Overview of the X-57 Structural Requirements, Modifications, and Airworthiness

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Outline

• X-57 Maxwell Overview
• Structural Design
• Static Structural Analysis and Airworthiness
  – Mod II
  – Mod III
  – Mod IV
• Aeroelasticity

X-57 Wing loading 45 lb/ft²

Tecnam P2006T Wing loading 17 lb/ft²

June 17-21, 2019
**X-57 Maxwell Overview**

**Goals:**
- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

**Mod I**
- Ground validation of DEP
- Flight testing of baseline Tecnam P2006T

**Mod II**
- Ground and flight test validation of electric motors, battery, and instrumentation.

**Mod III**
- DEP wing development and fabrication
- Flight test electric motors relocated to wingtips on DEP wing including nacelles (but no DEP motors, controllers, or folding props).

**Mod IV**
- Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

**Spiral development process**
- Build – Fly – Learn

**Achieves Mod IV (Low-Speed) Objectives**

**Table: Development Phases**

<table>
<thead>
<tr>
<th>Mod</th>
<th>SRR</th>
<th>Preliminary Design</th>
<th>PDR</th>
<th>Detailed Design</th>
<th>CDR</th>
<th>Hardware Fabrication</th>
<th>System Integration and Testing</th>
<th>Flight Testing</th>
<th>Complete</th>
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<td>Y19 1Q</td>
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<td>Y21 3Q</td>
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</tbody>
</table>

**Timeline:**
- Y15 4Q: 2017 Q4
- Y16 4Q: 2018 Q1
- Y17 1Q: 2018 Q2
- Y19 1Q: 2018 Q3
- Y20 2Q: 2018 Q4
- Y21 3Q: 2019 Q1

**AIAA Aviation 2019**

**June 17-21, 2019**
X-57 Participating Organizations

- **NASA Langley**: Vehicle, Wing, Performance, Controls IPTs
- **NASA Armstrong**: Power, Instrumentation IPTs, Flight Ops
- **NASA Glenn**: Battery Testing, Thermal Analysis, HL Motor Controller Development (Mod IV)
- **Empirical Sys. Aero.**: Prime contractor
- **Scaled Composites**: Mod II Integration (batteries, motors, controllers, cockpit)
- **Joby Aviation**: Mod II Cruise Motor & Controller development
- **Xperimental**: Wing design and manufacturing
- **Electric Power Sys.**: Battery development
- **TMC Technologies**: Software V&V
- **Tecnam**: Baseline COTS airframe without engines

June 17-21, 2019

AIAA Aviation 2019
Structural Design/Analysis Roles

- **Mod II**
  - Scaled Composite – design, analysis and integration (batteries, motors, controllers, cockpit)
  - Joby Aviation - the Cruise Motor structural design and analysis

- **Mod III**
  - Xperimental LLC has lead role in Mod III/IV wing design and analyses
  - Wing IPT (AFRC & LaRC) provides verification and oversight for wing design/analyses

- **Mod IV**
  - ESAero - high-lift system (blade, hub and tail nacelle) structural design and analysis
  - GRC - heat sink design and analysis
  - Zone 5/Trust Automation - high-lift motor and nacelle structures design and analysis

**Responsibility:**
- Provide structural design requirements and airworthiness approach (AFRC)
- Oversight for all structural design/analyses (AFRC & LaRC)
- Conduct airworthiness design reviews (AFRC)
- Support structural ground and flight testing (AFRC)

- AFRC and Flight Safety Review Board have final technical authority
- ESAero is the Prime contractor and has lead role in structural design and analysis
X-57 Structural Design Criteria

• X-57 Wing will be designed for MTOW 3000 lbs (Tecnam P2006 MTOW is 2712 lbs)
  – To prevent overloading the wing and fuselage structure, maneuver load factor and landing load factor will be limited

• The primary structures are designed to meet the X-57 loads requirements
  – Mod II: Cruise motor, new motor mount and its supporting structure, battery mount, floor structure, equipment support structure and fuselage
  – Mod III: Composite wing and wing/fuselage attachment
  – Mod IV: High-Lift assembly structure

