Conceptual Design of a Tiltduct Reference Vehicle for Urban Air Mobility

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Revolutionary Vertical Lift Technology (RVLT) Project

Advanced Air Vehicle Program, NASA Aeronautics Research Mission Directorate

Aeromechanics for Advanced Vertical Flight Technical Meeting

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Outline

1. Background
   - Technical Challenge & UAM Reference Vehicles
   - Sizing Mission
2. Tiltduct Design Process
   - Configuration Exploration
   - Duct aerodynamics & geometry selection
   - NDARC model setup, design trades, and tuning
3. Results
   - Comparisons with other NASA UAM reference vehicles
4. Conclusions
5. What's Next

Motivation: Urban Air Mobility (UAM)

Technical Challenge: "Tools to Explore the Noise and Performance of Multi-Rotor UAM Vehicles"

GAP

A validated and documented methodology for assessing tradeoffs between noise and efficiency of UAM vehicles does not exist, preventing:

- Assessment of noise impact of UAM vehicles on the community
- Exploration of feasible noise mitigation strategies
- Assessment of vehicle performance requirements imposed by low-noise designs.

OBJECTIVE

Provide the community a validated and documented set of tools for assessing tradeoffs between the noise and performance of VTOL UAM aircraft.

UAM Reference Vehicles

Customers

- NASA, other Government agencies, industry, contractors, academia

Applications

- Common reference models for researchers across UAM community
- Investigate vehicle technologies & identify enabling technologies
- Expose design trades and constraints
- Focus tool development towards needs of UAM
- Simulate vehicle operations; e.g. fleet noise, air traffic integration
- Airworthiness & certification
- Passenger acceptability

Requirements

- Representative of industry configurations & technologies
- Consistent, known assumptions
- Fully documented & publicly available

Quiet Single Main Rotor Helicopter

Side-by-Side Helicopter

Quadcopter

Lift-plus-Cruise

Tiltwing

Tiltduct

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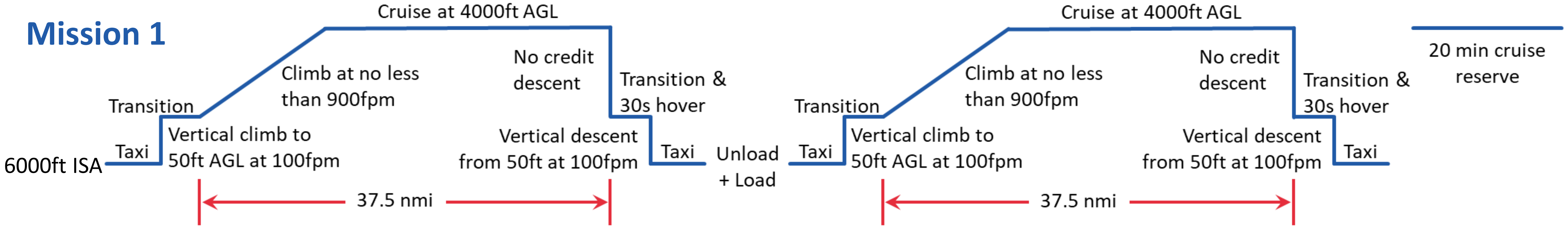
Sizing Mission

Mission 1

Most constraining mission from *Patterson et al.*, 2018[1]

- 6 passenger payload (1200 lb)
- 6,000 ft ISA takeoff
- Two 37.5 nmi hops into 10 kt headwind
- 20 min cruise reserve at long-range cruise speed



Mission 2

Emergency battery sizing: 2 mins at hover out of ground effect power (30C discharge rate)

Condition 1

Flat-rated MTOW: HOGE at 6000 ft ISA and 100% MRP

Condition 2

Maneuver margin: 500 ft/min cruise climb at 10,000 ft ISA, 100% MRP, DGW.

[1] Patterson, M. D., Antcliff, K. R., and Kohlman, L. W., *A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements*, AHS Forum 74, May 2018.

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Why Tiltduct?

- Vectored thrust: higher cruise speed than a helicopter or multirotor
- Acoustics: potential to reduce, shield, and/or redirect noise
- Aerodynamics: duct augments thrust, improving hover thrust-to-weight ratio
    - Increases slipstream wake area, reducing slipstream velocity & induced power
- Shrouds:
    - Improve safety during ground handling
    - Improve public perception (lack of open rotors)
    - May mitigate effects of blade-off events

Priorities for future research:

- Quantify noise benefit achievable
- Investigate credible technologies; e.g., acoustic liners, flow control, blade spacing, soft stators
- Improve conceptual design & analytical tools

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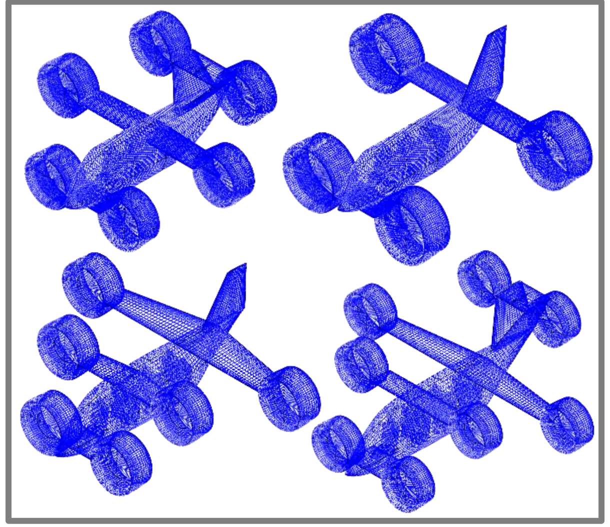
Tiltduct UAM Reference Vehicle: Design Process

