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

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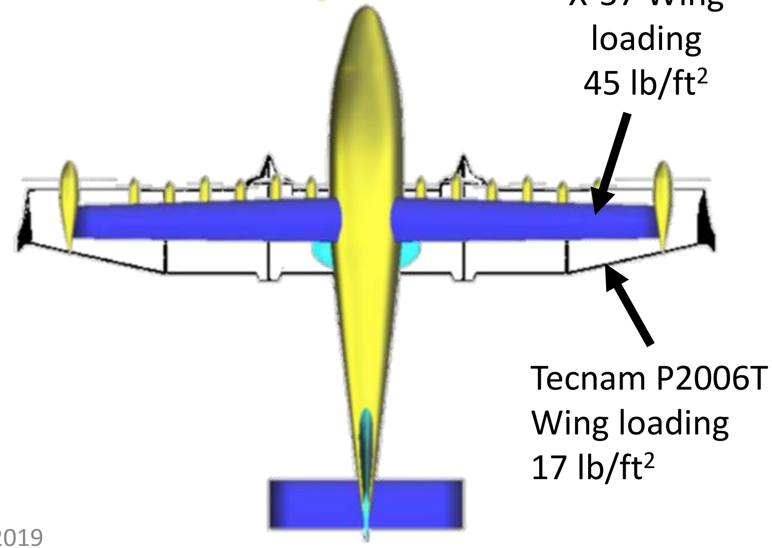
Outline

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



X-57 Maxwell Overview

Mod	SRR	Preliminary Design	PDR	Detailed Design	CDR	Hardware Fabrication	System Integration and testing	Flight Testing	Complete
I									
II			Y15 4Q		Y16 4Q			Y20 2Q	
III					Y17 1Q			Y21 3Q	
IV			Y19 1Q						

Mod I

Ground validation of DEP

Flight testing of baseline Tecnam P2006T

Goals:

- Establish Baseline Tecnam Performance
- Pilot Familiarity

Mod II

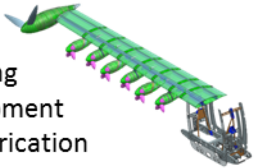
Ground and flight test validation of electric motors, battery, and instrumentation.

Goals:

- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

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).

Achieves Mod III (High-Speed) Objectives

Mod IV

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

Achieves Mod IV (Low-Speed) Objectives

Spiral development process
- Build – Fly – Learn

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)

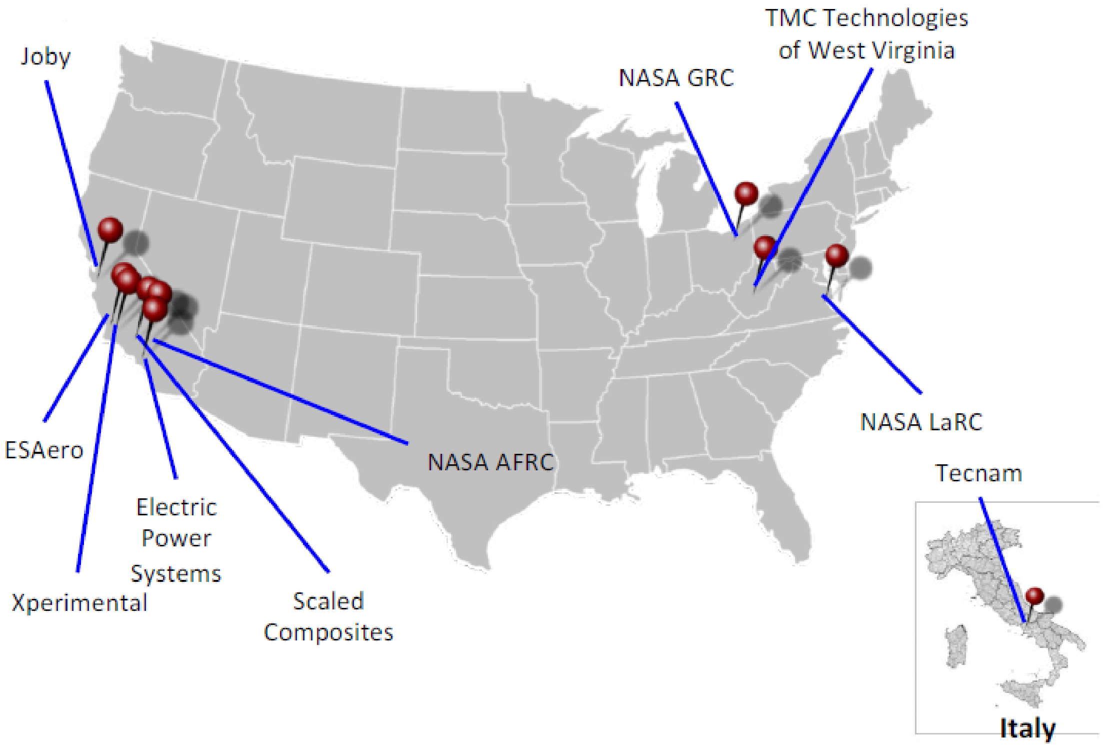
Joby Aviation: Mod II Cruise Motor & Controller development

