X-57 High-Lift Propeller Control Schedule Development

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The NASA X-57 distributed electric propulsion flight demonstrator uses a high-lift propeller system to maintain low-speed capability with a highly loaded, cruise-efficient wing. Previous research showed that the control scheme for the high-lift propellers was a crucial factor to enable an adequate balance between stabilized glideslope control and appropriate lift margin during the approach-to-landing phase of flight. This paper expands the high-lift propeller control considerations to include all phases of low-speed flight, including preflight, taxi, takeoff, initial climb, approach, and landing. Two control modes, termed *airspeed* and *fixed* mode, are developed in this paper. The *airspeed* mode varies propeller torque based on equivalent airspeed to account for different phases of ground and flight operations. The *fixed* mode operates the high-lift propeller system at a fixed rotational speed to account for failures in the air data system, preflight checkout, and high-performance takeoff operations. Modeling of the high-lift propellers within the X-57 low-speed flight envelope shows that (1) the structural rotational speed limit of the propeller blades limits their effectiveness at higher altitudes and airspeeds, (2) the speed setting of the *fixed* mode is set by the maximum torque of the *airspeed* mode, and (3) minimizing the potential for windmilling in non-standard conditions sets the torque schedule at higher speeds. Additionally, the *fixed* mode is shown to provide an increased climb rate during normal takeoff operations.

I. Nomenclature

BEMT	=	blade element momentum theory
C_P	=	propeller power coefficient
C_Q	=	propeller torque coefficient
C_T	=	propeller thrust coefficient
DEP	=	distributed electric propulsion
ERRA	=	2013 Edwards Range Reference Atmosphere
J	=	propeller advance ratio
KEAS	=	knots equivalent airspeed
g	=	acceleration due to gravity
h	=	altitude
HLP	=	high-lift propeller
MSL	=	mean sea level
N	=	propeller rotational speed
Q	=	torque
RPM	=	revolutions per minute
std	=	1976 U.S. Standard Atmosphere
V_{ref}	=	reference landing approach speed
V_{S0}	=	minimum steady flight speed in the landing configuration
V_{S0hl}	=	minimum steady flight speed in the landing configuration with high-lift propeller system active
η	=	propeller efficiency
σ	=	standard deviation of a normal distribution

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II. Introduction

NASA's X-57 "Maxwell" is a flight demonstrator for distributed electric propulsion (DEP) technology. This technology can dramatically reduce the energy required for flight through substantial increases in aerodynamic and propulsive efficiency. DEP results from the confluence of *distributed propulsion* (the integration of propulsive devices strategically placed about the airframe to yield system-level benefits), and *electric propulsion* (the use of electric machines to drive propulsive devices). The X-57 is demonstrating this technology through successive retrofits, called "Mods" (short for "modifications") [1]. The sequence of these "Mods" are shown in Fig. 1, which shows the evolution of the aircraft from a general aviation baseline in Mod I to a fully distributed-electric flight demonstrator in Mod IV.

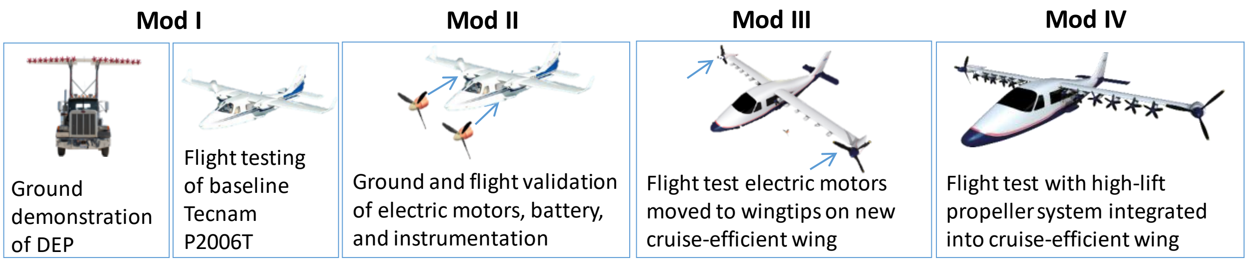


Fig. 1 X-57 development through multiple "Mods" [1].

The X-57 Mod IV configuration employs multiple forms of DEP to yield a substantial increase in cruise efficiency without sacrificing low-speed flight capability [1]. The two types of DEP on X-57 Mod IV are wingtip-mounted cruise propellers that are operated throughout the flight envelope and 12 smaller high-lift propellers (HLPs) and motors that are only operated in low-speed flight. A rendering of the X-57 Mod IV configuration with the 12 HLPs deployed is shown in Fig. 2.

Fig. 2 A rendering of X-57 Mod IV with high-lift propellers deployed.

The HLPs are one of the unique, enabling features of the X-57's increased aerodynamic efficiency. The wing of the original production airplane, a Tecnam P2006T [2], is lightly loaded (~17 lb/ft^2) to enable low minimum flight speeds that are typical of this class of aircraft. The X-57 is retrofitted with a more highly loaded wing (~45 lb/ft^2) in the Mod III and IV configurations, which yields much higher aerodynamic efficiency at the target cruising speed of 130+ knots. However, the flap system for the X-57 Mod III wing [3] does not recover the low-speed capability of the original aircraft wing and flap system of the Tecnam P2006T or the X-57 Mod II configuration. The HLPs of the X-57 Mod IV configuration are designed to increase the dynamic pressure over the majority of the wing when the aircraft is operated at low speeds, resulting in the capability to produce more lift in this low-speed region. This enables the X-57 with the highly loaded Mod III/IV wing planform to recover the low-speed flight capabilities of the original, lightly loaded Mod II wing planform. Hence, X-57 Mod IV can fly at speeds as low as the original production aircraft, enabling good takeoff and landing performance, but using far less energy in cruise flight, which is where the aircraft spends most of its time in a nominal mission.

Although the HLPs primarily enhance lift at low speeds, they also provide thrust while operating. This thrust can enhance takeoff performance, leading to shorter ground rolls and increased initial climb rates; however, this thrust can be a challenge during the final approach and landing segments. When on final approach to land, the goal is generally to have a stabilized approach in which the aircraft descends at a constant airspeed. Typically, this airspeed is quite low, with a small but sufficient margin above the stall speed in the landing configuration to deal with changes in environmental conditions (e.g., winds) and pilot technique. Throughout the approach segment, the propulsive thrust is generally quite low to maintain the desired descent glideslope and low airspeed. The addition of thrust from the HLPs, which can be substantial at low speeds, may conflict with the desire to descend at a low airspeed.

The design of the X-57 HLP system considered the potential conflict of HLP thrust with the ability to descend in the landing configuration. This included the general arrangement and number of HLPs [4], as well as the variation in HLP control during the approach airspeed corridor [5]. As the design of the X-57 has progressed, additional factors have been brought to light regarding desired control parameters, response to off-nominal situations, and ground operations. This paper describes the method used to build the control philosophy that will govern X-57 HLP operations in consideration of these additional factors.

III. Background

The design of the X-57 HLP system, which includes the HLPs and associated power and command systems, has evolved over the life of the project. Much of the work in this paper is developed from insights and models created by the X-57 project and related research over the years. This section summarizes some of the unique design, performance, and aircraft system-level implications of the HLP system planned for use on X-57 Mod IV.

A. High-Lift Propeller Design

The chief intent of the X-57 HLP system is to maintain the original, weight-adjusted power-off stall* speed in the landing configuration, denoted as V_{S0}, of the baseline Tecnam P2006T aircraft [1]. At the X-57's estimated weight of 3,000 pounds, the original Tecnam P2006T has an estimated V_{S0} of 58 knots equivalent airspeed (KEAS). The X-57 Mod IV has an estimated V_{S0} (without HLPs running) of 73 KEAS, owing to the much higher wing loading of the cruise-efficient wing. Hence, the targeted stall speed with the HLP system active, denoted as V_{S0hl}, is 58 KEAS. The lift coefficient associated with this V_{S0hl} at 1g is 3.95, referenced to the X-57's reference wing area of 66.67 ft^2.

The interaction of the HLPs with the X-57's wing creates a fairly complex flowfield that may not be adequately captured by the design tools used for the initial design of the HLP system. As such, the system was initially designed to produce 10% more lift than required at V_{S0hl}. In addition, otherwise marginally beneficial effects of operating propellers at elevated angles of attack were deliberately neglected, such as the component of thrust from the HLPs that operates in the lift direction (e.g., thrust vectoring), or the normal force component of the propeller. The resulting design goal was a maximum wing lift coefficient† of 4.35 at V_{S0hl} [6].