Evaluation of >30 Past/Current Designs

	Industry Tiltducts	NASA Tiltduct
Gross Weight (lb)	1800 - 7000	~6000
No. of Propulsors	2 - 36	6
No. of Passengers	0 - 10	6
Wingspan (ft)	0 - 50	36
Cruise speed (kt)	60 - 350	150
Range (nm)	40 - 500	75

Initial Configuration Sketches & Downselection



Duct Literature Review

- Aerodynamic characteristics
- Hover, edgewise, axial flight
- VZ-4, X-22, Hamilton Standard

Duct Geometry Selection

- Duct area ratio
- Duct length
- Blade geometry
- Acoustical considerations

Duct representation in NDARC

- Duct aero representation
- Duct weight estimation

Design trades & model refinement

- Cross shafting versus direct drive
- Disk loading and duct area ratio trade study
- Tune induced power to empirical data

Initial Sizing & OML Complete

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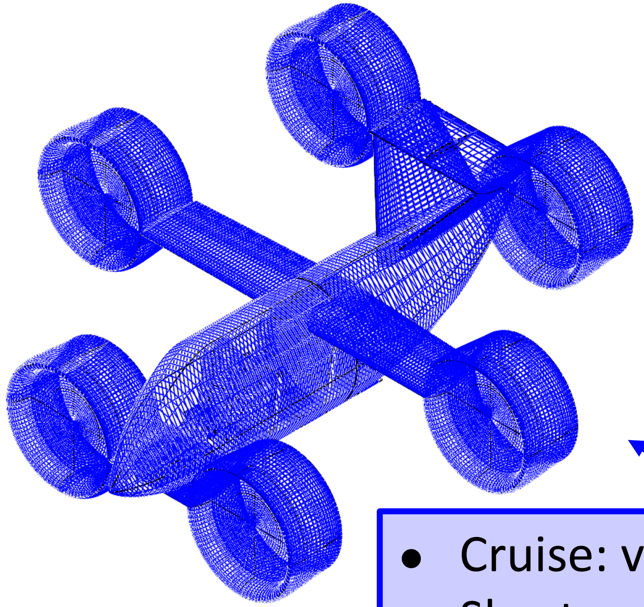
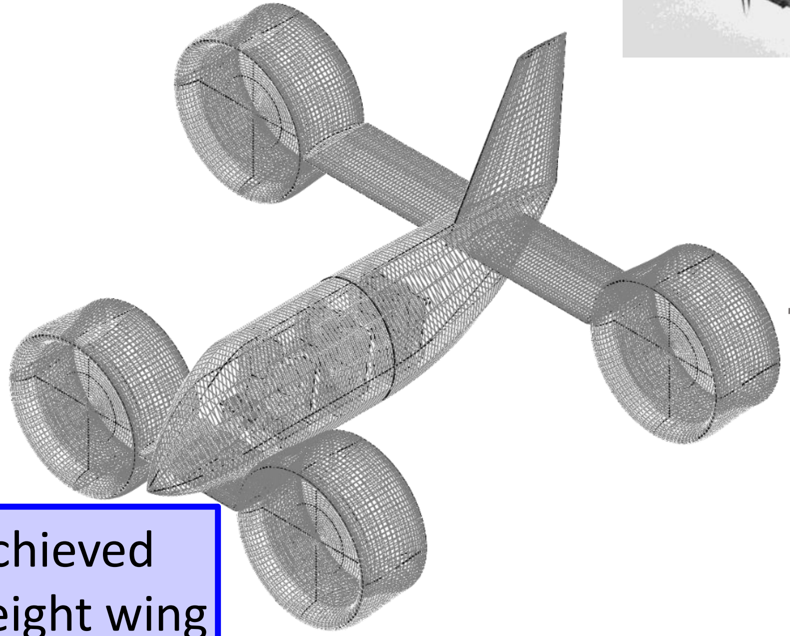
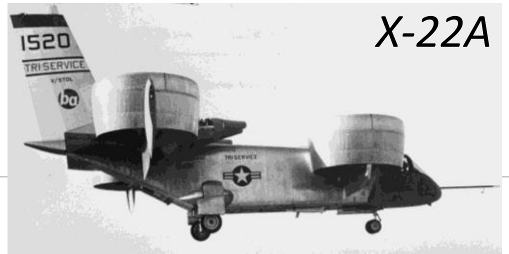
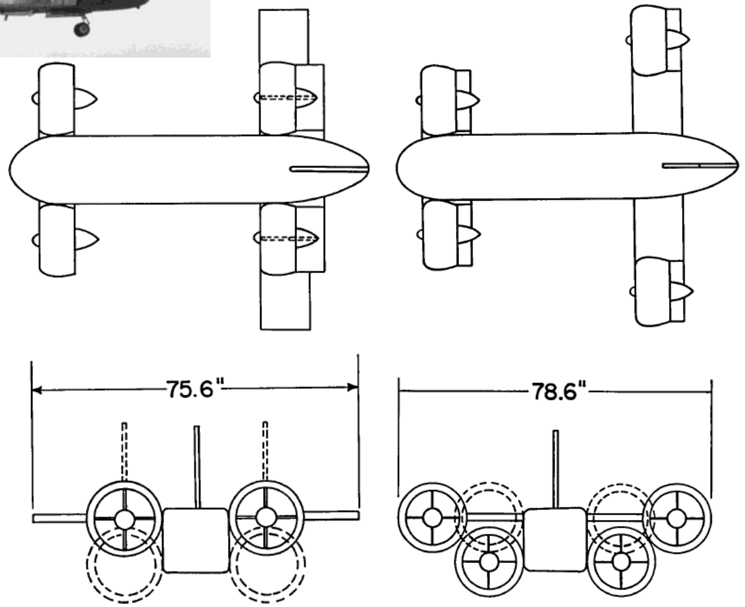
Configuration Exploration