• Aircraft Structural Safety of Flight Guidelines AFRC G-7123.1-001 along with industry standards is being use as a guideline
  – 2.25 FS – for metallic structures if structural design is verified by analysis only
  – 3.00 FS – for composite structures if structural design is verified by analysis only (when using well established composite processes and materials)
  – 1.80 FS – for either metallic or composite structure when verified by proof tests to 120% of flight limit loads

• All structure MUST have positive Margin(s) of Safety
Composite Structures Verification and Validation (V&V) Process

- Building-block approaches for testing and analysis
- Contractors provide their composite cure process, process specification, and process control for AFRC review and approve
- The coupon testing and verification requirements have to negotiate with project management regarding risk and budget
X-57 Airworthiness Approach

### Ultimate Factors of Safety for Mod II

<table>
<thead>
<tr>
<th>Structure Type</th>
<th>Factor</th>
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<tbody>
<tr>
<td>Metallic structures - verified by analysis only</td>
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<tr>
<td>Composite structures - verified by analysis only</td>
<td>3.0</td>
</tr>
<tr>
<td>Existing primary and original structures</td>
<td>1.5</td>
</tr>
<tr>
<td>Non-primary structures and no structural analysis</td>
<td>N/A</td>
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### Ultimate Factors of Safety for Mod III Wing

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<th>Component</th>
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</tr>
<tr>
<td>Instrumented for loads monitoring during envelope expansion</td>
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</tr>
<tr>
<td>Control surface system and linkage: Metallic structures – verified by analysis only</td>
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### Ultimate Factors of Safety for Mod IV HL System

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X-57 Mod II

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Mod II Loads Requirements

- Due to the max gross weight increased, Mod II maneuver limit load factor will be reduced and limited to 3.4g
- The primary structures are designed for
  - Flight Maneuver and Ground loads
  - Emergence landing / Crash Loads: The items of mass within cabin that could injure an occupant, will be secured to fuselage structure to withstand the 18g cash loads conditions.
- Cruise Motor, Motor Mount and Nacelle/Pylon are designed for
  - Flight Maneuver and Ground loads
  - Powerplant loads (Thrust, Torque, P-factor, and Gyroscopic)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Design Limit Load Factor (g)</th>
<th>Factor of Safety</th>
<th>New metallic structure</th>
<th>Exiting structure</th>
<th>Condition</th>
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</thead>
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<tr>
<td>Down, Nz</td>
<td>3.4</td>
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<td>Maneuver loads</td>
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<td>Forward, Nx</td>
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<td>Sideward, Ny</td>
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<td>Up, Nz</td>
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<td>2.25</td>
<td>1.5</td>
<td>Maneuver loads</td>
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<tr>
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<td>-2</td>
<td>2.25</td>
<td>1.5</td>
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X-57 Mod II VN Diagram
Cruise Motor Design and Analysis

Design Loads
- Flight maneuver loads
- Ground & landing loads
- Powerplant loads (applied at the propeller CG)
  - Max thrust
  - Max torque
  - P-factor loads
  - Gyroscopic loads

Cruise motor design

Modal analysis: First Bending Mode 154Hz – 9240 RPM
Mod II Motor Mount Design

Design Loads
- Flight maneuver loads
- Ground & landing loads
- Powerplant loads
  - Max thrust
  - Max torque
  - P-factor loads
  - Gyroscopic loads

Strain Gages Instrumentation

Motor Mount and Truss
4130 Welded Stress Truss
Motor adapter

FEM Analysis
Static, Buckling, and Modal analysis

Motor mount loads calibration test
Develop load equation for in-flight Torque and Thrust measurement

Integration (Top View)
X-57 Battery Integration

Design Loads

- Flight maneuver loads
- Crash loads

Contactor pallet (left and right)

Fwd Battery Mount

Aft (Cargo) Battery Mount

Battery Venting

Battery Venting (3” dia)
Hermetically seals battery smoke/eject from cabin volume

June 17-21, 2019

AIAA Aviation 2019
X-57 Aircraft Modification

Air Data Probe

Air Data Boom 100600-01

Adapter
Tube
Bulkhead Fitting
Nose Fit (Proof test 100%)