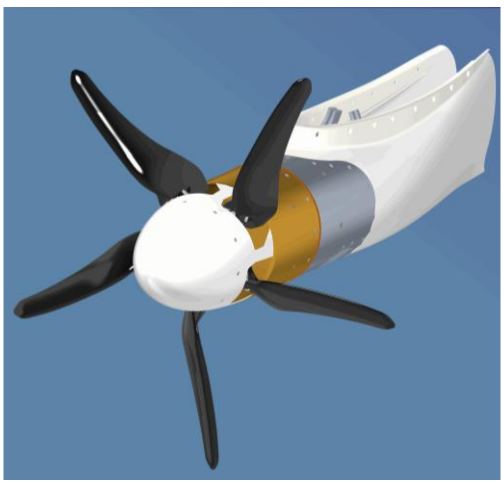
Legacy decisions from NASA's LEAPTech experiment [7] influenced the design of the X-57 HLPs. The propeller rotational‡ tip speed was constrained to 450 ft/s during the initial design cycles [8][9]. This tip speed is about half that of modern high-performance propellers during takeoff, which introduces the potential for a dramatic reduction in noise. The design studies considered only 3- and 5-bladed propellers based on the heuristic that an odd number of blades reduces acoustic signature when operating in front of a wing. The MH114 airfoil [10] of the LEAPTech propellers was retained for the X-57 HLPs, largely based on the original LEAPTech success with integrating these airfoils into a conformal folding design [11].

The HLPs are designed as fixed-pitch propellers, given the expected complexity and mass penalty of integrating blade pitch actuation into the assembly. Furthermore, the HLPs only need to operate at low speeds, and propeller pitch actuation is generally preferred when operating over wide speed ranges. The propellers were designed to avoid significant stalling of the blades above 30 KEAS and provide some lift augmentation up to at least 90 KEAS [12], with the design point from a lift augmentation perspective occurring at the V_{S0hl} target of 58 KEAS. Subject to these considerations, the chord and twist distribution of the HLP system were selected to provide a near-uniform axial velocity profile aft of the propeller disc. The main advantage of such a profile is a predictable variation on local angle of attack on the wing behind the HLPs as the angle of attack of the main aircraft is varied [13].

* "Stall speed" is used throughout this paper, though it refers to the minimum demonstrated steady flight speed. The X-57 flight research program does not currently include investigation of the aircraft's stall characteristics.
† This lift coefficient is referenced to the aircraft speed, V_{S0hl}, not the accelerated flow downstream of the HLPs.
‡ The term "rotational tip speed" here simply refers to the speed of the propeller tips in static conditions and is used to differentiate from helical tip speed that also takes into account the forward velocity of the vehicle.

The diameter of the HLPs was determined by attempting to minimize the power required for lift augmentation while still ensuring that the thrust generated by the HLPs did not conflict with the ability to capture an appropriate glideslope during the approach-to-landing phase of flight. Smaller diameter propellers distributed upstream of the leading edge of the wing are generally favored due to the lower thrust produced for the same axial velocity increase over the wing. However, if the propeller size is decreased too substantially, the lift augmentation provided for a given increase in axial velocity behind the HLP disc generally decreases. Consequently, if HLPs are too small, not only is additional power required to create the desired lift augmentation, but also the thrust produced from the smaller diameter propellers can increase. Therefore, the design of the HLP system must strike a balance between the power required and thrust produced to generate the desired lift augmentation while allowing the aircraft to still descend along a reasonable approach profile [4][5][12].

To reduce drag, the X-57 HLP blades are designed to fold and conform to their respective nacelle when not in use. The folding mechanism is designed for simplicity; it uses a single, lightly-spring-loaded hinge point for passive operation. The blades deploy due to centrifugal force at a few hundred RPM. To generate conformal-folding designs, the blade rake and skew (which are roughly analogous to wing dihedral and sweep, respectively) are varied along the blade radius [14]. The low tip speed of the HLPs introduces another benefit that proved crucial to the design of the folding blades of the HLPs: the ability to change the rake and skew of the blade with very little performance penalty [15]. A summary of the salient design characteristics of the X-57 propeller is given in Fig. 3. The detailed HLP blade profiles can be extracted from the X-57 Common Reference Model [16].



- 5 blades, 1.89 ft (0.576m) Diameter
- 91.1 Activity Factor
- Design Condition
  - Sea Level, 1976 US Standard Atmosphere
  - 58.0 KEAS (23.9 m/s) Freestream Velocity
- Performance @ Design Condition
  - 4550 RPM @ 450 ft/s (137 m/s) tip speed
  - 14.3 hp (10.7 kW) Shaft Power
  - 16.2 ft-lb (22.0 N-m) Shaft Torque
  - 48.2 lbf (215 N) Gross Thrust
  - 1.11 Integrated Lift Coefficient

Fig. 3 Summary of X-57 high-lift propeller characteristics.[§]

The single-hinge-point design of the HLP has one major drawback: the local blade pitch angle changes as a function of the deployment angle of the blade. Given that the blades are passively actuated, the centrifugal force dominates the operational deployment angle of the propeller. The current blade design neglected this effect (given that the actuation mechanism was designed well after the propeller design studies). Current analyses indicate that the center of mass of the current blade design will not allow the blades to deploy to a disc fully normal to the propeller axis of rotation; rather, the blades are anticipated to deploy to approximately an 80° angle from the axis of rotation. Although this has a negligible effect on the effective propeller disc diameter, it reduces the net blade pitch by approximately 2.5°to 4.5°, depending on radial location. Preliminary analysis indicates that the lift augmentation goals of the X-57 can be met with this configuration by operating the propellers slightly faster than the original 450 ft/s tip speed design intent, which will be confirmed through more detailed analysis and testing. The performance models used to generate the results in this paper account for the current best estimate of this effect, which indicate a ~400 RPM increase in rotational speed at the design point is necessary as compared to the rotational speed shown in Fig. 3. The power absorbed by the propeller increases as well, given the desire to maintain the torque at this higher rotational speed.

[§] The astute reader will note the mix of U.S. Customary and SI units in this paper, with some preferences given to U.S Customary units (e.g., thrust in lbf, velocity in KEAS, altitude in ft), and some to SI (e.g., torque in Nm). This is related to a project decision that keeps electric-motor-related units in SI, which include motor power and torque, but otherwise prefer U.S. Customary units. Whenever convenient, units are provided in both forms in this paper.

B. High-Lift Propeller Performance

Typical aircraft will stall at a constant equivalent airspeed in a given high-lift configuration, load factor, and aircraft weight, regardless of altitude.** We previously showed in Reference [5] that fixed-pitch HLPs should be operated at a constant torque to maintain a constant V_{S0hl} regardless of altitude. Since the advance ratio of the propeller blade depends on true airspeed (rather than equivalent airspeed), the rotational speed of a fixed-pitch HLP must increase with altitude at a constant equivalent airspeed in order to absorb a constant torque. Hence, operation at a fixed equivalent airspeed and torque requires more power as altitude increases. There are, consequently, two practical limits to HLP performance at altitude: the maximum rotational speed of the propeller and the maximum power output capability of the aircraft electrical system. The structural loads of the X-57 HLP blades and retention assembly limit HLP operation to a maximum of 5460 RPM. This rotational speed limitation determines the altitude ceiling for full HLP lift augmentation.†† The power distribution limits are more complex, as the electrical power required is dependent on the high-lift motor and X-57 power distribution system efficiency. Generally, altitude limits associated with electrical power distribution are set by the maximum current draw in the power electronics at the lowest expected voltage. In the latest X-57 design, the HLP structural limit is the active constraint, albeit not by much.

Performance at speeds other than V_{S0hl} must be managed as well, since normal flight operations are conducted at higher speeds. The certification basis of the Tecnam P2006T in the United States includes the provisions for Airworthiness Standards for Normal Category Airplane in Title 14 of the Code of Federal Regulations (CFR), section 23 (14 CFR §23) through Amendment 57.‡‡ This includes 14 CFR §23.73, which defines the reference landing approach speed, denoted by V_{ref}, as no less than 1.3 times the stalling speed with the wing flaps in the landing configuration. If this same philosophy is applied to approach operations in the X-57 with the flaps extended to the approach position and the HLP system active, the X-57 must be able to maintain a traditional glideslope at V_{ref} without accelerating due to the residual thrust of the high-lift propellers. We previously evaluated multiple control schemes for the HLP system to determine a method that would allow for predictable glideslope control while providing adequate lift margin in the approach corridor. We found that these characteristics were attainable with a scheme that, as the aircraft decelerates, linearly increases torque from near-zero at a specified higher airspeed to full torque at V_{S0hl} [5]. If the higher-airspeed zero-point torque is chosen to be near the typical flap deployment speeds, there is the added benefit of keeping the propeller rotational speed low at higher airspeed, which helps prevent the HLPs from violating any structural rotational speed limits. One consequence of this control philosophy is that it requires the HLP control system to have knowledge of the current equivalent airspeed, which introduces additional failure modes associated with loss of airspeed data.

Given the potential for HLP thrust to conflict with the ability to control glideslope during approach, our previous research was largely focused on development of a control philosophy in the approach corridor that allowed for glideslope control while maintaining adequate margin over V_{S0hl} to account for atmospheric variation (e.g., low-level wind shear) and pilot control technique. Solving this problem seemingly would also solve the problems associated with adequate lift generation during takeoff post-rotation, but does not account well for operations after landing touchdown or on ground roll prior to takeoff. It also does not take advantage of the large thrust generation capability offered by the HLPs for high-performance takeoffs. These items are addressed in subsequent sections of this paper.

C. Aircraft System Architecture

The X-57's power and command system architecture encompasses the energy storage, distribution, power generation, and data/control management functions. The power and command system includes a high-voltage "traction" system to provide power for the propulsion systems (analogous to a fuel system in a combustion-powered aircraft); a low-voltage "avionics" system to provide power for the control, communication, and instrumentation systems; and a number of data networks to provide communication. The reader is referred to the work of Clarke et al. [17] or the numerous presentations and design reviews on the X-57 Technical Papers site [18]§§ for more information.