Xperimental: Wing design and manufacturing

Electric Power Sys.: Battery development

TMC Technologies: Software V&V

Tecnam: Baseline COTS airframe without engines



Structural Design/Analysis Roles

- 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

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

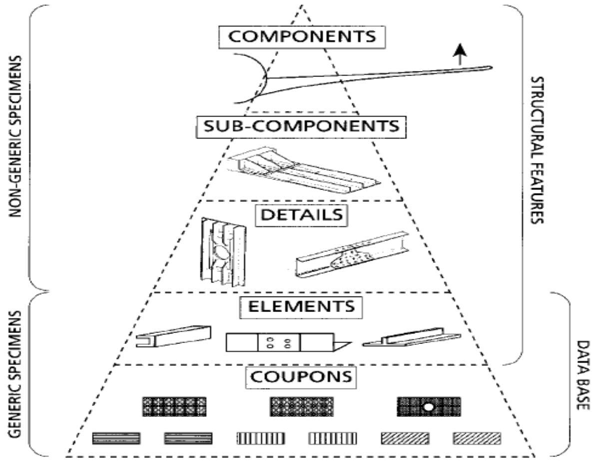
- ESAero - high-lift system (blade, hub and tail nacelle) structural design and analysis
- GRC - heat sink design and analysis
- Zone 5/Trust Automation - high-lift motor and nacelle structures design and analysis

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

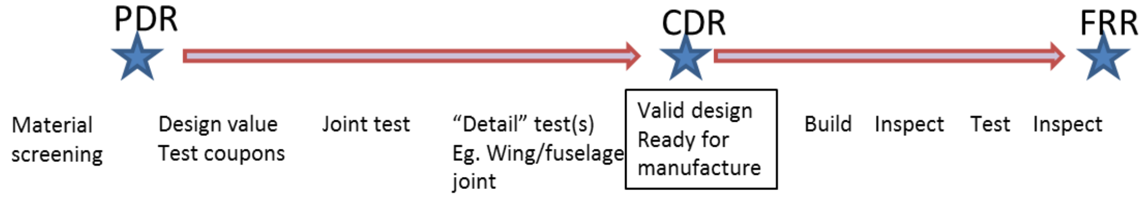
Composite Structures Verification and Validation (V&V) Process

- 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



From: MIL-HDBK-17-1F (2002)

Composite life cycle



X-57 Airworthiness Approach

- Mod II

Ultimate Factors of Safety for Mod II	
Metallic structures - verified by analysis only	2.25
Composite structures - verified by analysis only	3.0
Existing primary and original structures	1.5
Non-primary structures and no structural analysis – verified by proof test	N/A

- Mod III

Ultimate Factors of Safety for Mod III Wing	
Mod III Wing: metallic or composite structure • Verified by proof tests to 120% of flight limit loads • Instrumented for loads monitoring during envelope expansion	1.8
Control surface system and linkage: Metallic structures – verified by analysis only	2.25

- Mod IV

Ultimate Factors of Safety for Mod IV HL System	
Metallic structures if structural design is verified by analysis only	2.25
Composite structures - verified by analysis only	3.0
Hub, Blade retention structures - verified by proof tests to 200% of max centrifugal load.	>2.0

X-57 Mod II

Ultimate Factors of Safety for Mod II	
Metallic structures - verified by analysis only	2.25
Composite structures - verified by analysis only	3.0
Existing primary and original structures	1.5
Non-primary structures and no structural analysis – verified by proof test	N/A

Mod II Loads Requirements

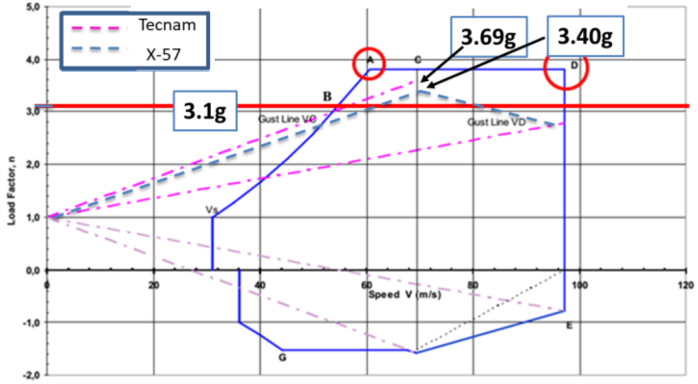
- Due to the max gross weight increased, Mod II maneuver limit load factor will be reduced and limited to 3.4g
- The primary structures are designed for
  - Flight Maneuver and Ground loads
  - Emergence landing / Crash Loads: The items of mass within cabin that could injure an occupant, will be secured 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)

Critical Load Cases for primary structure

	Design Limit Load Factor (g)	Factor of Safety		Condition
		New metallic structure	Exiting structure	
Down, Nz	3.4	2.25	1.5	Maneuver loads
Forward, Nx	-18	1	1	Crash loads
Sideward, Ny	+/-4.5	1	1	Crash loads
Up, Nz	-6	1	1	Crash loads

	Design Limit Load Factor (g)	Factor of Safety		Condition
		New metallic structure	Exiting structure	
Down, Nz	3.4	2.25	1.5	Maneuver loads
Forward, Nx	-3	2.25	1.5	Maneuver loads
Sideward, Ny	-1.33	2.25	1.5	Maneuver loads
Up, Nz	-2	2.25	1.5	Maneuver loads

