X-57 Flight Performance and Failure Considerations

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X-57: A Steady Cadence of Changes

Mod I: Baseline performance of gasoline-powered aircraft

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

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

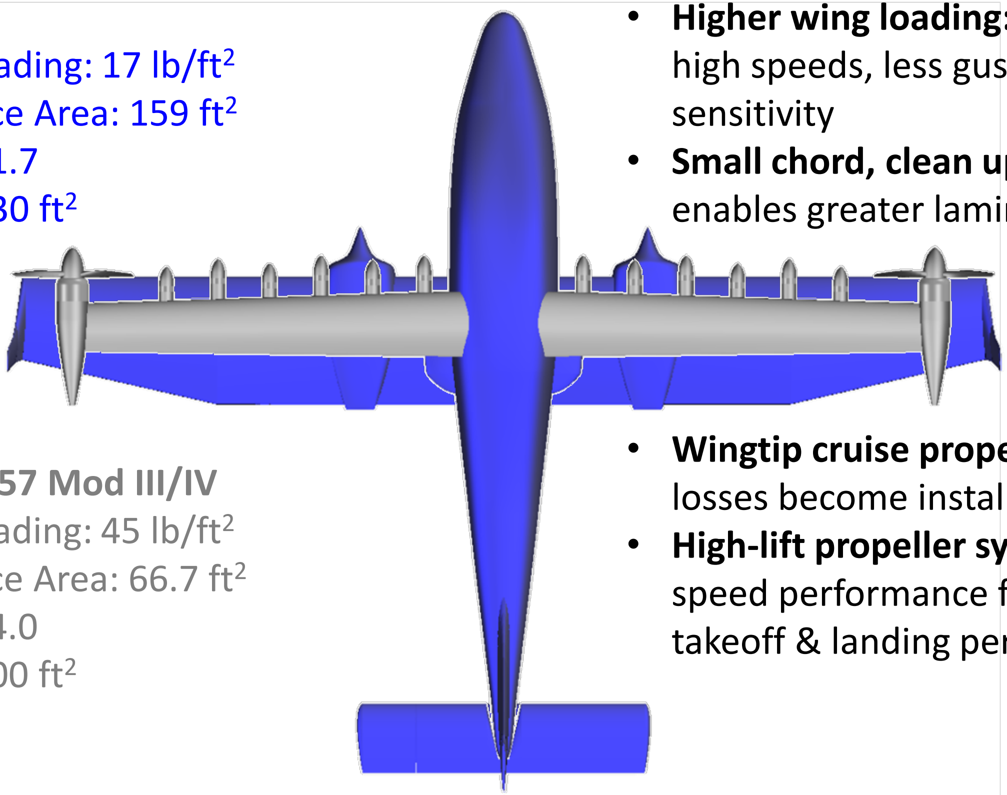
Mod IV low-speed: High-lift propeller takeoff, landing, handling qualities

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

Challenge: Achieve adequate performance in each Mod

P2006T → X-57

P2006T
Wing Loading: 17 lb/ft^2
Reference Area: 159 ft^2
C_{Lmax}: ~ 1.7
S_{wet}: ~ 730 ft^2



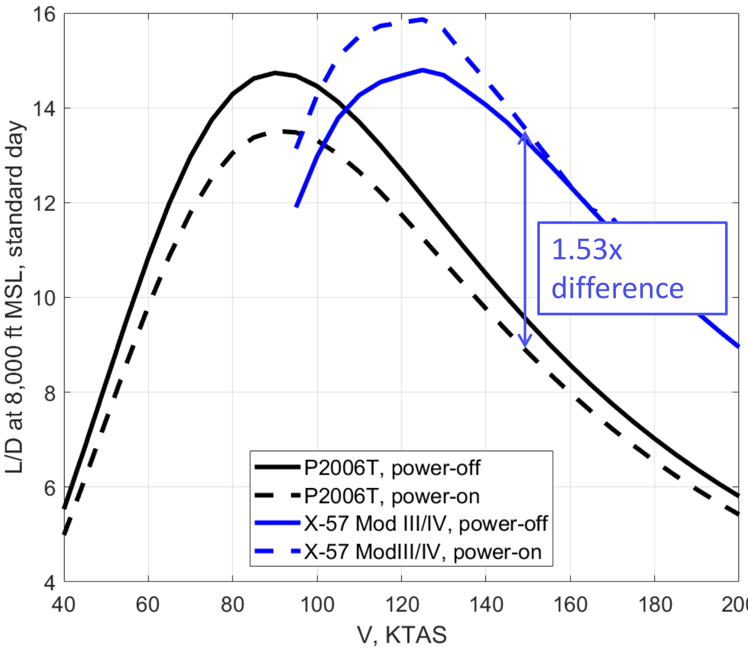
NASA X-57 Mod III/IV
Wing Loading: 45 lb/ft^2
Reference Area: 66.7 ft^2
C_{Lmax}: > 4.0
S_{wet}: ~ 600 ft^2

- **Higher wing loading:** more efficient at high speeds, less gust/turbulence sensitivity
- **Small chord, clean upper surface:** enables greater laminar flow
- **Wingtip cruise propellers:** installation losses become installation gains
- **High-lift propeller system:** maintains low-speed performance for comparable takeoff & landing performance

Efficiency Benefits of DEP Configuration

- 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

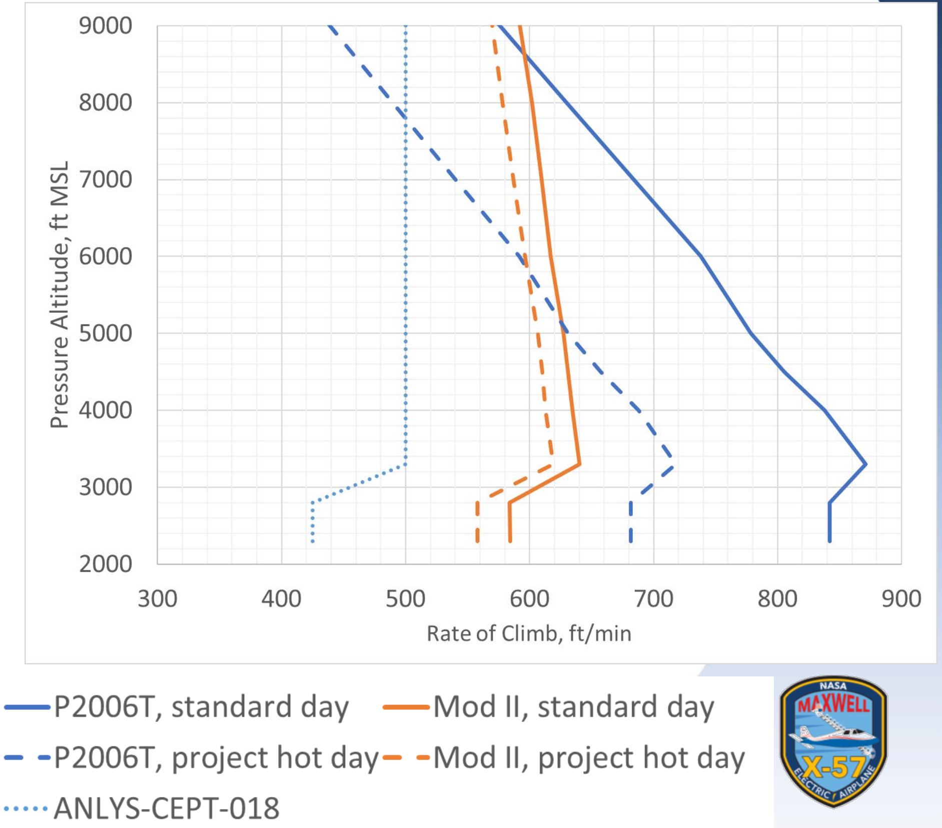
Aircraft & Power Setting	L/D (max / 150 KTAS)	Comparison to P2006T (max / 150 KTAS)
P2006T power-off	14.7 / 9.5	--
P2006T power-on	13.5 / 8.8	--
X-57 power-off	14.8 / 13.3	1.00 / 1.40
X-57 power-on	15.9 / 13.5	1.17 / 1.53



