

National Aeronautics and
Space Administration



Aircraft Performance Considerations for High-Lift Propeller Systems

Presentation to ASTM F44.20 Flight Subcommittee

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Meet “Maxwell”



- X-57 is NASA’s Flight Demonstrator for *Distributed Electric Propulsion Technology (DEP)*
- **Project Goals:** generate data and procedures and share these with academia, industry, standards organizations, and regulators to enable design and certification of DEP concepts
- **Project Approach:** spiral development through multiple design “Mods”



Mod I: Baseline performance of gasoline-powered aircraft



Mod IV: High-lift propeller takeoff, landing, handling qualities

Together:
Comprehensive impact of electric propulsion technologies on aircraft design, performance, efficiency, acoustic signature, and operations



Mod II: High-voltage powertrain integration, impact of electric retrofit



Mod III: Impact of cruise-sized wing, wingtip propellers



P2006T → X-57

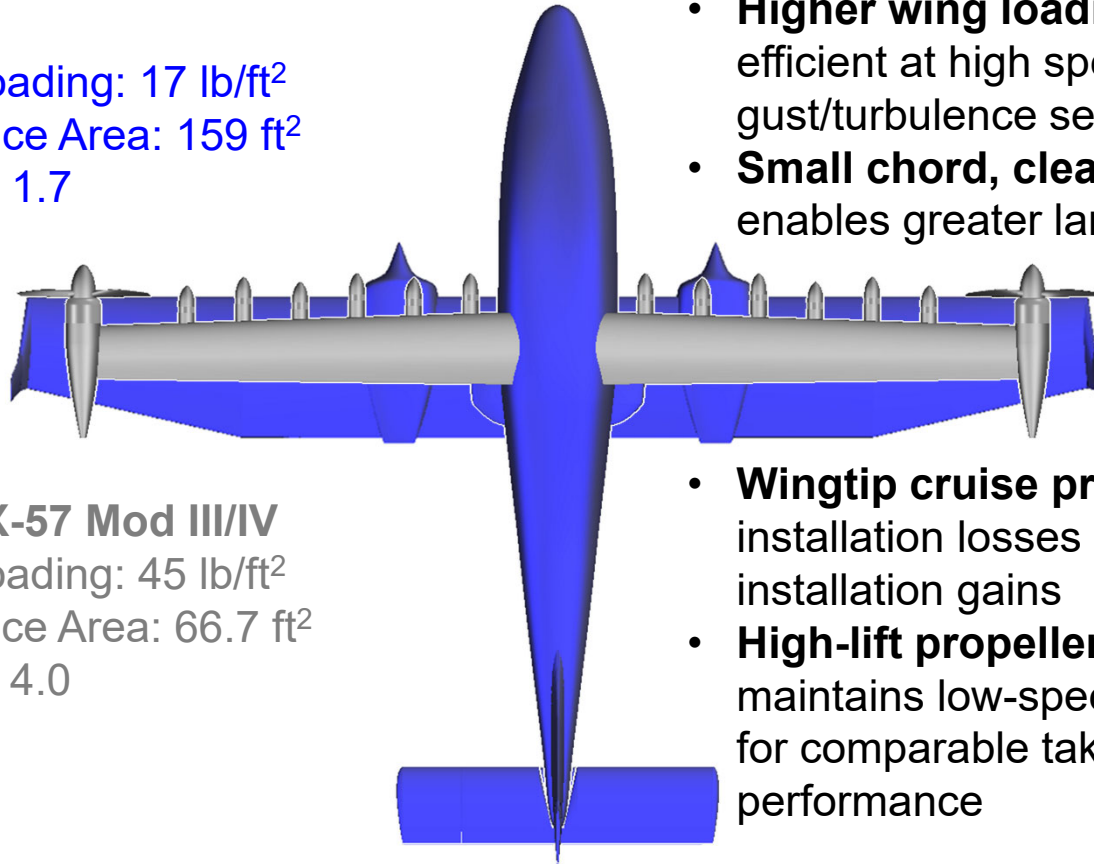


P2006T

Wing Loading: 17 lb/ft²

Reference Area: 159 ft²

C_{Lmax} : ~ 1.7



- **Higher wing loading:** more efficient at high speeds, less gust/turbulence sensitivity
- **Small chord, clean upper surface:** enables greater laminar flow

NASA X-57 Mod III/IV

Wing Loading: 45 lb/ft²

Reference Area: 66.7 ft²

C_{Lmax} : > 4.0

- **Wingtip cruise propellers:** installation losses become installation gains
- **High-lift propeller system:** maintains low-speed performance for comparable takeoff & landing performance

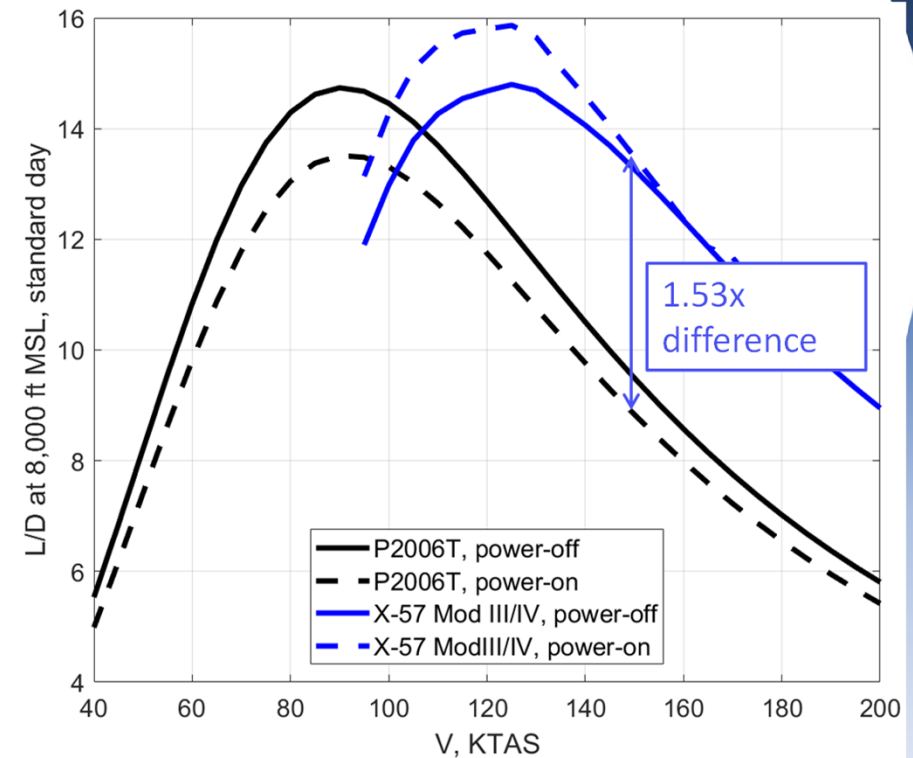


Portfolio of Aero-Propulsive Benefits



- Biggest efficiency improvement due to electrification (30% to 90% efficient – 3.0x)
- High-speed L/D improvement
 - Smaller wing shifts max L/D to higher speeds
 - Wingtip-mounted props turn power-on installation loss into installation gain

Aircraft & Power Setting	L/D (max / 150 KTAS)	Comparison to P2006T (max / 150 KTAS)
P2006T power-off	14.7 / 9.5	--
P2006T power-on	13.5 / 8.8	--
X-57 power-off	14.8 / 13.3	1.00 / 1.40
X-57 power-on	15.9 / 13.5	1.17 / 1.53