X-57 Mod II VN Diagram

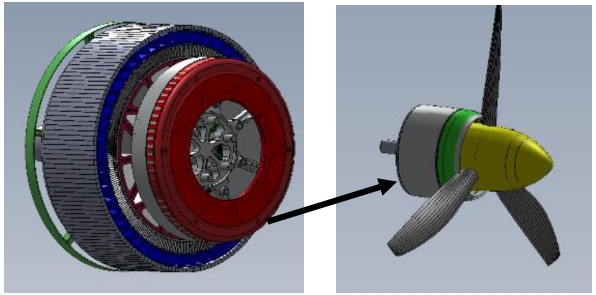


Cruise Motor Design and Analysis

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



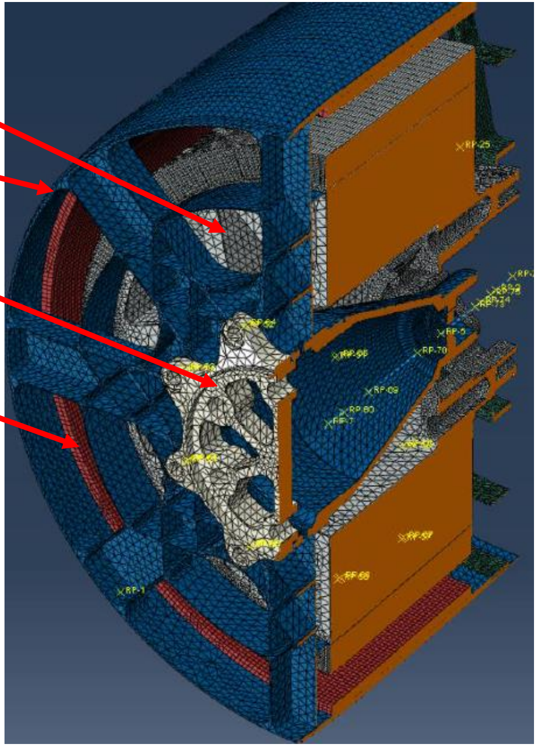
Cruise motor structure

Stator: AL7075-T6

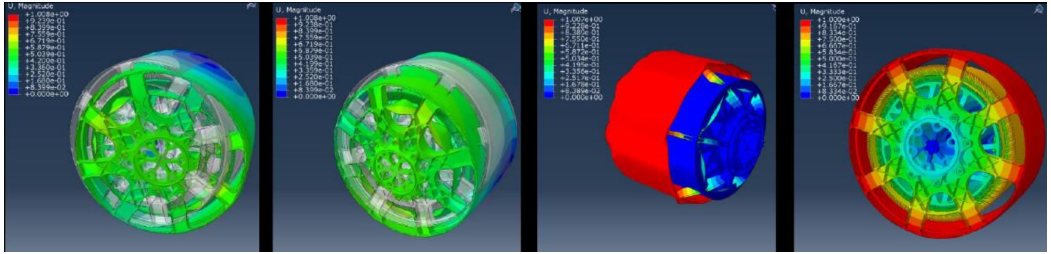
Rotor

Propeller Mount

Magnets



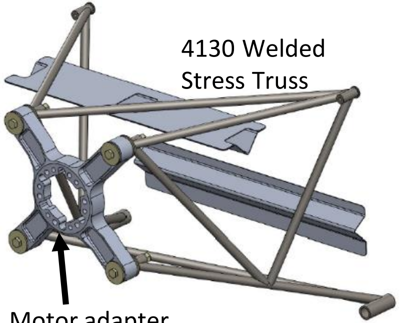
Modal analysis: First Bending Mode 154Hz – 9240 RPM



Mod II Motor Mount Design

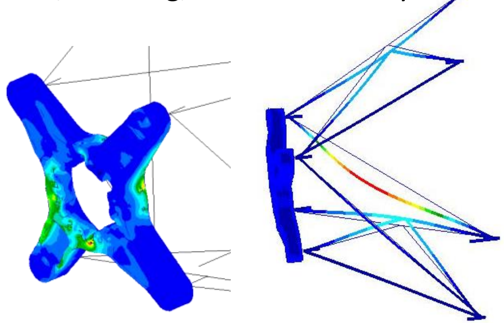
Design Loads
- Flight maneuver loads
- Ground & landing loads
- Powerplant loads
    - Max thrust
    - Max torque
    - P-factor loads
    - Gyroscopic loads

Motor Mount and Truss

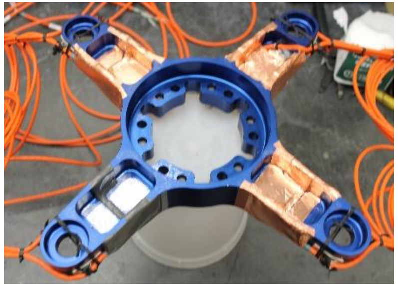


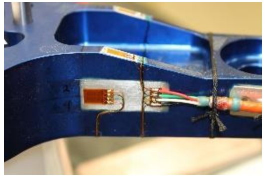
FEM Analysis

Static, Buckling, and Modal analysis



Strain Gages Instrumentation





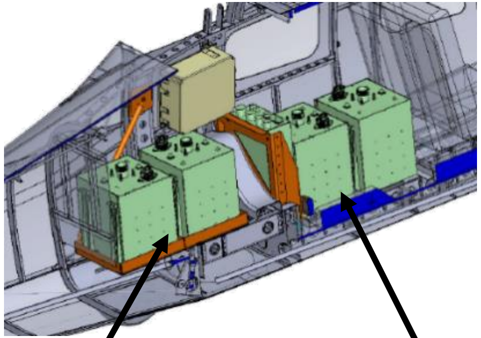
Motor mount loads calibration test

Integration (Top View)