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

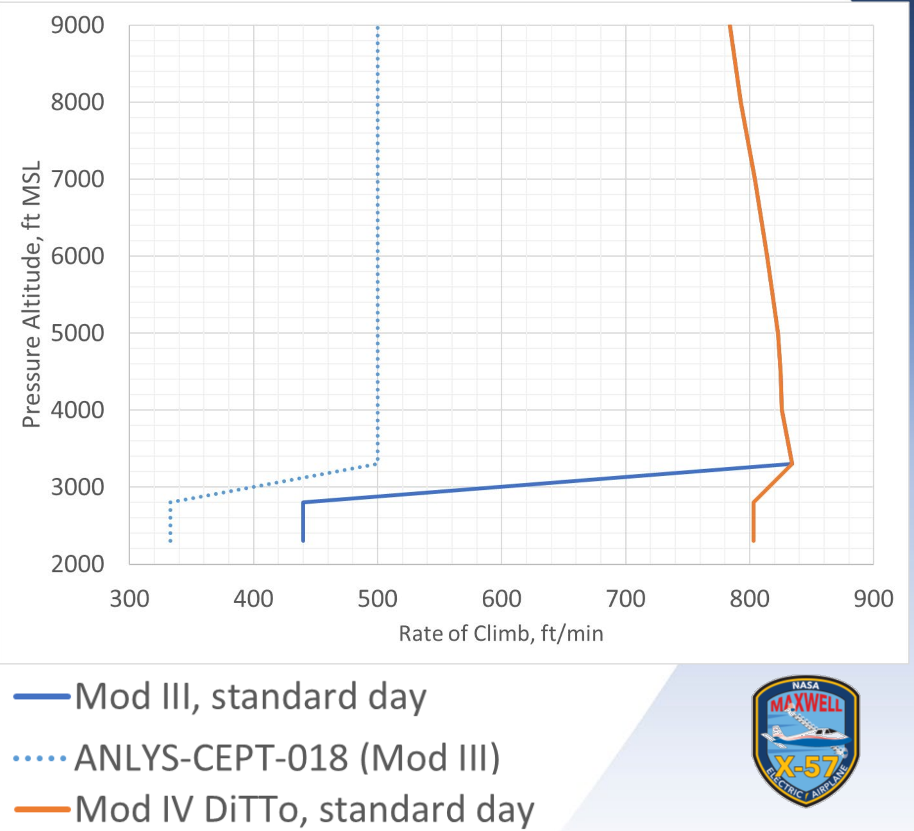
Mod II Climb Performance

- Mod II is similar to the stock P2006T, but has vastly different power characteristics
  - Gross weight impacts climb performance (3000 lbs vs. 2712 in P2006T)
  - Differences in landing gear techniques (Tecnam recommends retracting gear as soon as airborne; X-57 kept gear down until reaching 500 ft AGL)
  - Differences in propeller (larger diameter 2-blade propeller on P2006T vs. smaller diameter 3-blade propeller on Mod II)
  - Differences in power characteristics
    - Standard sea level peak power similar between two aircraft (73.5 kW for P2006T vs. 72.1 kW for Mod II
    - Standard sea level MCP differences (69 kW for P2006T vs. 60.1 kW for Mod II)
    - Electric motors act as turbonormalized engine – no power lapse with altitude



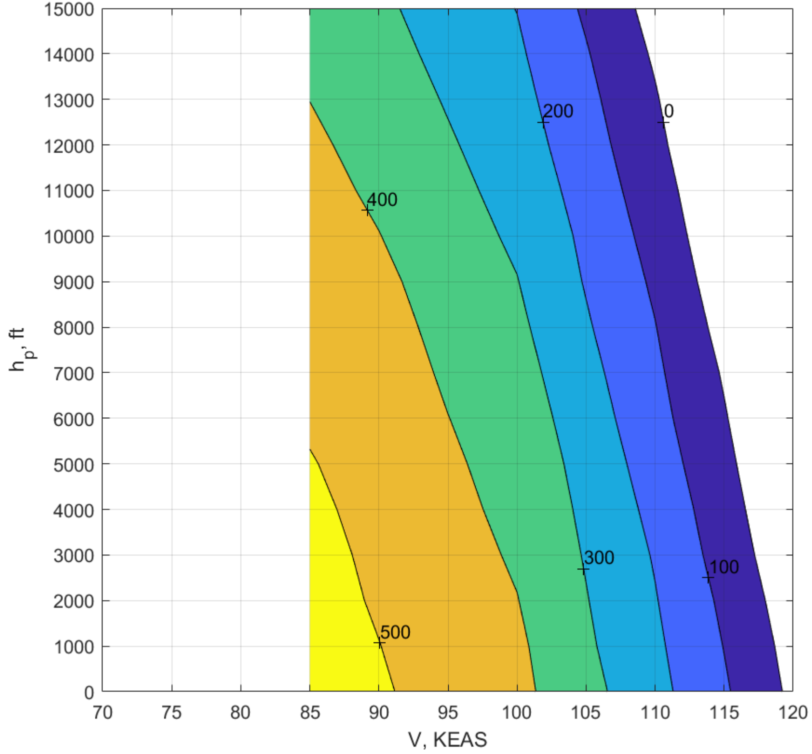
Mod III/IV Climb Performance

- Mod III initial climb performance limited by stall speed in takeoff configuration
  - Higher climb speed with gear down robs rate of climb
  - Flight below minimum control speed while at full power leads to potentially hazardous situation
- Mod IV Distributed Thrust Takeoff (DiTTo) used to augment initial climb rate and increase safety
  - Wingtip motors at reduced power (1800 RPM & full torque = ~2/3 peak power)
  - Operate with high-lift motors in fixed RPM mode (more later)
  - Climb speeds still high – does not take “credit” for stall speed reduction of high-lift propellers
- Plots shown for 3,000 lbs; gross weight increased to 3,200 lbs in later iterations

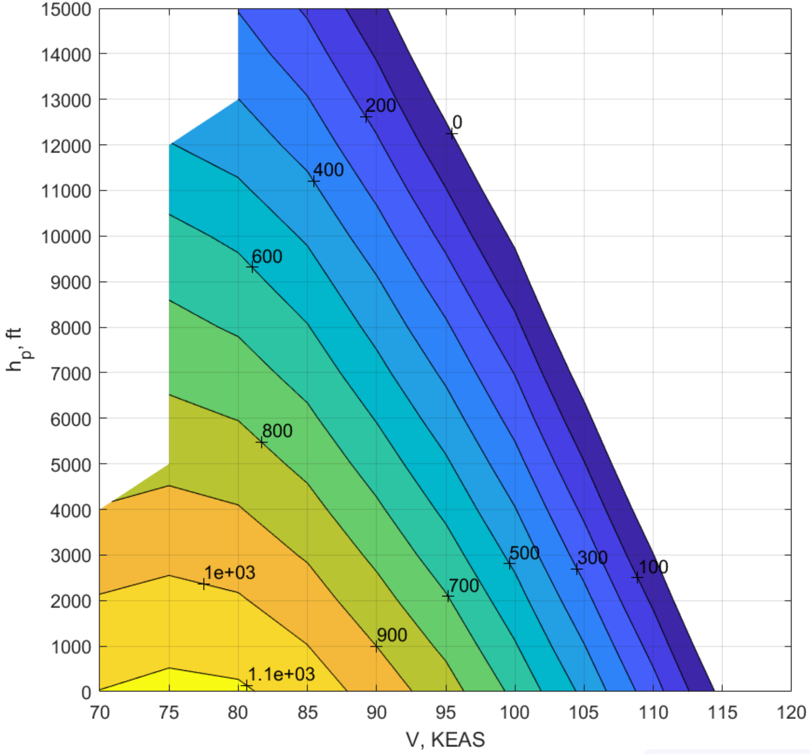


Takeoff Climb Performance Mod III/IV

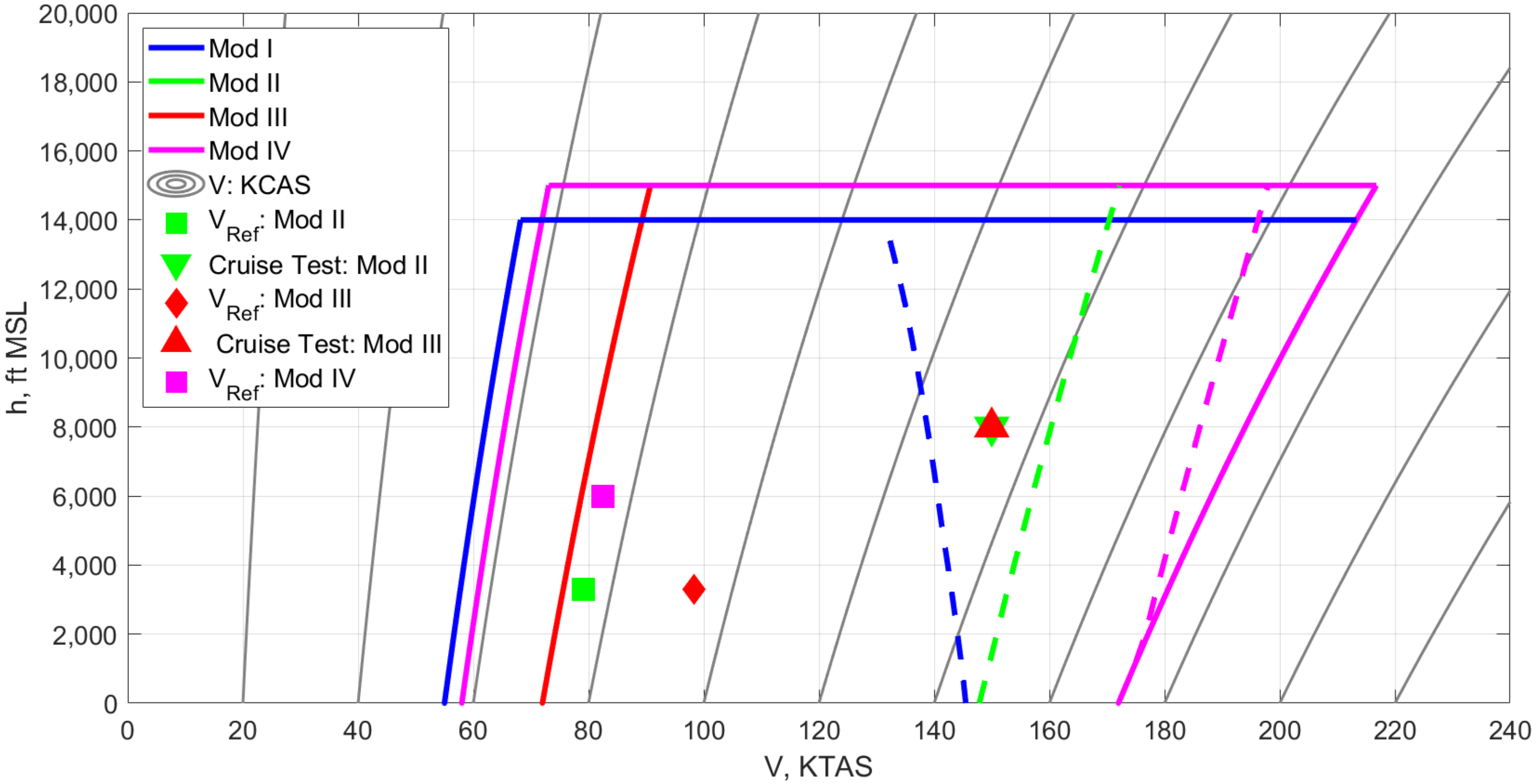
Rate of climb (ft/min): Mod III, takeoff configuration, peak power, no HLPs