(3.0x electric) x (1.53x powered L/D at cruise) ~ 4.6x efficiency improvement



High-Lift Propeller Systems

- X-57 Mod IV includes a DEP system with two wingtip-mounted cruise propellers and 12 high-lift propellers (HLPs) distributed along the leading edge of the wing
- The HLPs are designed only to augment lift at low speeds, and otherwise are turned off and passively fold against their nacelles for high-speed flight
 - Like other high-lift devices, HLPs are an *integral part of the low-speed aircraft configuration*
- The HLPs enable increased aerodynamic efficiency in high-speed flight, without unduly sacrificing low-speed capabilities
- HLPs introduce new considerations for vehicle performance and operation related to “stall speed” and associated safety margins



X-57 Mod IV in Low-Speed (Takeoff/Landing) Configuration

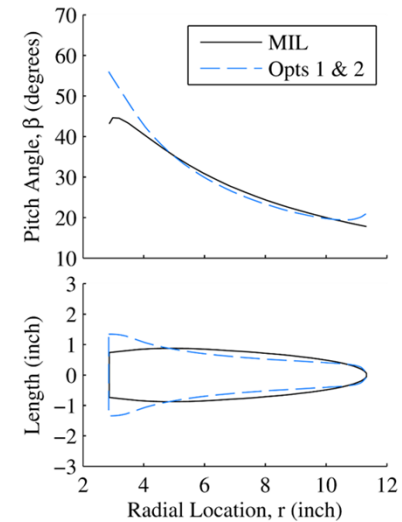
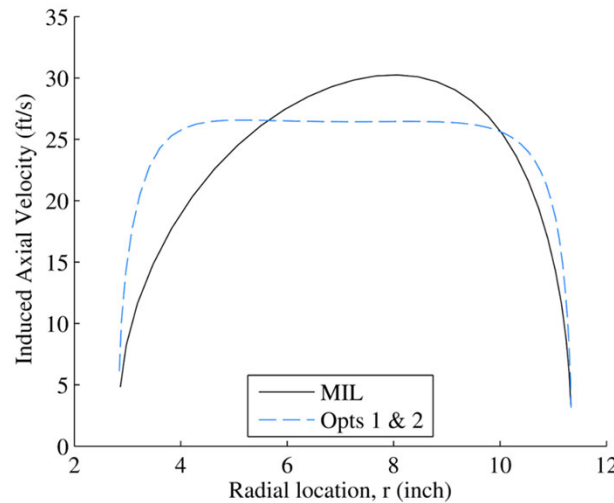


X-57 Mod IV in High-Speed (Cruise) Configuration

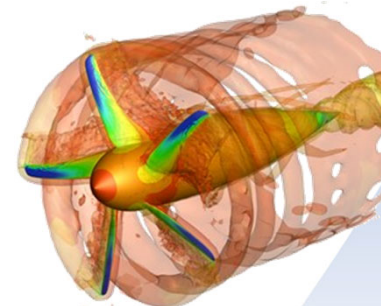
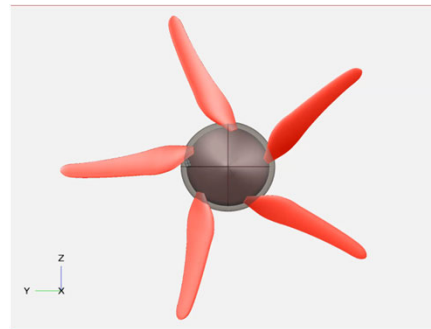


High-Lift Propeller Design

- High-lift propeller blades designed very differently from traditional propellers
 - Uniform velocity profile vs. most efficient thrust velocity profile
 - Rake and skew varied to enable conformal fold to minimum drag position when not in use
 - Low-noise features (blade count, tip speed)
- Operation while landing a driver for number, diameter of propellers
 - More is better (to a point)
- Passive deploy and stow
 - Later testing showed that blade CG position impacted full deployment



Comparison of high-lift propeller profiles vs. traditional (MIL) designs



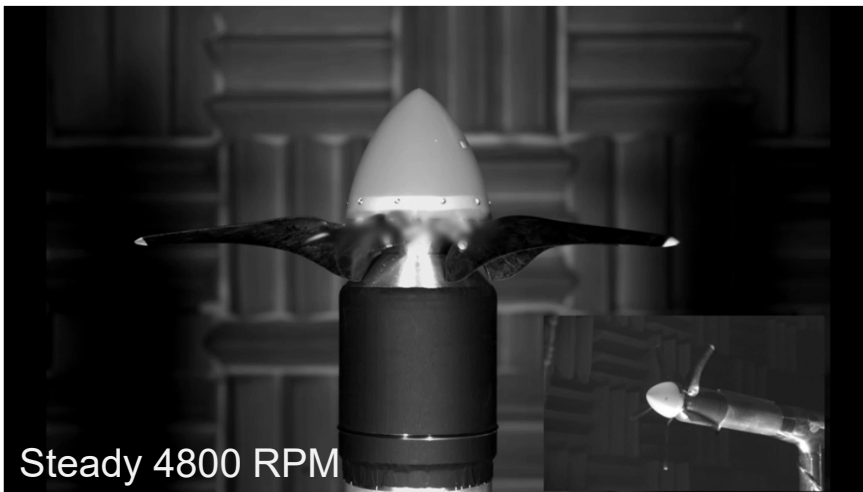
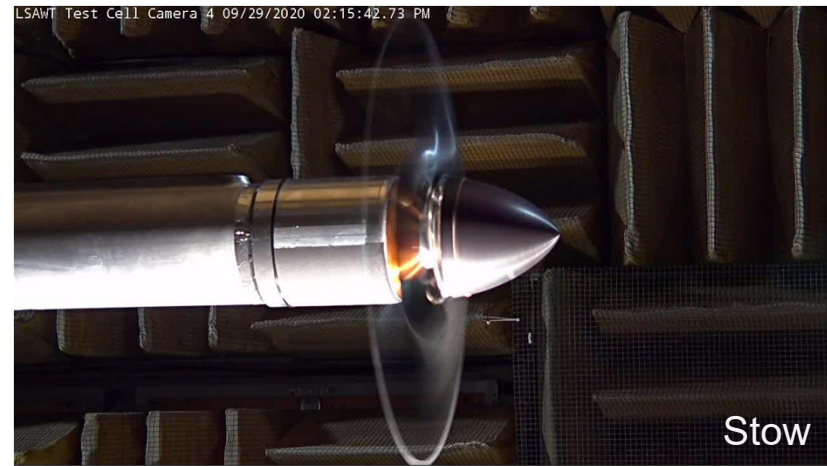
M. D. Patterson, J. M. Derlaga, N. K. Borer, "[High-Lift Propeller System Configuration Selection for NASA's SCEPTOR Distributed Electric Propulsion Flight Demonstrator](#)," AIAA-2016-3922, June 2016

B. L. Litherland, M. D. Patterson, J. M. Derlaga, N. K. Borer, "[A Method for Designing Conformal Propellers](#)," AIAA-2017-3781, June 2017

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Aircraft Performance Considerations for High-Lift Propeller Systems

