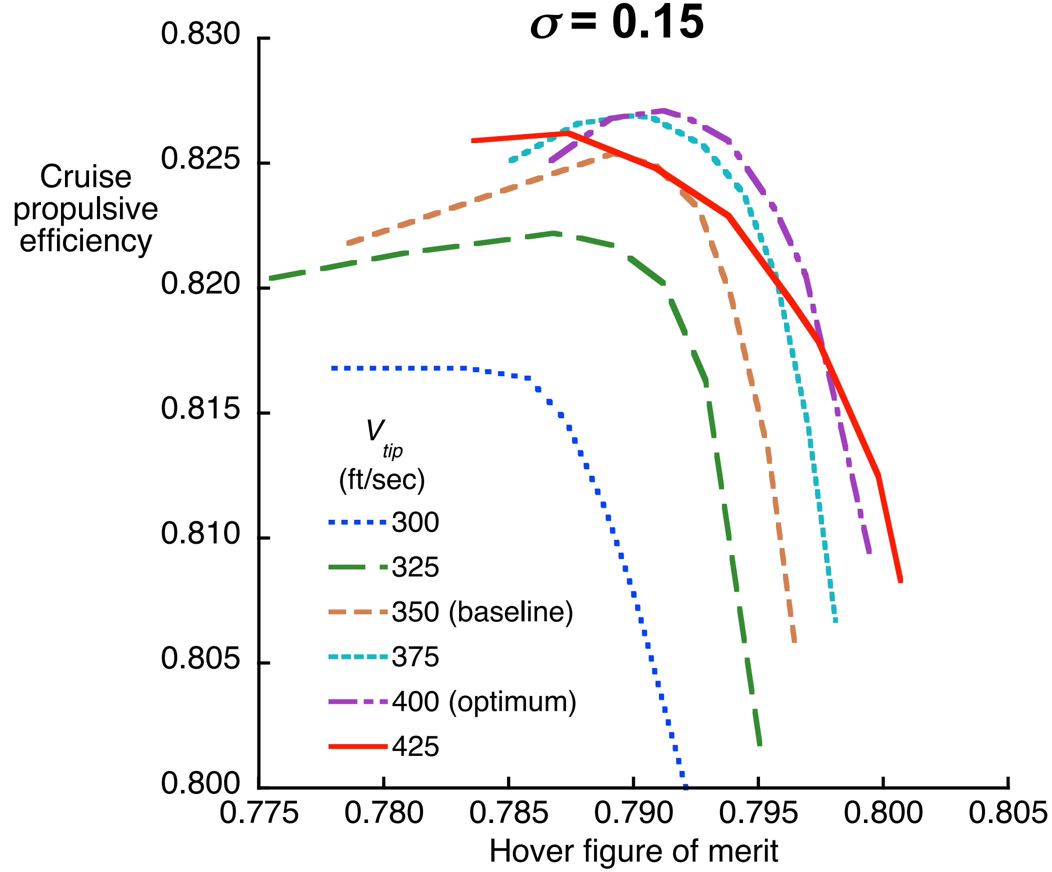
C_T = 0.0215

Cruise trim:

300 knots

C_T = 0.0113

Twist map boundaries, σ = 0.15



Recommendations for LCTR2 Design Studies

- Integrate optimized rotor performance into aircraft design synthesis.
- Investigate effects of blade loading in hover, cruise and turns.
- Analyze aeroelastic stability, including whirl flutter, in detail.
- Explore tip speed variations in greater detail, including effects on noise.
- Include rotor/wing interference in rotor optimizations.
- Optimize rotor for turns, not just axial flow (hover and cruise).
- Investigate higher-order rotor optimizations (e.g. non-linear twist & taper).

Implications for Code Development

Need more fully coupled sizing and aeromechanics analyses to identify optimum designs.

Require more detailed analysis early in design process:

blade loading

rotor/wing interference

rotor/wing lift sharing

Implies more capable design tools (e.g. NDARC) than currently available.

Implications for Test Data Requirements

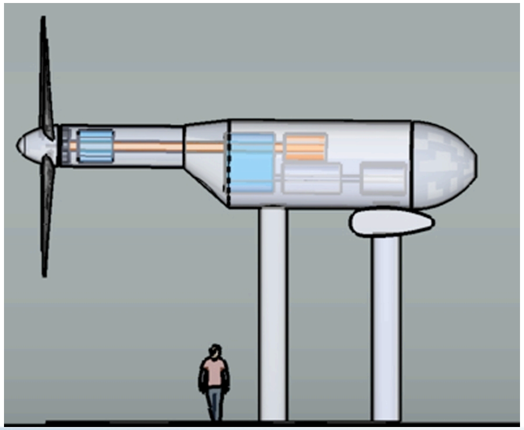
Need more thoroughly calibrated aeromechanics code *and* design code.

Have only two data sets for large-scale, high-speed proprotor performance: XV–15 and JVX.

- **Both 3 blades, gimballed, similar twist and tip speed.**
- **NO variations in taper, twist, sweep, etc. tested at high speed.**

NO completely successful whirl-flutter tests for proprotors since WRATS/V-22.

Need test data to feed back into analyses.



Acknowledgements

Collaborators and Coauthors:

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Recent and Upcoming LCTR2 Publications

- Acree, Yeo & Sinsay, "Performance Optimization of the NASA Large Civil Tiltrotor," IPLC, London, UK, July 2008.

- Yeo, Sinsay & Acree, "Blade Loading Criteria for Heavy Lift Tiltrotor Design," AHS Tech. Specialists' Meeting, Dallas, TX, Oct. 2008.

- Acree & Johnson, "Aeroelastic Stability of the LCTR2 Civil Tiltrotor," AHS Tech. Specialists' Meeting, Dallas, TX, Oct. 2008.

- Background publications:

  Acree, "Calculation of JVX Proprotor Performance and Comparisons with Hover and High-Speed Test Data," AHS Specialist's Conference on Aeromechanics, San Francisco, CA, Jan. 2008.

  Acree, "Modeling Requirements for Analysis and Optimization of JVX Proprotor Performance," AHS 64th Annual Forum, Montréal, Canada, April 2008.

Questions?