X-57 Structural Dynamics (Analysis & Testing)

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Structural Dynamics Discipline Tasks

- Cross center team: LaRC-D206, LaRC-D308, and AFRC-560
- Evaluate airworthiness of X-57 aircraft sufficient to satisfy flight test objectives
- Validate FEM to provide confidence in Mod II/III/IV aeroelastic predictions

Aeroelasticity Requirements
- Tecnam Reports
- Aircraft CAD and measurements
- Mod II Weight and Balance Tracker
- AFG-7123.1-001 Rev A-1

Flutter and Structural Dynamics Analysis
- Classical Flutter
- Whirl Flutter
- Fan plots for motor RPMs
- Component vibration loads

Flight Test Plan
- Flight Envelope
- Go-no-Go Instrumentation
- Flight test points
- Control Room plan

Control Room
- Monitor SF/ST parameters
- Verify test point completion

Post-test Data Analysis
- Compare to pre-test predictions
- Monitor vibration environment for critical components

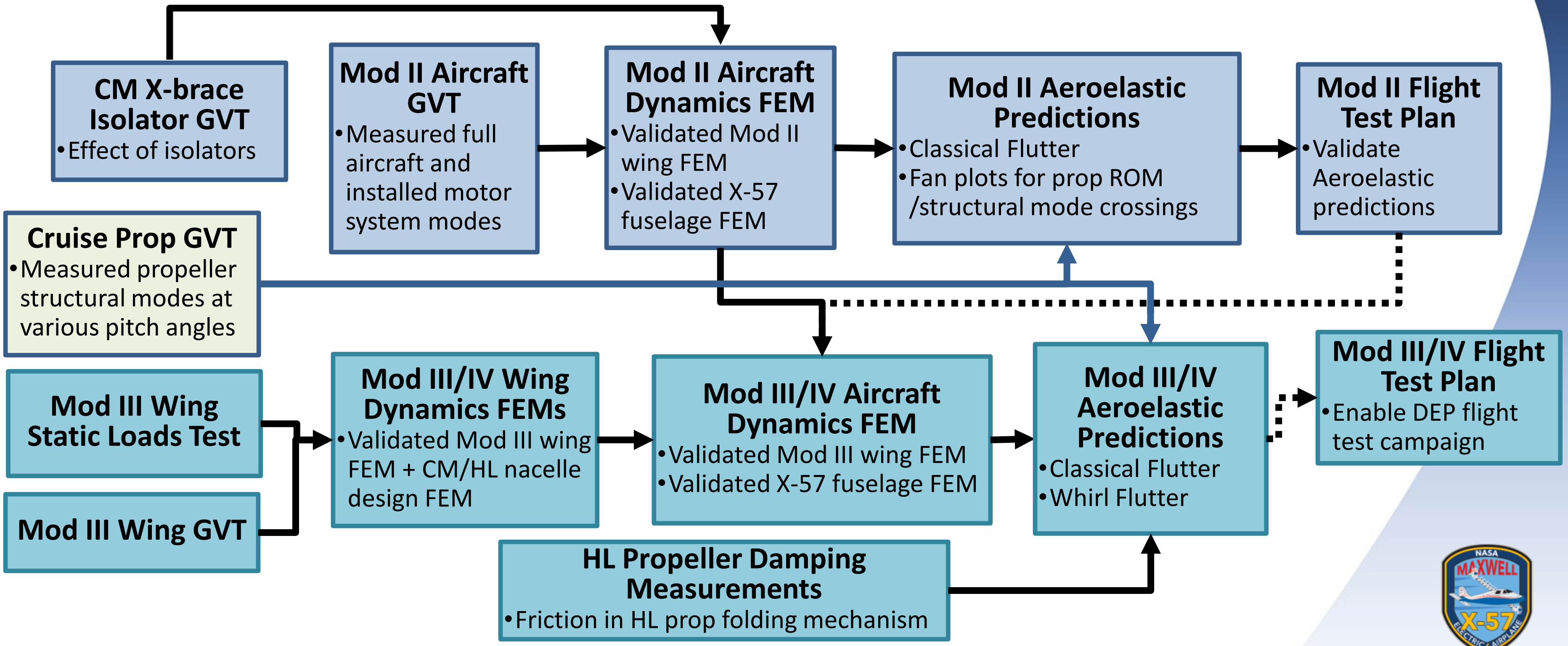
Ground Test
- Mod II aircraft GVT
- Prop/hub GVT
- Mod III wing GVT
- Ground motor run vibration measurements

Dynamics FEM
- FEM correlation and updates using test data

IF large differences in predicted behavior

Validated Structural Dynamics FEM

- Leveraged GVTs and Wing Loads calibration test to validate new and existing X-57 aircraft structure



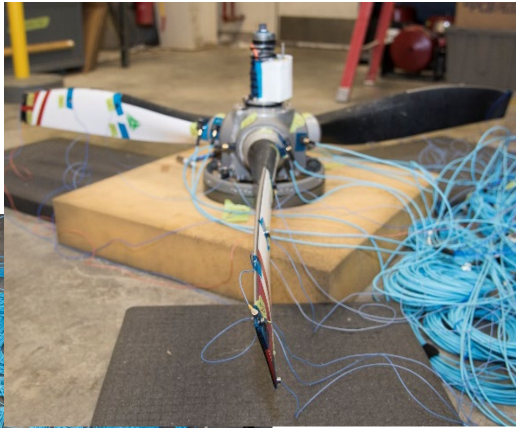
Aeroelasticity Highlights

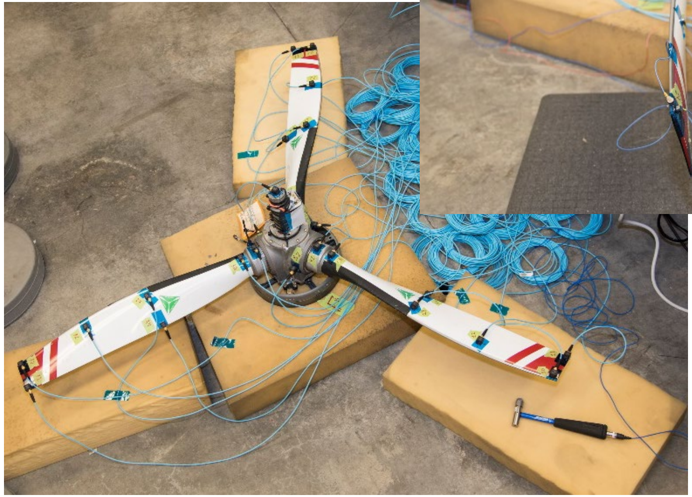
Structural Ground Testing

Structural Ground Tests (1)

- Cruise Propeller GVT on Foam (Feb 2018)

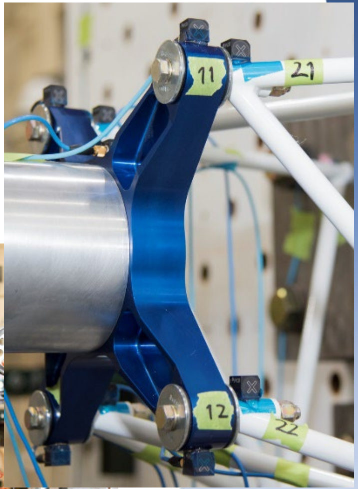
Measured structural modes at multiple blade pitch angles

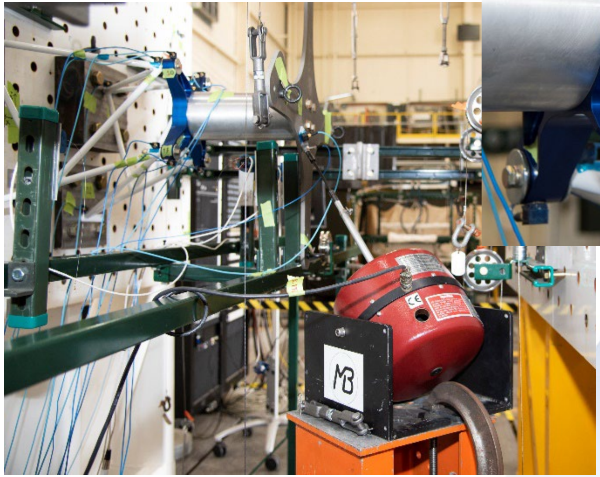




- X-brace Isolator GVT (Apr/May 2018)

Quantify dynamics of using isolators in Cruise Motor X-brace





Structural Ground Tests (2)

- Mod III Wing GVT (May/Jun 2019)

CM Mass substitute plates

Provided correlation data for wing and flap structure
- Short-chord, large-span flaps posed potential flutter concern

GVT conducted prior to the fabrication and installation of the wingtip cruise motor (CM) nacelles, and distributed high lift (HL) motor nacelles

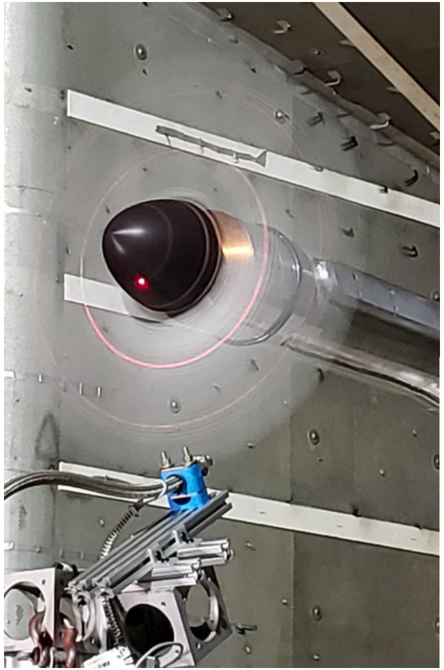
Structural Ground Tests (3)

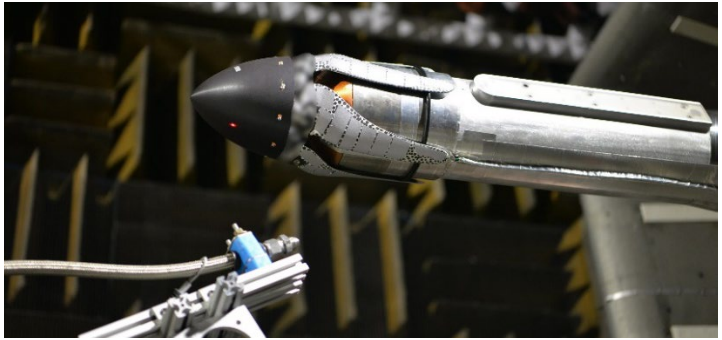
- Mod II Full Aircraft GVT (Dec 2019)
  - Bungee soft-support provided >6x separation between rigid body and elastic modes
  - Provided correlation data for Mod II aircraft FEM; 324 accel measurement channels
  - Fuselage and empennage FEM components reused for Mod III/IV FEM

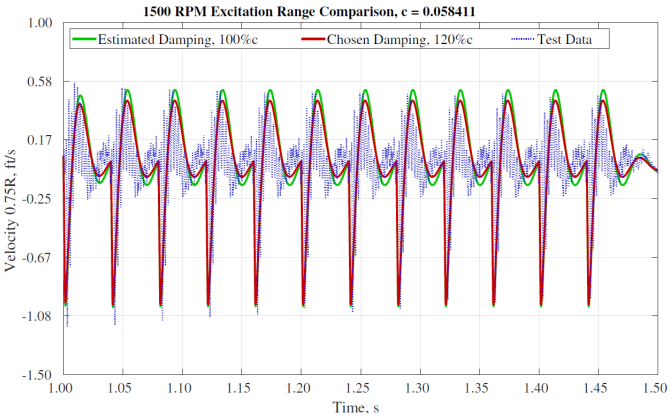
Mod II GVT on Bungee Soft Support

Structural Ground Tests (4)

- LSAWT HL Propeller Damping Measurements (Jun 2021)







Measured aerodynamic and friction damping for HL propeller by exciting blade folding mechanism using pulses of compressed air.

Alleviated concerns of rotor instability at low forward velocities initially predicted by whirl flutter simulations.

Instabilities predicted due to novel HL motor hinge geometry, built-in pitch/twist, and unmeasured friction at folding blade hinge

Aeroelasticity Highlights

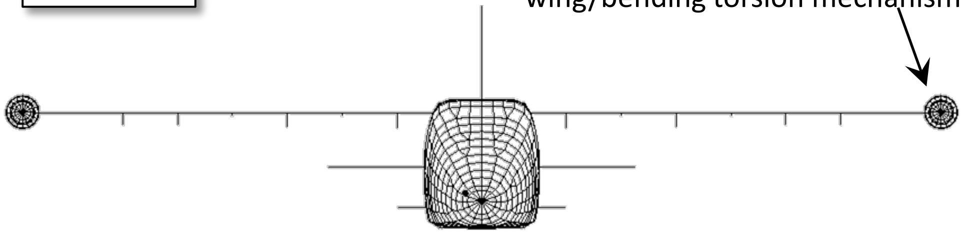
FEM modeling and Flutter Analysis

Mod III vs IV : Classical Flutter Predictions

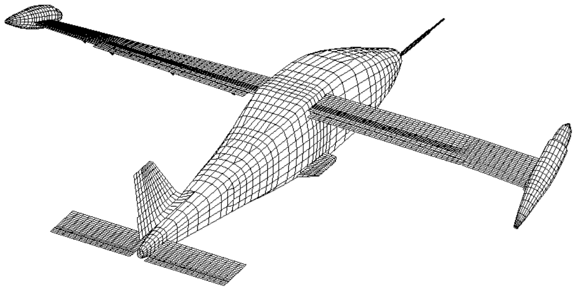
- The distributed HL motors serve as passive wing flutter suppression

Mod III

Wingtip Motor mass - adverse location for wing/bending torsion mechanism

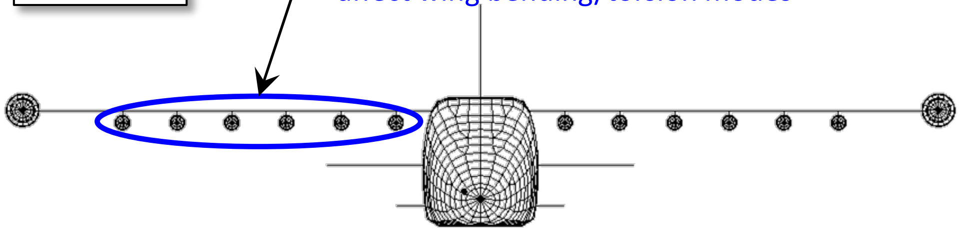


Mod III – 1st Flutter Mode

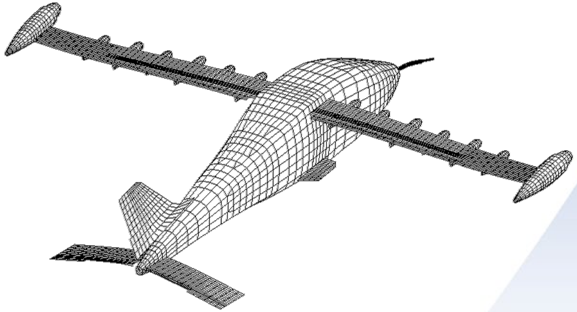


Mod IV

HL motor distributed lumped masses affect wing bending/torsion modes



Mod IV – 1st Flutter Mode



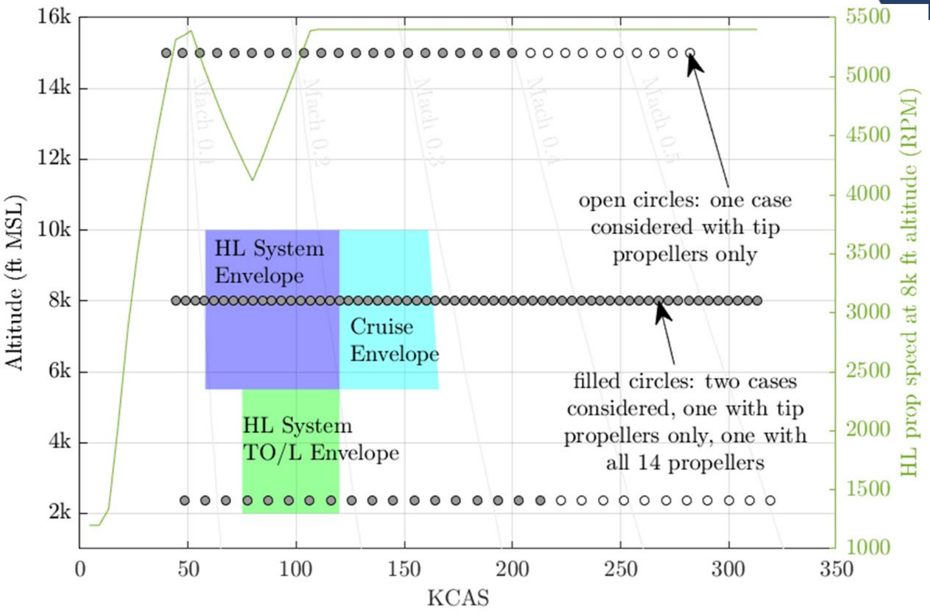
Mod II/III/IV Whirl Flutter Predictions

- Whirl flutter analysis performed early in the program drove wing design requirements (driven by concerns of large motors at wingtips and 14 motors)
  - Required first cruise nacelle flexible mode >55 Hz
  - Result was a very stiff wing that had good aeroelastic properties