Rate of climb (ft/min): Mod IV, takeoff configuration, 63% power, HLPs in fixed mode



Flight Envelopes



High-Lift Propeller Systems

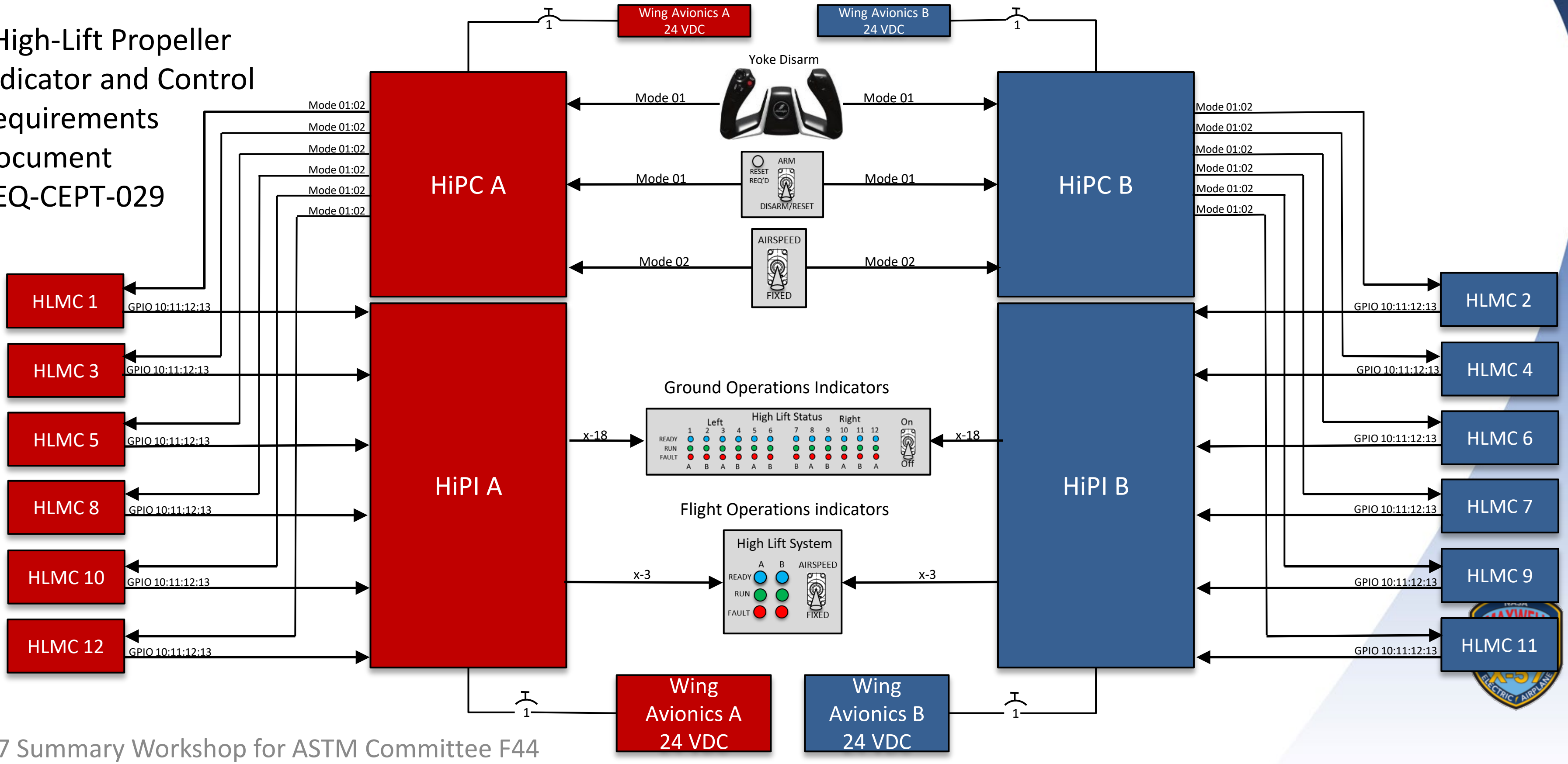
- X-57 Mod IV features 12 high-lift propellers (HLPs) distributed along the leading edge of the wing
- The HLPs are designed to augment lift at low speeds, and otherwise are turned off and passively fold against their nacelles
  - Like other high-lift devices, HLPs are an *integral part of the low-speed aircraft configuration*
- HLPs have two control modes
  - *Airspeed* mode sets the HLP RPM based on air data and is meant primarily for landing
  - *Fixed* mode sets the HLP RPM to 4800 RPM and is meant as a contingency mode if air data is lost
    - Fixed mode found also used in nominal operations: takeoff and runup

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

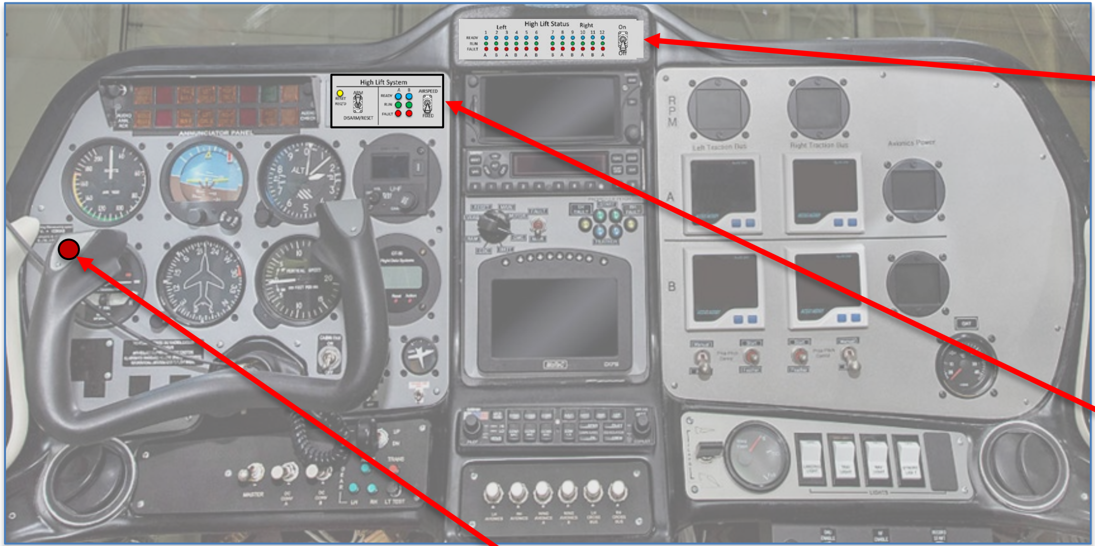
X-57 Mod IV in High-Speed (Cruise) Configuration

High-Lift Propulsion Indicators (HiPI) and Control (HiPC)*

*High-Lift Propeller Indicator and Control Requirements Document REQ-CEPT-029



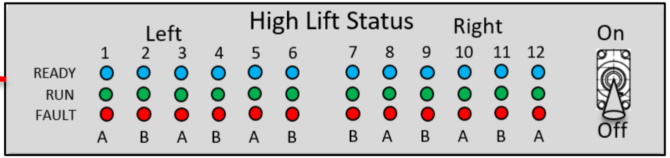
Mod IV Cockpit Modification for High Lift System



Yoke Disarm Switch

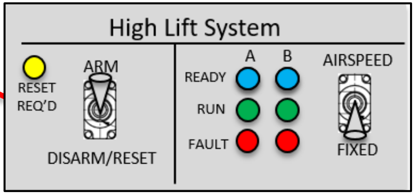
- **Function** – Disarms all High Lift Systems
- **Switch Type** - Momentary Push Button Switch

High Lift System Ground Crew Indictors



- Switch will turn LEDs off for flight
- Locking Switch

High Lift System Flight Control and Pilot Indicators



Arm/Disarm Command

- **ARM** - Commands all HLMC to ARM mode
- **DISARM/RESET** - Commands all HLMC to DISARM mode. Will also reset faults.
- Locking Switch
- **RESET REQ'D** – Indicator immediately turns yellow when Yoke Disarm is engaged. Moving from ARM to DISARM/RESET turns off indicator