** "Altitude" here and generally elsewhere in this paper refers to the properties of the 1976 US Standard Atmosphere in the troposphere. Hence, increasing altitude results in decreased air density.

†† In other HLP implementations, acoustic or compressibility effects may also be present, but these are less of a problem due to the low helical propeller tip speeds in the X-57 operational envelope.

‡‡ In August 2017, the United States significantly changed the airworthiness rules for Normal Category Airplanes with the introduction of 14 CFR §23 Amendment 64, which renumbered the rules and moved a number of airworthiness standards to consensus standards. The content of the currently accepted practice for reference approach speeds has been moved to ASTM International Standard F3179/F3179M, Standard Specification for Performance of Aircraft, but the guidance for V_{ref} remains essentially the same as quoted in this paper.

§§ This website is updated frequently and includes many of the non-copyrighted references cited in this paper.

Certified aircraft generally require the ability to completely isolate a failure in the thrust generation, power generation, energy storage/distribution systems, and associated control components, such that a single failure anywhere in these systems cannot cause more than one propulsion unit to go offline. For example, multi-engine aircraft need to have at least as many fuel tanks as engines, as well as the ability to isolate these fuel tanks. However, these requirements for complete isolation of failures is based on assumptions of there being only a small number of conventional combustion engines on the aircraft, and, because aircraft using DEP technology violate these assumptions, the requirement for complete isolation of all single failures in DEP architectures must be reconsidered.

The X-57's power and command system architecture is designed to provide marginal, but not necessarily full performance capability in the event of any single failure. This is a similar philosophy to the baseline Tecnam P2006T, since, as a two-engine airplane, it can provide marginal performance due to any single failure in the propulsion-related systems by flying on one engine. The highly distributed nature of the X-57 propulsion system enables generally more favorable performance following a single failure than the conventional twin-engine baseline. For example, loss of one of the two independent traction battery systems results in a symmetric loss of power to six of the 12 HLPs and a loss of half available power to the two wingtip-mounted cruise motors. Although a failure of one battery system does also result in a potential loss of lift due to the symmetric loss of half of the HLPs, the flight speeds for normal operation are selected such that this failure will not result in a sudden, inadvertent stall.

One exception to this one-fault-tolerant design philosophy is the air data system. The air data probe, seen pointing prominently out of the nose of the aircraft in the rendering in Fig. 2, is designed to provide high-quality air data to the onboard instrumentation system. It is located well ahead of the nose of the aircraft to minimize the impact of the operation of the HLP system or other configuration changes on the accuracy of the air data. The stock air data system on the P2006T fuselage is not able to provide the same level of quality, particularly given the potential influence of the HLPs on the flowfield near the stock system's static port on the aircraft fuselage. As noted in the previous subsection, the control philosophy of the HLP system during approach to landing includes a variation of HLP torque with equivalent airspeed, which would normally require that the air data system could provide data in a fault-tolerant fashion. Given that this is not meant to be a certified aircraft, the project chose to not install a fully fault-tolerant air data system, but rather develop an approach to check the air data system for errors and enact a reversionary control mode if the air data is found to be faulty. The reversionary mode is described later in this paper.

D. Reference Atmosphere

The X-57 program is presently only considering flights within the Dryden Aeronautical Test Range co-located with NASA Armstrong Flight Research Center and Edwards Air Force Base in Edwards, California. However, the DEP technology tested on X-57 is meant to be generalizable to aircraft that may perform anywhere in the world; so, the project philosophy has been to use the 1976 U.S. Standard Atmosphere [19] during creation of design data for publication. The X-57 Environmental Test Plan considers the atmospheric environment in Edwards, including the 1983 Edwards Range Reference Atmosphere (ERRA) [20] and a more recent 2013 update [21]. While the designs are generally presented per the 1976 U.S. Standard Atmosphere, some of the control modes discussed in this paper are impacted by the project requirement to operate in the 3σ temperature range of the 2013 ERRA. In particular, some of the high-speed, low-torque operating control schedule adjustments discussed in this paper are determined based on hot-day performance in Edwards.

IV. Control Schedule Development

An HLP control schedule is necessary to ensure adequate, controllable, and predictable performance throughout the appropriate portions of the X-57 Mod IV operational envelope. Like other high-lift devices, the X-57 HLP system is designed to operate within a speed and altitude range that is a subset of the entire operational envelope of the aircraft. Even with operational restrictions, a control schedule and associated control modes are necessary to enable typical and off-nominal operations with the HLP system active.

The high-lift motor controllers for the X-57 have an inner control loop that governs motor speed.[***] The controller is assigned a motor speed target and adjusts the motor torque (subject to various error checks and limitations) to achieve the target speed. Primarily because of this inner control loop, which is specifically designed to govern motor

[***] This is partially an artifact of the fixed-pitch high-lift propellers, since the propellers cannot be used to independently govern motor speed. Conversely, the X-57 cruise motor controllers command torque (as input by the pilot "throttle" levers), and motor speed is governed by the controllable-pitch cruise propellers (as input by the pilot "propeller" levers). The cruise motor controllers monitor motor speed to ensure that no torque command can be issued that would result in a significant overspeed event, but otherwise do not directly govern motor speed.

speed, the X-57 Power and Command team prefers rotational speed control schedules for the high-lift propellers. An outer-loop motor controller, which includes a pilot-initiated control mode selection, determines the motor speed command that is sent to the inner-loop controller. The two main motor control modes for this outer-loop controller are described in this section.

In our previous paper [5], we proposed a control philosophy that varied HLP torque as a function of equivalent airspeed regardless of altitude. In order to control the propeller rotational speed instead of motor torque, a control schedule is required to account for both equivalent airspeed and altitude. Although this adds an additional variable to the HLP control schedule, development of a two-dimensional HLP control schedule is not particularly difficult since airspeed and altitude are already reported from the existing research air data system.

A. Airspeed Control Mode

As noted in the previous section, the approach and landing corridor, bounded at the lower end by V_{S0hl} and an upper HLP speed limit well above V_{ref}, has been researched in detail. We previously asserted that operation below V_{S0hl} should be characterized by operation at constant torque; such constant torque operation should generally result in slightly reduced propeller rotational speed as airspeed reduces until the blade stall, which is designed to occur at less than 30 KEAS per the original design requirements. The airspeed for "pitch-out"—when the torque of the blades goes to near-zero—is a parameter available to the designer (within reason) and was selected such that this speed exceeded the estimated power-off stall speed in the cruise configuration for the X-57. As such, the "pitch-out" airspeed was selected to be 95 KEAS.

As the design of the X-57 has progressed, it has become necessary to consider detailed control concepts outside of the approach corridor ranges. Operation at high speeds beyond the "pitch-out" speed may result in windmilling of the propeller—that is, having the HLPs expand the streamtube, thus producing drag and reducing lift on the wing rather than contributing positively to thrust and lift. Additionally, windmilling propellers tend to be a critical condition for the onset of whirl flutter, so the project preferred an operational philosophy that always applies a small, positive torque from the "pitch out" airspeed to the maximum HLP operations airspeed.

At the other end of the spectrum, it became clear that it would be very difficult to control and slow the airplane during rollout on the runway after touchdown if a design torque value at V_{S0hl} was maintained by the HLPs at all speeds below V_{S0hl}. However, dropping the torque quickly below V_{S0hl} seemed contrary to prudent safety practices; specifically, if the X-57 were to inadvertently decelerate below V_{S0hl} during flight tests, the decreasing torque would further reduce the lift generated by the wings, exacerbating the likely stall condition. Due to this concern, the torque remains constant from V_{S0hl} to several knots below V_{S0hl}, before linearly ramping down to a low torque value. Finally, initial taxi operations and checkout on the ground require an ability to verify operation of the HLPs without generating much thrust, so low-speed control of the aircraft on the ground is maintained.

A notional plot of HLP torque vs. equivalent airspeed in shown in Fig. 4 that reflects the operating philosophies in the various operating regions described above. Because this approach varies HLP control with airspeed, it is dubbed *airspeed* mode. Note that Fig. 4 shows torque on the y-axis to illustrate the relative HLP torque in each operating mode; the actual control schedule is based on the estimated RPM to achieve a target torque level.

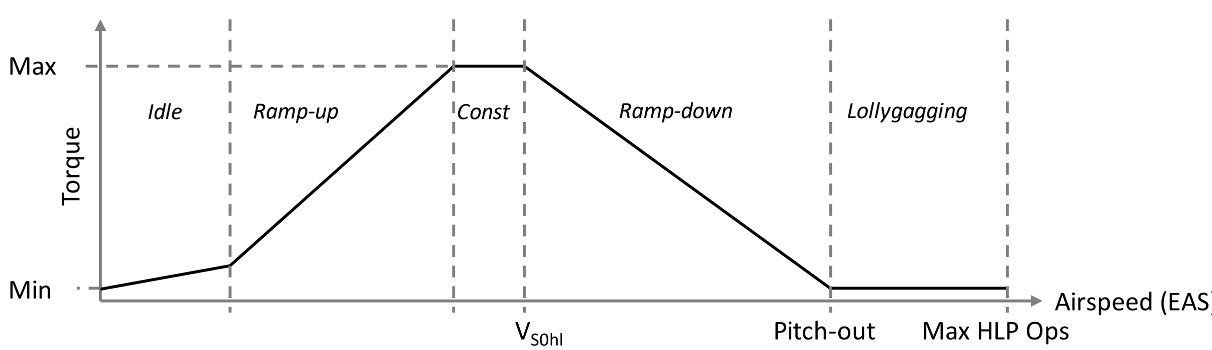


Fig. 4 High-lift propeller control philosophy – airspeed mode.