- Extensive simulations using CAMRAD and DYMORE indicated no Whirl flutter instabilities for Mod III/IV aircraft
  - CAMRAD simulations grounded by prop GVT data
  - Mod IV HL motor simulations with folding blades grounded by friction measurements performed during LSWAT testing
  - Whirl flutter not a concern for Mod II/III/IV unless structural failure in motor mount occurs; unlike transport category certification (14 CFR 25.629) no NASA requirement to be whirl flutter free even after single-link failure in motor mount

Whirl Flutter Analysis Highlights

- Mod III and IV evaluated for whirl flutter stability using CAMRAD II (v5.0) and Dymore 5 analysis codes
  – CAMRAD: Eigenvalue solution approach, used frequency and modes shapes from NASTRAN solution
  – Dymore: Time domain perturbation approach, used Herting reduction of NASTRAN model
- Propeller blade rigid vs flexible modeling found to have little effect
- HL propeller hinges always included
- Conservative free shaft BC for cruise and HL prop shafts (shaft allowed to flex at motor connection point)



- Large analysis matrix
  – 0 thrust and 0 torque trim conditions
  – Tip motor RPM: cruise, takeoff, 10% overspeed
  – HL motor RPM: 0, scheduled, 10% overspeed

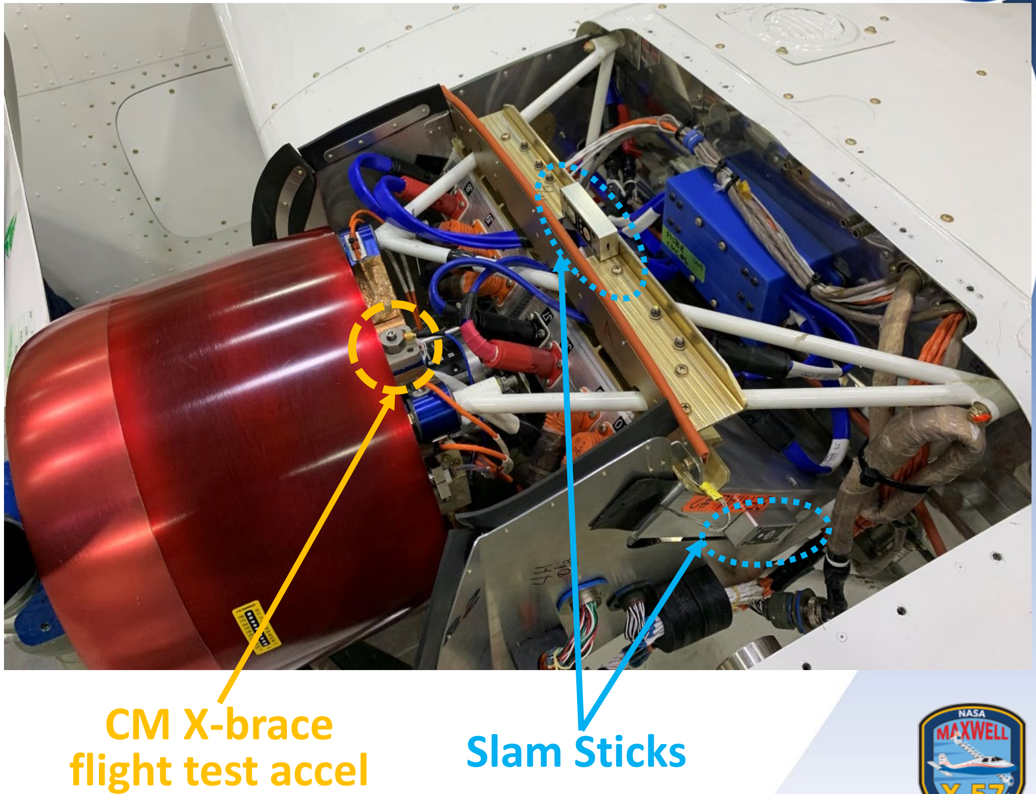
Cruise Motor Vibration Highlights

Cruise Motor Vibration Background

- Expected electric motor vibration environment to be more benign than comparable power-class combustion motor
  - Rotax 912S (73.5 kW / 100 hp, 5800 RPM max)
  - Gearbox to operate propeller at lower RPM
- X-57 Electric 72 kW class cruise motors are:
  - Air-cooled
    - No pumps for liquid cooling
    - Very high switching frequency to meet thermal efficiency target
  - No additional accessory units (e.g. alternator)
  - Direct Drive at 2700 RPM max

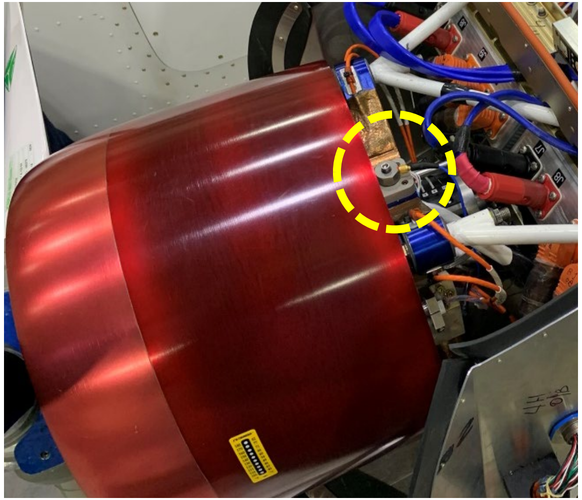
CM Vibration Environment Measurement

- After installing propeller onto CM rotor, Mod II Motor System dynamically balanced using commercial aircraft propeller balancer (Cobra II) to ≤0.07 IPS at 1700 RPM
- Majority of X-57 CM vibration environment data measured during Mod II ground motor runs utilizing Slam Sticks (enDAQ Shock & Vibration Sensors)
- enDAQ independent vibration measurement tool enabled data acquisition while EMI and aircraft instrumentation system troubleshooting was ongoing

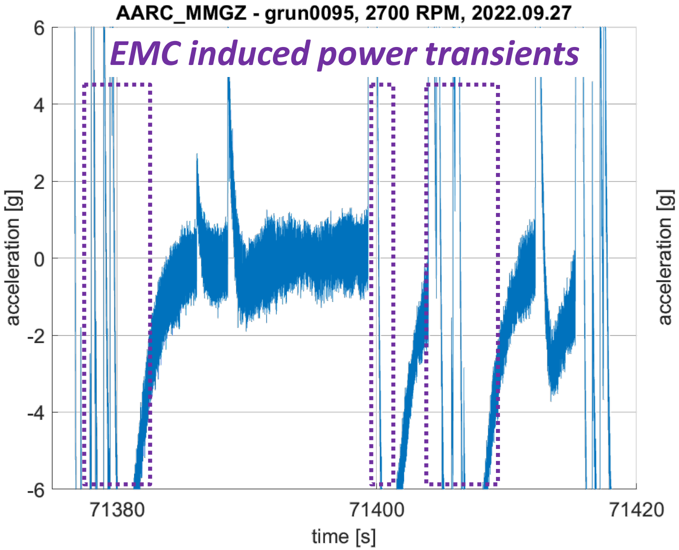


EMI Challenge for Measuring Motor Vibrations

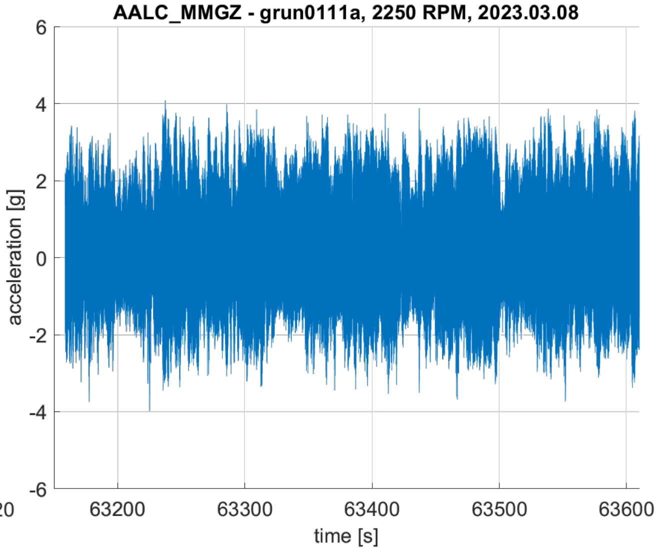
- Had Cruise Motor accelerometer on X-brace for monitoring motor vibration during flight test campaign
- Could not gather reliable data from this accelerometer until EMC issue was solved by grounding the CM rotor and stator through slipring
- Loss of isolation resulting from rotor-stator capacitive discharge (due to all AC motor phases not being balanced in frequency, phase, and amplitude)



Before slipring grounding Mod



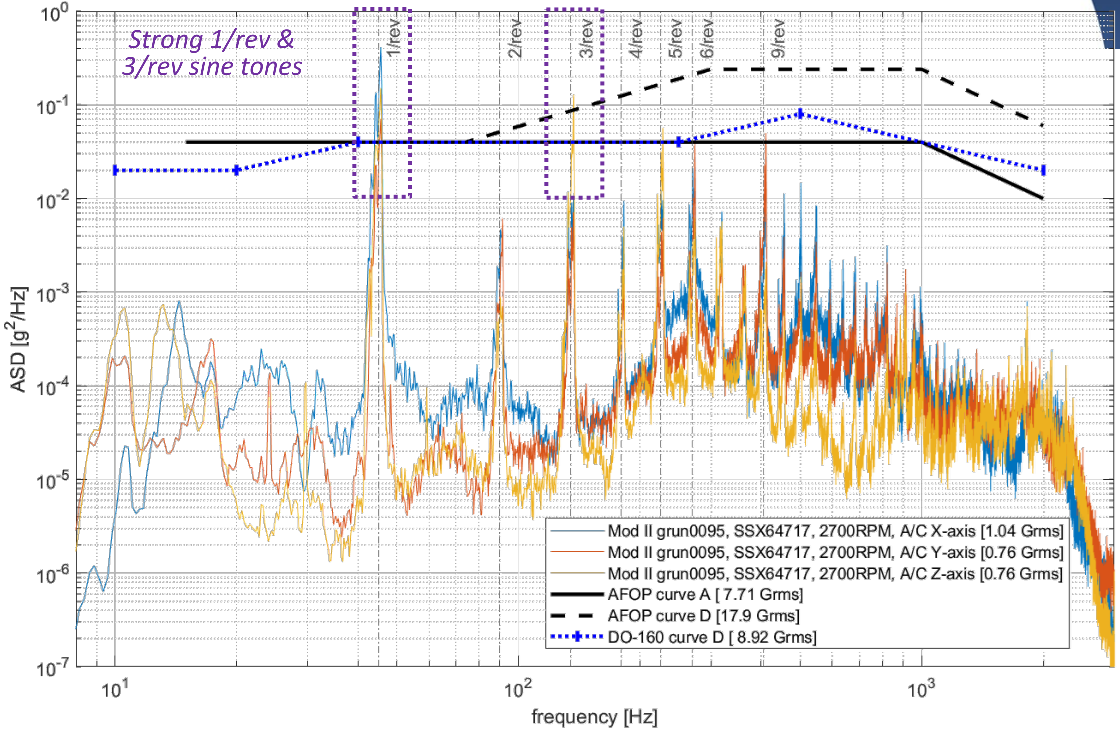
After slipring grounding Mod



Electric vs Gas Motor Vibration Levels (1)

- X-57 CM Vibration measured during ground run at 2700 RPM (max)
  - 1.04 Grms, upper truss
  - 2.3 Grms, X-brace
  - sine-on-random vibration environment character
  - electric motor prop/motor RPM harmonics clearly discernable over much lower magnitude random vibe spectrum

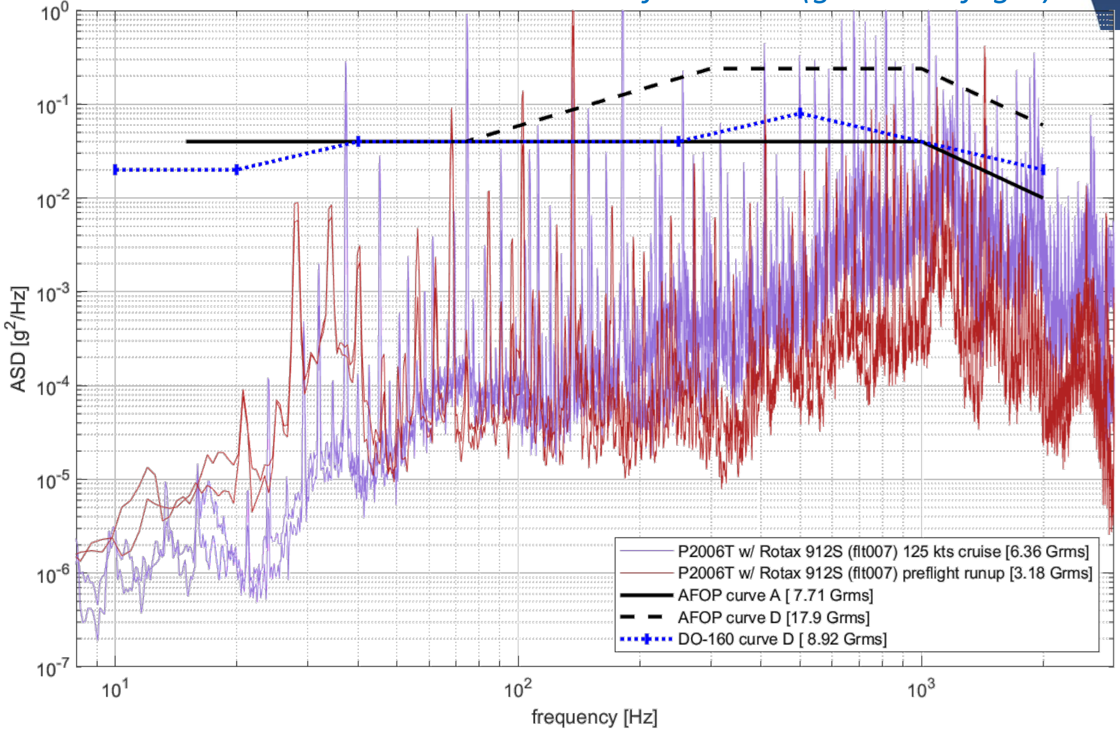
Measured on Mod II Motor Truss – No Isolators on motor



Electric vs Gas Motor Vibration Levels (2)

- Vibration measured on P2006T truss downstream of engine isolators
  - 3.18 Grms, preflight runup
  - 6.36 Grms, 125kts cruise
  - AFOP and DO-160 curves are consistent with P2006T Rotax 912S measured vibration
  - DO-160 Fixed-wing turbofan Curve D chosen for random vibe illustration since DO-160 Ch.8 specifies sinusoidal curve for fixed-wing reciprocating aircraft