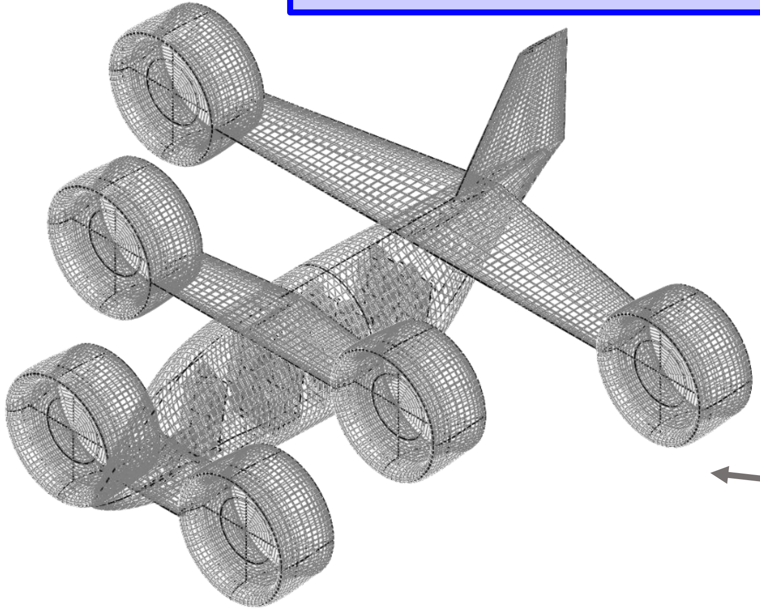
- Cruise: vertical separation achieved
- Shorter wingspan; lighter weight wing
- Hover: preferred thrust distribution

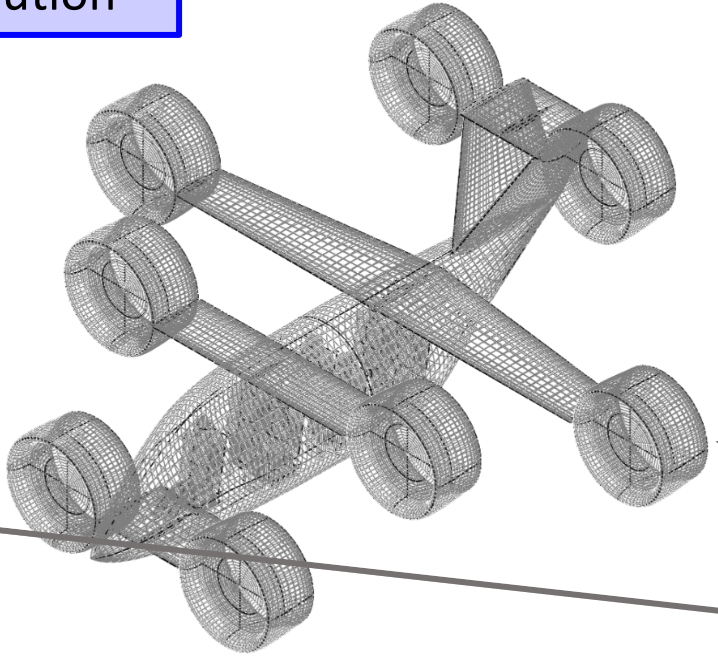




NASA TN D-1481

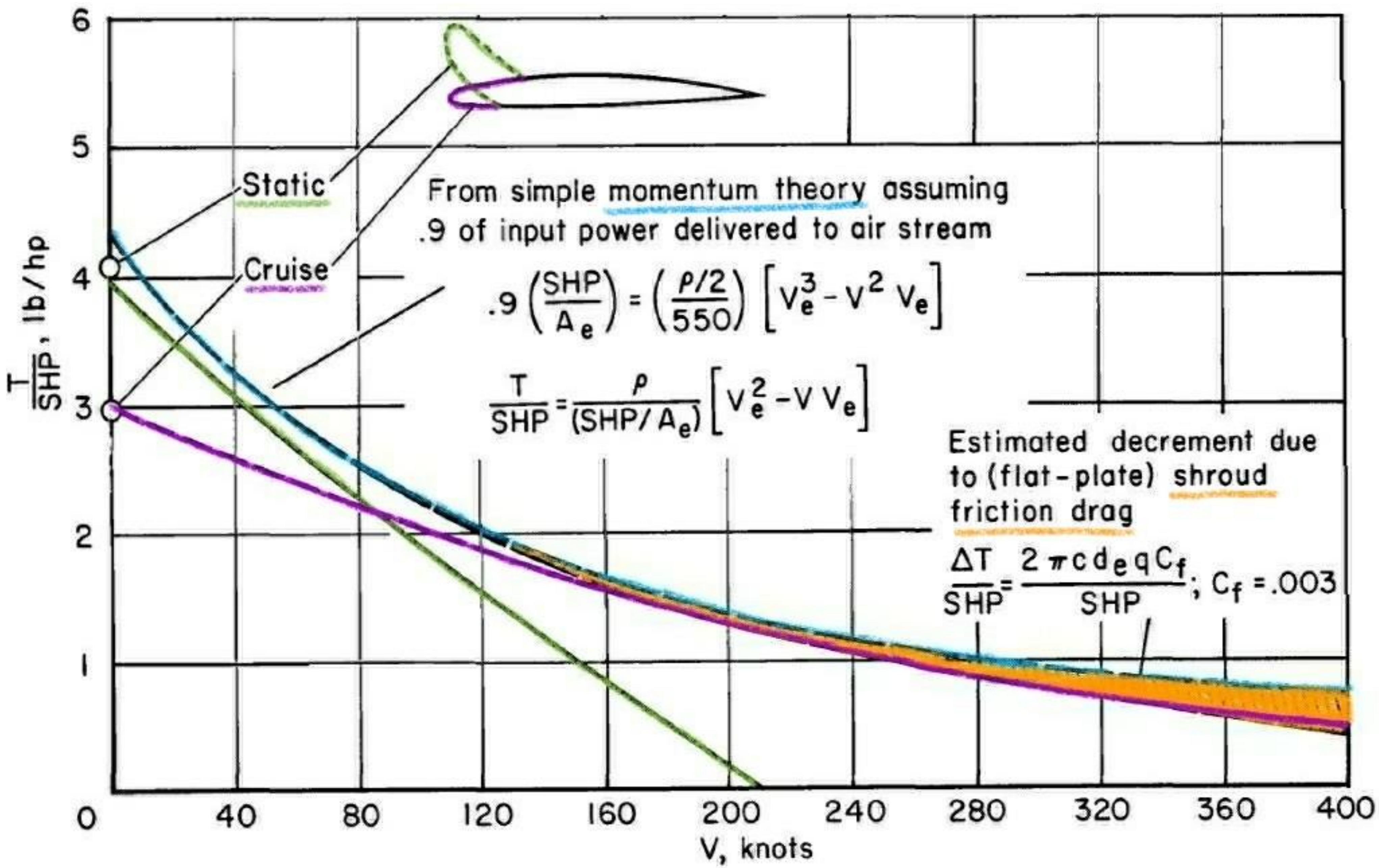
- Identical tilting ducts: ease production & maintenance
- Rotors: collective controlled
- Turboelectric propulsion
- Landing gear: retractable