AIRSPEED/FIXED Command

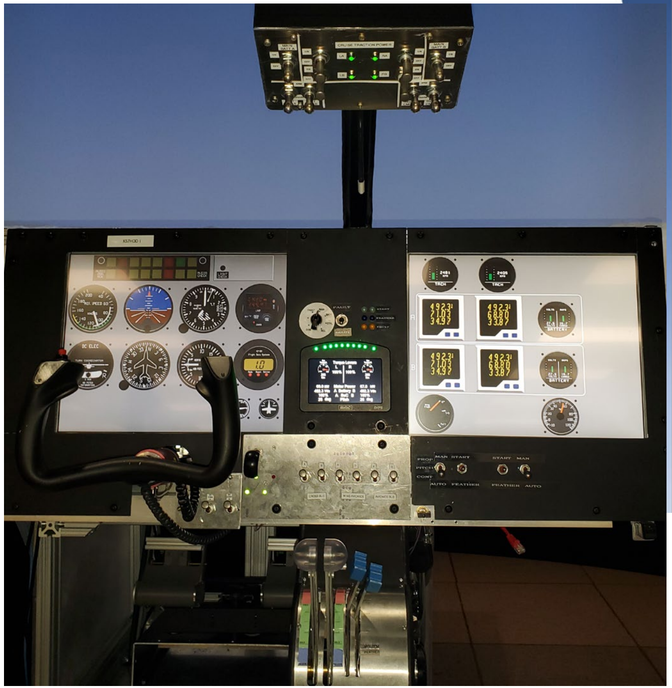
- **Airspeed** – HLMC uses an airspeed schedule to command an RPM to the high-lift motor
- **Fixed** – HLMC commands a fixed RPM to the high-lift motor
- Operator can switch between Fixed and Airspeed modes without disarming the HLMC

AFRC Piloted Simulator Cockpit

- Simulator cockpit uses a combination of aircraft switches and simulated instrument panel
  - Simulates start up and shutdown procedures based on aircraft cockpit video
  - Provides aural alerts and visual emergency alerts during failure scenarios
    - Synched with motor, propeller and power failures
- Capability to switch between Mod II and Mod III/IV cockpit

Mod II Aircraft

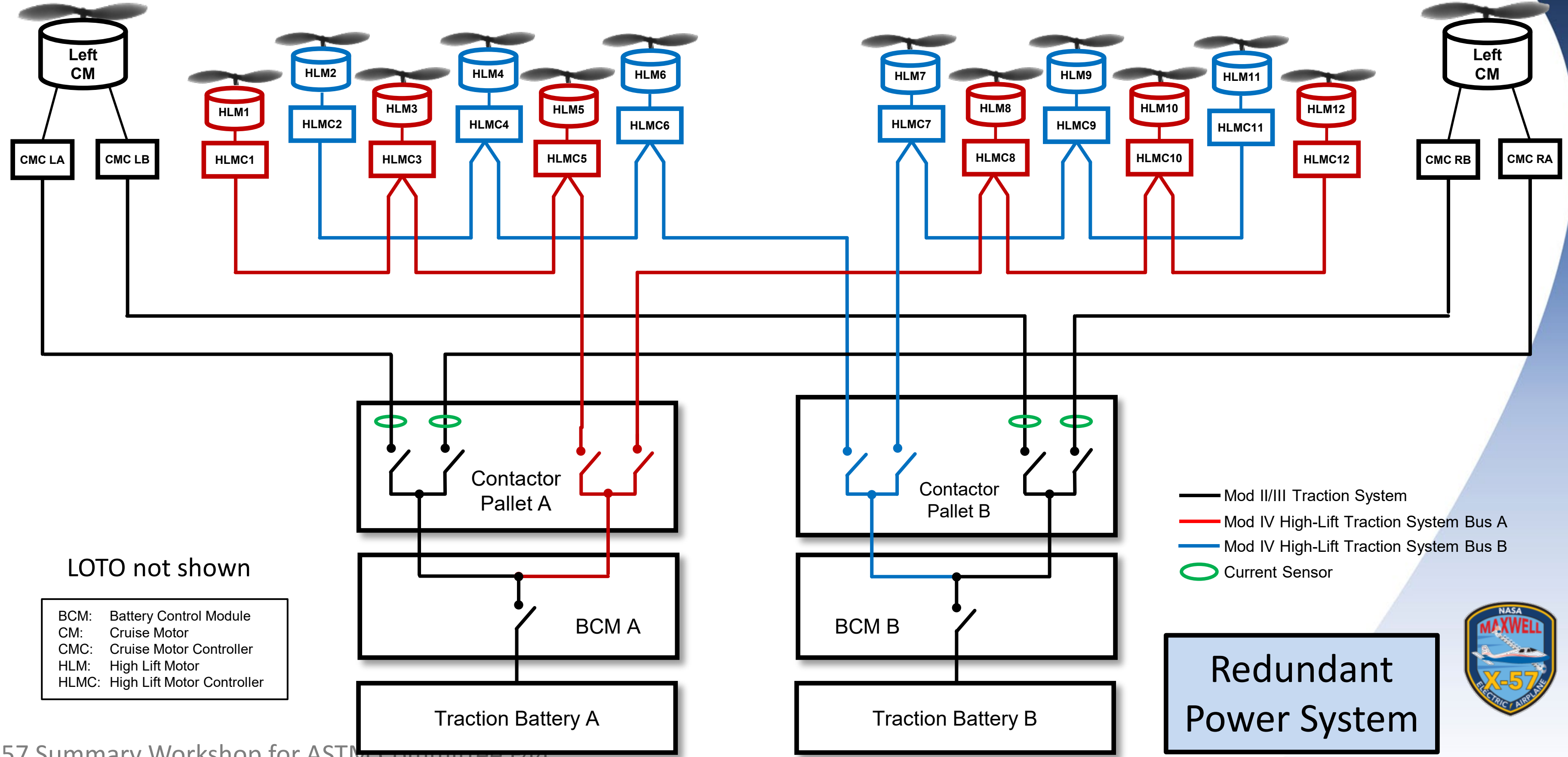
Mod II Piloted Simulator



Piloted Sim Evaluations and Training

- Sim Evaluations examine off nominal conditions in each Mod
  - Single motor failures, propeller failures, electric failures, etc.
    - Developed and evaluated key mitigations to cruise motor failures via failure scenarios
  - Atmospheric variations such as crosswinds or hot days
- Pilot Checklist and Emergency Procedure (EP) developed with simulation inputs
  - Determined takeoff procedures for altitude above ground to retract gear and maximum altitude for straight-ahead landing
- Provided simulation data to Structures, Dynamics, and Performance IPTs
  - Help set limits and confirm predictions for flight test planning
- Pilot Simulation Training
  - Practice all planned test maneuvers, takeoff procedures, and EP within six months of first flight to maintain pilot proficiency
  - Plan to perform full mission rehearsals and EP refresher training 1-2 days before flight mission

Mod IV Traction Power System

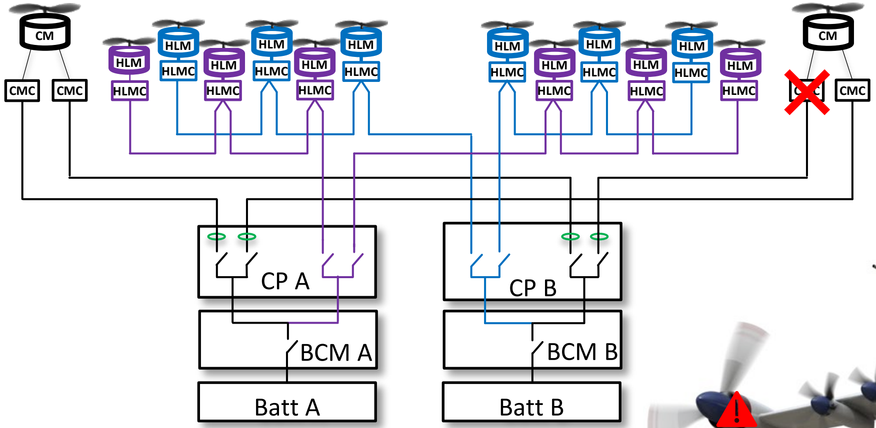


LOTO not shown

BCM:	Battery Control Module
CM:	Cruise Motor
CMC:	Cruise Motor Controller
HLM:	High Lift Motor
HLMC:	High Lift Motor Controller

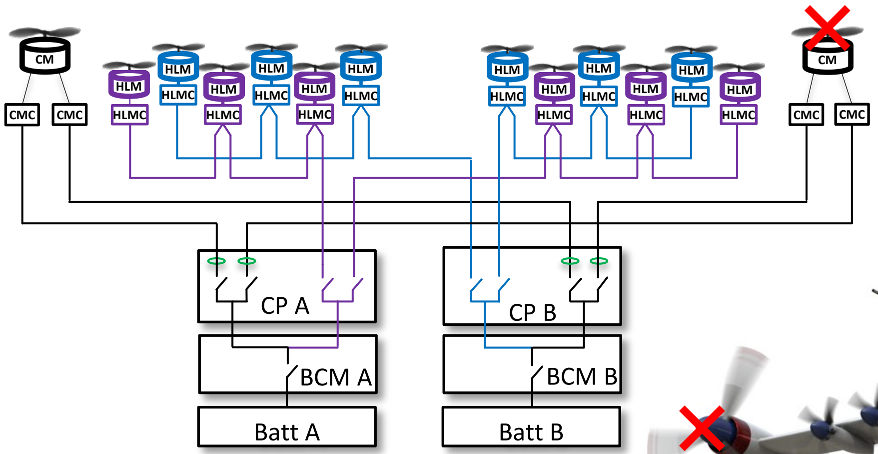
Redundant Power System

Simulated Failures: CMC



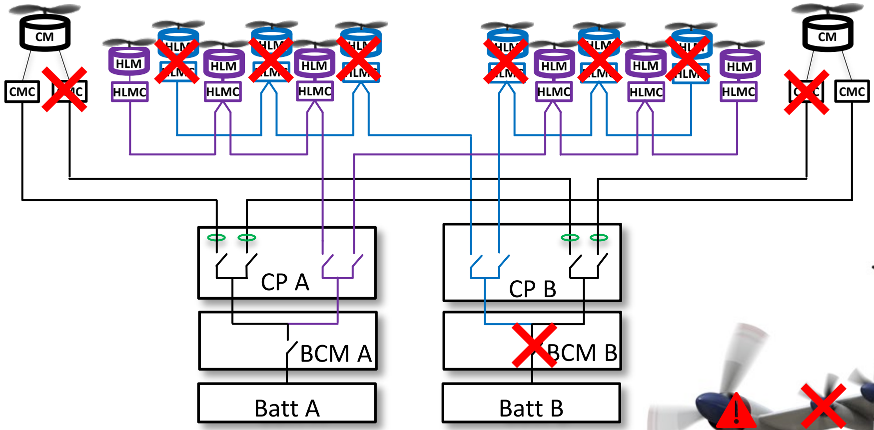
- Results in half power to one cruise motor
- Able to maintain altitude and airspeed
- Manageable through pilot training and mission energy management
- Pilots evaluated failure as level 1 handling qualities with no improvement needed