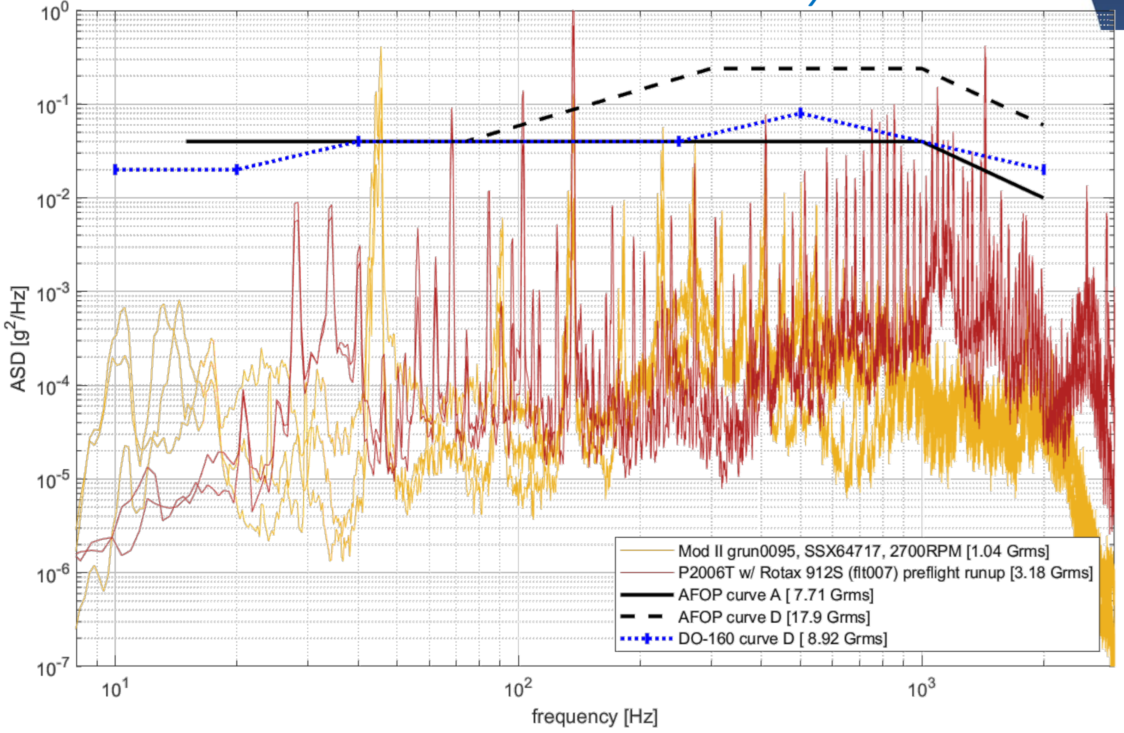
P2006T Motor Truss – downstream of isolators (ground & flight)



Electric vs Gas Motor Vibration Levels (3)

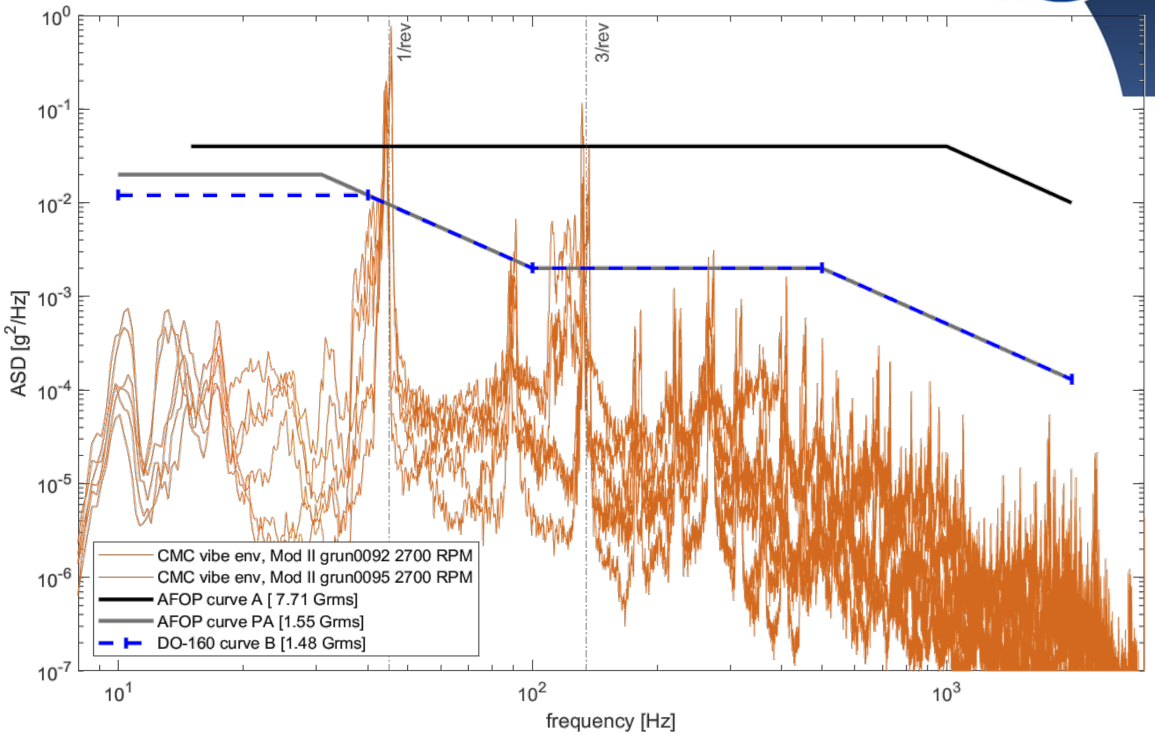
- Ground run vibration: X-57 at Max RPM vs. Tecnam P2006T
  - X-57 CM w/o isolators vibrations at, or below Rotax 912 w/ isolators
  - Vibrations >700Hz greatly reduced for electric cruise motor compared to reciprocating engine
  - AFOP and DO-160 seem extremely conservative for electric motors

Mod II Cruise Motor vs Rotax 912S Overlay



Measured CMC Vibration Environment

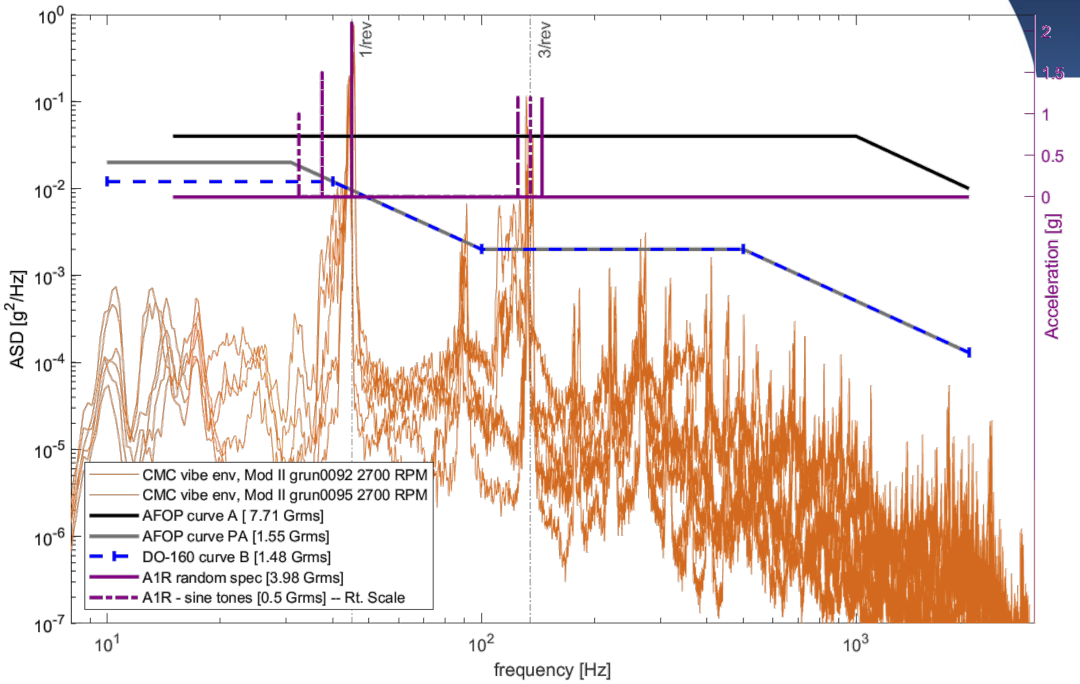
- CMC-measured vibration data during Mod II ground motor runs shown by orange data.
- For Mod II installation, CMCs mounted on vibration isolators (reduced vibrations above 400 Hz).
- No isolators planned for Mod III/IV wingtip CMC installation



AFOP curve A: Light Prop aircraft isolator-mounted equipment
AFOP curve PA: Transport aircraft isolator-mounted equipment
DO-160 curve B: Fixed-wing Turbofan equipment rack

Updated CMC Vibration Test Profile

- X-57 CMC units proto-qualified using A1R vibration test curve (4.5 Grms); vs AFOP curve A+3dB (10.9 Grms)
- Options after XM3 CMCs failed in environmental vibe test Aug 2022:
  1. Redesign CMCs
  2. Reevaluate Mod II vibration Mod environment
- A1R provides conglomerated margin for: installation differences, motor/prop imbalance, prop damage, differences between flight and ground environments, and Mod II and Mod III/IV configurations

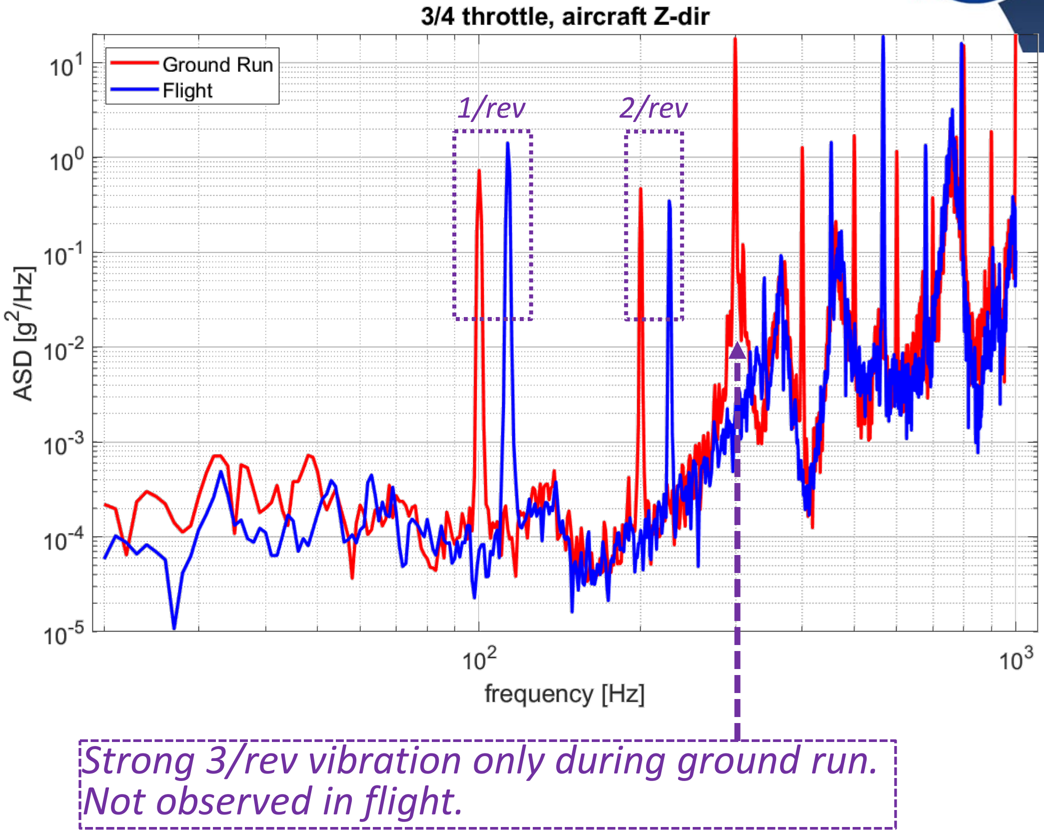


AFOP curve A: Light Prop aircraft isolator-mounted equipment
AFOP curve PA: Transport aircraft isolator-mounted equipment
DO-160 curve B: Fixed-wing Turbofan equipment rack

Ground vs Flight Motor Vibration Levels

- AFRC Model Lab RC Aircraft motor vibration data
  - Is also direct drive motor (no gearbox), and uses a 3-blade propeller just like X-57
  - Ground run motor vibration levels higher than Flight levels

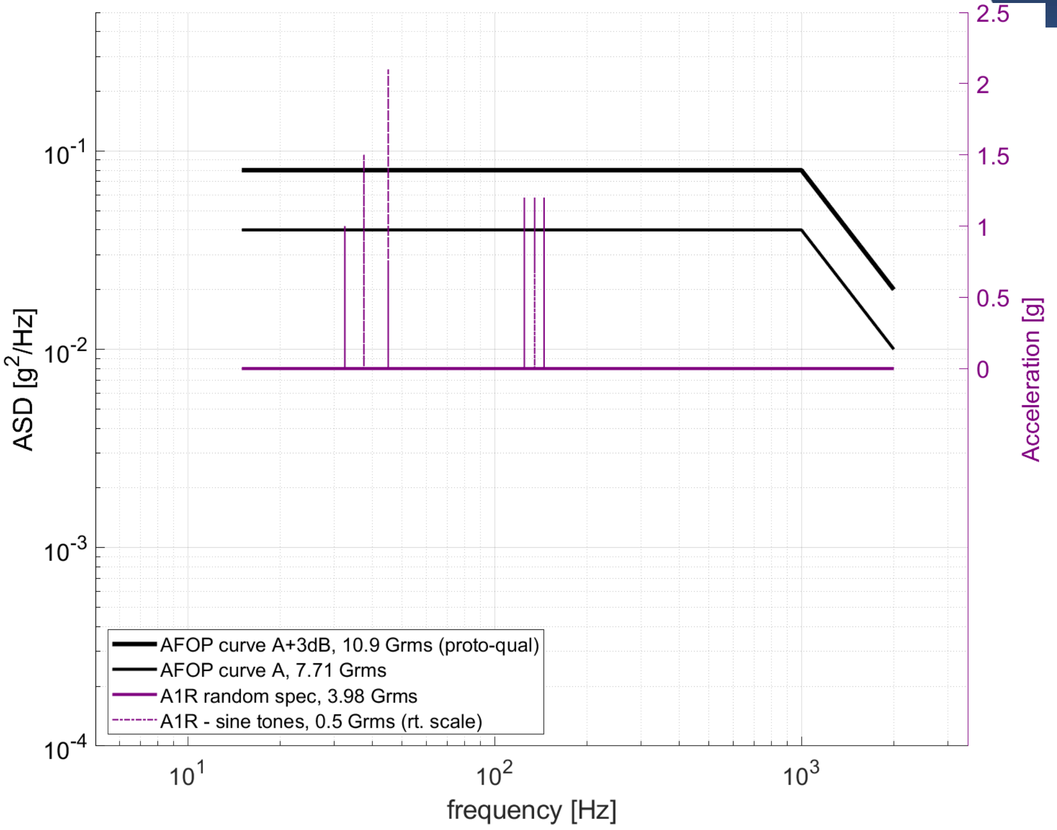
AFRC Model Lab aircraft motor



A1R Compared to AFOP-7900.3-004 and DO-160 Guidance

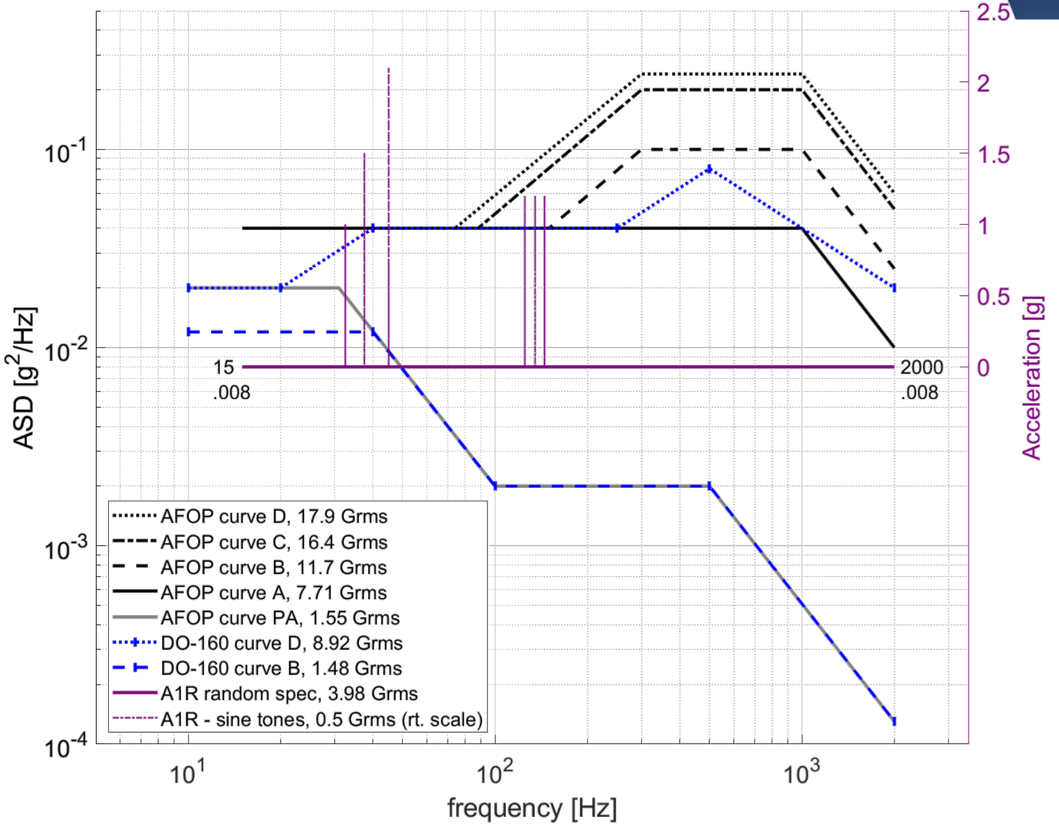
- A1R Sine-on-Random test curve for CMCs [4.5 Grms total]
  - Based on measured vibration data from actual installation environment
  - Not reduced for $f > 500$ Hz
  - P2006T motor accelerometer data showed high frequency content increase between flight environment and ground engine run and taxi environments