Secondary Egress

Equipment Pallet (co-pilot seat)

Cockpit Display

June 17-21, 2019

Upgraded 4-point harness

Per AC21-34 SHOULDER HARNESS - SAFETY BELT INSTALLATIONS & AC 43.13-2B Ch 9 SHOULDER HARNESS INSTALLATIONS:
**X-57 Mod III**

### Ultimate Factors of Safety for Mod III Wing

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X-57 Wing Design

- Designed and Fabricated by Xperimental
- Composite: semi-monocoque wing
- Single and continuous main spar: responsible to carry normal and axial loads (shear and bending)
- Working skin: buckling free and responsible to carry torsional loads
- Front and rear spars used to receive external loads (nacelles and controls)
X-57 Wing Loads Analysis

- Total 20 load cases
- Flight loads
  - Maneuver load factor (+3.42 / –1.37g)
  - Asymmetric thrust at takeoff and at cruise
- Ground loads
- Powerplant loads
  - Max cruise and High-Lift motor thrust and torque
  - P-factor and Gyroscopic loads

Aerodynamic loads (wing and control surface loads)

Load application using RBE3 and CFD surface pressure mapped on the wing surface

**Mod II and IV V-n Diagram (3000 lbs)**

**Case #** | **Airspeed** | **Load Factor** | **Weight** | **CG position** | **Altitude** | **Description**
---|---|---|---|---|---|---
1 | 89kEAS (Vs) | +1.0 | 133SN | 4044.81mm | 0 ft | Vl – 1g ASL
2 | 152kEAS (Vs) | +2.91 | 133SN | 4044.81mm | 0 ft | Vi max re de stail ASL
3 | 190kEAS (Vs) | +3.42 | 133SN | 4044.81mm | 0 ft | Vl – positive maneuver ASL
4 | 190kEAS (Vs) | +3.42 | 133SN | 4044.81mm | 0 ft | Vl – positive maneuver ASL
5 | 190kEAS (Vs) | +1.71 | 133SN | 4044.81mm | 0 ft | Vl – negative gust ASL
6 | 190kEAS (Vs) | +1.0 | 133SN | 4044.81mm | 15000 ft | Vl – 1g, high altitude
7 | 152kEAS (Vs) | +2.91 | 133SN | 4044.81mm | 15000 ft | Vl max re de stail high alt.
8 | 164kEAS (Vs) | +1.0 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
9 | 164kEAS (Vs) | +1.2 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
10 | 164kEAS (Vs) | +2.8 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
11 | 164kEAS (Vs) | +3.42 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
12 | 164kEAS (Vs) | +3.42 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
13 | 164kEAS (Vs) | +2.8 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
14 | 164kEAS (Vs) | +2.8 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
15 | 164kEAS (Vs) | +2.8 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.
16 | 164kEAS (Vs) | +2.0 | 133SN | 4044.81mm | 15000 ft | Vl – positive maneuver high alt.

**Load Factor**

<table>
<thead>
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<th>Case #</th>
<th>Airspeed</th>
<th>Altitude</th>
<th>Description</th>
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<tr>
<td>17</td>
<td>164</td>
<td>133SN</td>
<td>4044.81mm</td>
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<td>18</td>
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<td>19</td>
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**CG position**

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X-57 Wing Structures Airworthiness Approach

- To demonstrate and validate the structural integrity of the wing for flight
- Design to 1.8, Proof to 1.2, Full flight instrumentation, Fly to 1.0

Design Limit Load (DLL)

<table>
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<tr>
<th>DLL</th>
<th>Description</th>
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<tbody>
<tr>
<td>180%DLL</td>
<td>Structural Margins Greater Than or Equal to zero</td>
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<tr>
<td>120%DLL</td>
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</tr>
<tr>
<td>100%DLL</td>
<td>Pre-Test Inspection (NDI)</td>
</tr>
<tr>
<td>0%DLL</td>
<td>Aero and Inertia Design Load</td>
</tr>
</tbody>
</table>