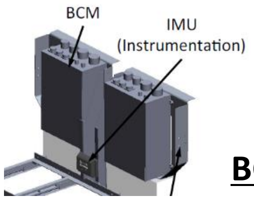
X-57 Battery Integration

Design Loads

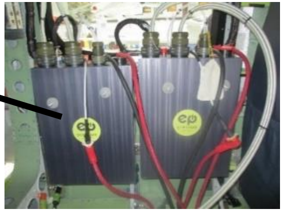
- Flight maneuver loads
- Crash loads



Contactor pallet (left and right)

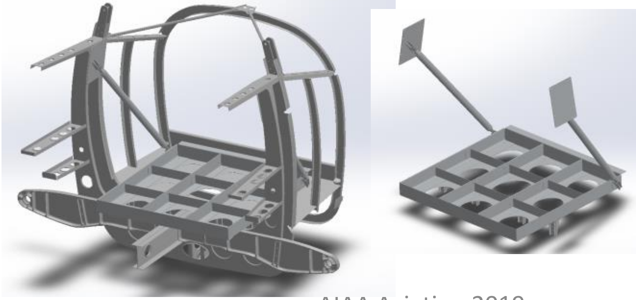


BCM

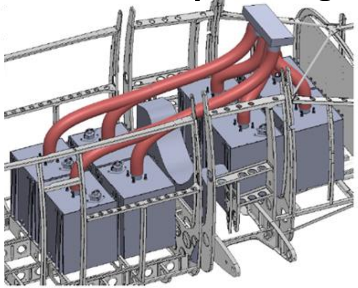


Fwd Battery Mount

Aft (Cargo) Battery Mount



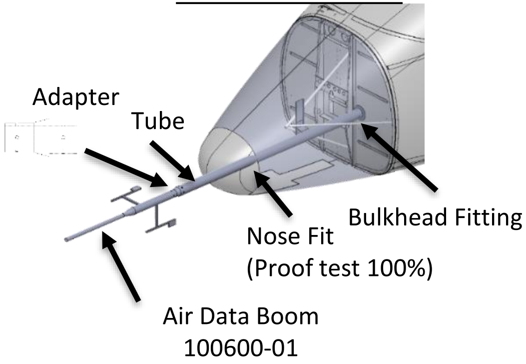
Battery Venting



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

X-57 Aircraft Modification

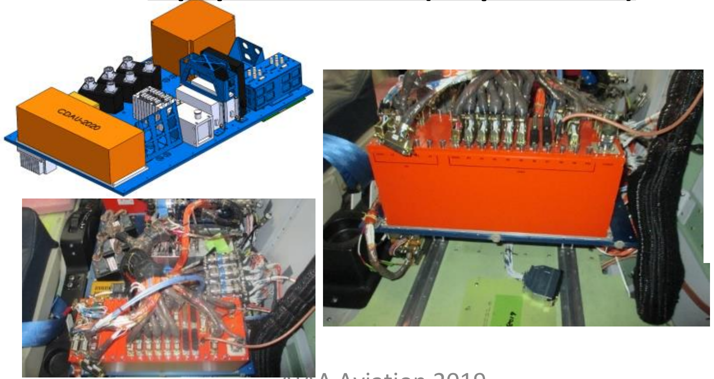
Air Data Probe



Secondary Egress

Cockpit Display

Equipment Pallet (co-pilot seat)

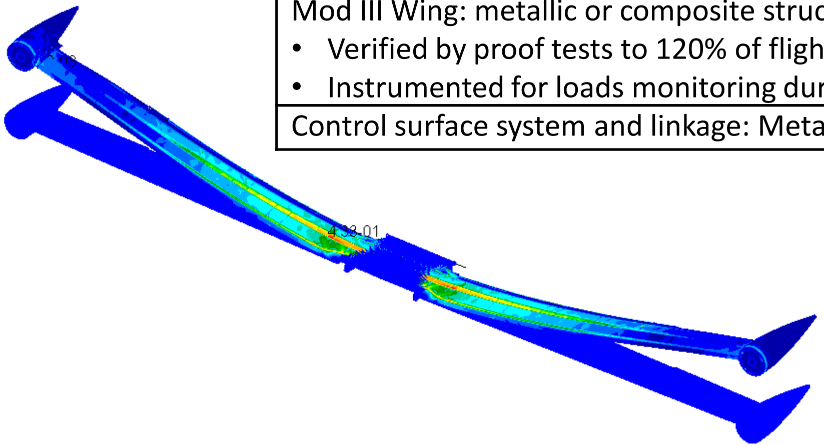


Upgraded 4-point harness

Per AC21-34 SHOULDER HARNESS - SAFETY BELT INSTALLATIONS & AC 43.13-2B Ch 9 SHOULDER HARNESS INSTALLATIONS:

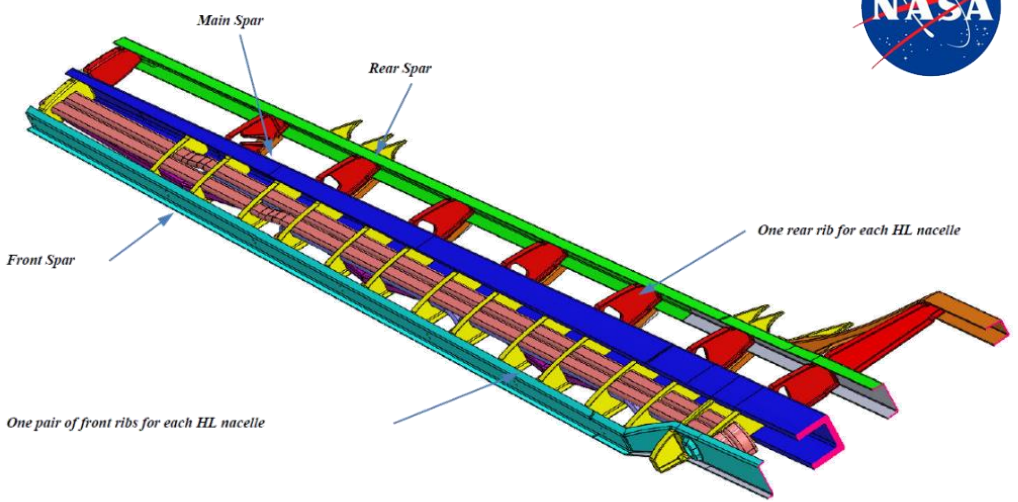
X-57 Mod III

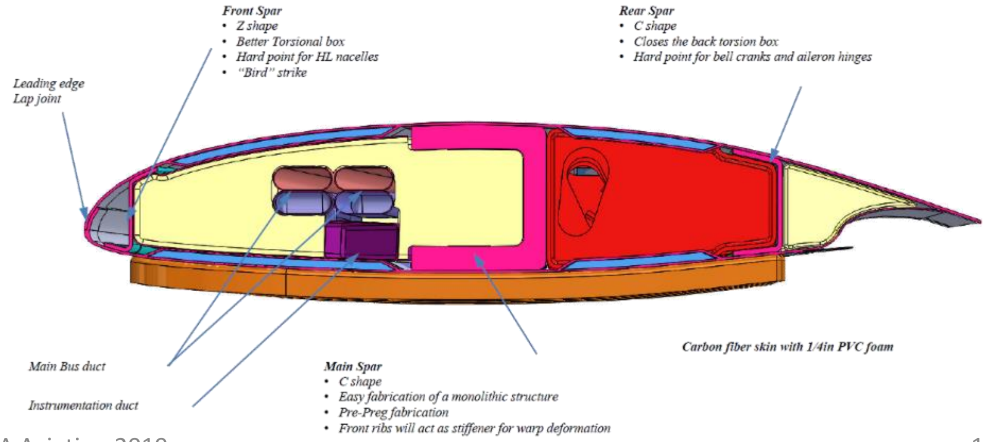
Ultimate Factors of Safety for Mod III Wing	
Mod III Wing: metallic or composite structure • Verified by proof tests to 120% of flight limit loads • Instrumented for loads monitoring during envelope expansion	1.8
Control surface system and linkage: Metallic structures – verified by analysis only	2.25



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)