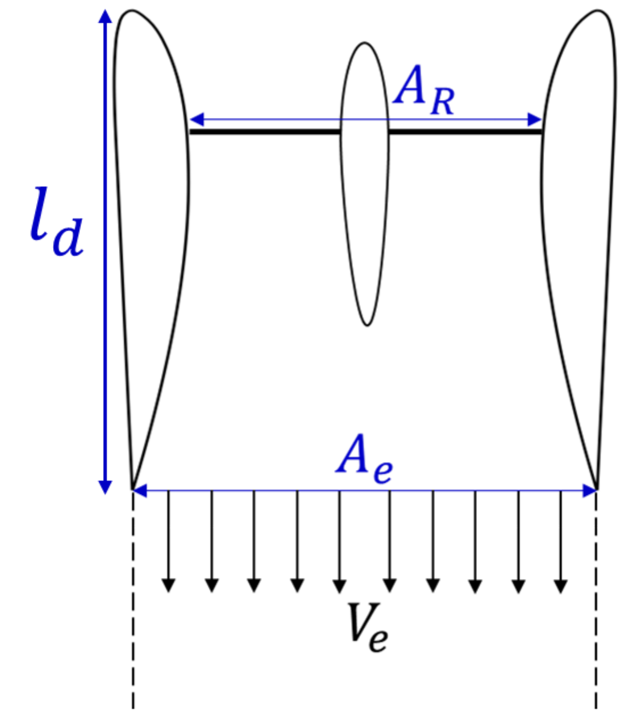




Rear wing lower for structural reasons: duct wake impinges on rear wing

Hover vs. Cruise Flight



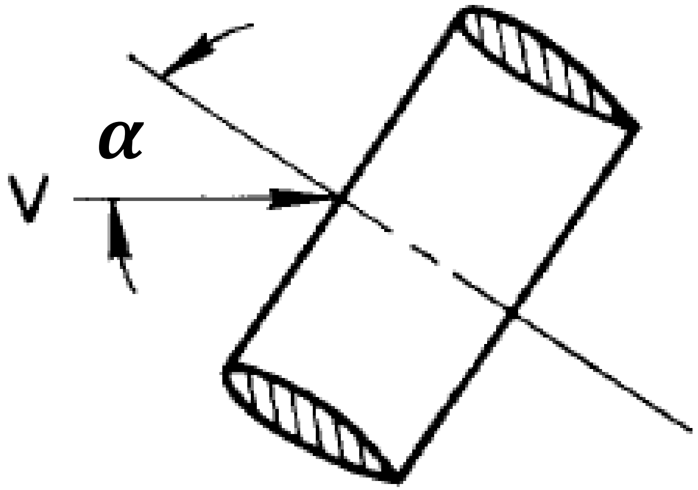


- Duct design is a tradeoff between hover and cruise performance
- Ducts act similar to annular wings

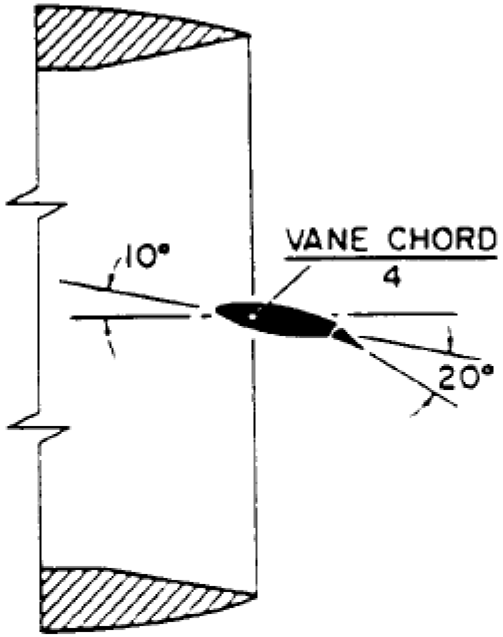
Mort, K. W., *Performance Characteristics of a 4-Foot-Diameter Ducted Fan at Zero Angle of Attack for Several Fan Blade Angles*, NASA TN D 3122, December 1965.