We define the desired behaviors in each of the regions shown in Fig. 4 as follows:

- **Idle**: This is a low-airspeed region that allows for predictable response during ground testing and other low-airspeed ground operations, such as taxiing. This is the one control mode where the desired motor speed is not (generally) set by a target torque; rather, a constant motor speed is selected that gives predictable results to control room and/or cockpit displays for diagnostics. The *airspeed* control schedule in this paper applies this control philosophy below 15 KEAS to allow for a moderate taxi speed and/or winds. Furthermore, pitot-static derived air data as used on the X-57 (and most aircraft) is highly inaccurate at low speeds and may ultimately set the upper bound for airspeed in this control region.
- **Ramp-up**: This region linearly increases the torque from the upper end of the idle region to some airspeed slightly under V_{S0hl} at which the maximum design torque of the HLPs is applied. This gradual increase gives a smooth application of power if this control mode is used during takeoff, and allows for a reduction in thrust if the mode is active while the vehicle is slowing to a stop under heavy braking.[†††] The *airspeed* control schedule in this paper applies this control philosophy from 15 to 50 KEAS.
- **Constant**: This region maintains a constant torque from some airspeed less than V_{S0hl} to V_{S0hl}. Motor speed will generally increase slightly from the activation airspeed to V_{S0hl}. The rationale for constant torque in this region is to maintain a reasonable amount of lift augmentation in flight if the aircraft inadvertently slows below V_{S0hl}, though it could also conflict with touchdown and subsequent ground handing while executing near-full-stall landings. The *airspeed* control schedule in this paper applies this control philosophy from 50 to 58 KEAS.
- **Ramp-down**: This region linearly decreases the torque from the maximum (design) value at V_{S0hl} to some low, but positive, torque value, at the desired pitch-out airspeed. This gradual torque reduction enables glideslope control during the approach corridor while maintaining an appropriate margin over stall to account for off-nominal operations. The *airspeed* control schedule in this paper applies this control philosophy from 58 to 95 KEAS.
- **Lollygagging**:[‡‡‡] This region maintains a minimum torque value from the pitch-out airspeed to the maximum HLP operating airspeed. A minimum, positive torque is desired to reduce the potential for onset of whirl flutter. The maximum HLP operating airspeed is a function of maximum operating temperature, maximum operating altitude, maximum propeller rotational speed, and desired margin over the torque required to meet those conditions. The *airspeed* control schedule in this paper applies this control philosophy from 95 to 120 KEAS.

B. Fixed Control Mode

The airspeed control mode described above enables a balance of lift and thrust as appropriate for operations on approach to landing, but it is not necessarily ideal for other operations. The low motor speed in the idle region enables predictable control and taxi, but it does not enable the pilot to check high-power operation prior to flight (akin to the standard "runup" check performed by most small aircraft prior to takeoff). Additionally, the ramp-up and ramp-down regions reduce the torque that is otherwise available to assist takeoff operations during the ground roll and initial climb phases. Furthermore, the *airspeed* control mode in the current X-57 architecture is not robust to failures in the air data system or the communication system that passes the air data to the high-lift motor controllers. Without a reversionary mode, any individual high-lift motor controller may also suffer a failure of its onboard data system that causes it to lose communication with the incoming air data stream, leading to incorrect commands. Operation at a predetermined, fixed motor speed can address each of these concerns; therefore, we propose a second operational mode, termed *fixed* mode, which sets a constant rotational speed target for the HLPs in the outer loop of the high-lift motor controllers.

For *fixed* mode, a fairly high motor speed can be selected that does not violate the maximum expected motor torque, but is high enough for (1) preflight checkout ("runup" check), (2) high takeoff thrust, and (3) robust operation in the face of failure of the air data or motor controller communication systems. Each high-lift motor controller will enter the fixed mode either upon receiving a valid mode command from the cockpit or upon a number of different errors that can be addressed locally at the individual high-lift motor controllers (e.g., communication timeout, invalid/mismatched air data, etc.).

[†††] As will be discussed later, airspeed mode is not the preferred mode for takeoff nor is it expected to be the appropriate operating mode well after touchdown. This operating mode philosophy is discussed here for completeness and allows for variations in pilot technique to be explored in the X-57 simulations as well as potentially in flight test.

[‡‡‡] Typically defined as "to dawdle." This is also an obscure reference to a certain 1988 movie about baseball.

Unfortunately, operation at fixed motor speeds will lead to performance lapse as air density decreases (e.g., altitude increases), though this is not a major limitation for takeoff and landing operations, which tend to take place at lower altitudes. Also, a high, fixed motor speed will likely exacerbate problems with excess thrust conflicting with glideslope control in the approach-to-landing corridor. Conversely, there are some airspeeds and altitudes (likely near the "constant" region of the airspeed control mode) for which a fixed motor speed may result in slightly less lift augmentation than the airspeed mode. Because a sudden, contingency-based mode switch of all the high-lift propellers from airspeed to fixed mode could occur (e.g., during an air data system failure) resulting in a sudden loss of lift, it is likely best from a safety perspective for the fixed mode motor speed setting to be fairly high, to minimize the loss of lift. The fixed motor speed also cannot be too high, as it may lead to excessive thrust loads in near-static conditions on the ground (particularly on colder days).

C. Operation and Control Mode Selection

The high-lift system has three primary cockpit controls—a high-lift system arm/disarm switch, a high-lift system mode control switch, and an emergency disarm switch [22]. The arm/disarm switch is located next to the aircraft flap control switch, since the system will be operated in conjunction with the flap system during low-speed operations. The mode control switch is located near the main annunciator panel in the pilot's primary field of view and is used to select *airspeed* or *fixed* modes. The secondary disarm switch is a guarded switch located on the pilot's control yoke that can only be used to disarm an armed high-lift system.

Other cockpit controls are used to provide control and power to the high-lift motor controllers. The low-voltage wing avionics power switches enable power to the processing and communication elements of the high-lift motor control system. High-voltage traction power is enabled from the traction battery and contactor pallet switches. All of these power switches are arranged such that an inadvertent switch operation will result in a symmetric loss of half of the HLPs.

Although the normal operating procedures for X-57 Mod IV have not been finalized at this time, the current proposed HLP operating approach is as follows:

- **Preflight/taxi/runup**: To conserve power, ground operations (such as taxi to the runway) are conducted by low thrust from the cruise motors only. The high-lift system is powered (by both avionics and traction power systems), but not armed. To test the system prior to takeoff, the control mode switch is moved to *airspeed*, and the arm/disarm switch is moved to *armed*, bringing the HLPs to their *idle* region rotational speed. High power is tested by moving the mode switch to *fixed* and then back to *airspeed* to conserve power once the check is completed.
- **Takeoff**: The aircraft is taxied into position with the HLP system armed in *airspeed* mode and the HLPs operating in the *idle* region. If a high-performance takeoff is desired, the pilot switches to *fixed* mode as (s)he advances the cruise motor power controls to takeoff power. Otherwise, takeoff can commence in *airspeed* mode with reduced climb performance (as compared to that in *fixed* mode).
- **Cruise climb transition**: After reaching a safe altitude for gear retraction and at an airspeed above the "pitch out" point, the pilot retracts the landing gear, disarms the high-lift system, retracts the takeoff flaps, and sets cruise climb power and airspeed.
- **Approach to landing**: At a typical airspeed where the pilot would deploy the initial flap setting prior to landing, but above the high-lift propeller "pitch-out" speed, the pilot verifies *airspeed* mode, deploys the initial flaps, and arms the high-lift system. At this point, the pilot commences with a normal landing approach, including selection of landing flaps, landing gear, and appropriate airspeeds (of V_{ref} or higher), until the landing flare or after touchdown. If the pilot is floating in the landing flare or is just post-touchdown, the secondary disarm switch on the yoke can be triggered by the pilot to quickly reduce the HLP system thrust and the associated lift augmentation, putting additional weight on the wheels to enhance ground control and braking.

Contingency operations are still being explored, though a few overriding philosophies have emerged from initial piloted simulations. Given the long runways available to the X-57 at the planned test site, any fault that occurs with the HLP system will generally result in acceleration to beyond the "pitch-out" airspeed and deactivation of the HLP system for the remainder of the flight. If such a fault were to occur during approach to landing, the landing can be discontinued if sufficient battery energy remains; alternatively, if sufficient runway remains, the aircraft can accelerate to the "pitch-out" airspeed or above, the pilot can disarm the HLP system, and the landing point can be re-designated farther down the runway. The current rotation and climb-out speeds in takeoff are set such that any credible failure of the HLP system after rotation results in adequate performance and controllability to land straight ahead if enough runway remains, or to reach pattern altitude and execute a cautionary landing with the HLP system deactivated.