High-Lift Propeller Operation

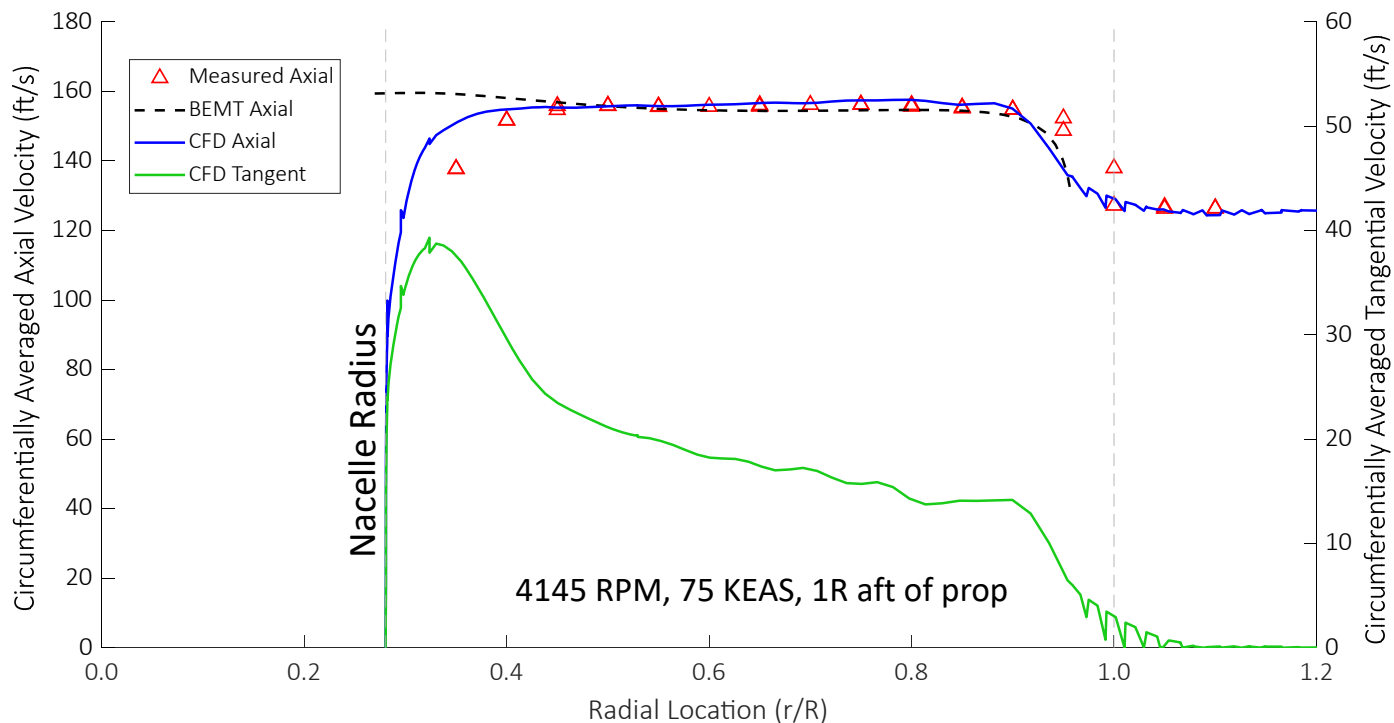


B. L. Litherland, N. K. Borer, N. S. Zawodny, "[X-57 'Maxwell' High-Lift Propeller Testing and Model Development](#)," AIAA-2021-3193, August 2021
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Aircraft Performance Considerations for High-Lift Propeller Systems

Axial Velocity Measurements

- Lift augmentation benefit comes from increased axial velocity behind HLP
 - Low order (BEMT) model captures axial velocity quite well
 - Experiments validate uniform axial velocity profile that is also captured with CFD predictions



4145 RPM, 75 KEAS, 1R aft of prop



B. Litherland, N. Borer, N. Zawodny, Z. Frederick [“X-57 “Maxwell” High-Lift Propeller Test for Improved Thrust Measurements and Slipstream Velocities,”](#)
AIAA, June 2022

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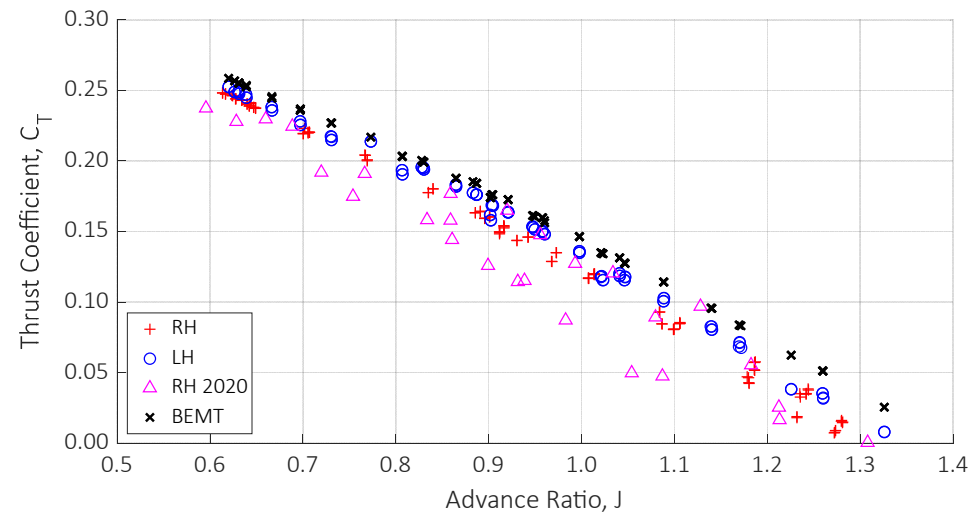
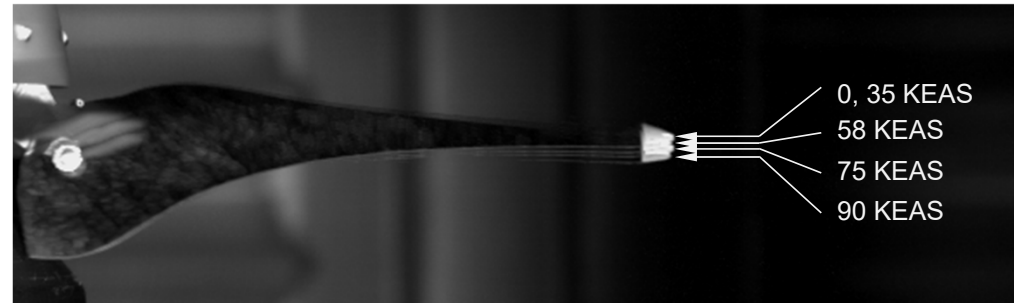
Aircraft Performance Considerations for High-Lift Propeller Systems

Blade Manufacturing Improvements



- 2020 test campaign showed difference between left- and right-hand blade performance
 - Noticed some deflection of blades from high-speed imagery
 - Narrowed down issue to material property differences
 - Imposed blade mass tolerance to 0.025 oz (~1%) for entire family of blades
- 2022 test campaign showed negligible difference in performance with improve mass tolerance
- Closely tracked blade element momentum theory (BEMT) predictions

Digital multiple exposure of high-speed imagery

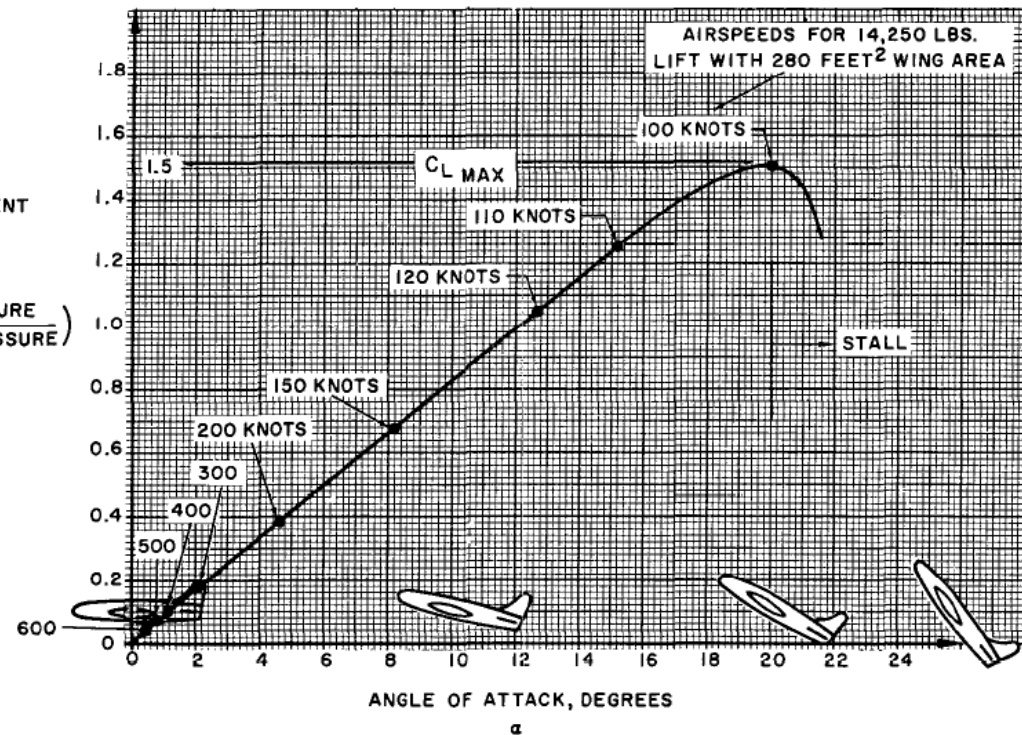


“Stall Speed”