Large angles of attack

- Positive angles of attack: pitch-up moment, due to:
  - Moment arm of duct shroud normal force
  - Differential thrust on duct lips
- Horizontal exit vane with 25% chord flap
  - Mitigate pitching moment variation during transition flight
- Lip separation:
  - Separation occurs on lower lip first
  - Full stall of lower lip should be avoided (increased power, noise, blade stresses)
  - Lip radius can improve separation characteristics
  - Stall of upper lip was unlikely and uneventful
- Lip stall limited vehicle descent rate
  - Lip separation mitigation is important → vortex generators, flow control, variable geometry.
  - Improve wing effectiveness in descent to unload ducts → high lift devices



Duct cross section at angle of attack



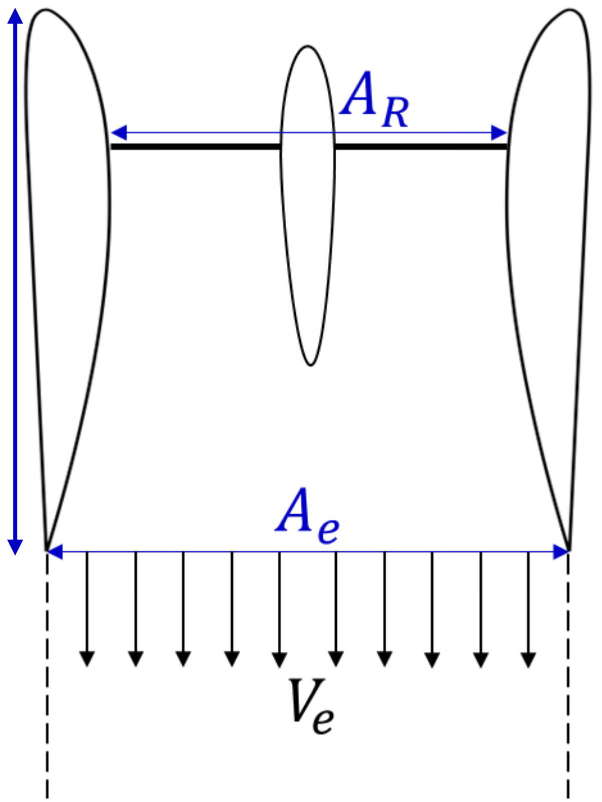
Limitation: high disk loading of empirical data (125-250 lb/ft^2)

Duct Geometry Selection

Deduced from Hamilton Standard Shrouded Propeller Test Program[1]:

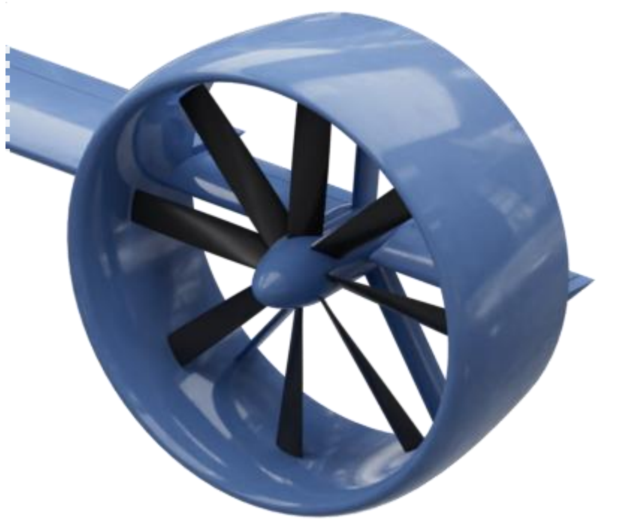
- Duct area ratio, $\sigma = 1.00 - 1.15$
- Duct chord length, $l_d = R$, proprotor radius
- Proprotor chordwise location: 40% chord
- Proprotor blades: 8 blades, based on Hamilton Standard

$$\sigma = \frac{A_e}{A_R}$$



Qualitative design assumptions:

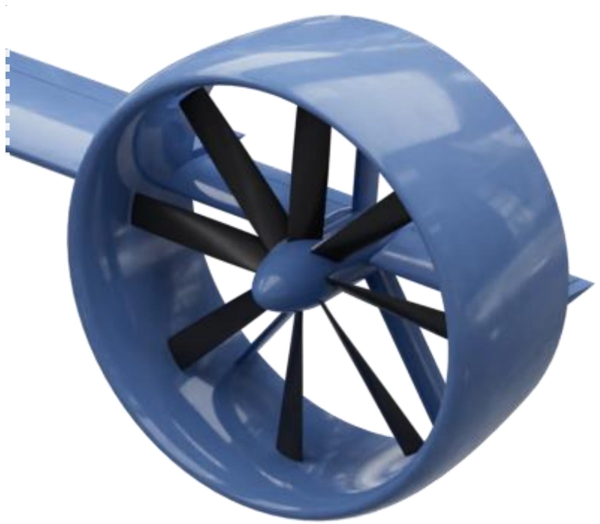
- Our vehicle performance estimates assume that the duct is designed for no separation in hover while maintaining acceptable cruise performance
    - Recommend variable geometry inlet to improve cruise efficiency
- Exit vanes:
    - Aerodynamically designed; consider swirl recovery if beneficial
    - Horizontal exit vane spar as extension of wing spar



[1]Black, D. M., and Wainauski, H. S., *Hamilton Standard Shrouded Propeller Test Program, Vol I-IV*, HSER 4348, Hamilton Standard, 1967.