V. Operational Estimates

Development and testing of the HLPs is ongoing, but a number of models have been developed to estimate the performance of both the HLPs and their aggregate effect on the vehicle. These models have been used to develop operational envelopes and procedures that include the control modes described above. This section presents a summary of the HLP performance modeling to date and the operational envelopes that have been generated with these models.

A. Propeller Performance

The X-57 project team has developed models for the HLPs that include actuator disc approximations, blade-element momentum theory (BEMT) representations, and unsteady Navier-Stokes solutions. A BEMT model that has been calibrated to selected Navier-Stokes solutions is employed to generate full performance envelopes for the HLPs. The current X-57 BEMT model is captured in the CROTOR [23] extension to XROTOR [24], and gives reasonably accurate results as compared to the Navier-Stokes solutions on the early blade designs [14]. The CROTOR BEMT model does not represent the rake and skew distribution of the foldable HLP but has been tuned to the Navier-Stokes solutions that include rake and skew to reasonable accuracies (generally within 2-3%).

One of the recent changes has been the realization of the impact of the blade center of mass on blade deployment angle. As noted earlier, the passive actuation for the blades results in a deployment angle of approximately 80° from the axis of blade rotation, resulting in a slight reduction in the blade pitch. A comparison of the BEMT-derived results for the partially folded blade as compared to the original fully deployed blade in terms of the propeller efficiency η, the thrust coefficient C_T, the power coefficient C_P, and the torque coefficient C_Q vs. the advance ratio J is given in Fig. 5. The reader is referred to reference [25] for a definition of these non-dimensional parameters.

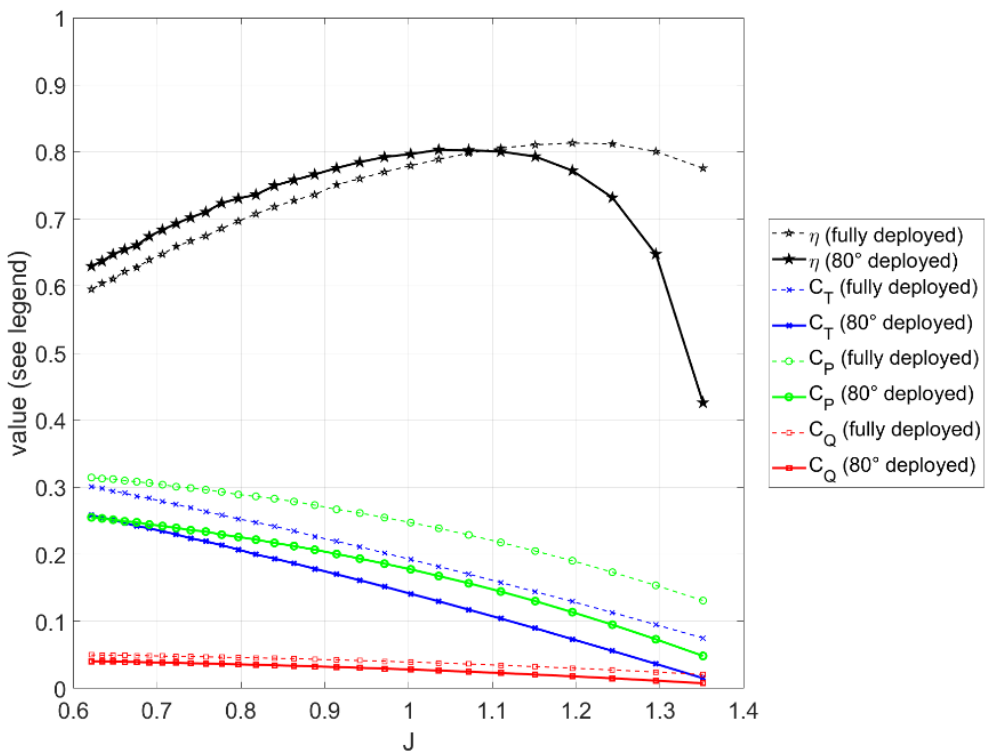


Fig. 5 Comparison of blade-element momentum theory models of high-lift propellers.

The design operating advance ratio at V_{S0hl} of the original fully deployed propeller is 0.683. In order to absorb the same torque as the original fully deployed design, the advance ratio of the partially deployed propeller needs to drop to 0.627—an increase in the design point rotational speed by approximately 400 RPM. This rotational speed increase has the impact of reducing the operational ceiling of the HLPs, as will be shown in the next subsection. Data is provided in Fig. 5 for both the fully deployed and partially deployed propeller models for comparison with previous references, which all assumed the fully deployed propeller; the results that follow will only consider the most up-to-date, partially deployed model.

B. Operational Envelope

The partially deployed propeller model shown in Fig. 5 (labeled as "80° deployed") was used to generate performance estimates for the X-57 propeller control speed schedules in *airspeed* and *fixed* modes. The *airspeed* mode was generated largely by solving for the propeller rotational speed that could meet the notional torque schedule shown in Fig. 4 using CROTOR [23], with the following assumptions:

- The maximum propeller torque is set to 22.0 Nm (16.2 ft-lbf), which is the design target for lift augmentation for the X-57 at 58 KEAS, 3000 lbf (13340 N) gross weight plus a 10% lift margin. This torque is applied to the "constant" region of the torque schedule.
- The minimum allowable propeller torque is set to 1.0 N-m (0.74 ft-lbf). This lower limit provides a small margin over the propeller windmilling, which is generally a critical condition for whirl flutter. The minimum torque is generally only applied to the "lollygagging" region of the torque schedule, though it is occasionally an active constraint at the higher-altitude "idle" regions.
- The maximum propeller rotational speed is set to 5400 RPM. This limit is slightly lower than the propeller structural limit load observed at 5460 RPM, to allow for some tolerance in the motor speed control loop. Since this was a structural constraint, it takes precedence over minimum or maximum torque conditions in the control schedule.
- The minimum propeller rotational speed is set to 1200 RPM. This speed is ultimately selected because it would absorb slightly more than the minimum desired operational torque with the aircraft at the Edwards Air Force Base field elevation on a 3σ hot day using the 2013 ERRA. This constraint only affects the "idle" region, and the X-57 team desired a stable, repeatable value for HLP speed for ground testing and initial preflight inspection.
- The HLP rotational speed values are designed to the 1976 U.S. Standard Atmosphere, but the constraints noted above are also applied to operation in the 3σ extreme temperatures of the 2013 ERRA.

The resulting *airspeed* mode propeller rotational speed schedule and corresponding torque values are shown in Fig. 6. For convenience, the regions from Fig. 4 are overlaid onto Fig. 6 and all subsequent airspeed mode plots in this paper. The critical aircraft speeds—V_{S0hl}, V_{S0}, and V_{ref}—are also overlaid on these and subsequent plots as appropriate.

One of the first insights observed from Fig. 6 is that the altitude for maximum lift augmentation is limited. This can be inferred by inspecting the propeller speed and torque in the "constant" torque region between 50-58 KEAS. Per Fig. 4, this is the region where the torque should be at its maximum value. As noted in Section III, the lift augmentation associated with HLP operation is directly proportional to the torque absorbed by the HLP. As altitude increases, air density decreases, and the true airspeed increases. In order to absorb the same amount of torque, the HLP must spin at a faster speed. Between 6000 and 7000 ft mean sea level (MSL), the HLP hits the rotational speed limit of 5400 RPM. Consequently, the torque is gradually reduced at higher altitudes, which has the effect of limiting the lift augmentation available. The net effect is that operations above 6000 ft MSL using this schedule will not receive the same level of lift augmentation, and, therefore, the actual V_{S0hl} will increase.[§§§]

The rotational speed limit also comes into play in the high-altitude, high-speed corner of the envelope shown in Fig. 6. Here, even as the minimum torque constraint becomes active, the true airspeed is high enough that the propeller needs to rotate faster than the maximum RPM of 5400 to meet the minimum torque value of 1.0 Nm (0.74 ft-lbf). Since the maximum propeller speed limit is derived from structural concerns, the speed limit is the driving constraint. Given that the propeller will be windmilling (operating at low or negative torque) in this region, it is an area of increased concern for whirl flutter. This will have little impact operationally, since it will be uncommon to ever engage the HLP system in these higher-speed, higher-altitude flight conditions.

Two other seemingly curious phenomena are shown in Fig. 6. The propeller speed undergoes an inflection at 90 KEAS, even though the boundary of the control region from "ramp-down" to "lollygagging" occurs at 95 KEAS. Furthermore, the torque in the "lollygagging" region is generally in the 2.0-4.0 N-m (1.5-3.0 ft-lbf) contour band, which is higher than the 1.0 N-m minimum torque value. These phenomena are a result of the requirement for the HLPs to maintain a minimum torque during a hot day at Edwards Air Force Base.

[§§§] As noted in Section III, the HLP design torque value includes a 10% lift margin and a number of simplifying assumptions regarding otherwise beneficial propeller forces for net aircraft lift generation. The actual stall speed in this configuration should be determined by tests, and, therefore, this statement is likely slightly conservative.