- AFOP Category III – Light Propeller Aircraft
  - AFOP Curve A – rigid/hard-mount vibe testing of equipment installed using isolators [7.71 Grms]
  - AFOP Curve A +3dB – for proto-qual [10.9 Grms]
  - A and A+3dB levels high enough so they also serve as workmanship screening

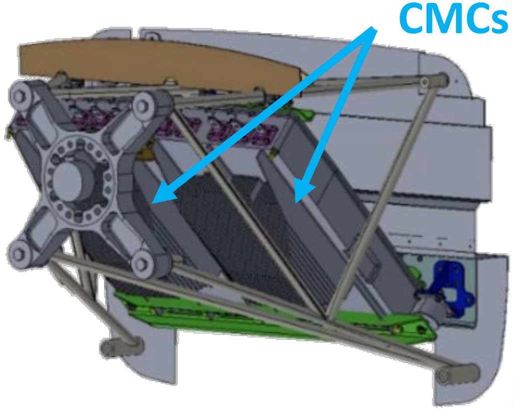


A1R Compared to AFOP-7900.3-004 and DO-160 Guidance

- A1R Sine-on-Random test curve for CMCs [4.5 Grms total]
  - X-57 Mod II/III/IV CMC proto-qual test level
- AFOP Category III – Light Propeller Aircraft
  - Curve D – engine and Gearbox equip.
  - Curve C – Nacelle and Pylon equip.
  - Curve A – rigid/hard-mount vibe testing of equipment installed using isolators
- AFOP Category V – Transport Aircraft
  - Curve PA – for rigid/hard-mount vibe testing of equipment installed using isolators
- DO-160, Ch. 8 – Fixed Wing Turbofan
  - Curve D – Nacelle and Pylon equipment
  - Curve B – Instrument Panel/Equipment Rack



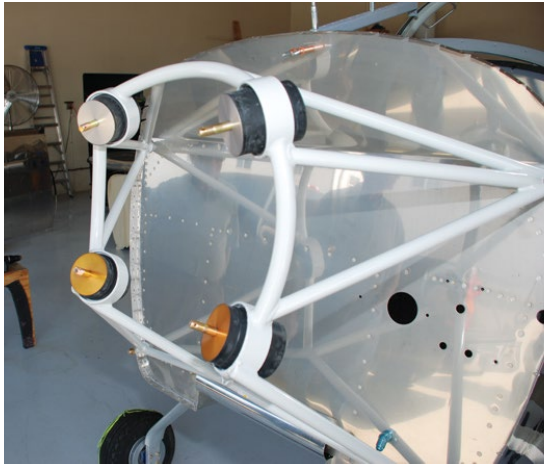
Vibration Test Takeaways



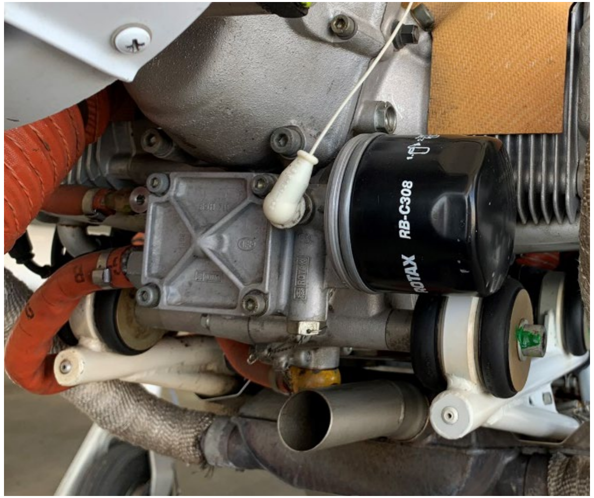
- Electric Motor Propeller Aircraft vibration environment much more benign than Gas Motor Propeller environment
  - Measured vibration for motor truss mounted CMCs, equivalent to equipment installed on isolators inside transport aircraft fuselage (AFOP-7900.3-004 curve PA)
- Since the aircraft was our integration testbed, X-57 spent significant run time in ground motor operation (consideration for A1R vibration test profile used)
- Had lot more vibration margin for CMC hardware than initially predicted using P2006T data. Until vibrations were measured on the Mod II aircraft, didn't know how much lower electric aircraft motor vibrations would be
- When working with limited quantity prototype hardware, always worth challenging assumptions and "standard" practices. Maybe consider, at least initially, under testing difficult-to-replace components
- X-57 Mod II vibe data show possibility of greater design space for electric aircraft parts

Electric Engine Mount Isolator Consideration

- Combustion motor practice uses engine vibration isolators to reduce vibration energy transmitted to motor truss and engine firewall
  - Elastomer isolators amplify displacement/vibration around their natural frequency, but provide isolation at higher frequencies
- *Are isolators required for electric motor installations?*



Nose firewall engine mount for IO-360

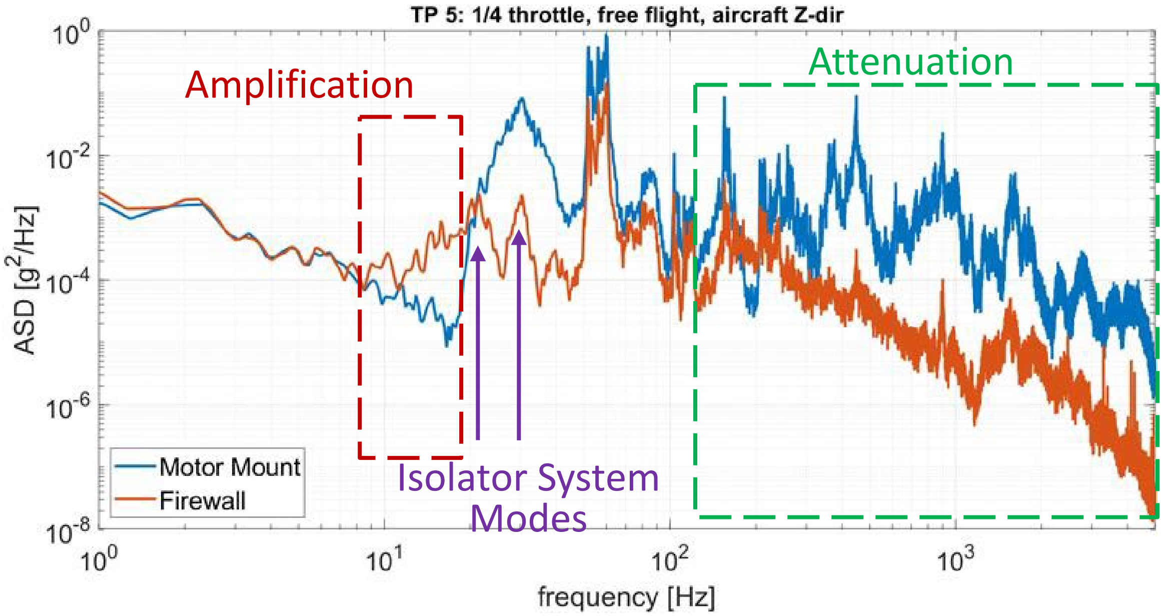


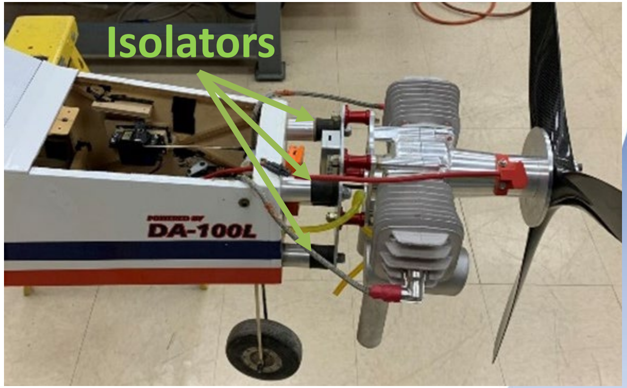
TG-14 Nose firewall engine mount for Rotax 912

Tecnam wing engine mount for Rotax 912

Engine Mount Isolator Vibration Effects

- Vibration data from AFRC Model Lab aircraft with isolators at four corners of motor mount; mount and firewall vibrations compared
- DA-100 and X-57 CM are both direct drive motors (prop RPM = engine RPM)

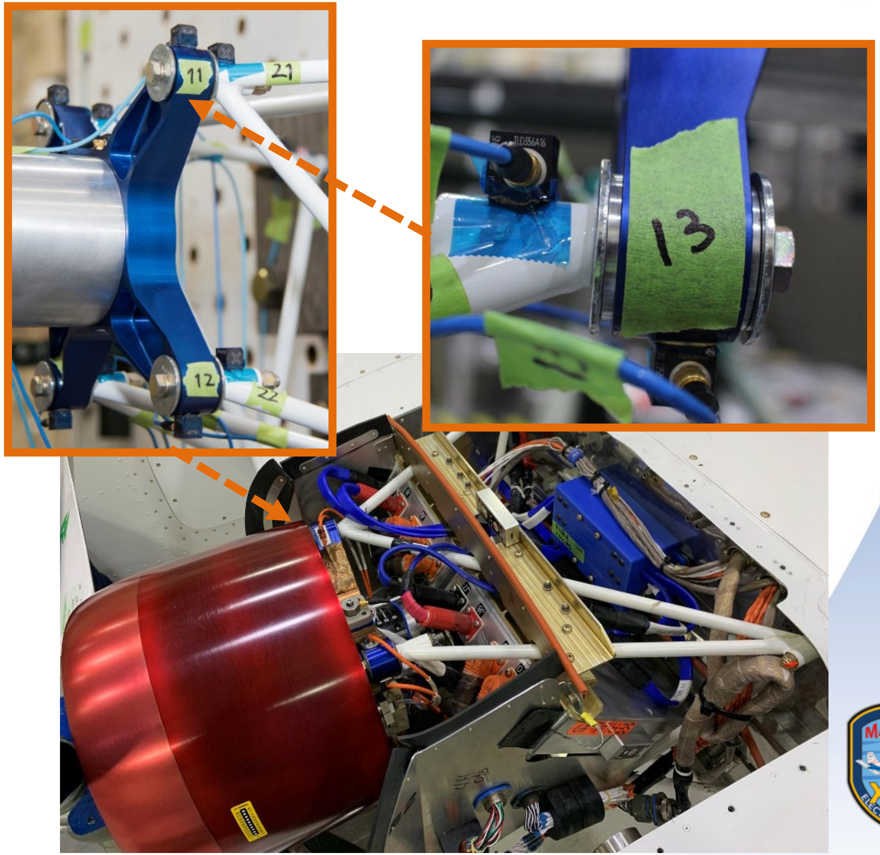




AFRC Model Lab aircraft motor with 4 corner- mounted isolators

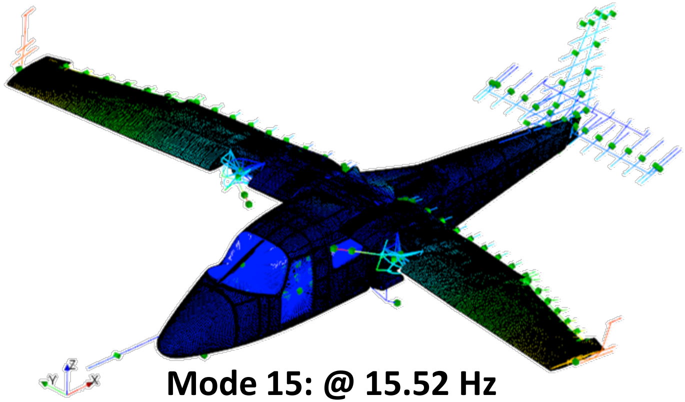
X-57 Engine Mount Isolator Decision

- Electric motors open up the option of *not using isolators* in motor installations
- X-57 eliminated isolators from Cruise Motor X-brace adapter
  - Lower vibrations produced by electric motor impart less energy into motor truss and wing firewall
  - Truss natural frequency outside motor operating RPM
  - Inspections of truss and firewall to mitigate fatigue concerns

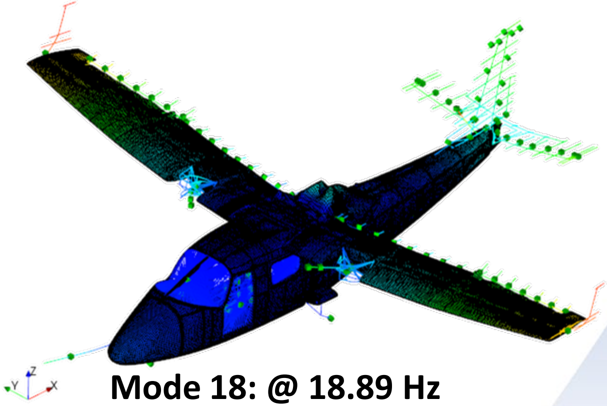


Predicted Aeroelastic Effect of Isolators

- Isolators in X-brace affect stiffness of X-57 cruise motor assembly, and therefore wing modes in frequency range of flutter mechanism
  - Motors make up significant portion of Mod II wing mass
- FEM with high stiffness X-brace isolators modeled predicted two wing fore-aft modes for Mod II aircraft (compared to one mode for rigid X-brace attachment)
  - Primary flutter-participant wing frequencies in 15-20 Hz range; prefer first Cruise Motor frequency (cantilever mode) >30 Hz to avoid coupling with wing modes



Mode 15: @ 15.52 Hz
Wing Fore-aft with Motor Lateral in-phase



Mode 18: @ 18.89 Hz
Wing Fore-aft with Motor Lateral out-of-phase

Summary of Aeroelasticity/Vibration Takeaways

- **Aeroelasticity**
  - FEM: Early FEM models can identify significant issues at beginning of design cycle, but results from still maturing FEM can linger with project for a while (hard to forget bad results)
    - Static loads tests and GVTs essential for validating new and existing aircraft structure
    - Beam FEM was not adequate for capturing X-57 flutter mechanism
  - Mod II predicted to have a reduced flutter boundary compared to donor P2006T aircraft
  - Mod III/IV predicted to have higher classical flutter boundary than Mod II, and no whirl flutter concerns due to NASA FEM-driven requirements during Mod III/IV wing development

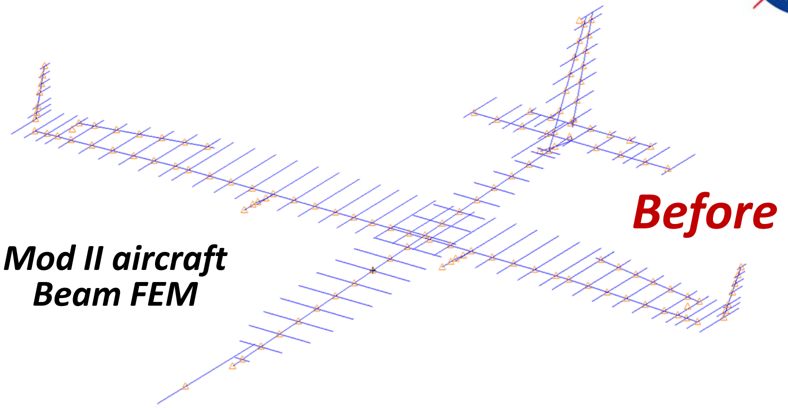
- **Motor Vibration**
  - Electric motor vibration levels significantly lower than gas motors of similar power-class
  - Since X-57 also served as systems integration testbed, avionics systems spent significant time operating in a ground vibration environment (which may be more severe than flight environment)
  - Consider whether isolators are really required in electric aircraft applications; isolators attenuate high frequency vibration, but also amplify motion at their natural frequency
  - EMC could pose issues when attempting to measure electric motor vibrations