- As a high-lift system, high-lift propellers are intended to be operated at the low-speed end of the flight envelope with a goal to enable operation at lower speeds than would otherwise be possible if they were not used
- The low end of the flight envelope is typically defined by “stall speed”
- Despite its name, “stall speed” from an airworthiness perspective is not necessarily when the wing of the aircraft experiences an aerodynamic stall
 - Aerodynamic stall is typically defined as when the wing has generated the maximum amount of lift possible for a given configuration and flight condition

$$C_L = \frac{\text{LIFT COEFFICIENT}}{\left(\frac{\text{LIFT PRESSURE}}{\text{DYNAMIC PRESSURE}} \right)}$$
$$\frac{L}{qS}$$



“Stall Speed” and Airworthiness



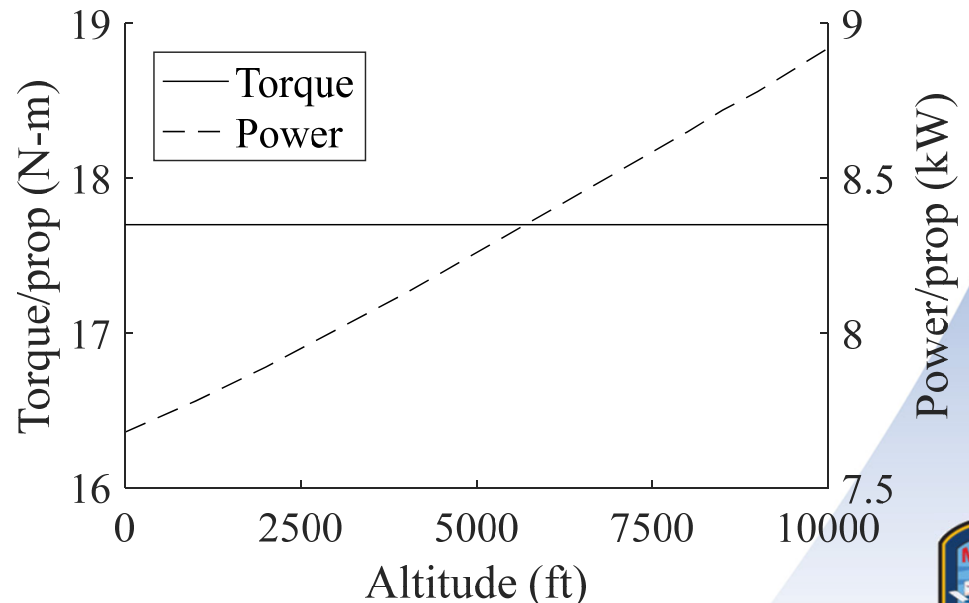
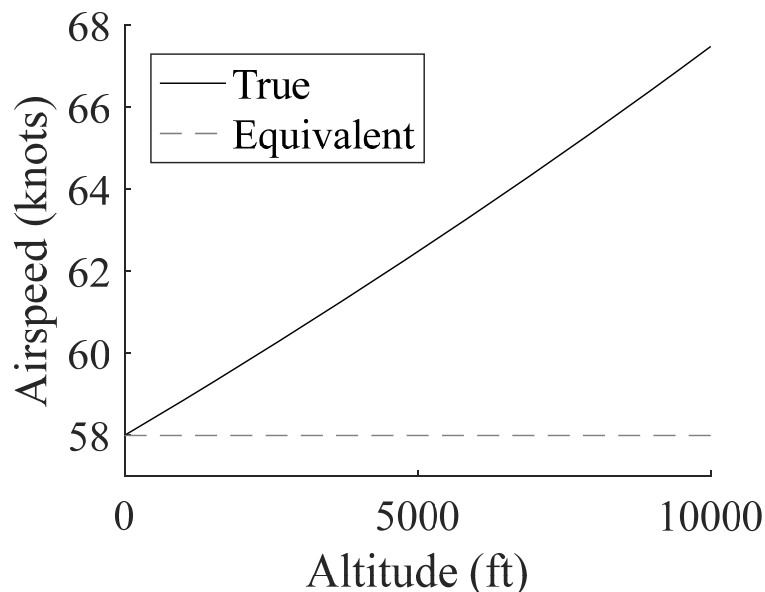
- “Stall speed” in the context of airworthiness refers to V_s , a speed used during design and certification
 - 14 CFR § 23.2110: *The applicant must determine the airplane **stall speed or the minimum steady flight speed** for each flight configuration used in normal operations, including takeoff, climb, cruise, descent, approach, and landing. The stall speed or minimum steady flight speed determination must account for the most adverse conditions for each flight configuration with power set at*
 - (a) *Idle or zero thrust for propulsion systems that are used primarily for thrust; and*
 - (b) *A nominal thrust for propulsion systems that are used for thrust, flight control, and/or high-lift systems*
- Key points for “stall speed”
 - Defined for multiple configurations; e.g. V_s (clean), V_{s1} (specified), V_{s0} (landing)
 - Defined by the most adverse set of nominal conditions; e.g., maximum certified takeoff weight, most forward center of gravity
- For many Part 23 airplanes, “stall speed” is defined by a flight maneuver
 - Formerly § 23.201(b), now ASTM F3180-21 section 4.2.2 used to identify “stall”



Stall Behavior with Airspeed



- X-57's HLPs were designed to maintain traditional stall behavior with airspeed
 - Equivalent airspeed for stall is constant with varying altitude; true airspeed for stall increases with altitude
- Requires constant torque for HLPs
 - Propeller RPM (and therefore power) increases with altitude to maintain this behavior
 - There may be an altitude below the service ceiling where the motor driving the HLPs hits a power limit or the propeller/motor combination hit a speed limit, which sets a ceiling on HLP-augmented ("blown") stall speed



M. D. Patterson, [Conceptual Design of High-Lift Propeller Systems for Small Electric Aircraft](#), Ph.D. thesis, Georgia Institute of Technology, May 2016
M. D. Patterson, N. K. Borer, [Approach Considerations in Aircraft with High-Lift Propeller Systems](#), AIAA-2017-3782, June 2017