Acoustics Considerations

- Maximum blade tip speed: 550 ft/s maximum
- Exit vanes:
  - Target large axial spacing from blades: to reduce noise
  - 5 exit vanes: to avoid exciting the modes that propagate efficiently in the duct at blade passage frequency[1]
- Acoustic liners:
  - Reduce noise radiation
  - Recent advances[2] in design & fabrication indicate these could be applicable to UAM vehicles, for example:



[1] Preliminary calculations; Tyler, J. M. and T. G. Sofrin, *Axial Flow Compressor Noise Studies*, SAE Technical Paper, 1962.
[2] Nark, D. M., and Jones, M. G., *An Investigation of Bifurcation Acoustic Treatment Effects on Aft-Fan Engine Nacelle Noise*, 25th AIAA/CEAS Aeroacoustics Conference, 2019.

NDARC Model Setup

- Baseline: tiltwing reference vehicle
- Additional aspects specific to the tiltduct:
  - Ducts modeled as “ducted fan” components in NDARC (momentum theory)
  - Duct lift at small angles of attack
    - Represented with zero-weight wings
  - Duct weight estimation: default model
  - Wing weight estimation: tiltrotor model
  - No control surfaces modeled
    - Allowed ducts to tilt for trim during cruise; maximum required tilt $\pm 1°$
  - Neglected component interference velocities (i.e., no wake interactions)

Duct design trades

7000 lb

6000 lb

Direct Drive

Gross Weight (lb)		Hover Disk loading (lb/ft^2)			
		25	30	35	40
Duct Area Ratio, σ	1.00	12070	7750	7420	8370
	1.10	9120	7090	6850	7570
	1.15	8660	6870	6640	7270

Cross Shafted

Gross Weight (lb)		Hover Disk loading (lb/ft^2)			
		25	30	35	40
Duct Area Ratio, σ	1.00	7450	6620	6540	7090
	1.10	6940	6200	6140	6640
	1.15	6770	6060	6000	6460

Final NDARC Tuning

Induced Power:

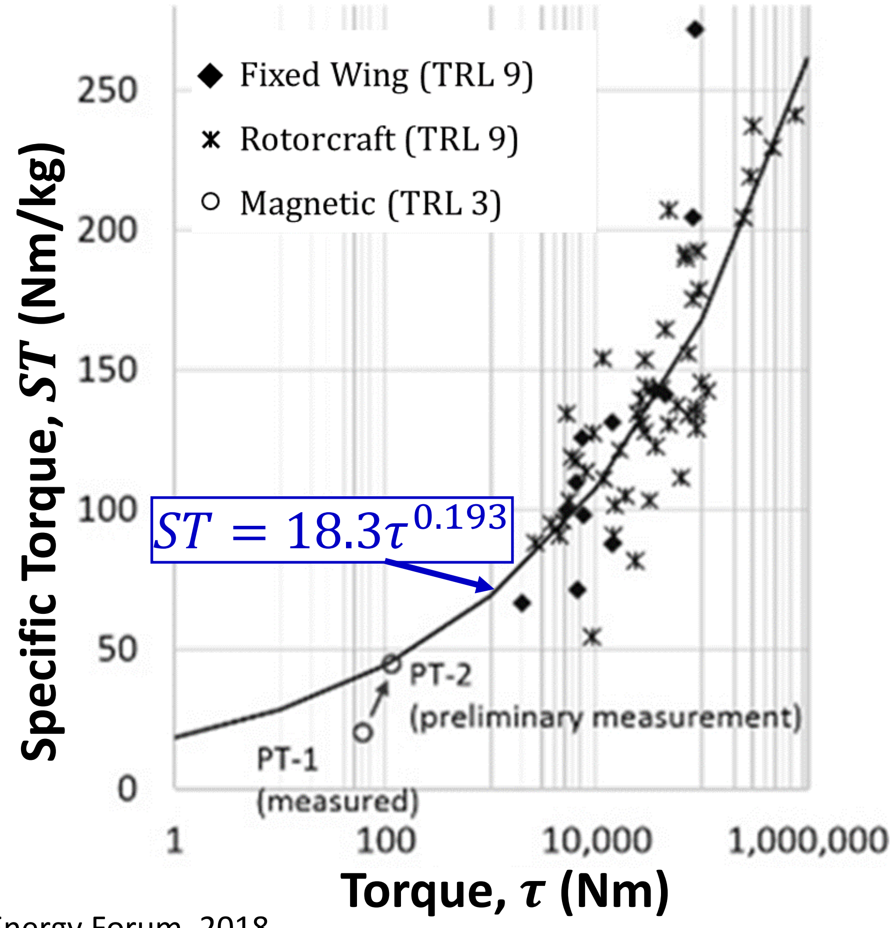
- Ducted proprotors reduce induced power for a given thrust, relative to an open proprotor
- X-22A tunnel test[1,2]:
  - Hover efficiency, $\eta_{hover} \approx 80\%$
  - Cruise efficiency, $\eta_{cruise} \approx 80\%$

$$C_{P_{hover}} = \frac{R}{\eta_{hover}\sqrt{A_e}} C_{T_{hover}}^{3/2}$$

$$C_{P_{cruise}} = \frac{C_{T_{cruise}}}{\eta_{cruise}} \left(\frac{V}{2Rn}\right)$$

Gearbox Weight:

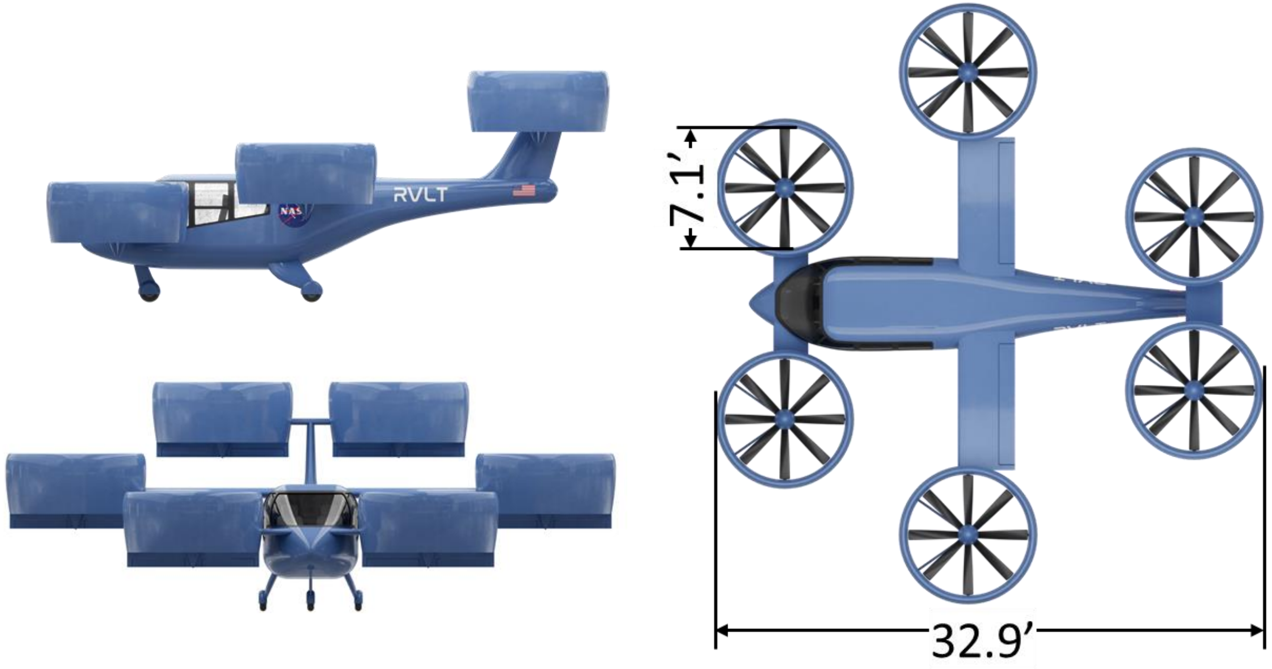
- Weight tech factor was tuned such that gearbox specific torque fell on trendline reported by Scheidler[3]



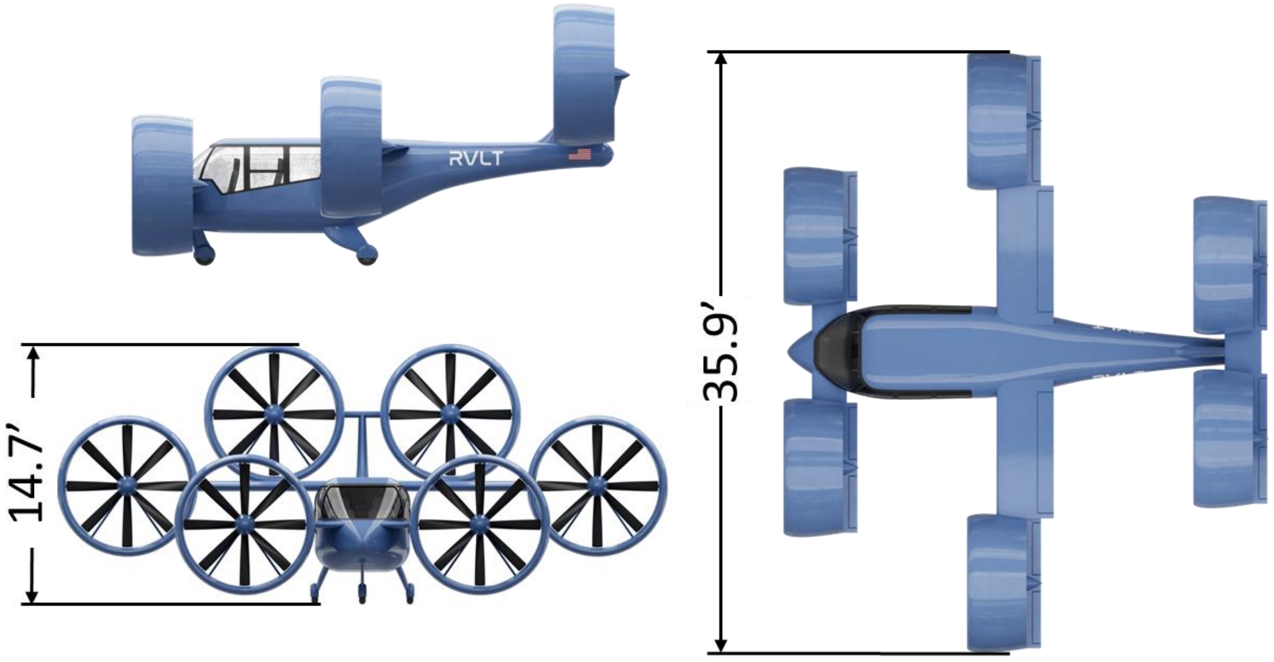
[1] K. W. Mort, B. Gamse, *A Wind-Tunnel Investigation of a 7-Foot-Diameter Ducted Propeller*, NASA TN D-4142, 1967.
[2] Based on traditional propeller definition of thrust coefficient.
[3] J. J. Scheidler, V. M. Asnani, and T. F. Tallerico, *NASA's Magnetic Gearing Research for Electrified Aircraft Propulsion*, AIAA Propulsion and Energy Forum, 2018.