NASA
MAXWELL
X-57
ELECTRIC AIRPLANE

Aeroelasticity Backup Slides

Initial Mod II Beam FEM Update Attempt

- Initially attempted to model Mod II aircraft using simple beam element representation
- Multiple attempts to update beam FEM and correlate to Mod II GVT data, yielded unsatisfactory results
  - Poor cross-orthogonality correlation; would have resulted in using 0% structural damping assumption for flutter predictions

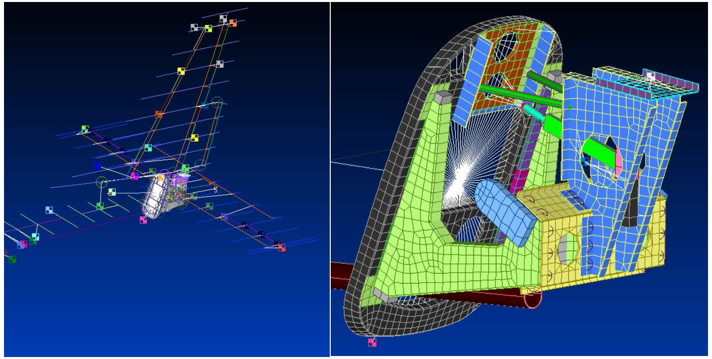


Cross-Orthogonality Comparison			Original FEM																				Freq Pct Diff
			7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
Otg	Test Shapes		8.25	8.94	10.01	13.07	14.64	14.76	15.13	17.53	17.63	17.74	17.77	19.30	21.54	23.43	25.13	26.87	27.09	28.06	28.93	29.03	29.19	
100	1	7.83	99																					5.3
95	2	9.09		54				31			30	33				38								-1.7
90	3	10.36			72			35			27						29							-3.4
85	4	11.49		38	42			42	33			46				18								54.4
80	5	12.14			24	44		15			55	35	28											45.2
75	6	13.68		59				23	48			48	17			20								-34.6
70	7	14.84						42			73		21			15								18.8
65	8	15.93		19	45			16	42		17	50				24	26							11.4
60	9	16.75					21			79				21										4.7
55	10	16.95		18	15			28	66		52	15				17	23							-10.8
50	11	17.53											89	31						15				1.4
45	12	19.11					37			50			41	44	17									-8.3
40	13	20.01					90											16						-26.8
35	14	20.69									92		20				18							-14.8
30	15	21.39									84	25	25			21								-17.6
25	16	21.95									56	57	26											-19.2
20	17	24.55								44					64			32						-12.3
15	18	24.78										25					27			17		76	15	17.1
10	19	26.38								17				28	21			19		81				6.4
5	20	27.25	21							40	20				38			31		35		16		-35.7

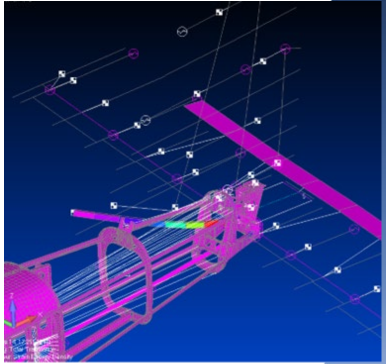
Beam FEM cross-orthogonality

Mod II Beam FEM & GVT Deficiencies

- Stabilator – zero pitching moment design great for pilot control/flying qualities, but more complex for structural dynamics analysis
  - Horizontal stabilizer attaches to the aft fuselage at two pivot points, each on a separate bracket
  - Zero pitching moment design utilizes a large counterweight
  - Unfortunately, stabilator mass balance not instrumented in Mod II GVT due to pre-GVT FEM modeling assumption



Improved FEM of Aft-fuselage/Stabilator Attachment



Stabilator mass balance not instrumented during GVT

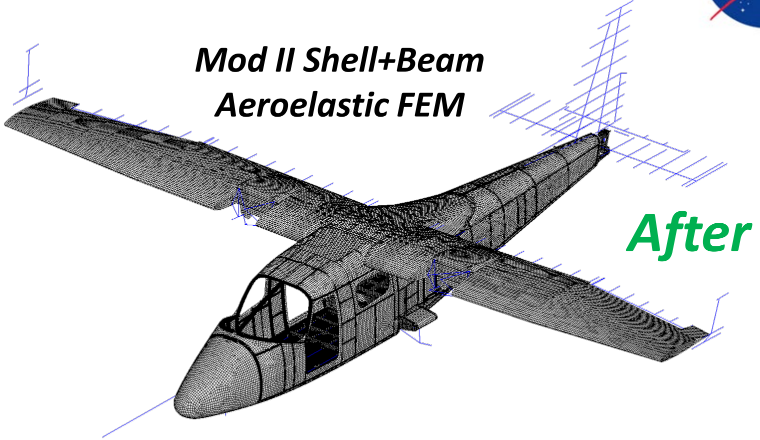
- Wing/fuselage interface – wing torsion box does not carry through motor attachment and passenger compartment areas
  - Middle wing is an open cross section; connected to the fuselage by 4 forks located near the corners. Could not be accurately modeled using a single spar beam.

Improved FEM of Wing/Fuselage Interface

Correlated Mod II Beam Aeroelastic FEM

- Shell element fuselage and wing models permitted reuse of correlated fuselage and empennage in Mod III/IV FEM models
- Correlation effort included verifying FEM properties against aircraft measurements where possible and adding model fidelity
- Mod II FEM vastly improved, but still does not meet requirements for fully-validated FEM
  - NASA-STD-5002 specifies for significant modes: [1] Natural frequencies within 5%, and [2] Cross-orthogonality > 0.9, with off-diagonal terms < 0.1
  - Correlation limited by placement of GVT accels due to fidelity of pre-test GVT models
- Many closely spaced modes near 17 Hz, with high off-diagonal terms
- Based on this, relatively high 50-60% flutter prediction margin for Mod II was chosen

Mod II Shell+Beam Aeroelastic FEM



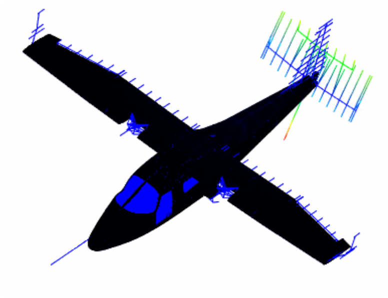
After

Cross-Orthogonality Comparison			FEM Shapes																		Freq
			7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Pct
Otg	Test Shapes		8.46	8.87	10.97	12.27	14.10	14.15	16.09	17.26	17.61	17.68	18.78	20.77	22.55	23.89	25.11	25.63	26.21	26.68	Diff
100	1	7.83	99																		7.9
95	2	9.09		94								23									-2.4
90	3	10.36		15	92	37															5.9
85	4	11.49			35	90	25						28								6.7
80	5	12.14					24		15	44			30				20				42.2
75	6	13.68					98						21								3.1
70	7	14.17					27	92						31							-0.1
65	8	14.84							99												8.5
60	9	15.93			17	23	24			90			61								8.3
55	10	16.75								27	95										5.1
50	11	16.95		18	17	22			16	67	18		82		25						10.7
45	12	17.53						15				97		16							0.9
40	13	19.11						23				26		95				20			8.7
35	14	20.01						92						32							-29.3
30	15	20.69					18		15				31		95						9.0
25	16	21.39													58	25	67	16	38		17.4
20	17	21.95		22			35			19			30				68	19	56		14.4
15	18	24.55												32				23		24	-15.4
10	19	24.78				15										82	26		41	18	-3.6
5	20	26.38												15		26		45	46	75	1.1
0	21	27.25																58	40		-5.9

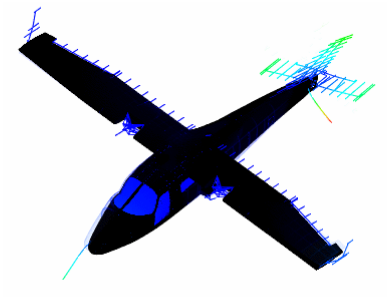
Shell+Beam FEM Cross-Orthogonality

Participant Modes in Mod II Flutter Mechanisms

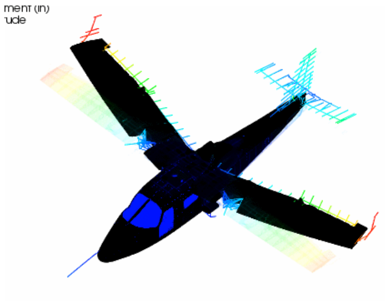
14.2 Hz (#12)
Stab rotation



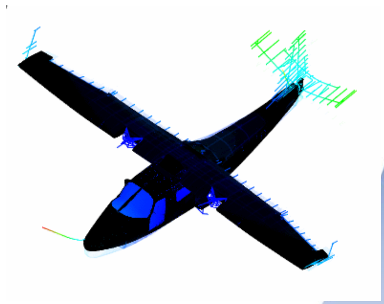
17.3 Hz (#15)
Stab roll, VT 1B



17.6 Hz (#16)
Tail Porpoising, Wing F/A



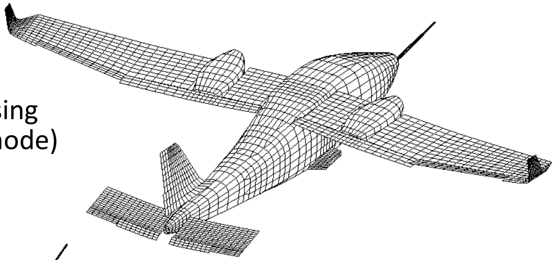
20.7 Hz (#18)
Fuselage 1B, Stab 1B



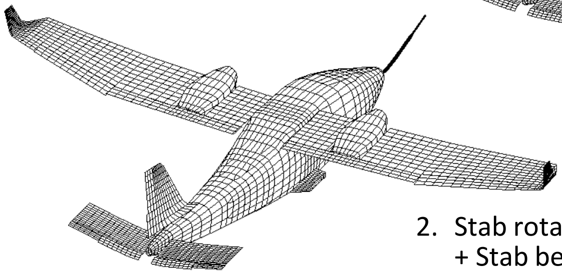
- 1st predicted flutter mechanism: Modes 12 & 16 (primary), Modes 15 & 18 (participants)
- 2nd predicted flutter mechanism: Modes 12 & 18 (primary)
- Closely spaced wing and empennage modes 14 – 20 Hz

ZAERO Mod II/III/IV Classical Flutter Predictions

- ZAERO Predicted Mod II flutter modes:



1. Stab rotation + Tail porpoising (driven by Wing Fore-Aft mode)



2. Stab rotation + Fuselage bending + Stab bending + Wing bending

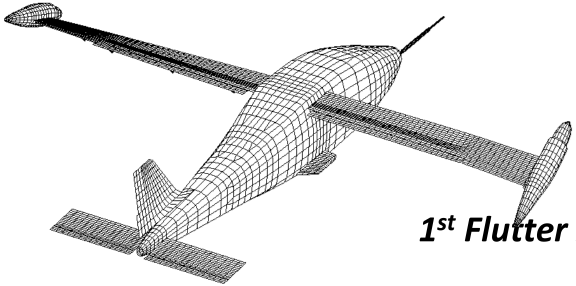
- Mod II trades P2006T wing weight for additional fuselage weight
  - Changes lower frequency of wing fore-aft mode, and reduce predicted flutter speed

- NASA FEM predicts P2006T flutter speed consistent with certified airframe
- Stabilator rotation mode participation across Mod II/Mod III/Mod IV configuration predicted flutter mechanisms

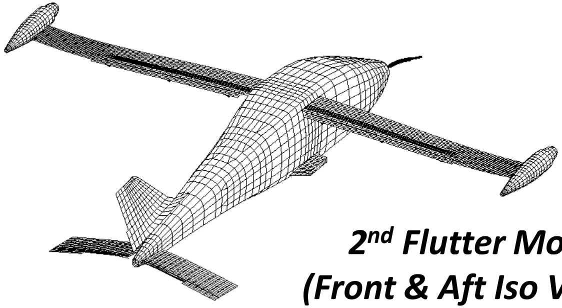
	Flutter Speed (KEAS)	Flutter Mode	Notes
NASA P2006 FEM	330 – 355 *	1st *	*does not cross 2% assumed damping for metallic structures
Mod II	270 – 284	1st	
Mod III	332 – 435	2nd	No distributed mass for HLM substitute nacelles
Mod IV	320 – 403	1st	

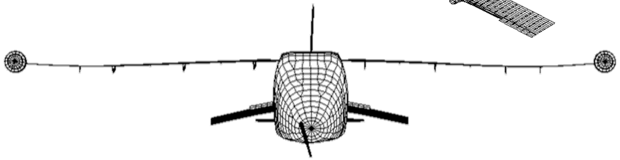
ZAERO Mod III/IV Classical Flutter Prediction

- ZAERO Mod III Predicted flutter modes:
  1. Wing bending + torsion
  2. Stab rotation + Fuselage bending + Stab bending



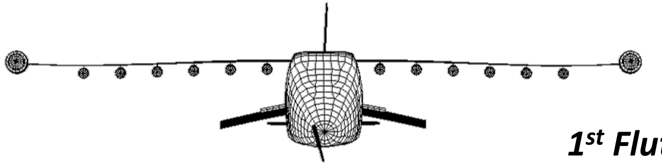
1st Flutter Mode

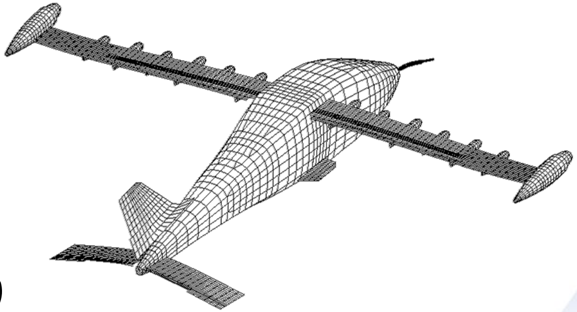




2nd Flutter Mode (Front & Aft Iso Views)

- ZAERO Mod IV Predicted flutter modes:
  1. Stab rotation + Fuselage bending + Stab bending





1st Flutter Mode (Front & Aft Iso Views)

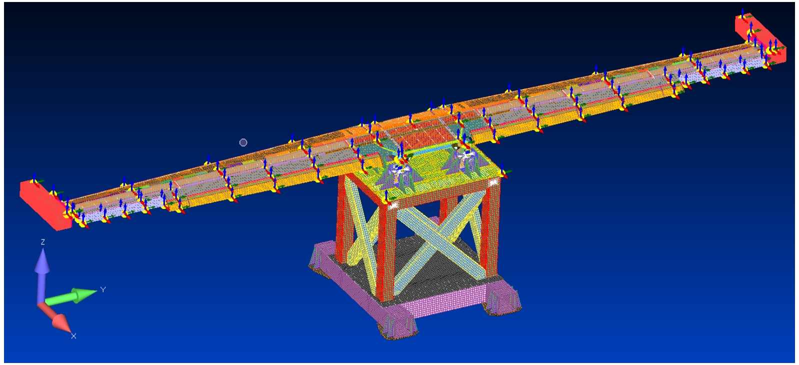
Mod III Wing GVT Correlation Highlights

- At Mod III wing GVT, fabrication of many wing flight components not yet complete: wingtip nacelles, HL nacelles/brackets, flap hinge lateral support brackets (connected to HL brackets)
  - Absence of flap lateral brackets resulted in heavily-damped flap lateral sway modes (flaps exhibited non-linear/loose mechanism modes)
- Flap setting (deployed vs stowed) had significant effect on control surface modes; flap contact effects had to be modeled for successful correlation
  - Contact between wing and flap not surprising given ~2 Hz 1st wing bending mode, and long-span/short-chord flaps supported by 3 hinges along span

Tradeoff for early GVT results to help identify significant issues, was correlation challenges posed by incomplete hardware

Mod III Wing FEM Correlation Methodology

- Utilized Guyan (Static) reduction to generate the Test Analysis Model (TAM). The reduced TAM is what is used to compare the finite element model to the test data.
  - This reduces the full FEM down to the degrees of freedom (DOF) that were measured in the modal test.
  - Performed the standard checks to ensure the reduced mass and stiffness matrices still accurately represent the full FEM.
  - Ideally, this process would guide the decision on where to place test instrumentation and where shakers would be required to excite all primary target modes.
  - The instrumentation placement used in the modal test shows it is only good to capture modes up to ~60 Hz at best for the purpose of correlation.
- After CAD vs FEM review is performed, the correlation effort is focused primarily on the joints, which is where most of the inaccuracy of the FEM is traditionally found.
  - CAD vs FEM review has to be done prior to any model correlation effort. Otherwise, optimization software will make un-realistic changes which will increase the inaccuracy of the FEM rather than make it better.
- Optimization of stiffness values throughout the FEM was performed utilizing ATA Engineering's Attune Software package.
  - A combination of strain energy distributions, past model correlation experience, and well defined limits for each parameter allow for all FEM modifications to be well grounded and justifiable.