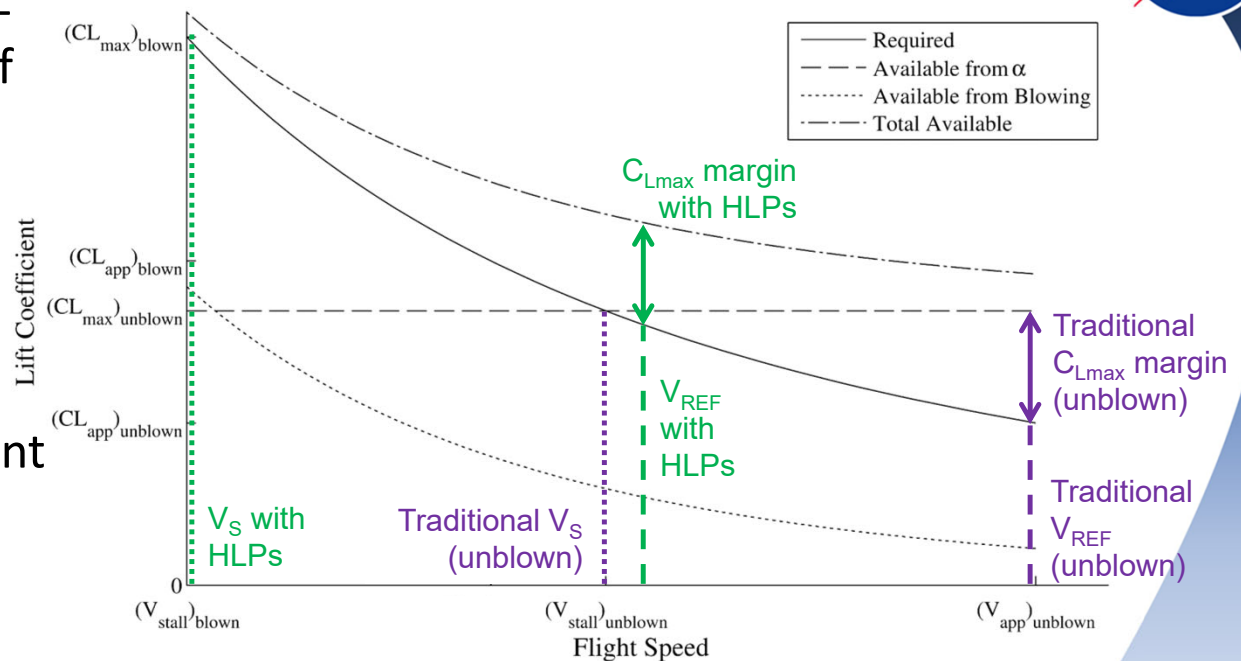
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Aircraft Performance Considerations for High-Lift Propeller Systems

Layered Low-Speed Margin



- Most operational speeds for low-speed performance are based off the “stall speed” (V_s)
 - For example, the reference approach speed (V_{REF}) is typically $1.3V_s$ in the landing configuration for Part 23 airplanes
- This is effectively a margin for operation below the lift coefficient at the stall speed, which is a surrogate for the maximum lift coefficient (C_{Lmax})
 - For traditional aircraft, margin below C_{Lmax} is directly related to margin below the critical angle of attack (α)
 - For aircraft with high-lift propellers, margin can come from blowing and α



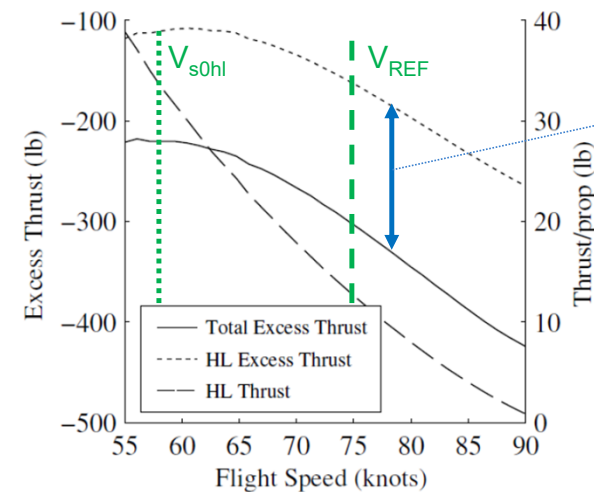
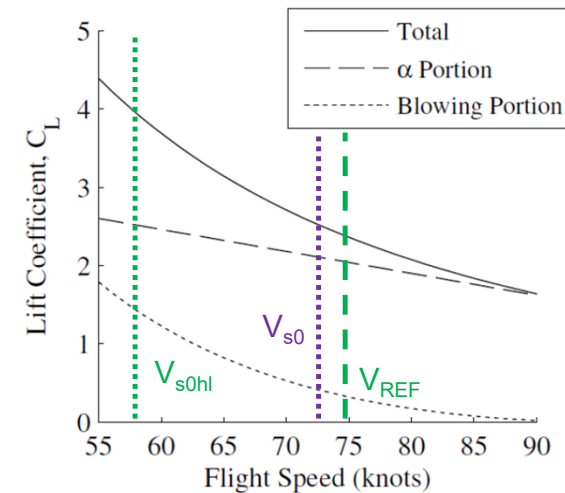
- Two “stall speeds” emerge:
 - V_s : “stall speed” without high-lift propeller operation
 - V_{shl} : “stall speed” with high-lift propeller operation



Approach Considerations



- HLPs augment lift but also produce thrust, which can cause challenges with descent to landing
- Control philosophy based on linear increase in torque as airspeed decreases up to design torque at V_{s0hl}
 - Linear variation in angle of attack margin with decreasing airspeed
 - Largest amount of blowing (and thrust) to speeds occurs at speeds below V_{REF}
- This HLP control approach yields two safety benefits
 - Change in blowing is automatic – significantly faster reaction time for blowing portion of margin, which is greater portion of margin at lower speeds closer to actual stall
 - Excess thrust deficit (which correlates with rate of descent) *decreases* with decreasing airspeed, effectively eliminating the feel of the “backside of the power curve”



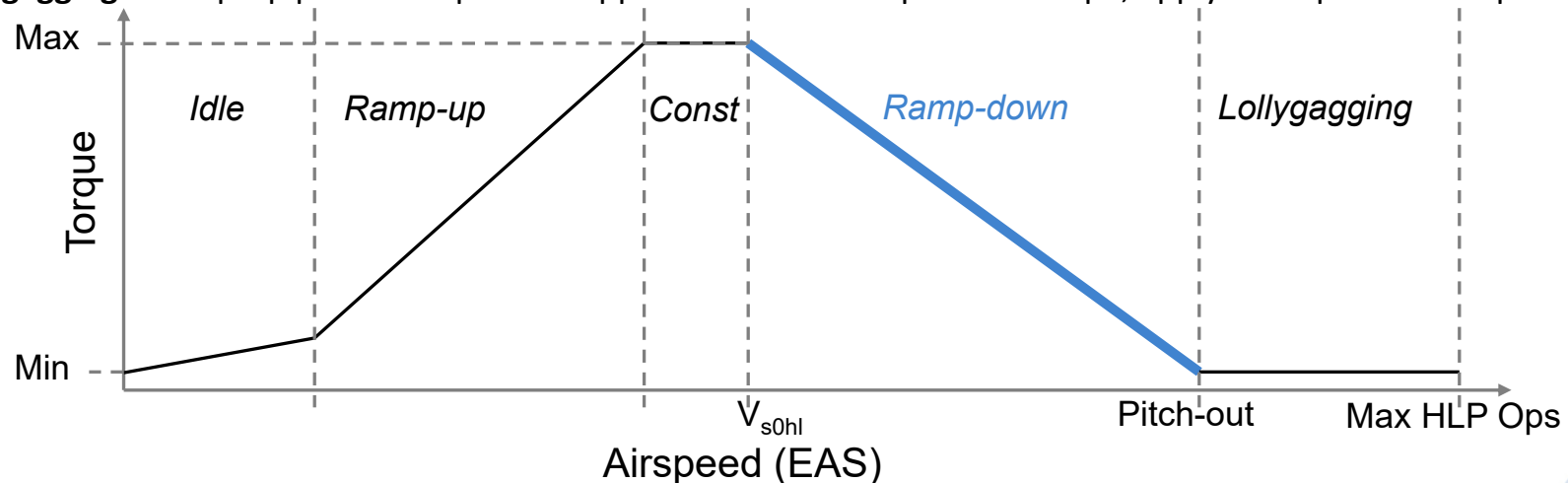
Max cruise propeller windmilling (“regen”) enables glideslope control