Resulting Tiltduct Vehicle

Hover



Cruise



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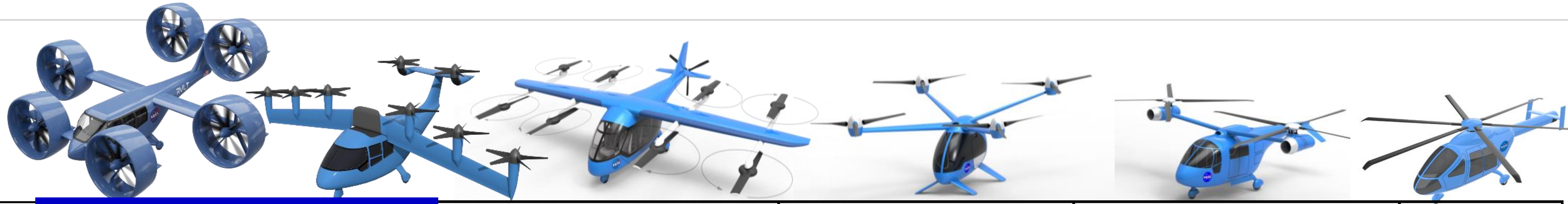
Results: Comparison of UAM Reference Vehicles to Date

High

Low



Vehicle Configuration	Tiltduct	Tiltwing	Lift-plus-Cruise		Quadrotor		Side-by-Side		SMR
Propulsion System	**DD TE**	**DD TE**	**DD TE**	**DD E**	**CS TS**	**CS E**	**CS TS**	**CS E**	**TS**
Design gross weight (lb)	7089	6750	8190	8210	3740	6480	3470	4900	3740
(Prop)rotor diameter (ft)	7.08	7.33	10	10	18.4	26.2	21	29.8	34.5
Hover disk loading, T/A_R	30	20	13.1	13.1	3.5	3	5	3.5	4
Aircraft hover figure of merit	0.76	0.7	0.63	0.74	0.69	0.7	0.69	0.68	0.62
Cruise airspeed, V_{br} (kt)	151	148	128	112	122	98	116	98	102
Block speed (kt)	115	117	101	91.7	105	87.1	97	82.6	77.4
$L/D_e = WV_{br}/P$	9.1	8.7	7.9	8.5	4.9	5.8	5.9	7.2	5.4
Cruise wing area (ft^2)	229	128	256	275	N/A	N/A	21.3	42.9	N/A
Energy burn (MJ)	3170	3280	4260	1110	2670	1070	2210	686	2550
Weight/lift power (lb/hp)	7.32	6.03	6.65	7.4	12.8	14	10.7	12.6	10.5
Weight/cruise power (lb/hp)	19.6	20.3	22.5	24.9	13.1	18.4	16.9	24.4	16.9

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Conclusions

- Both vectored thrust vehicles achieve notably higher block speeds than the other reference vehicles.
- Vehicle performance alone is not likely to be a key driver in the selection of a tiltduct over a tiltwing vehicle.
- If ducts do show significant improvements in acoustics, then acoustical priorities may provide a compelling reason to incorporate ducted proprotors on Urban Air Mobility aircraft.
- Historical data is based on ducted proprotors with high disk loadings. If ducted proprotors are to be designed for UAM, then additional research into acoustical and performance characteristics of ducted proprotors with low disk loadings is warranted.

Quiet Single Main Rotor Helicopter

Side-by-Side

Quadcopter

Lift-plus-Cruise

Tiltwing

Tiltduct

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What's Next?

Priorities for future research:

- Quantify noise benefit achievable
- Investigate credible technologies; e.g., liners, flow control, blade spacing, soft stators, etc.
- Improve conceptual design & analytical tools

RVLT Validation Test Campaign, FY20-25

- Duct in isolation, acoustical focus, US Army 7'x10' tunnel, NASA Ames, FY23-25
- Many other UAM-related tests

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Thank you!

Questions & Comments?

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NASA Six-Passenger Reference Vehicle OpenVSP, NDARC, and AIDEN models are available for download at:

sacd.larc.nasa.gov/uam

RVLT UAM Reference Vehicles: Paper References

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Tests in the RVLT Validation Test Plan

FY20

- *Multirotor Test Bed (MTB) - Entry 1 (7'x10')*
- *Aerodynamic and Acoustic Rotorprop Testing (AART)(40'x80')*
- *Propeller Test Rig - Acceptance Test (LSAWT)*

FY21

- *Electric Motor Noise Test (GRC ATL)*
- *Background Noise Test (14'x22')*
- *sUAS Optimized Noise Test (LSAWT)*
- *Small Ducted Rotor Acoustic Test (SHAC)*

FY22

- *Side-By-Side (SbS) Rig Entry 1 (7'x10')*
- *Moog SureFly Flight Tests*
- *Benchmark Hover Test (80x120)*
- *Tiltrotor Aeroelastic System Testbed (TRAST) (TDT)*
- *Multirotor Test Bed (MTB) - Entry 2 (7'x10')*
- *Vertical Lift Prop Noise Performance Test (14'x22') (Test starts in FY22 and completes in FY23)*

FY23-FY25

- *Side-By-Side Rig - Entry 2 (7'x10')*
- *Tilt Duct Checkout and Entry 1 (7'x10')*
- *Vertical Lift Prop Noise Acoustic Test (14'x22')*
- *Joint MTB and Tilt Duct Acoustic Test (40'x80')*
- *Tiltwing Performance Test (14'x22')*
- *Large MTB Performance/Acoustic Test (40'x80')*
- *Tiltwing Acoustic Test (14'x22')*