Yellow dots with coordinate systems represent where instrumentation was placed on the test article during modal testing

Mod III Deployed Flap Correlation

- As frequency increases, correlation always will degrade.
- The reduced finite element model loses its ability to accurately capture the reduced mass and stiffness above 60 Hz using the instrumentation set from the modal test.
- Fundamental wing modes and primary flap bending modes are well correlated.

Original FEM Cross-Orthogonality

FEM/Test Cross Orthogonality Table

			FEM Shapes																						Freq
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	Pct
Otg	Test Shapes		2.20	2.42	4.68	8.06	15.34	15.74	15.79	16.72	24.31	24.98	28.60	34.33	34.37	38.73	42.50	44.01	46.08	47.56	53.09	53.87	54.92	57.57	Diff
100	1	2.15	100																						2.4
95	2	2.26	5	100																			6		7.2
90	3	6.00			100																				-22.0
85	4	7.52				100																			7.3
80	5	14.74					99	9	6																4.1
75	6	15.63		7					9	99															7.0
70	7	17.45						78	61	7			11												-9.8
65	8	19.63					9	63	76	10															-19.6
60	9	22.81									99						5								6.6
55	10	23.37				5						99	12												6.9
50	11	30.57											24	27	90										12.4
45	12	32.58						5	5					92	27										5.4
40	13	34.11						6				10	87		17			38		5		11	5		-16.1
35	14	38.43	6								5		15		5		92	20	13	13	5				10.6
30	15	40.79							5				32		5	20	40	78		9		6			7.9
25	16	43.99	5		5								5			94	7	15		22	10		6	5	-12.0
20	17	46.73	5					6					13				10	15	5	29	60	56	37	14	13.6
15	18	47.59									5		9			18			9	91	17	11		6	-0.1
10	19	48.59	6		5						5					6	17	13		10	85	25	7	24	9.3
5	20	49.70	7							5	6					15	20			25	87		18	16	6.8
0	21	50.40		9			5					5	5					27			15	64	62	13	6.9
	22	56.34								6		5				13	15	13		16	17	24	55	61	2.2

Final FEM Cross-Orthogonality

FEM/Test Cross Orthogonality Table

			FEM Shapes																				Freq
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Pct
Otg	Test Shapes		2.23	2.43	6.01	8.14	15.44	16.84	17.29	18.33	24.44	25.16	34.36	34.49	39.35	42.37	43.56	45.52	49.55	53.72	54.77	59.10	Diff
100	1	2.15	100																				3.4
95	2	2.26	6	100																			7.4
90	3	6.00			100																		0.2
85	4	7.52				100																	8.3
80	5	14.74	5				100																4.8
75	6	15.63		7				99	6														7.7
70	7	17.45							99						9								-0.9
65	8	19.63								100													-6.7
60	9	22.81								5	99					6							7.1
55	10	23.37				5						99											7.7
50	11	30.57							6				96	12	5								12.4
45	12	32.58								9			11	96									5.9
40	13	34.11													96		10	13			7		15.4
35	14	38.43	6								5				12	65	68	18	6	5			13.3
30	15	40.79							5						8	41	10	86					11.6
25	16	43.99	5													70	61	14	32			10	-3.7
20	17	46.73	5						5						15	11		12	25	73	56		15.0
15	18	47.59									5					13	23	5	91	9	11	5	4.1
10	19	48.59	6		6						5					13	9	12	21	84	14	12	10.6
5	20	49.70	7					5			6					8	16	6	16	91	22		8.1
0	21	50.40		9			5					5			5			23			93		8.7
	22	56.34						7				6				5	13	9	15	14	12	81	4.9

NASA-STD-5002 states diagonal values > 90% and off-diagonal values less than 10% are required for all significant modes. This does not translate to ALL modes. Experience has shown it is very difficult to achieve these standards on complex aerospace hardware for all modes.

Mod III Slightly Deployed Flap Correlation

- The correlation of the slightly deployed flap configuration was not as good as either the fully deployed or fully stowed correlation.
- Analysis Modes 7 and 8 are so heavily damped out in the test data, an accurate modal extraction could not be obtained. They do exist in the test data, but they are not going to be easily excited.
- Fundamental wing modes and primary flap bending modes are still well correlated.

Original FEM Cross-Orthogonality

FEM/Test Cross Orthogonality Table

FEM Shapes

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Freq Pct
Otg	Test Shapes		2.17	2.35	4.62	7.37	15.11	16.32	19.07	19.27	22.74	23.54	31.87	33.10	33.17	38.02	41.60	42.24	45.99	47.87	48.86	49.17	49.76	51.48	51.72	54.55	58.13	Diff
100	1	2.08	100	6																5								4.0
95	2	2.24		100																	6		7			8		5.0
90	3	6.01			100																	5						-23.2
85	4	7.51				100																	6					-1.9
80	5	14.76	7				99				5									14	13	11	6					2.4
75	6	15.70		9				99				11									31	5	9					3.9
70	7	22.71					5	6			98	18								15	23		6					0.1
65	8	23.29				6		9			19	97								6	29		8					1.1
60	9	30.17							7				5	93	27													9.7
55	10	34.43								9			13	26	85		25	14		12	14	9	11	5	7			-3.7
50	11	38.54	5	5					5				36	6	5	5	45	74	20	52	27	27	21	8			8	9.6
45	12	39.93							9				82		7	29	31	25	15	7	10	22	10	6		5	13	-20.2
40	13	41.54	9	6							6		11	8	26	8	76	41	10	23	37		5	13	27	12		0.2
35	14	44.51								7			24		10	94		10	7			5						-14.6
30	15	47.10		7					5	6		5	7			16	5	15	29	45		34	36	43	59	48	12	9.8
25	16	48.30								15	7		5		12	15	5	17	91	63	27	41		13		14	5	-4.8
20	17	49.14							5	15			26			21	25	8	78	57	12	17	24	14	31	26		-6.4
15	18	49.89		7					5	10			14		5	7	7	17	46	6	14	69	29	50	53	35		-1.5
10	19	50.32		5				5		12		5	8			24	17	17	70	58	10	10	11	5	41	41	8	-8.6
5	20	54.50	7	7									5	7	24		15	8		17	15	22	38	46	56	34	30	-5.1
0	21	63.11					5			13			14		11	8	6	7		5		15	14	13	14	8	86	-7.9
	22	65.65					13	7			15				6	6	7		10	9	17	8	16	17	15	10	26	-11.5
	23	66.64		5			5	5			8	8	7								31		16	7	9	21	34	-12.8
	24	70.14	7		6		18				5		6	6	5		10			23	23	16	29	22	9	11	14	-29.1
	25	70.87		5				16		5				14							35	11	24	10	22		17	-31.1

Final FEM Cross-Orthogonality

FEM/Test Cross Orthogonality Table

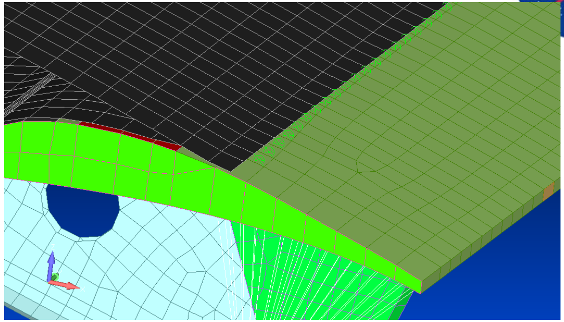
FEM Shapes

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Freq Pct
Otg	Test Shapes		2.22	2.42	6.02	8.16	15.59	17.02	18.02	19.13	24.43	25.10	34.24	34.29	41.20	42.62	44.40	44.96	49.80	54.52	55.53	59.85	Diff
100	1	2.08	100	7																			6.5
95	2	2.24		100																		8	8.0
90	3	6.01			100																		0.2
85	4	7.51				100																	8.6
80	5	14.76	5				99	6															5.6
75	6	15.70		7			6	99	6														8.4
70	7	22.71									99	5				5							7.5
65	8	23.29				5					5	99											7.8
60	9	30.17							6				88	40	6								13.5
55	10	34.43								9			37	82		8	22	14		9	5		-0.4
50	11	38.54	5										5		36	38	38	70	11	6	6		16.7
45	12	39.93							6	5			7		86	12	33	31	14				3.2
40	13	41.54	8	6							7		11	25	17	45	63	43		21	12		6.9
35	14	44.51								7				5	28	79	49		12			8	-4.2
30	15	47.10		6					6	5							10	23	30	56	68	7	17.9
25	16	48.30								16	7			11		7	14	20	89	12		15	3.1
20	17	49.14								15					17	7	19	12	82	32	29		1.3
15	18	49.89		6						11					9			22	51	44	65		11.3
10	19	50.32						5		12		6					16	24	73	44	30	22	-1.0
5	20	54.50	6	6									10	23			7			64	53	8	0.0

NASA-STD-5002 states diagonal values > 90% and off-diagonal values less than 10% are required for all significant modes. This does not translate to ALL modes. Experience has shown it is very difficult to achieve these standards on complex aerospace hardware for all modes.

Mod III Stowed Flap Correlation

- The correlation of the stowed configuration with cove contact springs was able to be significantly improved.
  - Contact was modeled with very flexible CBUSH elements < 5 lb/in stiffness
  - Right and left flap contact stiffness allowed to vary separately.
- Analysis Modes 7 and 8 are so heavily damped out in the test data, they could not be accurately extracted. They do exist, but they are not going to be easily excited.
- Fundamental wing modes and primary flap bending modes are well correlated in addition to some higher order flap bending modes.



Original FEM Cross-Orthogonality

FEM/Test Cross Orthogonality Table

FEM Shapes

Otg	Test Shapes		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Freq Pct Diff
			2.17	2.35	4.62	7.37	15.11	16.32	19.07	19.27	22.74	23.54	31.87	33.10	33.17	38.02	41.60	42.24	45.99	47.87	48.86	49.17	49.76	51.48	51.72	54.55	58.13	
100	1	2.13	100																	5								1.9
95	2	2.25		100																	8					5		4.4
90	3	6.21			100																	5						-25.6
85	4	7.88				100																	6					-6.5
80	5	14.82	7				99				5									16	13	10	5					1.9
75	6	15.77		9				99				11									31	5	9					3.5
70	7	22.78					5	6			98	18								16	24		5					-0.2
65	8	23.34				6		9			18	97								7	29	5	9					0.9
60	9	36.16												91	28			6		7	9	6			5			-8.5
55	10	40.89	7							5			11	20	65		63	12	8	28		9		5	22			-18.9
50	11	41.35	9												18		75	52	9	42	6	19			26	5		0.6
45	12	42.30	7	9							5			10	19	9	55	65		6	47		6	19	21	20	6	-0.1
40	13	44.26							23	7			10		18	89		21	7		11	11	12	6	8	14	5	-14.1
35	14	48.30							7	6			60	5	7	5	9	6	67	42	19	22	38	26		18		-4.8
30	15	52.32								8			40			26	6	5	68	42	12	41	34	48		11	12	-12.1
25	16	54.77	5	7			6	6					8	6			7	10	5	40	17	53	24	32	61	60	10	-5.6
20	17	57.21	5	6									5				22	16	10	22		19	30	38	51	47	33	-9.6
15	18	59.38	6	6			8	5					18				23	12	7	24		16	61	66	47	7	14	-13.3

Final FEM Cross-Orthogonality

FEM/Test Cross Orthogonality Table

FEM Shapes

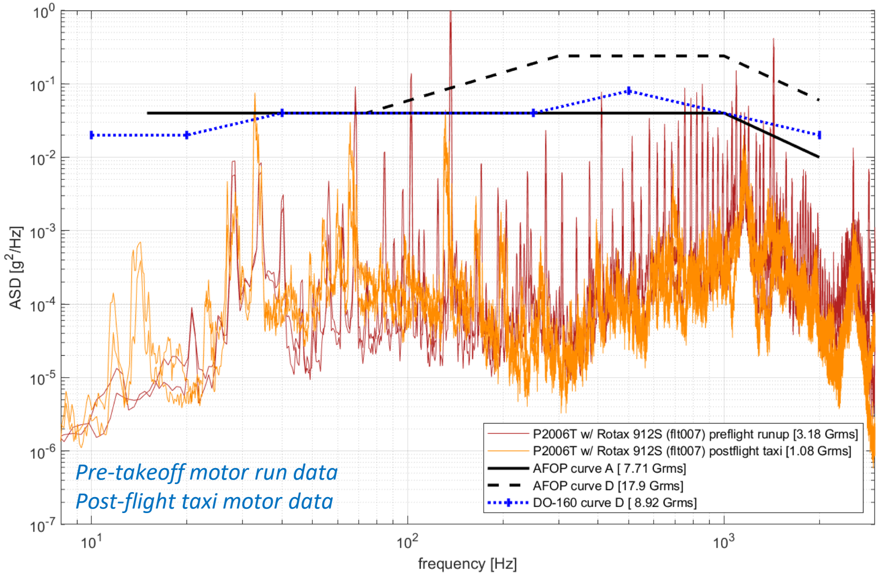
Otg	Test Shapes		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	Freq Pct Diff
			2.22	2.41	6.00	8.12	15.61	17.04	18.81	20.22	24.45	25.12	37.50	42.86	44.91	45.57	46.50	50.10	52.97	56.91	60.87	
100	1	2.13	100	5																		4.2
95	2	2.25		100																		7.1
90	3	6.21			100																	-3.3
85	4	7.88				100																3.0
80	5	14.82	5				99	7														5.3
75	6	15.77		7			6	99														8.0
70	7	22.78									99	5										7.3
65	8	23.34				6						99										7.6
60	9	36.16											95			5	5			6		3.7
55	10	40.89	6								5			36	87	20	13					9.8
50	11	41.35	9										7	37	19	87	6					10.2
45	12	42.30	6	8							5			25			91	11			6	9.9
40	13	44.26							17	13				80	10	27	40	23				-3.2
35	14	48.30								5				12		5	8	95	9			3.7
30	15	52.32												7		8			94		27	1.2
25	16	54.77	5	6			6	5				6	7			7				91		3.9
20	17	57.21		6															5	6	85	6.4
15	18	59.38	6	6			7				7										84	2.5

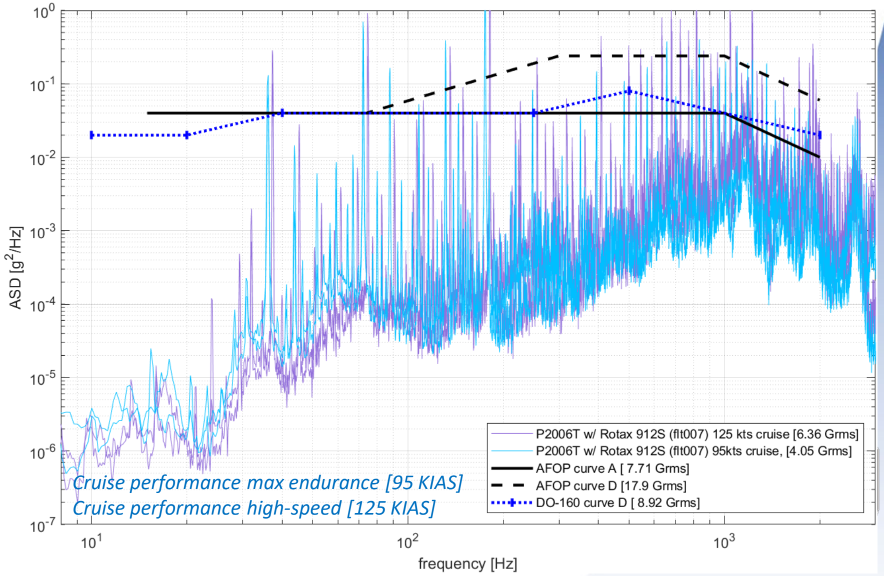
NASA-STD-5002 states diagonal values > 90% and off-diagonal values less than 10% are required for all significant modes. This does not translate to ALL modes. Experience has shown it is very difficult to achieve these standards on complex aerospace hardware for all modes.