HLP Airspeed Control Schedule Philosophy



- Need to consider operations throughout HLP envelope, including takeoff, climb, approach, and landing
- HLP control schedule (*airspeed* mode) generated for X-57 Mod IV flights considers several regions
 - **Idle:** very low airspeed (taxi-like), prefer predictable motor speed
 - **Ramp-up:** still well below flight speeds, increase torque with airspeed (also may help deceleration on landing roll)
 - **Constant:** slightly below V_{s0hl} , apply constant torque (predictable lift augmentation)
 - **Ramp-down:** from V_{s0hl} to prop pitch-out speed, decrease torque with increasing airspeed
 - **Lollygagging:** from prop pitch-out speed to upper bound of HLP speed envelope, apply small positive torque



→ Taxi out → Takeoff roll → Rotation → Initial Climb → Cruise Climb
 ← Taxi in ← Ground Roll ← Touchdown ← Final Approach ← Initial Approach



N. K. Borer, M.D. Patterson, "[X-57 High-Lift Propeller Control Schedule Development](#)," AIAA-2020-3091, June 2020

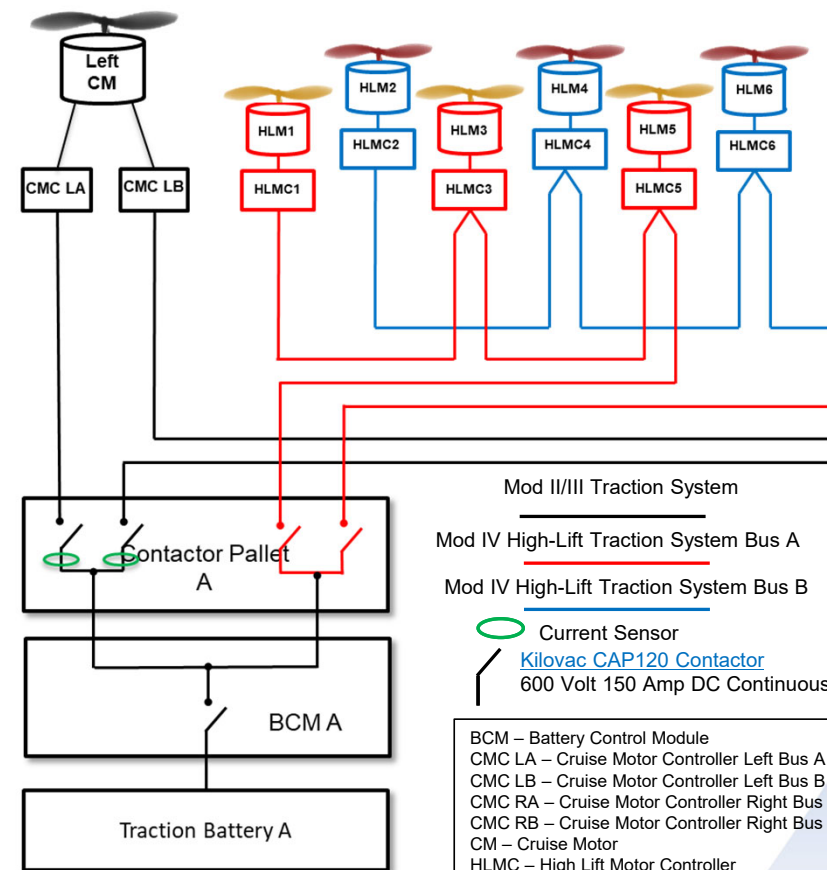
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Other HLP Operation and Control Considerations



- Motor control outer loop
 - Project chose to design high-lift motor inner loop controller for speed rather than torque control Atmospheric variation
- Environment
 - X-57 Environmental Test Plan considers operations over 3σ hot and cold variation of 2013 Edwards Range Reference atmosphere
- Design limits
 - Structural speed limit (5460 RPM)
 - Torque limits (22 Nm maximum motor output, 1 Nm minimum)
- Contingencies
 - Traction power system failures
 - Loss of air data/command signals introduces *fixed* mode (fixed motor speed commands)



Only half of system shown for clarity



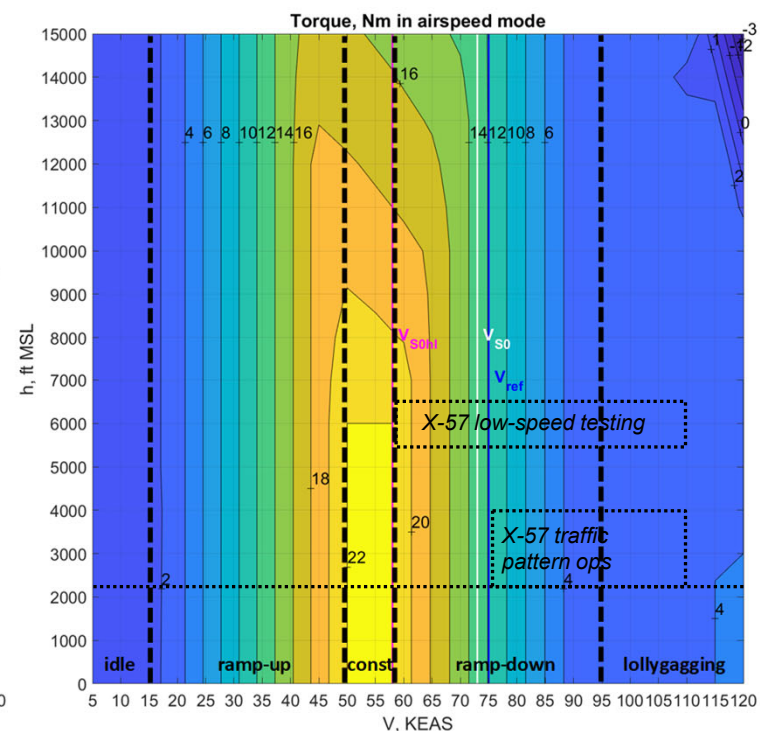
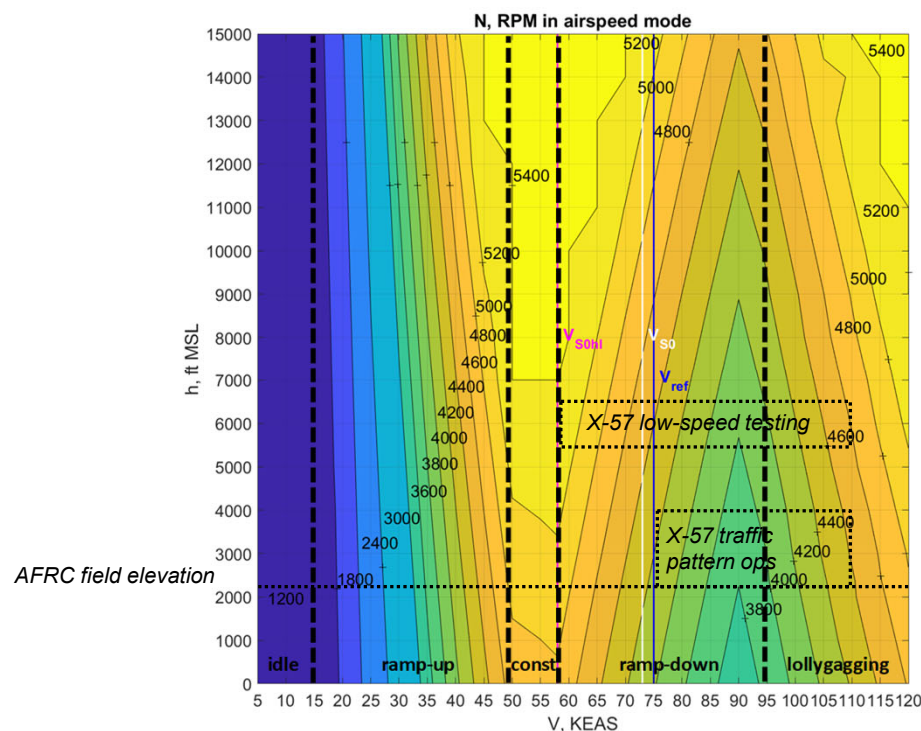
S. Clarke, M. Redifer, K. Papathakis, A. Samuel, T. Foster, "[X-57 Power and Command System Design](#)," IEEE, June 2017
 J. M. Maroli, B. A. Morris, J. A. Blystone, A. M. O'Connor, "[Utilizing Code Generation from Models for Electric Aircraft Motor Controller Flight Software](#)," AIAA-2023-4274, June 2023