- Design and Analysis FOS = 1.8
- Proof Test and Load Calibration
- Flight Test and Periodic Inspections

Flight Test Monitoring
Monitor loads at root inboard station
X-57 Wing Testing

- Proof and loads calibration testing
  - Will be conducted at AFRC in August 2019
  - Qualification test the wing structure to 120% Design Limit Load (DLL)
  - Qualification test cruise motor mount hard points to 120% DLL (axial in-plane)
  - Produce a database suitable for deriving wing load equations by applying a set of known loads and recording strain gage outputs
  - Verify the control surfaces (flaps and ailerons) are free of binding while the wings are loaded to 100% DLL.
  - Collect wing deflection measurement data for FEM model comparison and model tuning
- Ground Vibration Test (GVT)
  - Wing on proof test fixture
  - Identify the structural modes and the associated mode shapes as well as frequency and damping values of the wing before the integrated aircraft GVT
Fuselage Wing Attachment Structural Analysis

- Asymmetric thrust at take-off load case is the critical load case for the fuselage wing attachment.
- Require new wing attachment and new doubler
- Existing fuselage FS set at 1.5, same as Tecnam FS
- All new hardware FS set at 2.25 (no-test)

New wing attachment
- Drilled and tapped screws using Helicoil® threaded inserts (8 places)

New Doubler
- 0.08” thick
- 6.75” long

Factors of Safety
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<tr>
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<th>Existing FS Ult.</th>
<th>New FS Ult.</th>
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<tr>
<td></td>
<td>1.5</td>
<td>2.25</td>
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<tr>
<td>No-test FS</td>
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Asymmetric Thrust at Take-Off Case
- Inertia relief boundary conditions
  - Full thrust one side + Half thrust other side + 2.0 x VS 1g ASL
X-57 Mod IV

Ultimate Factors of Safety for Mod IV HL System

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Mod IV High Lift Concept Overview

- PDR completed in April, 2019
- Design Loads (Inertial, Thrust, Torque, Imbalance, P-factor, Gyroscopic, etc)
- Decoupled from motor operational dwell frequencies: 5460 RPM / 91 Hz.
- To avoid coupling with wing flutter modes

**Folding Propellers**
Blades fold back and “stow” onto Nacelle

**HL Exploded View**

**Structural Model**
Long Nacelle FEM
Short Nacelle FEM

HL Tail Nacelle
Mod IV Airworthiness Approach

• Design and Analysis
  – 2.25 FS (for metallic) and 3.0 FS (for composite).
• Hub, Blade Retention, and Counterweight Proof Test - Per 14 CFR 35.35(a)(b)(c) and AC 35-1
  – Proof test for a period of one hour to 200% maximum expected centrifugal load at max rpm operation
• Acceptance Testing
  – Each hub, blade retention system, and counterweights: proof test to 120% operational loads limits for 2 times of a normal flight operation hour (Whirl testing)
  – Each motor assembly: proof test to 120% of operational loads limits for 2 times of a normal flight operation hour
• Endurance/Fatigue Testing
  – HL assembly: test for 4 times the expected operation lifespan to the operational loads
• Periodic Inspections during flight operations
Aeroelasticity
Aeroelasticity: Airworthiness Approach

- Finite Element Model (FEM) development
  - Structural and Aero models
- Flutter analyses
  - Whirl Flutter: propeller/hub/motor/pylon assembly mounted to wing
  - Classical Vehicle Flutter: Bending/Torsion coupling
- Ground Vibration Test (GVT) to measure natural modes, frequencies and structural damping
  - Correlate structural model for final flutter analyses
  - Conduct multiple GVTs (prop & hub, wing on proof test fixture, wing on fit-check fuselage) to reduce project risk by not waiting for the integrated aircraft GVT
- Flight flutter testing for envelope clearance
  - Instrumentation distribution on aircraft
  - Control room monitoring

Component GVT

Wing on Proof Test Fixture GVT

Example: Cruise Prop/Hub GVT on Foam Soft Support

Soft Support (Bungee) Design for GVT

Support aircraft nose around NG bulkhead
Support MLG axles by attaching bungee support beams to jacks
Thank You