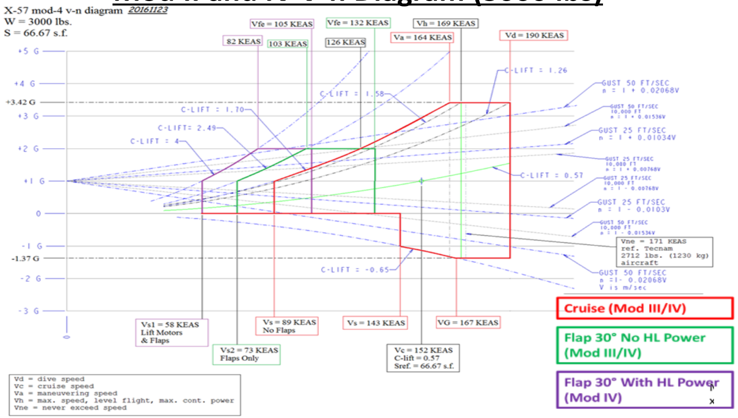




X-57 Wing Loads Analysis

- 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

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

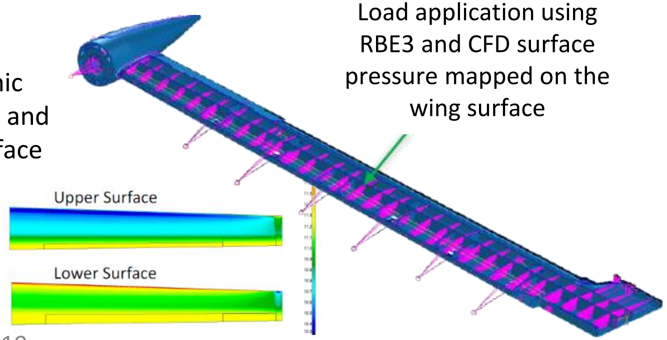


Case #	Airspeed	Load Factor	Weight	CG position	Altitude	Description
1	89kEAS (Vs)	+1.0	13351N	4044.81mm	0ft	Vs – 1g ASL
2	152kEAS(Vc)	+2.91	13351N	4044.81mm	0ft	Vc max nz due stall ASL
3	164kEAS(Va)	+3.42	13351N	4044.81mm	0ft	Va – positive maneuver ASL
4	190kEAS(Vd)	+3.42	13351N	4044.81mm	0ft	Vd – positive maneuver ASL
5	190kEAS(Vd)	-1.71	13351N	4044.81mm	0ft	Vd – negative gust ASL
6	89kEAS (Vs)	+1.0	13351N	4044.81mm	15000ft	Vs – 1g high altitude
7	152kEAS(Vc)	+2.91	13351N	4044.81mm	15000ft	Vc max nz due stall high alt.
8	164kEAS(Va)	+3.42	13351N	4044.81mm	15000ft	Va – positive maneuver high alt.
9	190kEAS(Vd)	+3.42	13351N	4044.81mm	15000ft	Vd – positive maneuver high alt.
10	190kEAS(Vd)	-1.71	13351N	4044.81mm	15000ft	Vd – negative gust high alt.
11	164kEAS(Va)	+2.99	13351N	4044.81mm	0ft	Asym – 100/75
12	164kEAS(Va)	+2.28	13351N	4044.81mm	0ft	Rolling at Va
13	164kEAS(Va)	+2.28	13351N	4044.81mm	0ft	Rolling at Va – max roll rate
14	190kEAS(Vd)	+2.28	13351N	4044.81mm	0ft	Rolling at Vd
15	190kEAS(Vd)	+2.28	13351N	4044.81mm	0ft	Rolling at Vd – max roll rate
16	130kEAS(Vf)	+2.00	13351N	4044.81mm	0ft	Flap

Case #	Airspeed	Load	Weight	CG position	Alt	Fx	Mx	My	Mz
17	164	+2.565	13351N	4044.81mm	0ft	1927	376.25	0	0
18	164	+3.42	13351N	4044.81mm	0ft	1400	318.75	0	0
19	164	+2.5	13351N	4044.81mm	0ft	1542	0	261.5	104.6

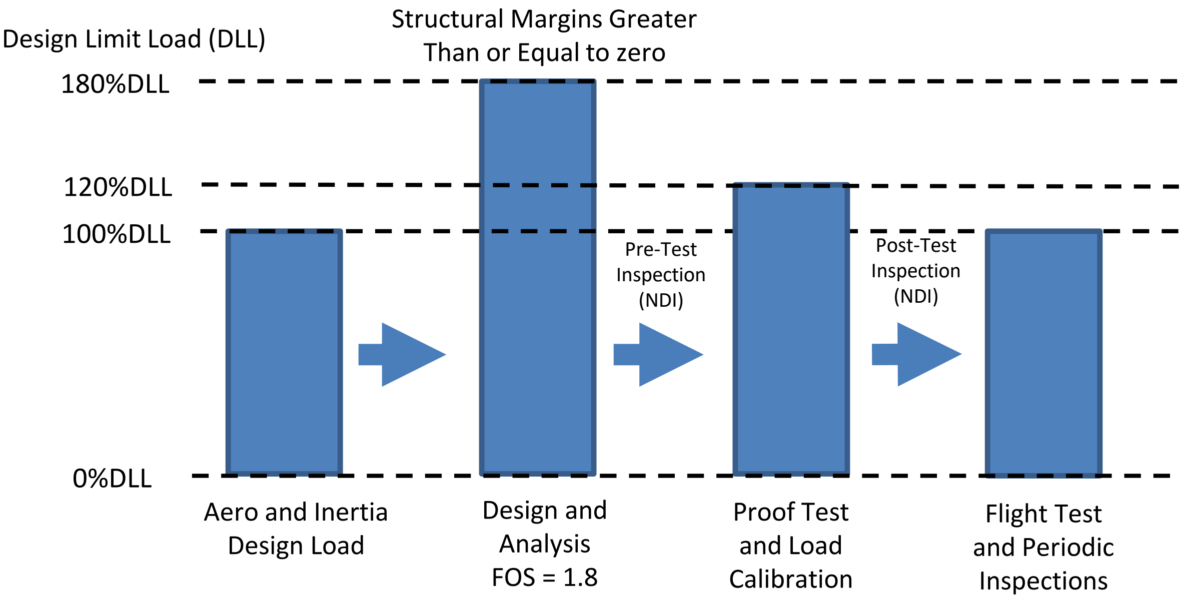
Aerodynamic loads (wing and control surface loads)