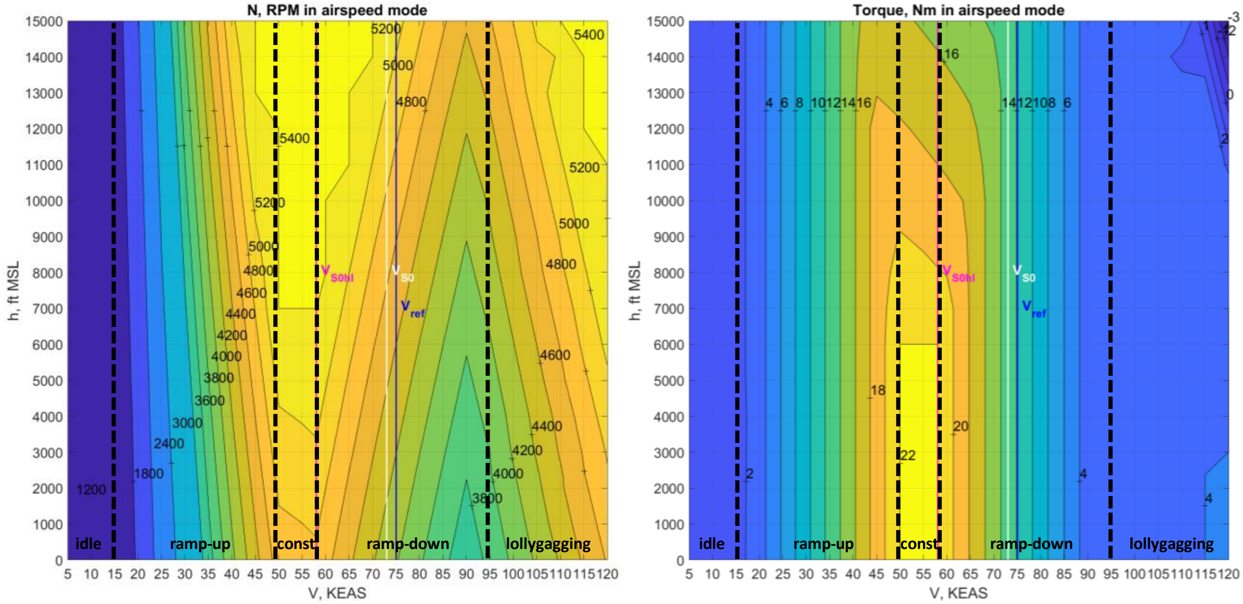


Fig. 6 High-lift propeller rotational speed schedule (left) and torque schedule (right) in *airspeed* mode. Torque estimates are given for operation in the 1976 U.S. Standard Atmosphere.

The difference in torque requirements of HLPs when operated according to the speed schedule shown in the left-hand side of Fig. 6 in the 1976 U.S. Standard Atmosphere (*std*) vs. the 2013 ERRA on a 3σ hot day is shown in Fig. 7. The contour band representing -1.5 to -2.0 N-m (-1.1 to -1.5 ft-lbf) begins between approximately 86 and 97 KEAS, depending on altitude. The design airspeed torque schedule in the standard atmosphere drops to 1.0 N-m (0.74 ft-lbf) at 95 KEAS, which would move this region into negative torque on a hot day at Edwards if no correction were made. Since the control schedule is based on propeller RPM and not torque, the RPM in this region is increased over the original design schedule (given generically in Fig. 4) so that torque does not become negative (that is, until hitting the propeller speed constraint of 5400 RPM). This causes an apparent shift in the transition speed from "ramp-down" to "lollygagging," and a small but higher torque than minimum in the "lollygagging" region for operations at cooler than Edwards hot-day temperatures.

Operation in the *fixed* mode is, by design, a much more straightforward control approach. The main desire is to pick a fixed RPM that does not violate the considerations for *airspeed* mode (maximum/minimum torque, maximum/minimum rotational speed) throughout the HLP control envelope of 0-120 KEAS and 0-15,000 ft MSL. Unfortunately, it is impossible to meet all of these constraints throughout the entire envelope. The more important considerations tend to be the maximums—violating the maximum rotational speed or the maximum torque could violate propeller structural strength and motor torque output constraints, respectively. As such, a propeller speed must be chosen such that some portion of the HLP control envelope will violate the torque lower bound and, therefore, will result in a windmilling propeller. We select the high-altitude, high-airspeed region of the performance envelope to experience windmilling because this portion of the flight envelope is the least likely to be encountered in X-57 flight tests. As of this writing, the *fixed* control mode rotational speed is 4800 RPM.

The torque contingency margin, defined as the difference in torque in the *fixed* mode vs. the torque in the *airspeed* mode, is depicted in Fig. 8. Operation at this rotational speed brings the propeller close to the design torque limit at low altitudes and low airspeeds but provides positive torque contingency margin in the event of a sudden switchover in control mode at V_{ref} at altitudes up to 8000 ft MSL. A sudden switchover of the entire HLP system from *airspeed* to *fixed* mode in the region of increased margin, demarcated by the yellow dot-dashed contour line towards the contours of positive torque margin in Fig. 8, will result in an increased lift augmentation and an increase in thrust. Although glideslope control may be marginal or impossible in this region (due to the increased thrust), this switchover gives the pilot ample time to isolate any failures, and, if necessary, land with the HLP system disarmed. Landing with a disarmed HLP system will require faster approach and touchdown speeds and more runway for rollout, but this is a manageable event, much like how aircraft may reconfigure to land after a failure in the flap system.

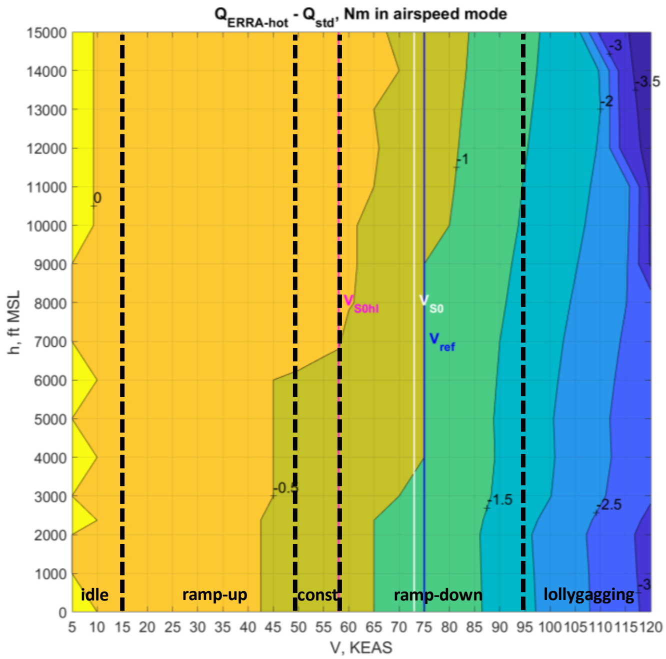


Fig. 7 Change in torque required from 1976 U.S. Standard Atmosphere to 2013 Edwards Range Reference Atmosphere 3σ hot day when operating at the airspeed mode propeller speed table seen in Fig. 6.

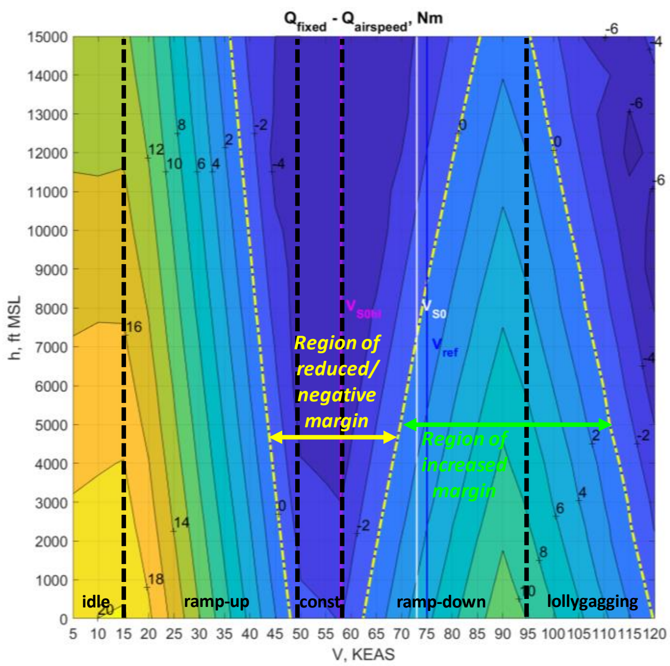


Fig. 8 Change in torque from fixed to airspeed mode, 1976 U.S. Standard Atmosphere.

Some regions with reduced or negative margin are also observed in Fig. 8. Operation in this region with a sudden switchover from *airspeed* to *fixed* mode will result in a reduction of lift and thrust, but not necessarily an immediate stall, as adequate HLP torque may be available to maintain lift at or near 1*g* because of the built-in HLP torque margin and other conservative design assumptions. The deficit of the region of negative margin is predicted to be less than 6.0 N-m (4.4 ft-lbf) below the *airspeed* control mode torque at any given point. The reduction in torque during switchover could result in an aerodynamic stall but does not result in a complete elimination of lift augmentation. Given that this region of low/negative margin occurs below V_{ref} (75 KEAS) for most landing altitudes, a 4800 RPM speed for operation in fixed mode seems to offer the best compromise in performance from a contingency perspective.