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HLP Performance in Airspeed Mode



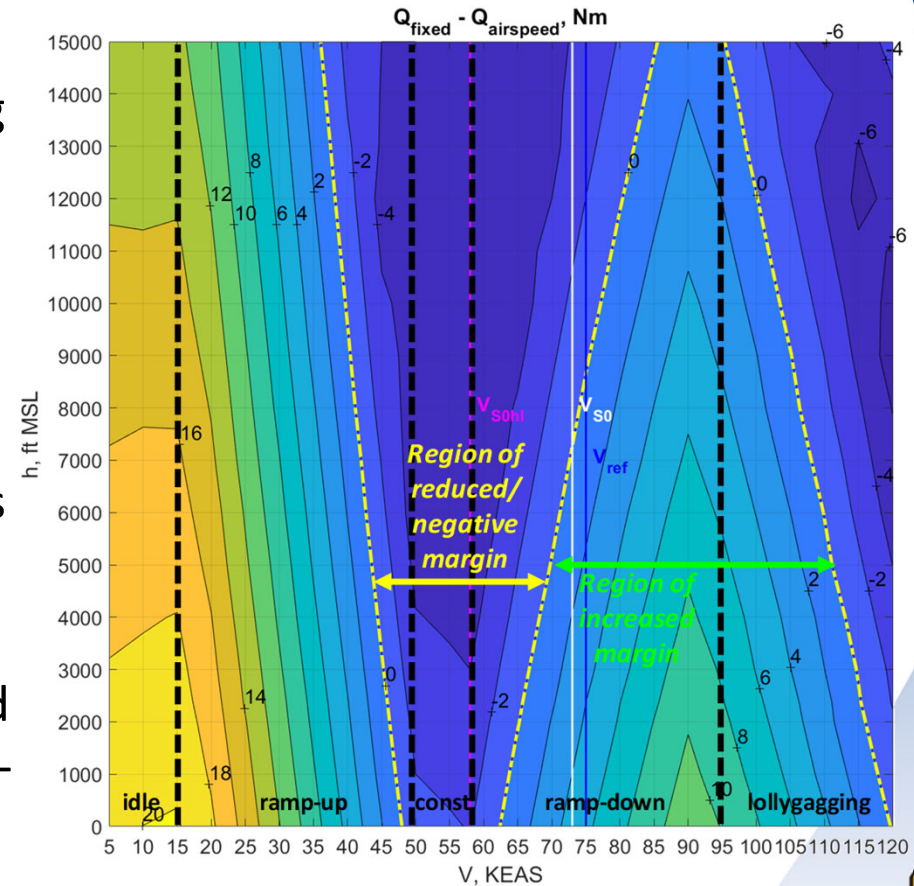
- Resulting HLP rotational speed control schedule for airspeed mode developed for HLP operational envelope from 0-120 KEAS, 0-15,000 ft MSL
- Rotational speed limits set lift augmentation ceiling, hot day set high-air-speed performance





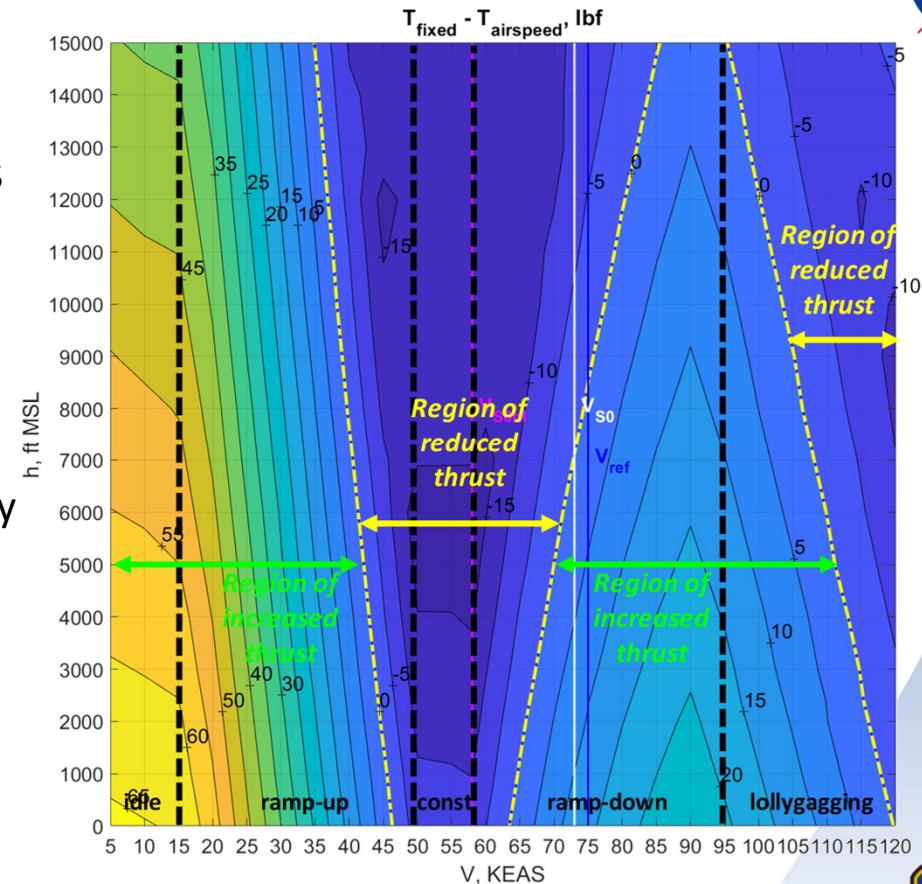
Impact of Sudden Switchover to Fixed Mode

- *Fixed* control mode initially added as a response to a contingency scenario dealing with loss of air data to the high-lift motor controllers – the motors will revert to fixed mode and control to 4800 RPM
- Torque is a surrogate for lift-augmentation capability, so chart on the right shows where how torque in *fixed* mode compares to torque in *airspeed* mode
- Lift augmentation in *fixed* mode at lower altitudes around reference approach speed is greater or equal to than *airspeed* mode – sudden switchovers will not induce a stall or cause loss of control