Simulated Failure: Prop Pitch Control



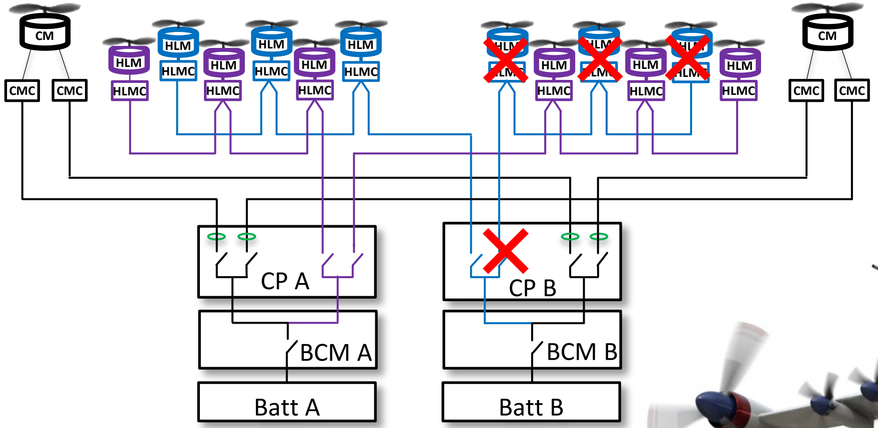
- Frozen or runaway propellor controller on one or both sides
- Minor impact on aircraft dynamics
- Not immediately noticeable without warning indicators or a change in power settings
- Evaluations of handling qualities found to be unnecessary

Simulated Failure: BCM



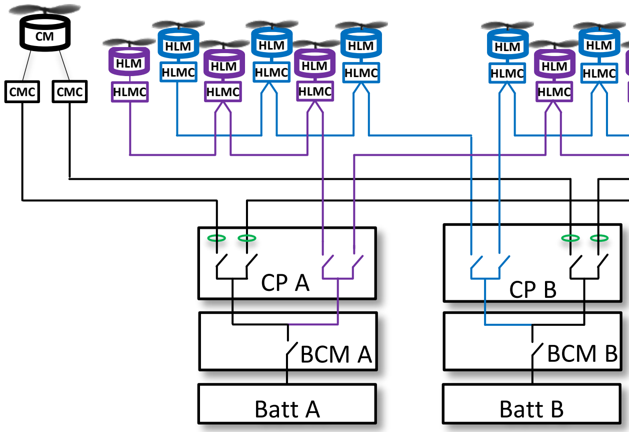
- Results in half power to both cruise motors, and loss of half of the HL propulsors
- Unable to maintain airspeed and altitude at certain flight conditions, initial transient is manageable
- Can fail both battery systems simultaneously for full power failure scenario
- Pilots evaluated failure as level 1 handling qualities with no improvement needed

Simulated Failure: High-Lift System



- Results in loss of three HL motors on one side
- Transient is manageable with training
- Largest impact during landing operations when HL motors are at highest power settings and cruise motors are at idle
- Pilots evaluated as level 1-2 handling qualities, where improvement is warranted but acceptable for test pilots

Simulated Failure: Cruise Motor

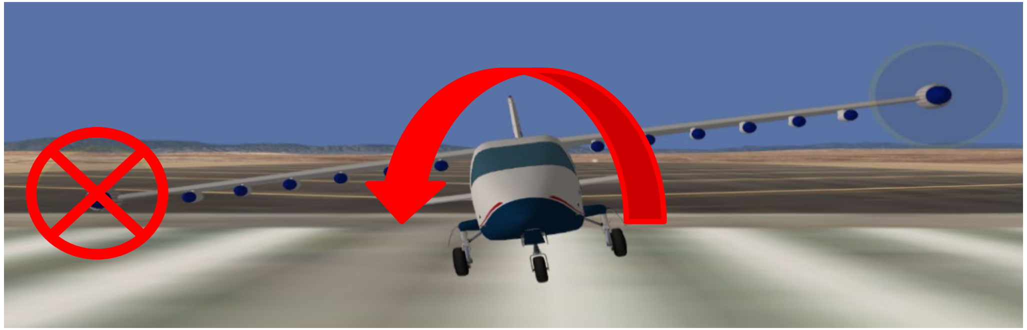


- Simulates complete loss of thrust to one or both cruise motors
  - Not a simulation of structural failure due to bearing failure
- In Mod III and IV, unable to maintain altitude and airspeed
- High workload during takeoffs due to large asymmetric transient combined with lack of control authority
- Pilots evaluated failure as level 2-3 handling qualities and necessitating improvements to the system or operations

- *Most failures are manageable through pilot training and energy management*
- *Cruise motor failures during takeoff require changes to takeoff operations or automatic supervisory system to mitigate*

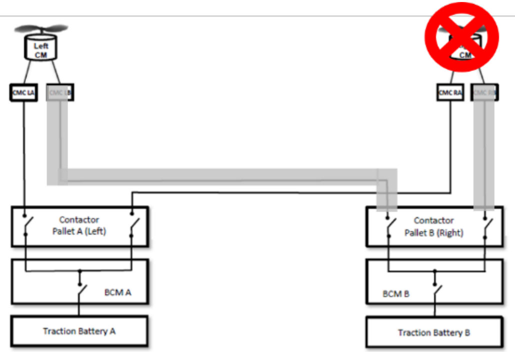
Mod III Full Power Single Motor Failure Study

- Pilot simulator evaluation found a full power, single motor failure during takeoff could be catastrophic
- Large yaw and roll rate potential
  - 3x moment arm of Mod II's
- Bank angle at touchdown
  - 7.3 degrees before propeller strike



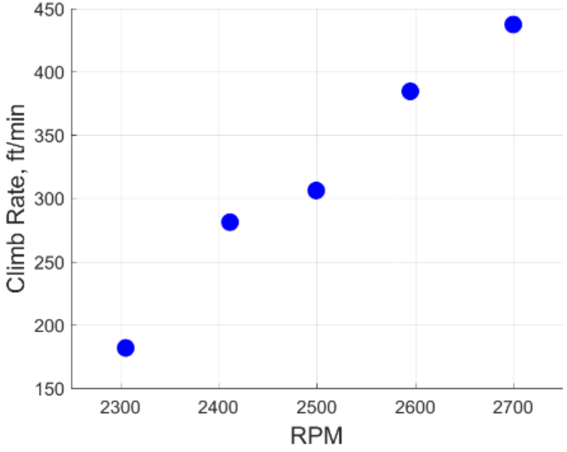
- Takeoffs conditions
  - Nominal takeoff
    - Vr = 88kts, Vy = 97kts, RPM = 2700 (max)
  - 3 strategies for asymmetric thrust mitigation
  - Multiple heights
    - 10, 50, 100, and 500 ft AGL
  - Cooper-Harper Ratings
    - Desired: < +/- 7 degrees bank at touchdown
    - Adequate: < +/- 9 degrees bank at touchdown

Asymmetric Thrust Mitigation Strategies



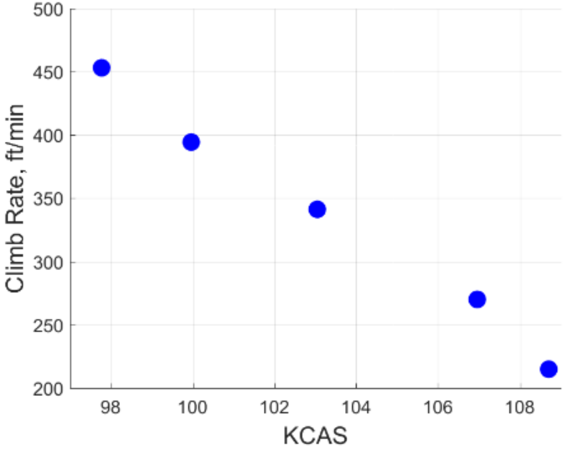
Automatic Thrust Inhibitor (ATI)

- Cuts power to healthy CMC
  - Reduce power by half
  - Once cut always cut
  - Responds in less than half a second
- Trade off between reduced asymmetry versus reduced power, possible false triggers, and development cost