C. Takeoff and Landing Operations

Section III included a discussion of the HLP integration into normal operations, and we suggested that takeoff in the *fixed* mode should result in a high-performance takeoff. This improved takeoff performance is due to the potential for greater net thrust over the takeoff run and during the initial climb prior to configuring the airplane for cruise climb. At a fixed propeller speed, the potential thrust advantage of the *fixed* mode throughout most of the takeoff corridor lapses with increased altitude and temperatures. The overall difference in thrust from the *airspeed* to *fixed* modes is shown in Fig. 9. For most altitudes shown in Fig. 9, the *fixed* mode thrust is higher than the *airspeed* mode thrust, implying a greater total thrust when integrated over a takeoff path at a fixed altitude. It also shows that the added thrust potential increases at lower altitudes. Given that most aircraft takeoff operations occur at fairly low altitudes (including the X-57, which will fly from a field elevation of approximately 2300 ft MSL at Edwards), using the HLPs in fixed mode should yield increased takeoff performance.

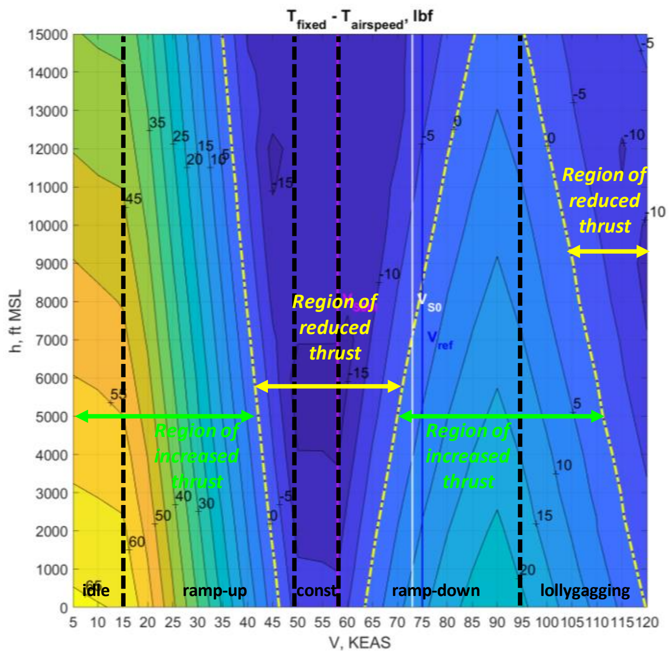


Fig. 9 HLP gross thrust in airspeed (left) and fixed (right) modes, 1976 U.S. Standard Atmosphere.

In addition to increased thrust throughout the takeoff ground roll, fixed mode operations should also result in an increase in climb rates after takeoff. The initial climb speeds of the X-57 are currently estimated to be between 84 and 96 KEAS,[****] and the HLP gross thrust in *fixed* mode is greater than the *airspeed* mode thrust at all but the highest altitudes in this speed band. The propeller efficiency of the HLPs is lower than the X-57 cruise propellers in this climb phase, however, so more power is used for the same amount of thrust production. Given the little time spent in this configuration (the current X-57 procedures call for a change to cruise climb at 500 ft above ground level), the impact to overall mission energy consumption is minimal.

The X-57 team conducted a series of takeoffs and landings in the X-57 piloted simulator to estimate the operational impact of HLP control modes. This simulation includes a detailed aerodynamics database developed over thousands of numerical simulations [26], including power-on effects from the wingtip propellers and HLPs [27]. The maneuvers, which were flown with the X-57 project pilots, included (1) a takeoff from a full stop and a climb to the traffic pattern, (2) a "touch-and-go" landing where the aircraft is reconfigured for takeoff without coming to a complete stop on the runway followed by a climb to the traffic pattern, and (3) a final landing to a full stop. Two trials were conducted: first, all operations with the HLPs in *airspeed* mode and, second, takeoffs in *fixed* mode and landings in *airspeed* mode. For this experiment, the pilots were instructed to consider the most aggressive scenario: takeoff at peak cruise motor power and initial climb at 84 KEAS. The resulting airspeed and rate of climb[††††] profiles are shown in Fig. 10.

[****] The X-57 project is using a risk-based approach to flight testing that includes climb speeds that are initially higher than otherwise optimal until the HLP system has been appropriately qualified in flight.

[††††] To smooth the otherwise instantaneous results of rate of climb, this information is presented in averaged 10-second increments.

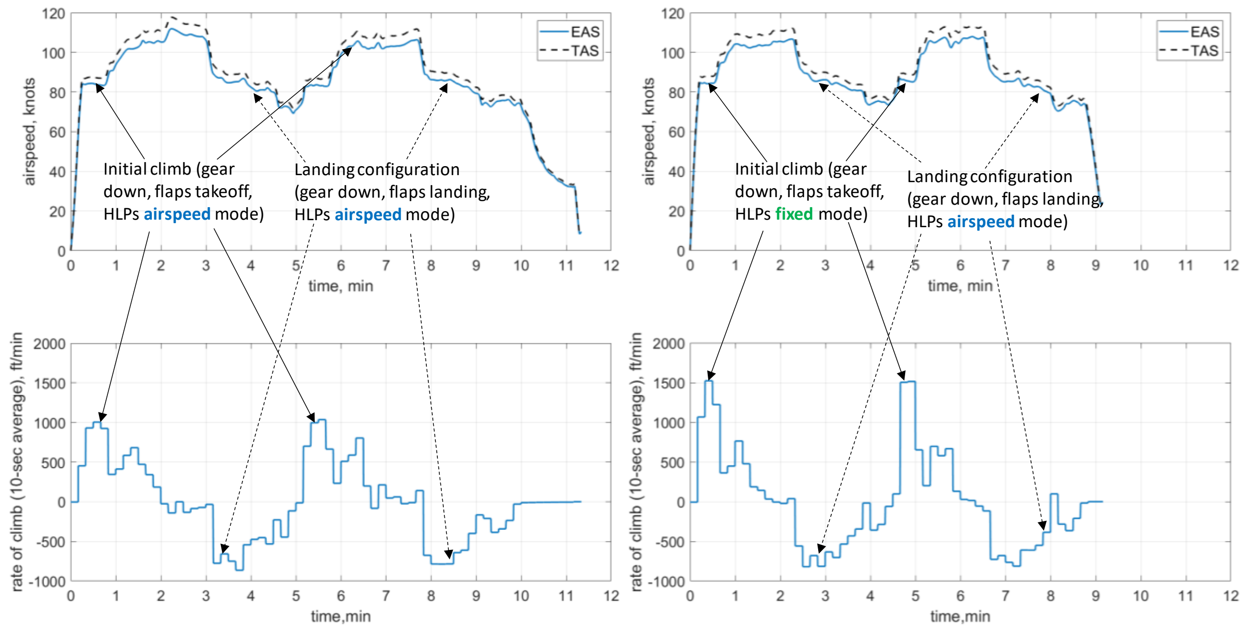


Fig. 10 Impact of HLP control mode on takeoff performance during simulated "touch-and-go" maneuvers in the X-57 piloted simulation, mean 2013 Edwards Range Reference Atmosphere.

Inspection of Fig. 10 shows that the initial climb segment rate of climb raises to approximately 1500 ft/min for the *fixed* mode takeoffs vs. 1000 ft/min for the *airspeed* mode takeoffs. This increase in climb rate will result in higher power consumption (and, despite the better rate of climb, increased energy consumption due to the lower HLP efficiency), but has other benefits. The total time in the initial climb segment is reduced, which reduces the exposure time for any system failures that may occur when the pilot's ability to react is reduced due to the low altitude and high drag of this configuration. The climb rates in either mode (*airspeed* or *fixed*) are substantially better than observed with the system deactivated; current estimates for the initial climb segment without the HLP system active and the wingtip cruise motors at their peak power are generally less than 500 ft/min. The aircraft in this configuration is extremely vulnerable to a sudden failure of the wingtip cruise motor or propeller, as this would introduce a large thrust asymmetry that cannot be adequately trimmed by the tail of the aircraft. HLP operation with the wingtip motors at peak power provides more control authority over the aircraft control surfaces in the event of this failure, and even allows for takeoff with the wingtip cruise motors operating at reduced power settings. The X-57 project is currently investigating takeoff procedures that use 50-70% of peak wingtip cruise motor power for takeoff with the HLPs in *fixed* mode at less aggressive (higher) initial climb speeds and have found adequate climb rates, improved pilot response time, and improved handling quality assessments under a number of different failure scenarios.

VI. Conclusions and Future Work

The HLP system on the X-57 enables the use of a highly loaded wing better suited for efficient cruise at higher airspeeds, while still enabling the low flights speeds of the original baseline Tecnam P2006T. Our previous work explored different control philosophies associated with the approach-to-landing segment of flight. That research concluded that a linearly increasing HLP torque profile with decreasing equivalent airspeed up to the stall speed in the landing configuration could be designed that enabled steady glideslope control but also yielded appropriate lift margins due to external effects (e.g., mild wind shear events). In this paper, we expanded the HLP control philosophy to include multiple operating modes and regions that enable robust operation throughout the entire low-speed flight envelope of the X-57. The *airspeed* mode control philosophy emerged as a torque schedule with multiple regions that enable operation in preflight, taxi, takeoff, approach, and landing. The *fixed* mode control philosophy emerged as a contingency control mode for use when airspeed data was unavailable to the HLP control system and also was identified as useful for high-performance takeoff operation.