Other Benefits of Fixed Mode

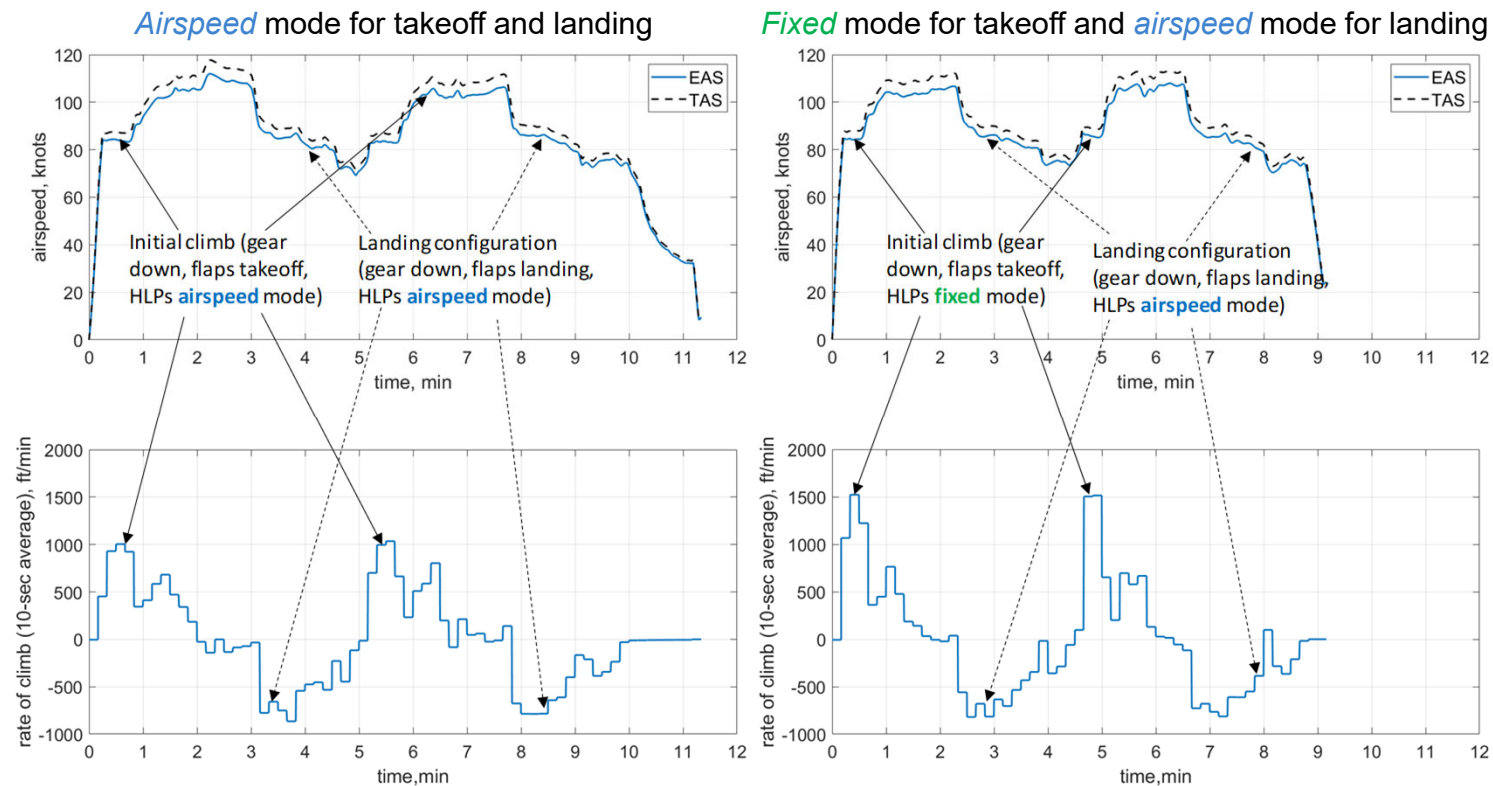
- Operation in *fixed* mode generates increased thrust throughout a significant portion of the HLP operational envelope as compared to *airspeed* mode
- *Fixed* mode operations should increase thrust available over the takeoff run and through initial climb
 - This will come at a reduced propulsive efficiency as compared to the X-57 cruise propellers
- *Fixed* mode also provides a high-power runup check during preflight operations



Comparison of Takeoff and Landing Performance



- Conducted takeoff and landing maneuvers in the X-57 piloted simulator to evaluate benefits of *airspeed* vs. *fixed* mode takeoffs
- Fixed mode takeoffs provided significant boost in climb performance



Key Takeaways



- HLPs are an integral part of an (equipped) aircraft's low-speed configuration
 - They define a “stall speed” for a configuration – they are used in normal operation
- HLPs are not designed like traditional propellers
 - Uniform axial velocity for robust angle of attack variation with airspeed
 - Passive folding approach introduces performance tradeoffs but reduces complexity
 - Thrust is a liability for approach but a benefit for takeoff – number and size is a key tradeoff, but must be able to control glideslope at reference approach speed
- HLPs enable additional degree of freedom for margin over stall – angle of attack *and* blowing
 - X-57 linear torque control approach to HLPs enables descent control while preserving safety benefits of closed-loop control and potential for greatly reduced sink rate near stall, speed-stable approach corridor
- HLPs introduce potential for ceiling for stall speed with increasing altitude
 - Power and propeller speed for a given lift increment (set by torque) increases with altitude
- Fixed control mode, introduced in X-57 for contingency reasons, offers benefits in nominal operations for takeoff



(Some) Publications Related to High-Lift Propellers



- M. D. Moore et al., "[High-Speed Mobility through On-Demand Aviation](#)," AIAA-2013-4373, August 2013
- M. D. Patterson, M. J. Daskilewicz, B. J. German, "[Conceptual Design of Electric Aircraft with Distributed Propellers: Multidisciplinary Analysis Needs and Aerodynamic Modeling Development](#)," AIAA-2014-0534, January 2014
- A. M. Stoll et al., "[Drag Reduction through Distributed Electric Propulsion](#)," AIAA- 2014-2851, June 2014
- N. K. Borer, M. D. Moore, A. R. Turnbull, "[Tradespace Exploration of Distributed Propulsors for Advanced On-Demand Mobility Concepts](#)," AIAA-2014-2850, June 2014
- M. D. Patterson, B. J. German, "Wing Aerodynamic Analysis Incorporating One-Way Interaction with Distributed Propellers," AIAA-2014-2852, June 2014
- N. K. Borer, M. D. Moore, "[Integrated Propeller-Wing Design Exploration for Distributed Propulsion Concepts](#)," AIAA-2015-1672, January 2015
- M. D. Patterson, M. J. Daskilewicz, B. J. German, "Simplified Aerodynamics Models to Predict the Effects of Upstream Propellers on Wing Lift," AIAA-2015-1673, January 2015
- M. Patterson, N. Borer, B. German, "[A Simple Method for High-Lift Propeller Conceptual Design](#)," AIAA 2016-0770, January 2016
- M. D. Patterson, "[Conceptual Design of High-Lift Propeller Systems for Small Electric Aircraft](#)," Ph.D. thesis, Georgia Institute of Technology, May 2016
- N. K. Borer et al., "[Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator](#)," AIAA-2016-3920, June 2016
- M. D. Patterson, J. M. Derlaga, N. K. Borer, "[High-Lift Propeller System Configuration Selection for NASA's SCEPTOR Distributed Electric Propulsion Flight Demonstrator](#)," AIAA-2016-3922, June 2016
- N. K. Borer et al., "[Comparison of Aero-Propulsive Predictions for Distributed Propulsion Configurations](#)," AIAA-2017-0209, January 2017
- B. L. Litherland, M. D. Patterson, J. M. Derlaga, N. K. Borer, "[A Method for Designing Conformal Propellers](#)," AIAA-2017-3781, June 2017
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- X. Fei, B. J. German, M. D. Patterson, "[Exploring the Effects of Installation Geometry in High-Lift Propeller Systems](#)," AIAA 2018-0277, January 2018.
- B. L. Litherland, J. M. Derlaga, "[A Performance Analysis of Folding Conformal Propeller Blade Designs](#)," AIAA-2019-3676, June 2019
- N. K. Borer, M.D. Patterson, "[X-57 High-Lift Propeller Control Schedule Development](#)," AIAA-2020-3091, June 2020
- B. L. Litherland, N. K. Borer, N. S. Zawodny, "[X-57 "Maxwell" High-Lift Propeller Testing and Model Development](#)," AIAA-2021-3193, August 2021
- B. Litherland, N. Borer, N. Zawodny, Z. Frederick "[X-57 "Maxwell" High-Lift Propeller Test for Improved Thrust Measurements and Slipstream Velocities](#)," AIAA, June 2022



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 - Transformational Aeronautics Concepts Program/Convergent Aeronautics Solutions Project



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