Low Power Takeoff

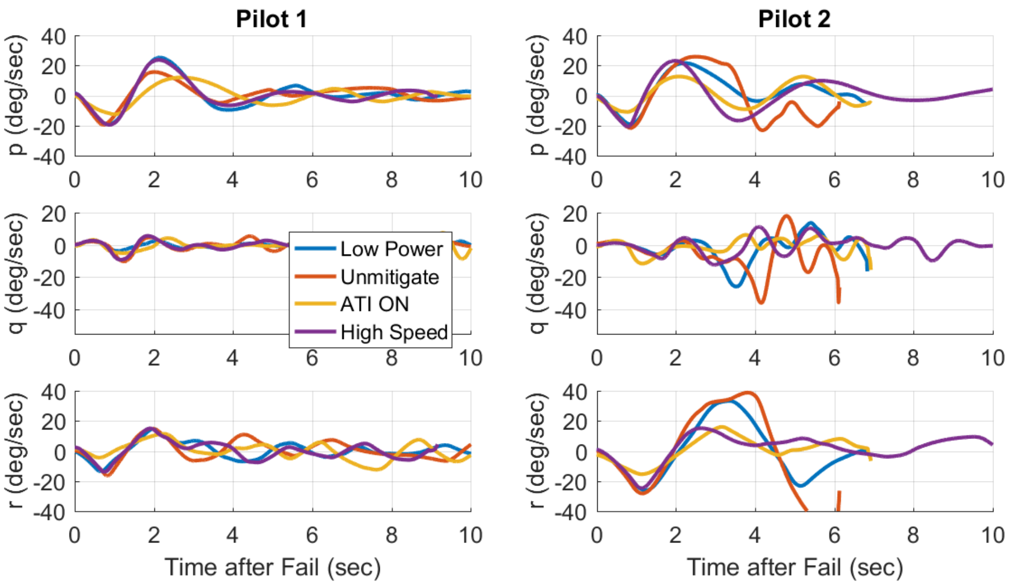
- Piloted sim study to determine minimum RPM takeoff
  - 2400 RPM based on pilot comments, ~270 ft/min
- Trade off between reduced initial thrust asymmetry versus climb out performance

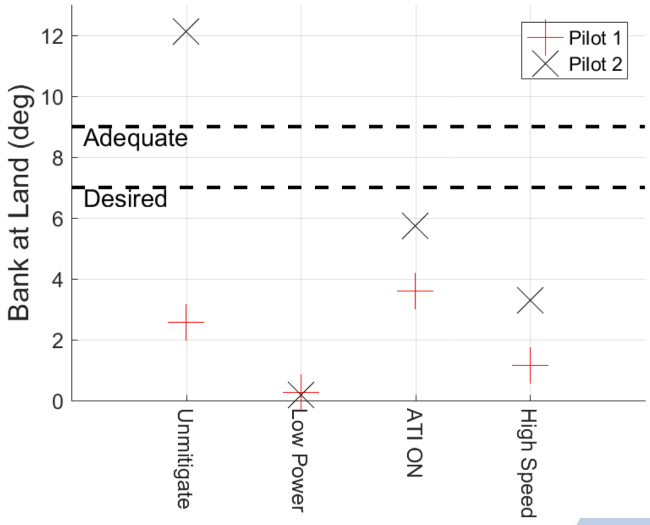


High Speed Takeoff

- Piloted sim study to determine highest climb out speed
  - Climb out at 103 kts based on pilot comments, ~ 340 ft/min
- Trade off between increase control authority versus climb out performance

Mod III Single Motor Failure Results



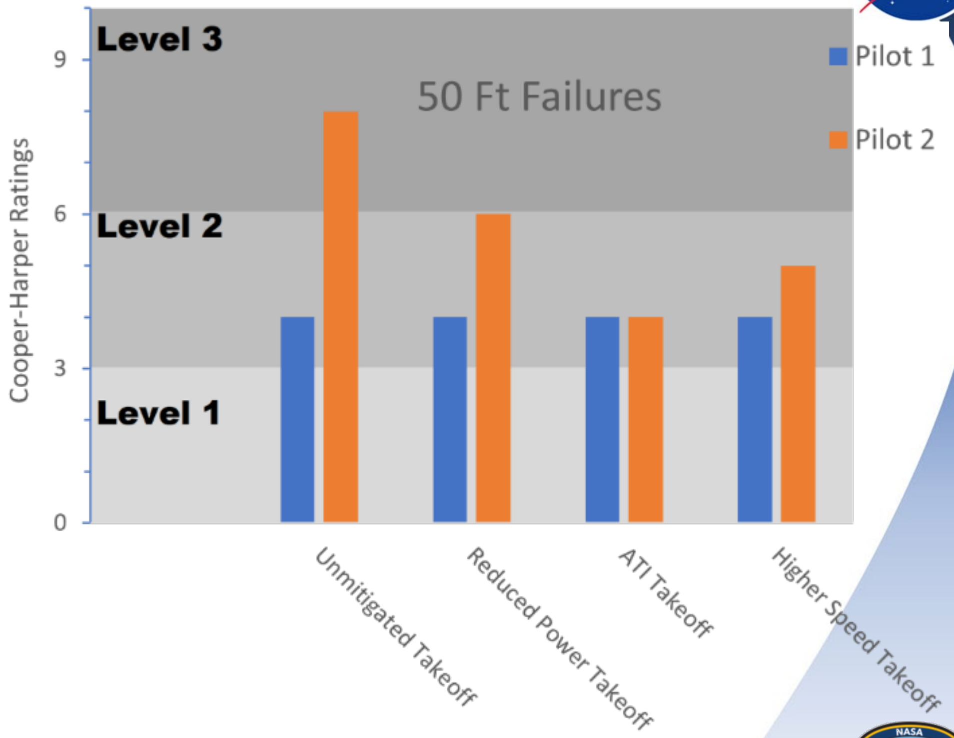


- Large roll and yaw rates develop for unmitigated, low power, and high-speed cases
- Pilots respond with no delay to failure
- ATI sees less rate buildup as other cases

- Pilot 1 and Pilot 2 achieved desired for all mitigated cases
- Significant improvement for Pilot 2

Mod III Single Motor Failure Flying Qualities

Failure Case	Pilot Comments
Unmitigated Takeoff	• No time for inputs other than open loop commands into power levers and control surfaces • Audio warning aids in response time to failure • Training will be key to survival
Reduced Power Takeoff	• Less power to maintain speed but able to get wings level • Felt the upset was a bit less dynamic but not much • Harder perform flare, harder touchdown
ATI Takeoff	• Less workload to recover wings level but worked harder to retain speed
Higher Speed Takeoff	• Upset was similar to nominal takeoff scenario • Had more control authority with rudder, had more speed for flare • Took more runway to reach height, potential to reach end of runway before gaining a safe altitude



Pilot assigned rating using CH flow chart
Level 1 = No improvement needed
Level 2 = Deficiencies warrant improvement
Level 3 = Deficiencies require improvement

Mod III Single Motor Failure Conclusions

- Pilots have to be on the failure as quick as possible or the rates would build up too quickly
- Required quick, open loop control inputs to recover wings level
- High workloads - the closer to the ground the more difficult
- Pilots thought training will be key to possibly manage the full motor out failure
- Pilots favored both using the ATI to reduce the asymmetry automatically and changing takeoff operations to use higher rotation and climb out speeds for greater control authority

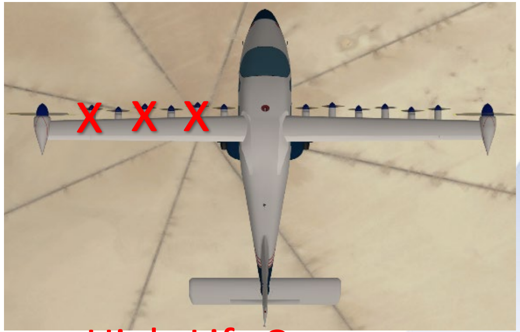
Distributed Thrust Takeoff (DiTTo)

- Strategy
  - Operate high-lift system in fixed-RPM mode during takeoff
    - Thrust distributed along the entire span of the wing
      - In fixed-RPM mode, high-lift thrust is not dependent on airspeed, constant 4800 RPM
    - Allows for reduction of cruise motor power
      - Reduce cruise motor RPM from 2700 to 1800
      - Cuts cruise motor power output by ~ 2/3 peak power at full torque
        - » Less thrust asymmetry upon failure

Motor Failure with DiTTo Sim Study

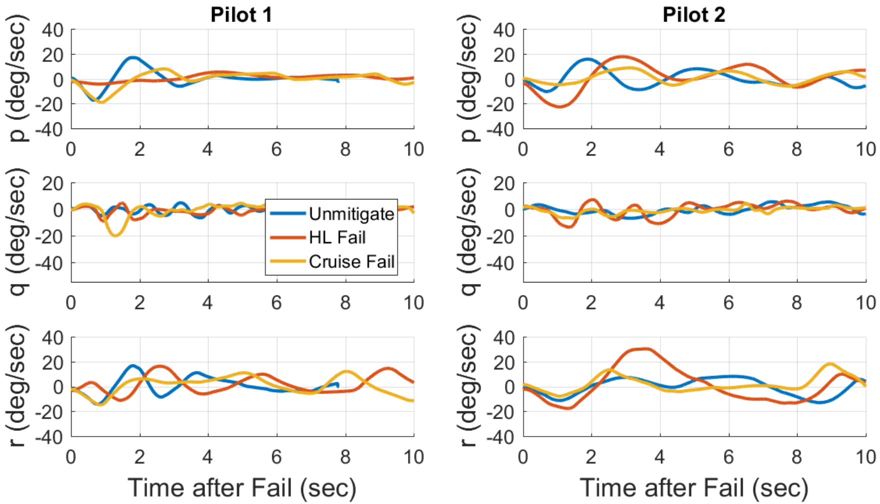
- Takeoff conditions
  - Unmitigated cruise motor failure (Mod III takeoff)
    - Vr = 88kts, Vy = 97kts, RPM = 2700 (max)
  - DiTTo High-lift system contactor failure
    - 3 motors on one side fail
    - Vr = 77kts, Vy = 84kts, RPM = 1800 (1700 min)
  - DiTTo Cruise motor failure
    - Vr = 77kts, Vy = 84kts, RPM = 1800
  - Multiple heights
    - 10, 50, 100, and 500 ft AGL
  - Cooper-Harper Ratings
    - Desired: < +/- 7 degrees bank at touchdown
    - Adequate: < +/- 9 degrees bank at touchdown