The X-57's reliance on a rotational speed control, rather than torque control, paradigm for the HLPs required the development of a propeller control scheme that considered variations in equivalent airspeed and altitude. Additionally, other constraints, such as maximum propeller rotational speed, maximum motor torque output, and the desire to avoid situations that could exacerbate whirl flutter onset (generally windmilling cases) shaped the resulting control envelope for the *airspeed* mode. Inclusion of these constraints created HLP performance ceilings—i.e., altitudes above which lift augmentation lapsed at a particular airspeed due to the activation of one of these constraints. For the X-57, the blade rotational speed limit causes the HLP performance ceiling to be reached between 6000 and 7000 ft MSL in the 1976 US Standard Atmosphere for airspeeds in the "constant" region of the *airspeed* control mode (in Fig. 4). This particular HLP performance ceiling is not necessarily extensible to other HLP configurations but is a factor that should be considered in generalized HLP design.

The impact of non-standard atmospheres also impacted the HLP control mode designs. The desire to prevent windmilling resulted in a higher rotational speed setting in the higher-speed region of the *airspeed* mode control envelope due to hot day operations. Similarly, the blade rotational speed again becomes active at higher altitudes and airspeeds (particularly on hot days), which results in further constraints on the HLP operational envelope.

The *fixed* mode rotational speed was set with a number of additional desires, but largely driven by the low-altitude, low-airspeed corner of the flight envelope. In this region, the torque absorbed by the propeller at a constant speed approached the maximum torque capability required in airspeed mode at the design condition. Allowing for a higher torque value in the *fixed* mode at these low-speed conditions would unbalance the design, since it would size high-lift motor torque to the *fixed* mode takeoff condition. Instead, selecting the *fixed* mode rotational speed based on a balanced torque requirement provided adequate margins near the approach speed due to a sudden switchover from *airspeed* to *fixed* mode in a contingency, but also yielded performance benefits when used as a primary mode for takeoff. Data taken from the piloted simulation verified that climb rates in the initial post-takeoff climb phase were substantially higher in *fixed* vs. *airspeed* mode. Although takeoff in *fixed* mode is slightly less energy efficient, it lowers the exposure time to failures close to the ground, which is an important safety consideration.

Much additional work remains. The X-57 project is investigating the use of the HLP system for all nominal takeoff operations as a means to reduce the hazard associated with a failure of one of the large, powerful wingtip cruise propulsors during takeoff. The HLP system in both control modes, but especially the *fixed* mode, has emerged as a promising means to enable takeoff with reduced cruise motor power, significantly mitigating the hazards associated with many different motor and power system failure scenarios. In addition, the project is developing improved performance models of the HLPs to better account for the impact of the passive blade folding mechanism, as well as developing the detailed HLP control system software and hardware. As these tasks progress, valuable information will continue to be discovered regarding HLP operation. The goal of the X-57 project is not simply to develop this knowledge for the operation of this one X-plane, but rather share this information as it is developed with the entire community so that other designs that could benefit from HLP systems can incorporate these lessons.

Acknowledgments

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References

[1] Borer, N. K., Patterson, M. D., Viken, J. K., Moore, M. D., Clarke, S., Redifer, M., Christie, R., Stoll, A., Dubois, A, Bevirt, J., Gibson, A., Foster, T., Osterkamp, P., "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator," 16th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, (AIAA 2016-3920), June 2016. doi: 10.2514/6.2016-3920

[2] "P2006T – Aircraft Flight Manual," Costruzioni Aeronautiche Tecnam S.r.l,, Doc. No. 2006/044, 4th Ed – Rev. 0, Italy, 2015.

[3] J. K. Viken, S. A. Viken, K. A. Deere, M. B. Carter, "Design of the Cruise and Flap Airfoil for the X-57 Maxwell Distributed Electric Propulsion Aircraft," 35th AIAA Applied Aerodynamics Conference, (AIAA-2017-3922), June 2017. doi: 10.2514/6.2017-3922

[4] M. D. Patterson, J. M. Derlaga, N. K. Borer, "High-Lift Propeller System Configuration Selection for NASA's SCEPTOR Distributed Electric Propulsion Flight Demonstrator," 16th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, (AIAA 2016-3922), June 2016. doi: 10.2514/6.2016-3922

[5] M. D. Patterson, N. K. Borer, "Approach Considerations in Aircraft with High-Lift Propeller Systems," 17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, (AIAA-2017-3782), June 2017. doi: 10.2514/6.2017-3782

[6] N. K. Borer, J. M. Derlaga, K. A. Deere, M. B. Carter, S. A. Viken, M. D. Patterson, B. L. Litherland, A. M. Stoll, "Comparison of Aero-Propulsive Performance Predictions for Distributed Propulsion Configurations," 55th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA-2017-0209), January 2017. doi: 10.2514/6.2017-0209

[7] J. Murray, J. Lechniak, "The LEAPTech Experiment: Approach, Results, Recommendations," National Aeronautics and Space Administration, August 2016. Available at https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160012394.pdf, accessed 20 April 2020.

[8] N. K. Borer, M. D. Moore, A. R. Turnbull, "Tradespace Exploration of Distributed Propulsors for Advanced On-Demand Mobility Concepts," 14th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum (AIAA-2014-2850), June 2014. doi: 10.2514/6.2014-2850

[9] N. K. Borer, M. D. Moore, "Integrated Propeller-Wing Design Exploration for Distributed Propulsion Concepts," 53rd AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2015-1672), January 2015. doi: 10.2514/6.2015-1672

[10] "MH 114 13.02% (mh114-il)," Airfoil Tools, http://airfoiltools.com/airfoil/details?airfoil=mh114-il, accessed 20 April 2020.

[11] A. M. Stoll, J. Bevirt, M. D. Moore, W. J. Fredericks, N. K. Borer, "Drag Reduction through Distributed Electric Propulsion," 14th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, (AIAA-2014-2851), June 2014. doi: 10.2514/6.2014-2851

[12] M. D. Patterson, "Conceptual Design of High-Lift Propeller Systems for Small Electric Aircraft," Ph.D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta, Georgia, August 2016.

[13] M. D. Patterson, N. K. Borer, B. J. German, "A Simple Method for High-Lift Propeller Conceptual Design," 54th AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA-2016-0770), January 2016. doi: 10.2514/6.2016-0770

[14] B. L. Litherland, M. D. Patterson, J. M. Derlaga, N. K. Borer, "A Method for Designing Conforming Folding Propellers," 17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum, (AIAA-2017-3781), June 2017. doi: 10.2514/6.2017-3781

[15] B. L. Litherland, J. M. Derlaga, "A Performance Analysis of Folding Conformal Propeller Blade Designs," AIAA AVIATION Forum, (AIAA-2019-3676), June 2019. doi: 10.2514/6.2019-3676

[16] "X-57 Maxwell Detailed CRM v.4.4.1," VSP Hangar, Open Vehicle Sketch Pad, http://hangar.openvsp.org/vspfiles/414, accessed 20 April 2020.

[17] S. Clarke, M. Redifer, K. Papathakis, A. Samuel, T. Foster, "X-57 Power and Command System Design," IEEE Transportation Electrification Conference and Expo (ITEC), June 2017, pp. 393-400. doi: 10.1109/ITEC.2017.7993303

[18] "X-57 Technical Papers," National Aeronautics and Space Administration, https://www.nasa.gov/aeroresearch/X-57/technical/index.html, accessed 20 April 2020.

[19] "U.S. Standard Atmosphere, 1976," National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, United States Air Force, NOAA-S/T 76-1562, NASA-TM-X-74335, Washington, D.C., October 1976.

[20] "Edwards AFB, California: Range Reference Atmosphere 0-70 km Altitude," Range Commanders Council, White Sands Missile Range, Document 366-83, August 1983.

[21] "Armstrong Flight Research Center, Edwards Air Force Base Weather: Climatology," https://weather.dfrc.nasa.gov/wxclimatology.htm, accessed 29 April 2020.

[22] "X-57 Cockpit Interface Control Document" ICD-CEPT-006, Revision A, National Aeronautics and Space Administration, May 2019.

[23] Esotec Developments, "CROTOR Extensions to XROTOR," http://www.esotec.org/sw/crotor.html, accessed 24 April 2020.

[24] M. Drela, H. Youngren, "XROTOR Download Page," http://web.mit.edu/drela/Public/web/xrotor/, accessed 24 April 2020.

[25] R. von Mises, *Theory of Flight*, Dover Publications, Inc., New York, 1959, chapter XI.

[26] S. Y. Yoo, J. C. Duensing, "Computational Analysis of the External Aerodynamics of the Unpowered X-57 Mod-III Aircraft," AIAA Aviation 2019 Forum, (AIAA-2019-3698), June 2019. doi: 10.2514/6.2019-3698

[27] J. Duensing, J. Housman, J. Jensen, D. Maldonado, C. Kiris, M. Frederick, S. Yoo, T. Bui, "Using CFD to Develop NASA's X-57 Maxwell Flight Simulator," presented at the International Conference for High Performance Computing, Networking, Storage, and Analysis, November 2019.