Vibration Backup Slides

Tecnam P2006T Ground vs Flight Motor Vibration Levels

- Tecnam P2006T (Mod I) w/ Rotax 912S and 2-blade propeller Test Data
  - Flight 007, Left Motor Truss Accelerometer
- Significant increase in vibrations for 200-3000 Hz region during flight at cruise speeds, compared to preflight engine runup and post-flight taxi
  - Behavior possibly related to combustion engine and gearbox vibrations
  - Unknown how Mod II electric motor flight environment differs from Mod II ground run environment

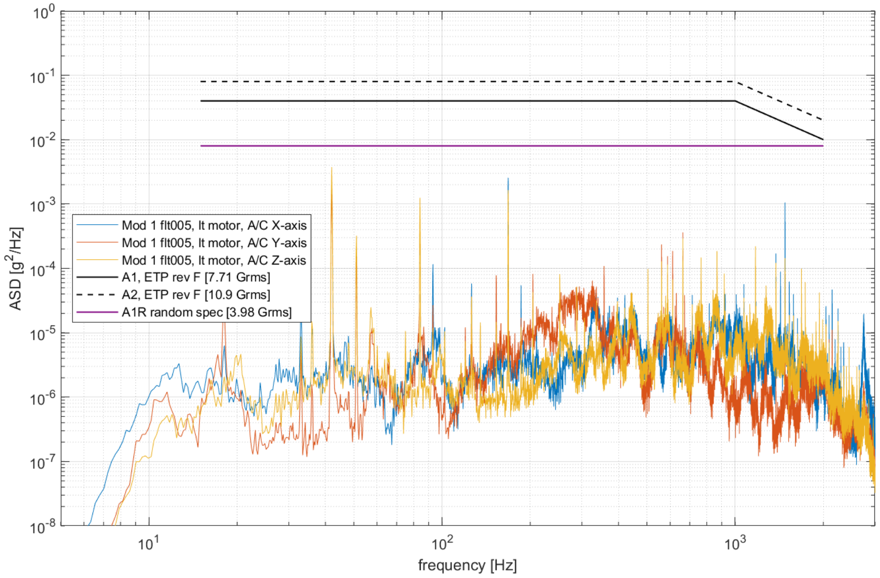




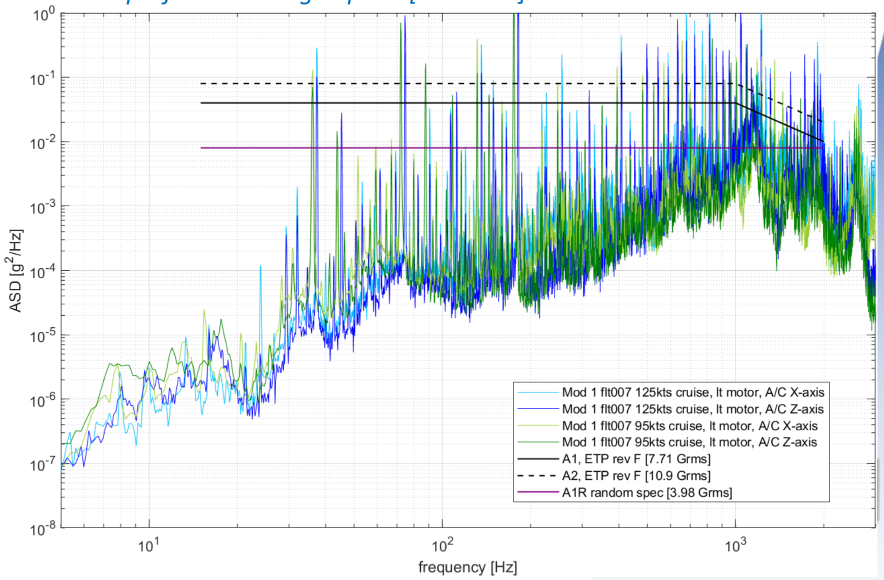
P2006T Flight 005 vs Flight 007 Motor Accel Data

- Mod I Flight 005 Lt Throttle idle, prop set to max RPM test point ASD (left plot)
  - 1-2 orders of magnitude lower vibration with prop windmilling compared Flight 007 ground run, taxi, and flight
  - Mod II CMC measured vibration environment 1 order of magnitude higher than simulated windmill for f<1000 Hz
- Mod I Flight 007 flight cruise points ASD (right plot)

Simulated 1 engine windmill on instrumented motor



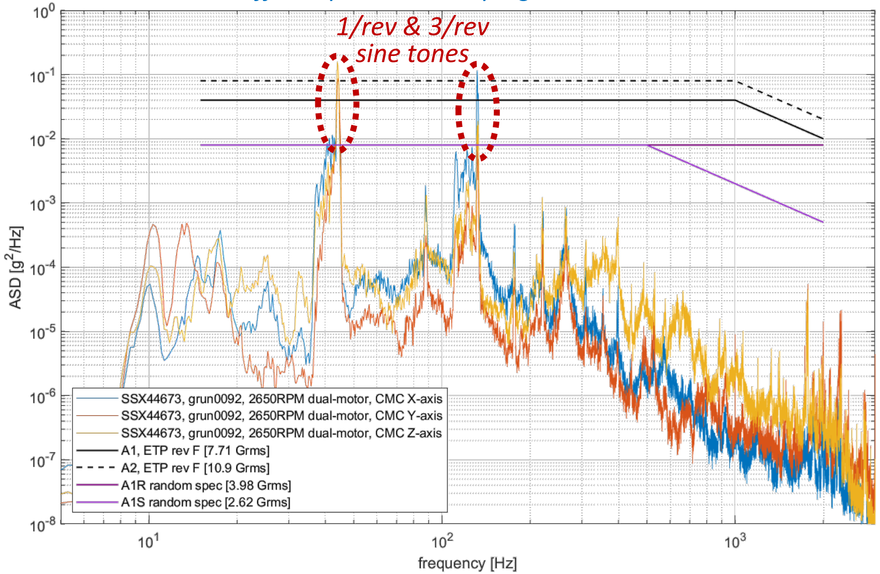
Cruise performance max endurance [95 KIAS]
Cruise performance high-speed [125 KIAS]



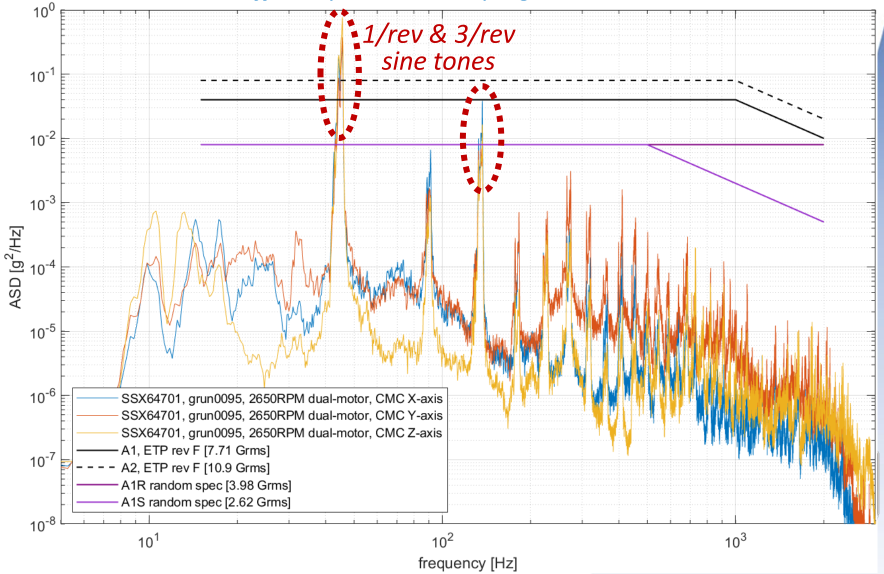
X-57 CMC Slam Stick Vibe – Left vs Right Motor

- Both SS data sets from dual motor ground runs at 2650 RPM; sine tones observed at 1/rev and 3/rev frequencies
- A1R SoR profile random spec level provides margin on left and right CMC dual-motor ground run data (09.01.2022 and 09.27.2022).
- Right CMC SS data indicate lower natural frequency of right CMC isolator installation. Indications: [1] higher 1/rev peak but lower 3/rev peak, and [2] random floor decreases at $f > 90$ Hz (compared to $f > 200$ Hz on left side)

Left CMC data (09.01.2022), full-fine prop pitch dual motor run
Left motor balanced to 0.03 IPS (NAMIS WR D-0220678 on 06.09.2022)
Installed-isolator stiffness provides damping >200 Hz



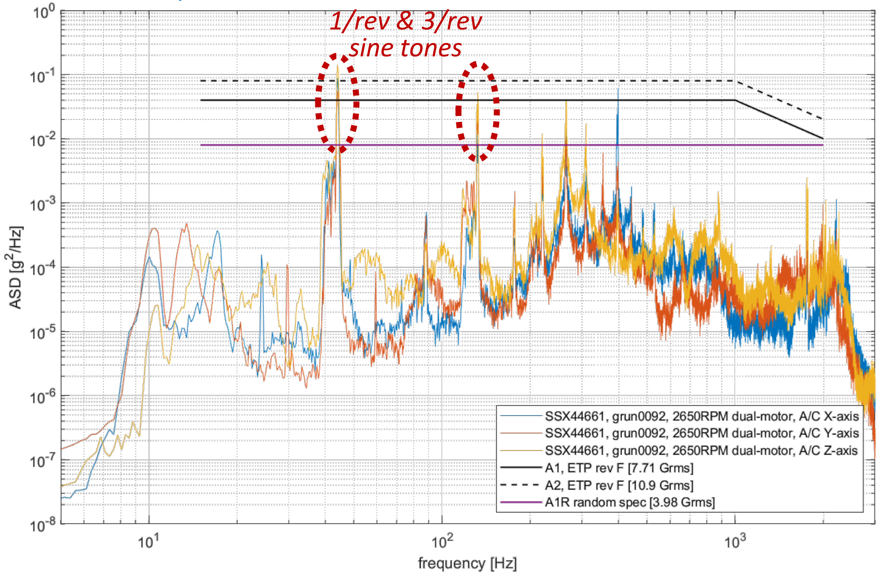
Right CMC data (09.27.2022), full-fine prop pitch dual motor run
Right motor balanced to 0.04 IPS (NAMIS WR D-0200895 on 04.28.2022)
Installed-isolator stiffness provides damping >90 Hz



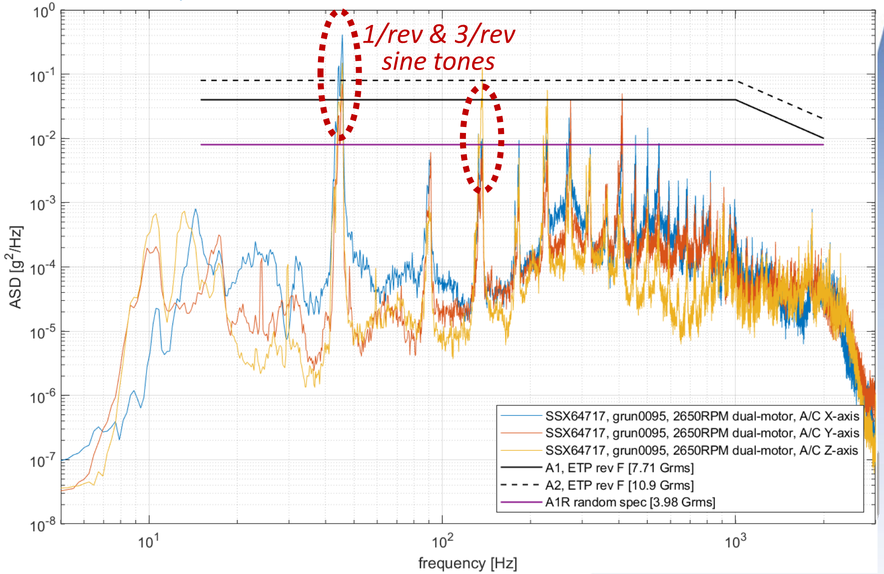
X-57 Mounting Rail Slam Stick Vibe – Left vs Right Motor

- Both Slam Stick data sets from dual motor runs at 2650 RPM; sine tones observed at 1/rev, 3/rev, and higher frequencies on upper mounting rail
- Right motor installation has higher level of vibration, and stronger sine tones for $f > 140$ Hz
- Motor mounts (white truss structure) not mirrored between left and right sides; translated (same part number used on left and right sides). Motor mounts are bespoke units (only 2 of 2 fabricated); unknown if both motor mounts have exactly same dynamic properties.
- Cruise motors rotate opposite directions; input vibrations resulting from cruise motor imbalance not the same to both mounting rails

Left upper mounting rail data (09.01.2022), full-fine prop pitch dual motor run. Left motor balanced to 0.03 IPS (NAMIS WR D-0220678 on 06.09.2022)



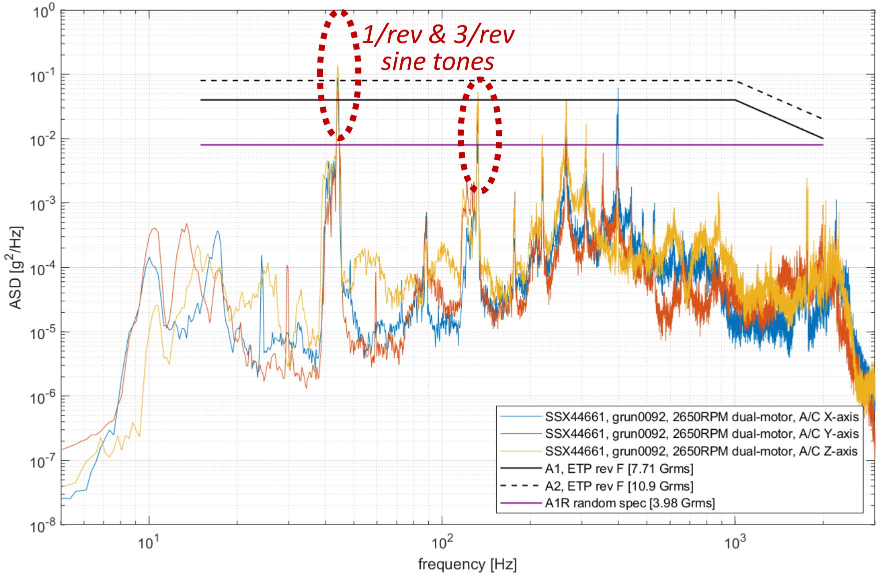
Right upper mounting rail data (09.27.2022), full-fine prop pitch dual motor run. Right motor balanced to 0.04 IPS (NAMIS WR D-0200895 on 04.28.2022).