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

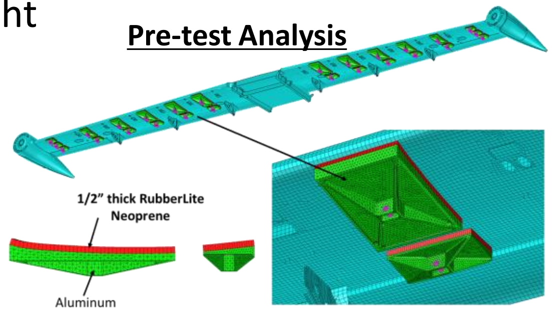


X-57 Wing Structures Airworthiness Approach

- 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

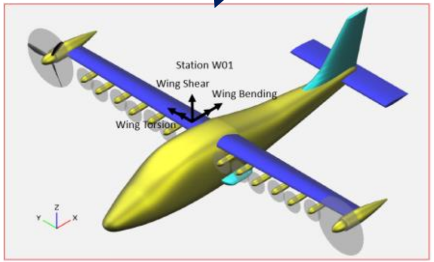


Pre-test Analysis



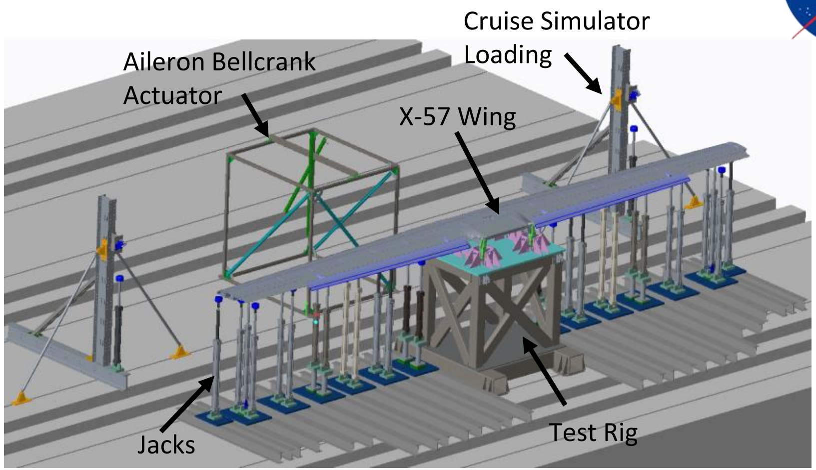
Flight Test Monitoring

Monitor loads at root inboard station



X-57 Wing Testing

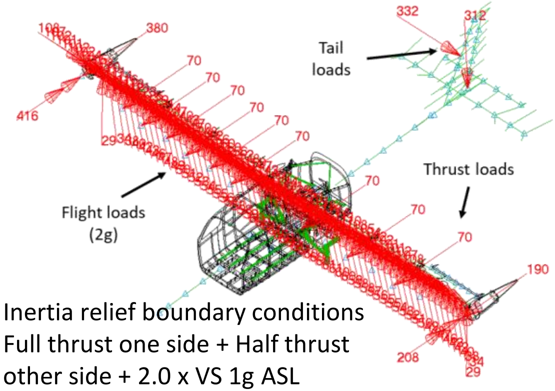
- Proof and loads calibration testing
  - Will be conducted at AFRC in August 2019
  - Qualification test the wing structure to 120% Design Limit Load (DLL)
  - Qualification test cruise motor mount hard points to 120% DLL (axial in-plane)
  - Produce a database suitable for deriving wing load equations 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



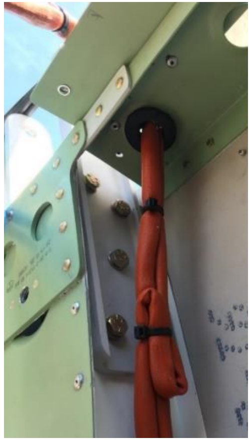
Fuselage Wing Attachment Structural Analysis

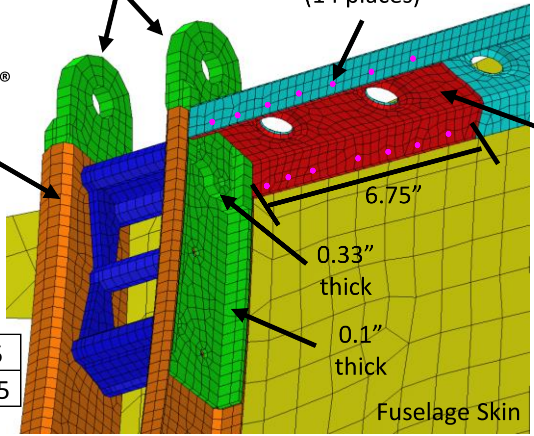
- Asymmetric thrust at take-off load case is the critical load case for the fuselage wing attachment.
- Require new wing attachment and new doubler
- Existing fuselage FS set at 1.5, same as Tecnam FS
- All new hardware FS set at 2.25 (no-test)

Asymmetric Thrust at Take-Off Case



Inertia relief boundary conditions
Full thrust one side + Half thrust other side + 2.0 x VS 1g ASL