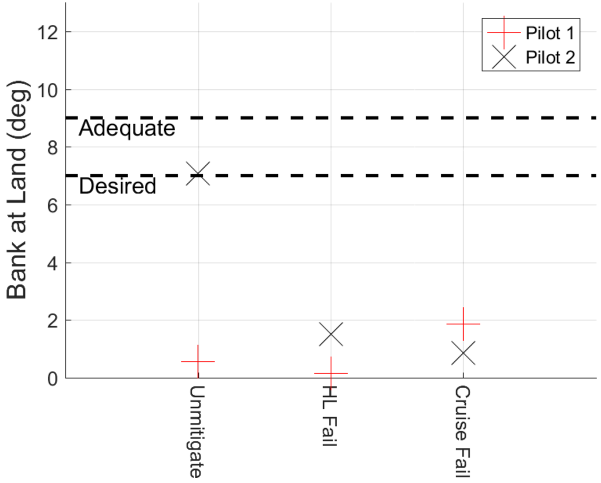
DiTTo Cruise Motor Failure (Cruise Fail)



High-Lift Contactor Failure (HL Fail)

Motor Failure with DiTTo Results



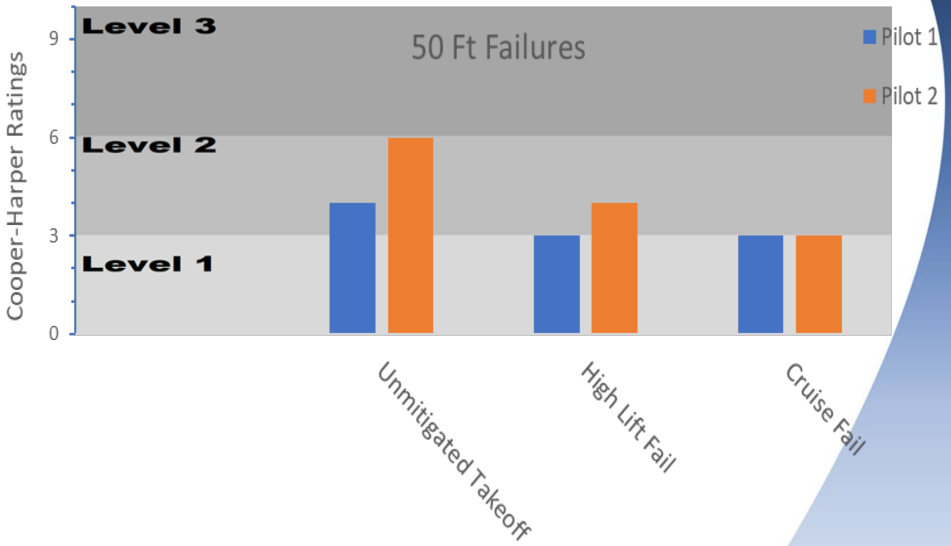


- DiTTo cases roll rates quickly reduced by both pilots
- Pilots respond with no delay to failure
- After recovery from DiTTo cases upset, the pilots were able to laterally work their way back to centerline

- Pilot 1 and Pilot 2 achieved desired for the DiTTo cases
- Pilot 2 achieved adequate for the unmitigated case

Motor Failure with DiTTo Flying Qualities

Failure Case	Pilot Comments
Unmitigated Takeoff	• No time for inputs other than open loop commands into power levers and control surfaces • Airspeed critical to recovery, very technique dependent • Training will be key to survival
DiTTo Cruise Motor Takeoff	• Lateral upset felt as dynamic as unmitigated case • Thought the upset was dynamic but controllable • Excess thrust help provide enough energy to recover and setup for touchdown
DiTTo HL Contactor Failure Takeoff	• Had plenty of energy to recover and correct back to centerline after upset • Used yoke disarm button quickly after failure to remove asymmetry • HDD warning lights helped diagnose failure



Pilot assigned rating using CH flow chart
Level 1 = No improvement needed
Level 2 = Deficiencies warrant improvement
Level 3 = Deficiencies require improvement

Motor Failure with DiTTo Conclusions

- DiTTo significantly reduces the pilot workload in the event of a cruise motor failure
  - After the failure, the high-lift system provides enough thrust for the aircraft to maintain altitude and airspeed while setting up for landing
- DiTTo introduces a new potential asymmetric event with the loss of several high-lift motors simultaneously
  - The asymmetry introduced with this event is easily overcome by the thrust from the fully throttled cruise motors

Lessons Learned

- Developing a simulator with high fidelity models allows pilots to become familiar with operating the research system early in the life of the Subproject
  - Key models for the X-57 simulator include the aerodynamic, failure modes, and battery models
- An accurate simulated cockpit provided an ability for pilots and HSI experts to evaluate and provide feedback on early prototypes of cockpit displays and alerts
- Having pilots fly and evaluate development models of the simulator can help quickly identify modeling errors

Backup

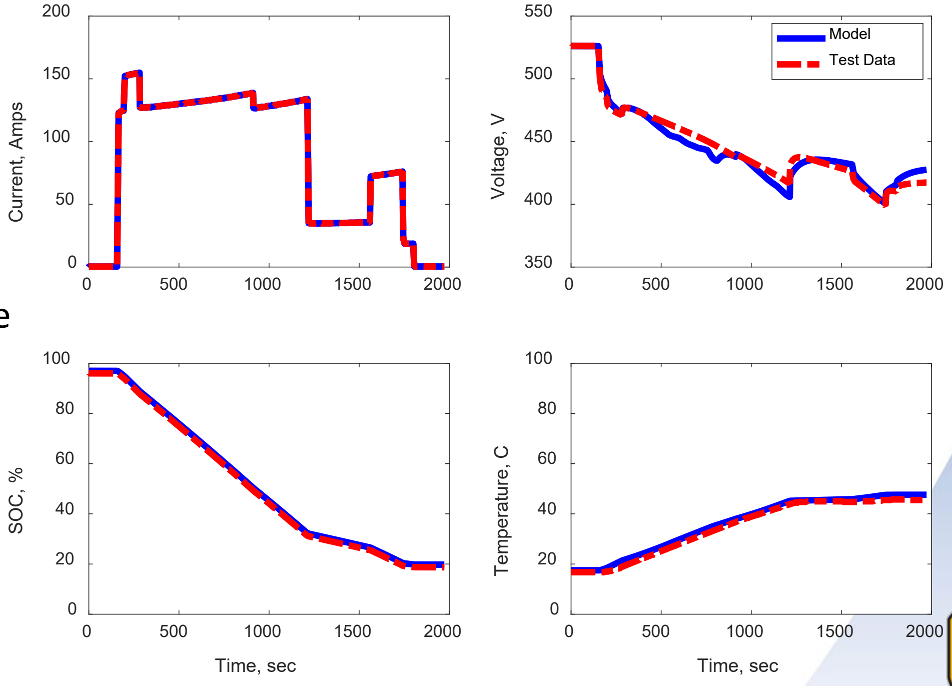
Propeller Model

- Constant speed system based on the MT Propeller system
  - Blade Element analysis (XROTOR) with detailed propeller geometry completed by X-57 Performance IPT
  - Derived from laser scan of propellor and calibrated to manufacturer-provided performance datasheet
    - Calibrated within 1% for all relevant areas of flight envelope
  - Ability to switch between auto and manual modes
    - Auto mode: Prop pitch controller responds to RPM command set by prop levers
    - Manual mode: Prop pitch controller respond to blade pitch command set by cockpit switches
  - Prop response was very slow. Prop pitch could take up to a minute to move from flat to fine pitch