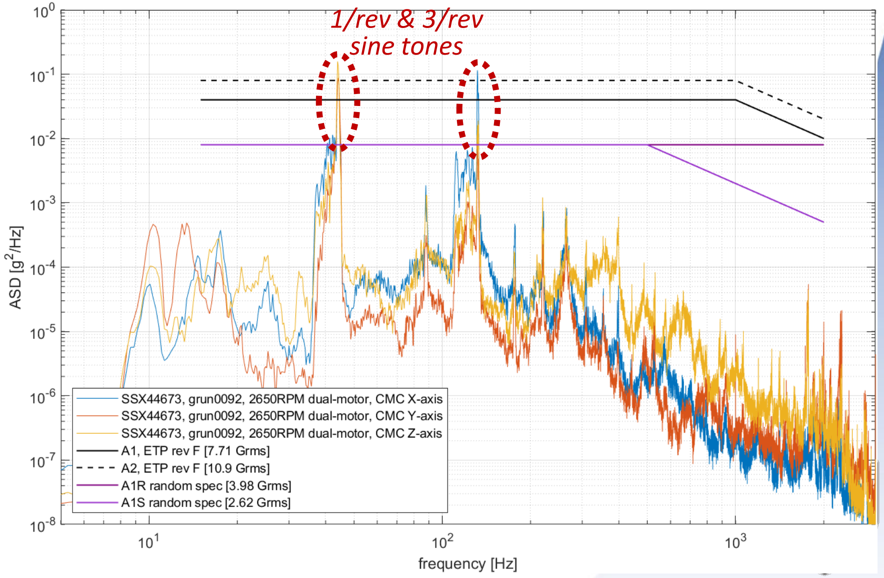
X-57 Left Motor Slam Stick Vibe – CMC vs Mounting Rail

- Left CMC 1/rev sine tone (right-side plot) similar in magnitude to left upper mounting rail 1/rev sine tone → no isolation provided for f<50 Hz
- Left CMC 3/rev sine tone (right-side plot) higher in magnitude than left upper mounting rail 3/rev sine tone → amplification near aircraft-isolator-installation natural frequency (f≈140 Hz); vibration damping f>200 Hz

Left Mounting Rail SS data (09.01.2022), full-fine prop pitch dual motor run.
Left motor balanced to 0.03 IPS (NAMIS WR D-0220678 on 06.09.2022)



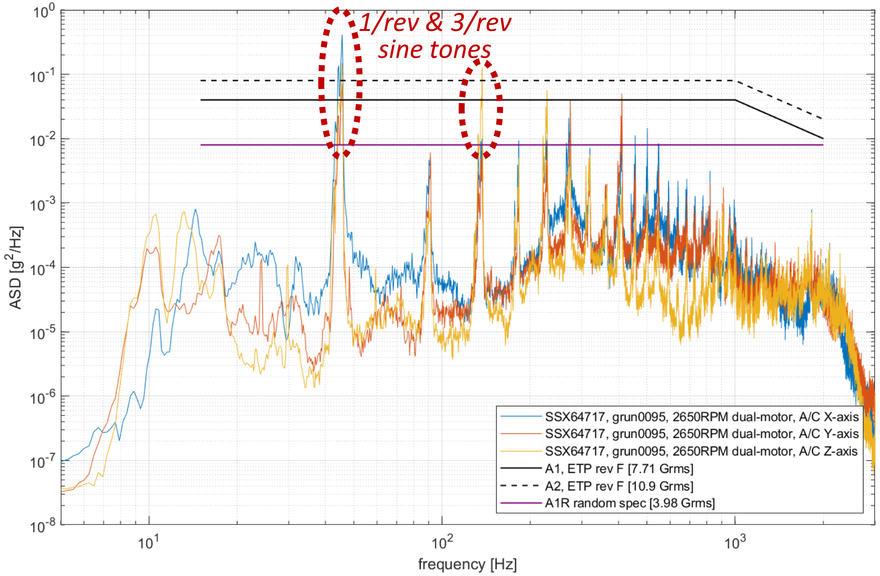
Left CMC data (09.01.2022), full-fine prop pitch dual motor run
Left motor balanced to 0.03 IPS (NAMIS WR D-0220678 on 06.09.2022)
Installed-isolator stiffness provides damping >200 Hz



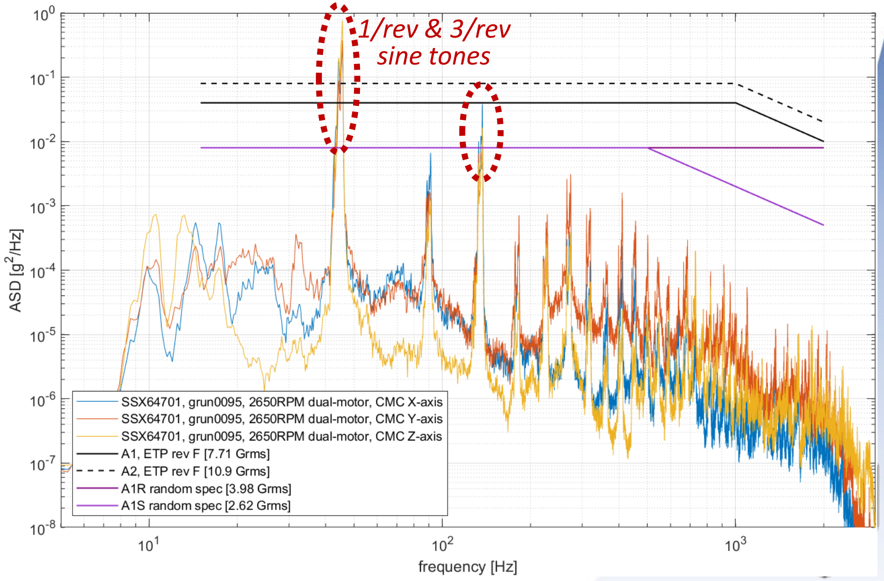
X-57 Right Motor Slam Stick Vibe Env – CMC vs Mounting Rail

- Right CMC 1/rev sine tone (right-side plot) slightly higher in magnitude than right motor upper mounting rail 1/rev sine tone → amplification around aircraft-isolator-installation natural frequency
- Right CMC 3/rev sine tone (right-side plot) lower than right motor upper mounting rail 3/rev sine tone → aircraft-isolator-installation vibration damping f>90 Hz

Right upper mounting rail data (09.27.2022), full-fine prop pitch dual motor run. Right motor balanced to 0.04 IPS (NAMIS WR D-0200895 on 04.28.2022)

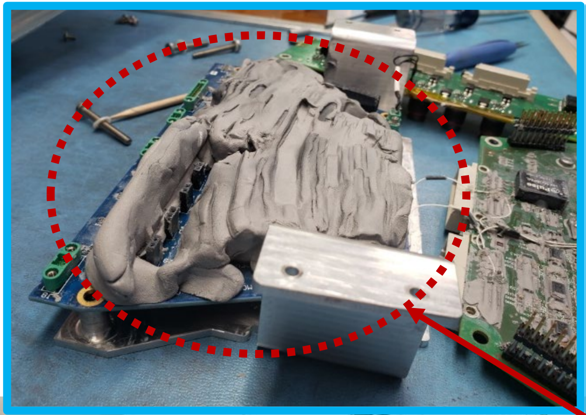


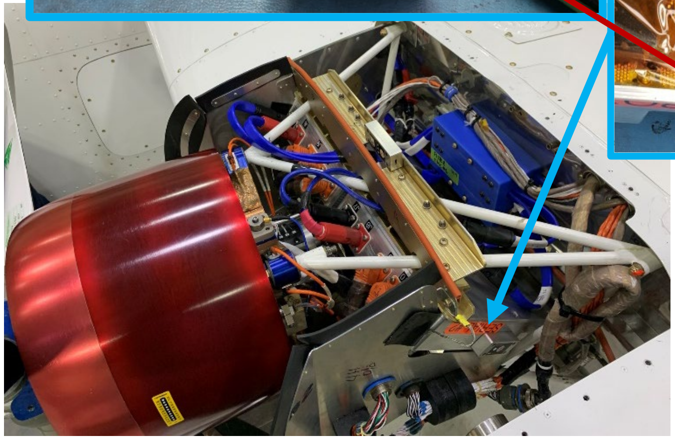
Right CMC data (09.27.2022), full-fine prop pitch dual motor run Right motor balanced to 0.04 IPS (NAMIS WR D-0200895 on 04.28.2022) Installed-isolator stiffness provides damping >90 Hz

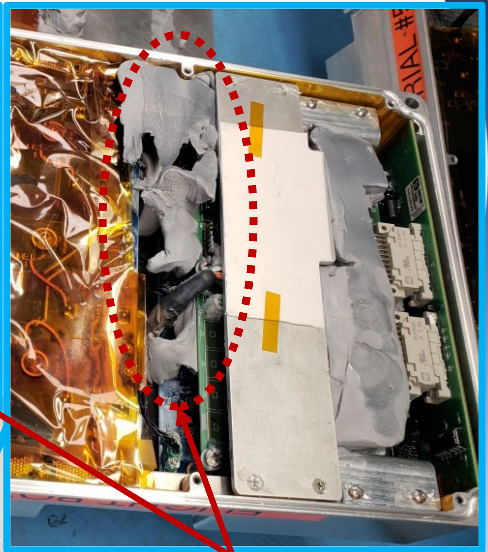


Increased Motivation for Measuring CM Vibrations

- In Aug 2022 discovered that XM3 CMC (2nd gen CMCs) unable to pass environmental vibe test at proto-qualification levels (Curve A + 3dB) due to thermal pad migration
- CMCs considered flight critical hardware (component failure could result in loss of thrust)
- Component-availability and time constraints drove use of multi-layer thermal gap filler pads for heat transfer between new and legacy circuit boards to case lid heatsink
- Low-frequency vibrations amplified by use of standard avionics-mounting isolators



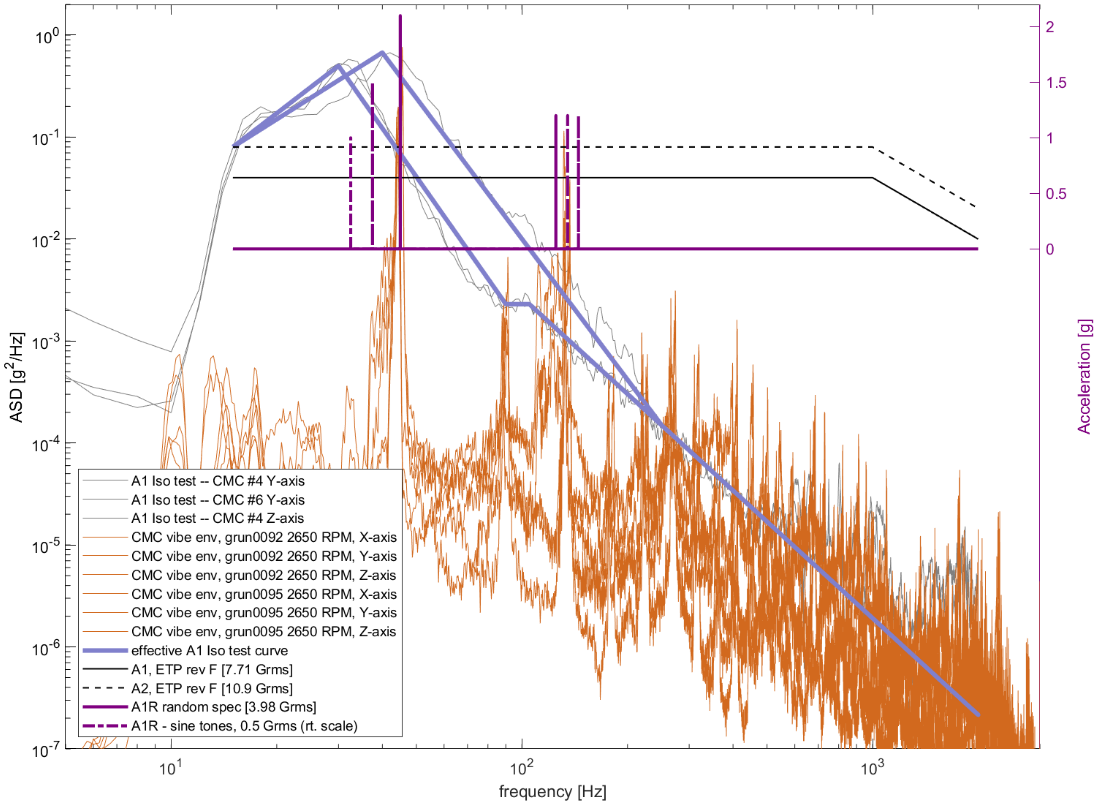




CMC Vibration Curve and Results Overview

- A1 curve – Acceptance level for isolator-mounted Cat III (AFOP-7900.3-004 curve A)
  - CMCs 1, 2, 3, 5, and 6 vibration tested to A1 acceptance level. Testing conducted on isolators; but exact aircraft setup could not be replicated on vibe table.
- A2 curve – Proto-qual level: AFOP-7900.3-004 curve A with 3dB margin
  - CMC 4 vibration tested to A2 proto-qual level. Thermal pad movement resulted in abrasion failure of low power boards. Testing conducted on isolators, but not exact aircraft setup.
- Mod II CMC vibration Slam Stick measurements → sine-on-random environment observed
- A1R curve – tailored Mod II vibration curve for no-isolator testing
  - Provides some conglomerated margin for left/right installation differences, motor/prop imbalances, potential propeller damage during taxi/flight, and differences between flight and ground environments
  - Exploratory vibe testing demonstrated no thermal pad movement for A1R. A1R derived from ground motor run SS data, with added margin for flight environment extrapolation based on Mod I data. Confirmed no thermal pad movement for A1R SoR test levels.
  - A1R – CMC 5 tested in all 3-axes. Experienced MOSFET temperature shift after last test was completed. CMC 7 test in Z-axis completed, but now stuck in disarming loop.
- A1S curve – modified A1R curve, reduces high frequency input to CMC. Reduction to account for high-frequency damping provided by aircraft isolator installation.
  - Given all vibe testing since 2020 BM2 testing was conducted on isolators, components likely never screened for higher frequency vibration.

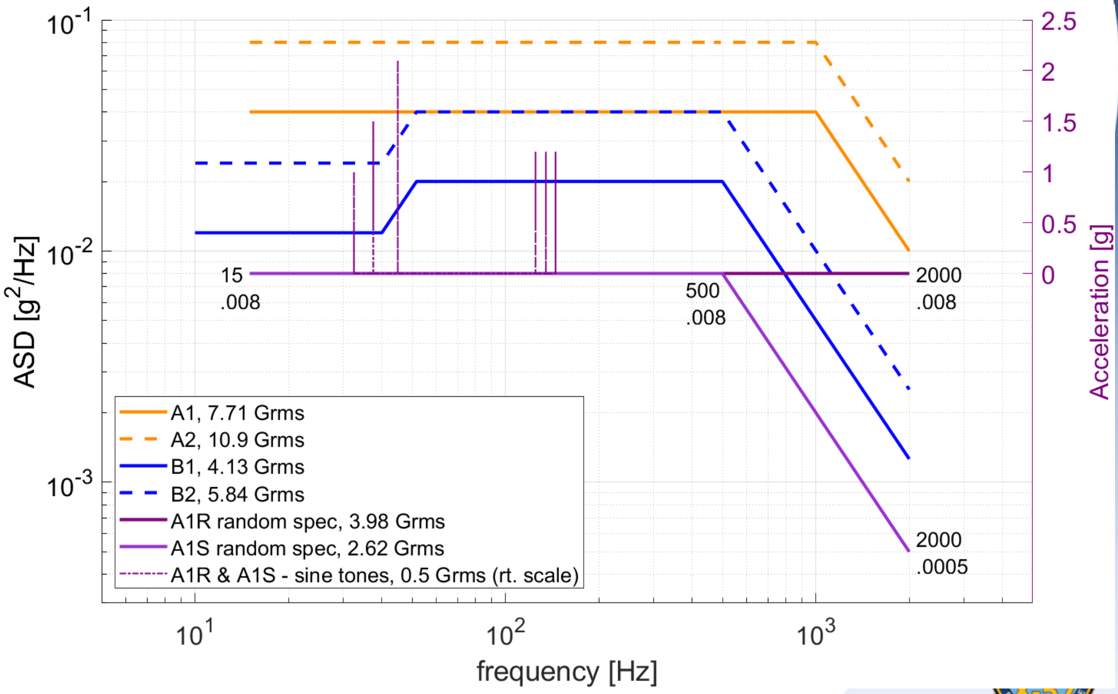
CMC Vibration Test Waiver Supporting Information



- CMCs 1, 2, 3, and 6 were intended to be tested to **A1**
- Due to isolators used on vibe table, CMCs 1, 2, 3, and 6 only effectively tested to **effective A1-Iso**
- CMC vibration environment measured during Mod II ground runs using Slam Sticks, shown by orange data
- **Effective A1-Iso** covers significant portion of the vibration environment measured during ground run, but Mod II installation environment has some areas of vibration exceedance
- CMCs 5 and 8 tested to updated **A1R Sine on Random** curve, which provides margin on top of highest amplitudes measured during A/C ground motor runs
  - Conglomerated margin for: installation differences, motor/prop imbalance, prop damage, differences between flight and ground environments, etc.

A1R and A1S Acceptance Hard-mount CMC Vibration Test Spec

- Pre and Post test Integrity Check – Sine Sweep
  - 20 – 2000 Hz, 0.1 peak, 4 octave/min, 2 sweeps (high → low, low → high)
- Sine on Random Test Curve
  - A1R Random vibration spec
    - .008 g^2/Hz at 15 Hz
    - .008 g^2/Hz at 2000 Hz
  - A1S Random vibration spec
    - .008 g^2/Hz at 15 Hz
    - .008 g^2/Hz at 500 Hz
    - .0005 g^2/Hz at 2000 Hz
      - 6dB/octave reduction >500 Hz (taking credit for isolators)
  - Sine tones
    - 30-35 Hz @ 1.0g peak
    - 35-40 Hz @ 1.5g peak
    - 40-50 Hz @ 2.1g peak
    - 100-150 Hz @ 1.2g peak



CM Vibration Velocity and Display Criteria

- X-brace flight accelerometer measured vibrations at 1/rev and 3/rev frequency bands for 600 - 2700 RPM, compared to published sinusoidal vibration standards for propeller balancing and aircraft environmental testing
- Increasing velocity criterion vibration results (IPS) and steady/slightly increasing displacement criterion vibration results (DO-160 comparison) indicate something is changing in the cruise motor at higher RPM