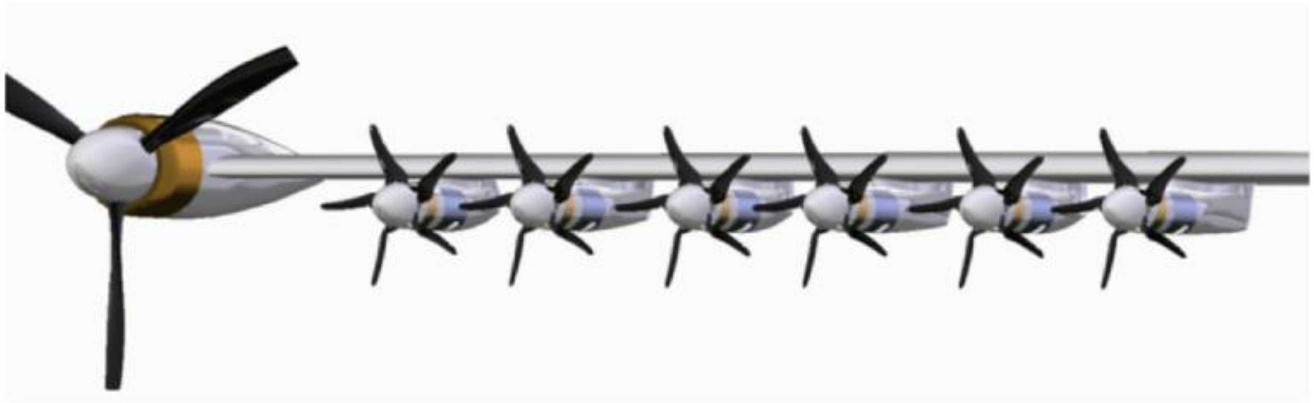
Factors of Safety

Existing FS Ult.	1.5
New FS Ult.	2.25

No-test FS

X-57 Mod IV

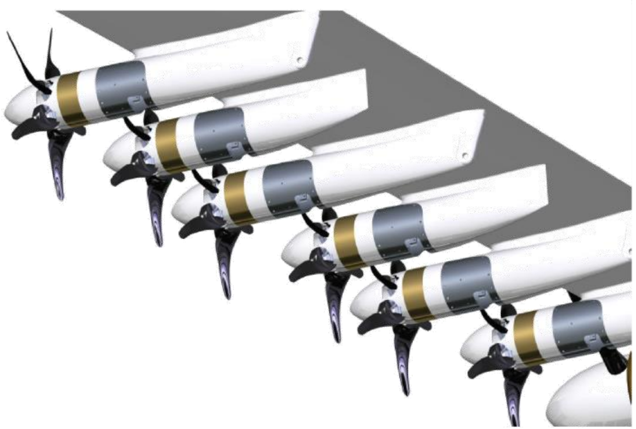
Ultimate Factors of Safety for Mod IV HL System	
Metallic structures if structural design is verified by analysis only	2.25
Composite structures - verified by analysis only	3.0
Hub, Blade retention structures - verified by proof tests to 200% of max centrifugal load.	>2.0



Mod IV High Lift Concept Overview

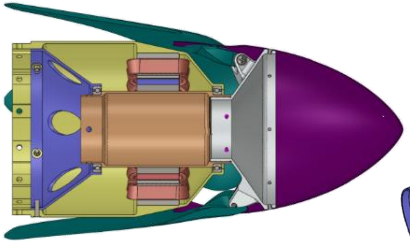
- PDR completed in April, 2019
- Design Loads (Inertial, Thrust, Torque, Imbalance, P-factor, Gyroscopic, etc)
- Decoupled from motor operational dwell frequencies: 5460 RPM / 91 Hz.
- To avoid coupling with wing flutter modes

HL Tail Nacelle

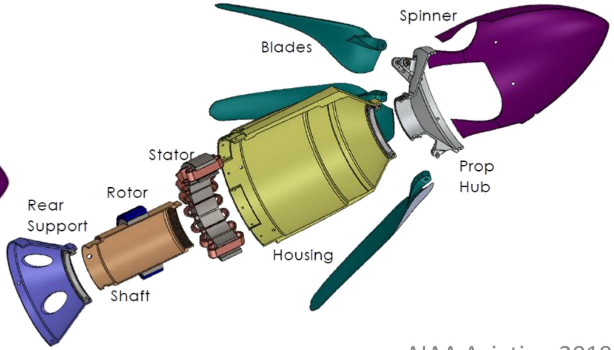


Folding Propellers

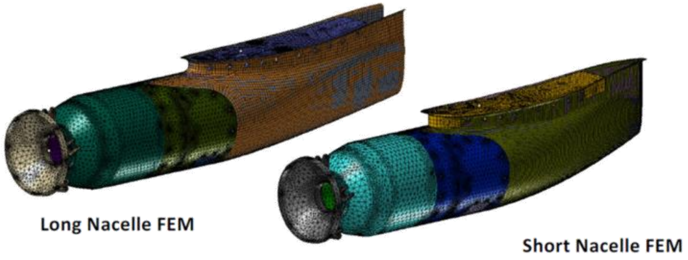
Blades fold back and "stow" onto Nacelle



HL Exploded View



Structural Model



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

Example: Cruise Prop/Hub GVT on Foam Soft Support

Wing on Proof Test Fixture GVT

Soft Support (Bungee) Design for GVT

Support aircraft nose around NG bulkhead

Support MLG axles by attaching bungee support beams to jacks

Thank You

X-57 Technical Document Portal *(https://nasa.gov/x57/technical)*