Battery Model

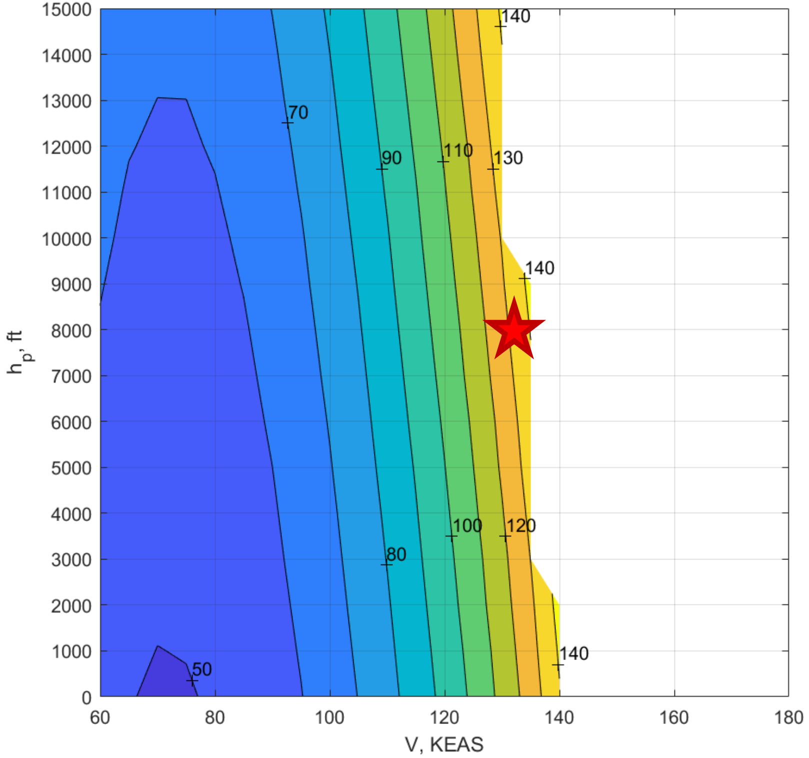
- Estimates of voltage, state of charge and cell temperature based on current draw
  - Thevenin Equivalent Circuit Model based on Subproject's Mission Planning Tool
  - Experimental data collected from battery cell testing matched with model computed values to determine Thevenin equivalent circuit variables
  - Predicts transient voltage effects throughout the power profile
  - Battery Performance Modeling on Maxwell X-57 - Jeffrey Chin
- Extensively used for mission planning and pilot rehearsal training

Battery Model vs X-57 Ground Run Comparison

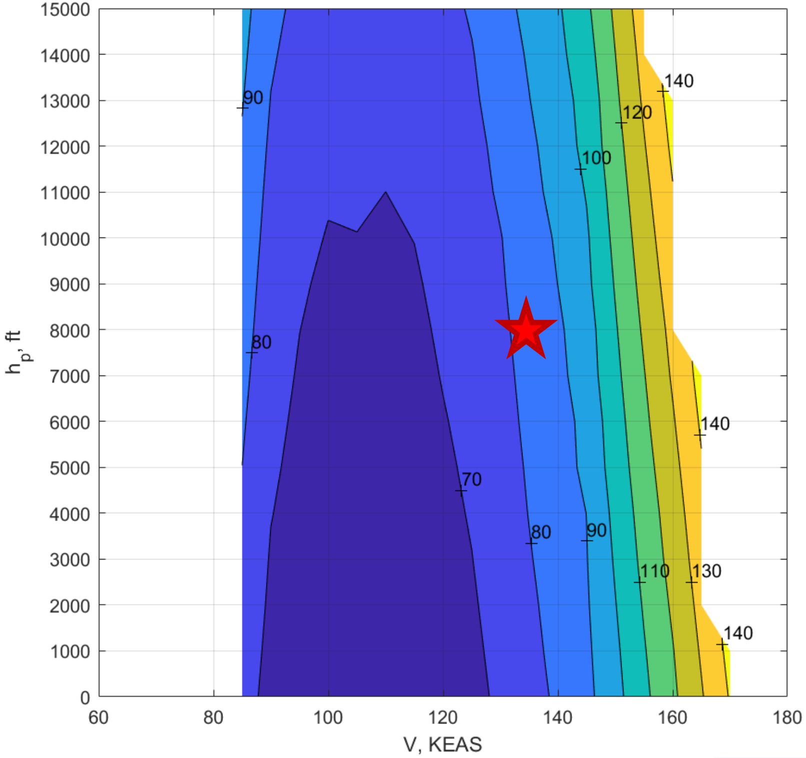


Cruise Performance

Mod II Cruise Motor Shaft Power, kW

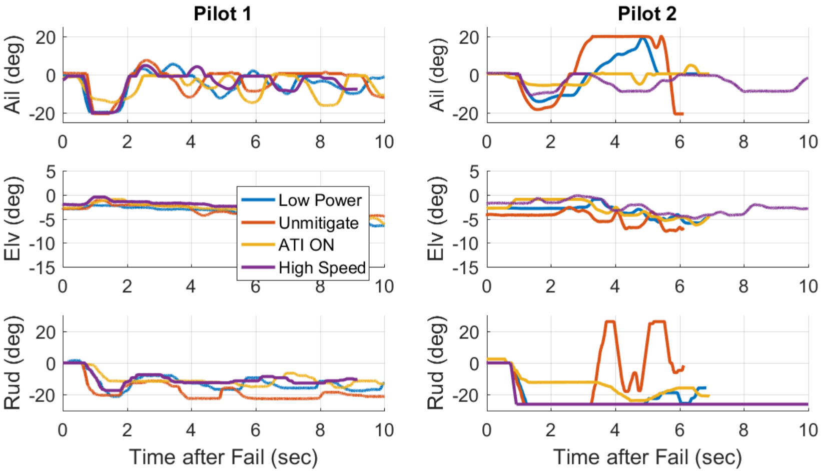


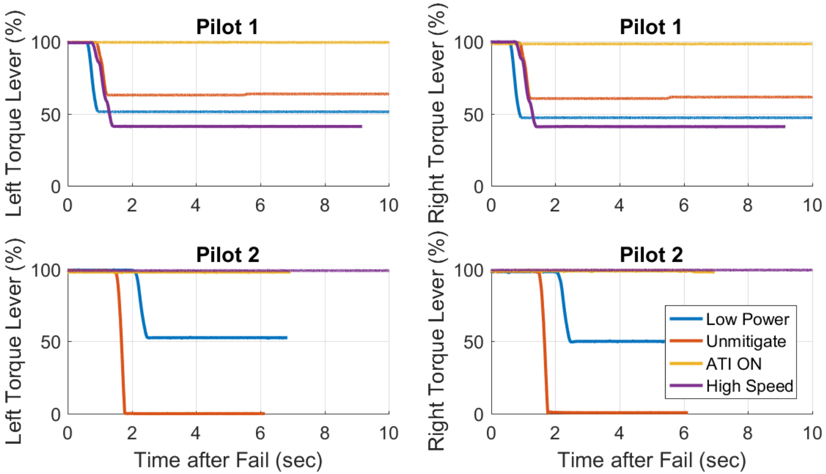
Mod III/IV Cruise Motor Shaft Power, kW



~30% reduction in power requirement at cruise evaluation point

Mod III Single Motor Failure
Pilot Control Inputs

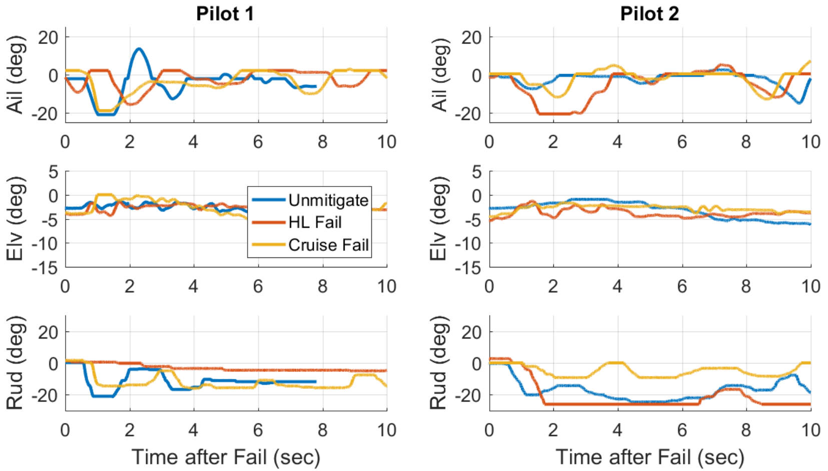


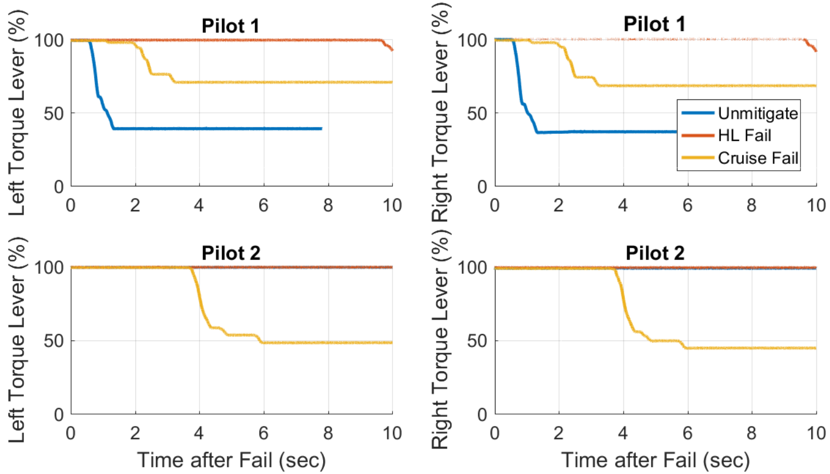


- Both pilots had quick, aggressive control surface inputs within the first second after failure
- ATI case require less aileron and rudder from pilots
- Pilot 1 inputted slight yoke push to recover airspeed

- Both pilots did not adjust torque lever for ATI case
- Pilot 1 pulled back torque lever halfway all other cases
- Pilot 2 pulled back torque lever full back for the unmitigated case

Motor Failure with DiTTo Control Inputs





- Both pilots had quick, aggressive control surface inputs within the first second after failure
- DiTTo HL failure pilot response similar to unmitigated case by Pilot 2
- DiTTo cruise motor failure require less control input to recover by both pilots

- Both pilots did not adjust torque lever for HL fail
- Pilot 1 pulled back torque lever halfway all other cases
- Pilot 2 pulled back torque lever full back for the DiTTo Cruise Fail