X-57 Cruise Motor GVT using Fixed-Base Correction Technique

Keerti Bhamidipati, Natalie Spivey, Scott Stebbins, Samson Truong, and Benjamin Park

Armstrong Flight Research Center
National Aeronautics and Space Administration
4800 Lilly Ave Edwards, CA 93523 USA

ABSTRACT
The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) completed a modal survey of the X-57 Maxwell aircraft cruise motor system to help inform cruise motor redesign efforts. X-57 Maxwell was an electric propulsion demonstrator aircraft developed by NASA to inform airworthiness standards for electrified-aircraft. The cruise motor system modal survey was completed in spring of 2023 utilizing the fixed-base correction (FBC) ground vibration test (GVT) technique developed by ATA Engineering, to decouple the motor modes from the aircraft modes. Previously during the full aircraft GVT, a detailed modal assessment of the cruise motors was not performed.

Owing to the X-57 project's phase in the aircraft development cycle when the motor redesign effort occurred, the cruise motor GVT could only be performed with the cruise motor system installed on the aircraft, with most of its installation hardware (wiring, baffling, sensors, etc.) attached. An impact hammer was used to provide excitation input at various locations within the tight confines of the cruise motor installation. To better support motor redesign efforts, the FBC methodology was utilized to fix, separate and de-couple the cruise motor modes from aircraft modal response. During the GVT, this required additional impact tap tests on candidate fixed-boundary points for each degree of freedom (DOF) to be fixed. Additional triaxial accelerometers installed at the candidate points were used to compute frequency response functions (FRFs) in X, Y, and Z directions to enable those DOFs to be numerically fixed. Test data was acquired using Hottinger Brüel & Kjær's LAN-XI data acquisition hardware and BK Connect software. FBC post-test processing was performed using the Structural Modification Using Frequency Response Functions (SMURF) technique with ATA Engineering's Interface between MATLAB, Analysis, Test (IMAT) software. Utilizing the FBC technique relieved test engineers from having to instrument the entire aircraft to identify and separate aircraft response from cruise motor modes of interest. The FBC technique also permitted structural analysis engineers to omit secondary components from their finite element model (FEM) of the cruise motor system. This FBC modal survey was successful, and the first time NASA AFRC utilized the FBC method on an aircraft rather than a test fixture, and also using an impact hammer rather than multiple shakers allowing significant project schedule and cost savings.

Keywords: modal survey, GVT, Ground Vibration Test, fixed base correction, X-57, Electric, aircraft, motor, cruise

1 INTRODUCTION

The X-57 Maxwell was an electric propulsion demonstrator aircraft developed by NASA to inform airworthiness standards for upcoming electrified-aircraft. The airframe is a modified general aviation Tecnam P2006T built by Costruzioni Aeronautiche Tecnam (Capua, Italy). [1-2] For the X-57 Mod II Maxwell configuration, two high-efficiency air-cooled electric motors powered by traction batteries replaced the OEM Rotax 912S gasoline engines.

Previously in late 2019, NASA AFRC's Flight Loads Laboratory (FLL) conducted a ground vibration test (GVT) on the X-57 Mod II aircraft, as shown in Figure 1, to gather data for correlating the aircraft finite element model (FEM). [3,4] A detailed modal assessment of the cruise motor assembly was not performed during the aircraft GVT, since the primary objective of that test was to develop a FEM for classical flutter analyses to evaluate the aeroelastic airworthiness of the X-57 Mod II aircraft and inform flight test planning. Additionally, a portion of the cruise motor system had previously operated on a ground propulsion test stand and demonstrated sufficient maturity to proceed with aircraft propulsion system integration. [5] The motor representation in the Mod II aircraft FEM consisted primarily of beam elements and concentrated masses connected to the aircraft wing. [4] Late in the aircraft project cycle, a potential mechanical failure mechanism with the cruise motor hardware was discovered. An effort to redesign some of the cruise motor mechanical interfaces was kicked off, and a motor GVT was performed to help inform the motor redesign effort. However, this GVT had to be performed with the cruise motor system installed on the aircraft, and most installation hardware (wiring, baffling, sensors, etc.) attached, as shown in Figure 2. The fixed-base correction (FBC) GVT technique developed by ATA Engineering was utilized to separate and de-couple the cruise motor modes from aircraft modal response. [6,7,8,9]

Figure 1: Previously conducted X-57 Mod II Aircraft GVT setup on soft supports to simulate a free-free boundary condition.

Figure 2: X-57 Mod II Cruise Motor GVT setup performed with aircraft on its landing gear.

2 TEST SETUP
The X-57 cruise motor GVT was conducted from April to May 2023 in Hangar 4840, Bay 5 at NASA AFRC, using an impact hammer to provide the input excitation force. No pre-test FEM predictions were available to assist in the planning of the test. Results from previous GVTs of the X-57 aircraft and components of the cruise motor system were used to inform accelerometer placement and focus frequencies of interest for target modes.

2.1 Test Article
The X-57 Mod II aircraft remained on-tires resting on the hangar floor for the duration of the GVT. The electric motor assembly is mounted onto the aircraft wing at the same four wing firewall mounting locations used by the OEM Rotax engines. A structural truss and X-brace motor adapter, interface the custom JM-X57 electric motor to the wing. The structural truss also provides a mounting location for the NASA-designed cruise motor controllers (CMCs) which convert DC battery power to AC current for the motor. For the GVT, cruise motor nacelle upper and lower covers were removed to allow GVT accelerometer installation on various components of the motor system. Baffling which directs cooling airflow through the motor and over the CMCs consists of left, bottom, and right pieces. The bottom baffling piece was also removed to allow GVT accelerometer installation and provide clearance to use the impact hammer on the X-brace, and slip ring components.

2.2 GVT Instrumentation

The data acquisition (DAQ) system used for this test consisted of Brüel & Kjær LAN-XI hardware and BK Connect software. Type 3050 and Type 3053 LAN-XI modules installed in 5-slot and 11-slots mainframes provided 126 channels of data acquisition. Triaxial accelerometers used at measurement locations were PCB model T356A16 made by PCB Piezoelectronics (Depew, NY). Impact excitation input was provided using a Dytran 5800B4 50-lb. impulse hammer with a soft polyurethane tip made by Dytran Instruments, Inc. (Chatsworth, CA).

A total of 37 triaxial accelerometers were used for the GVT measuring a total of 111 degrees of freedom (DOF). Table 1 lists the node numbering convention used for the accelerometer instrumentation attached to the cruise motor assembly. All accelerometers were attaching using hot glue. Mounting blocks were used as needed to orient each accelerometer into alignment with the aircraft coordinate system axes. Figure 3 depicts the locations of the accelerometer groups installed on the cruise motor for the GVT. Due to limited clearance in the aircraft installation, several of these accelerometers were difficult to install. The test display model (TDM) used to visualize mode shapes was constructed using BK Connect and is shown in Figure 4. Triangular elements represented the major components of the cruise motor system with trace lines connecting separate components. A single propeller blade, the propeller hub, and long truss elements were represented using trace lines only.

Table 1: GVT node numbering convention and group names for cruise motor accelerometer instrumentation.

Node Series	Node Group	# of Triaxial Accelerometers
1100	Cruise Motor Firewall	4
1200	Cruise Motor X-Brace Adapter	7
1300	Slip Ring Body	1
1400	Rotor	6
1500	Propeller Hub and Blade	3
1600	Stator	4
1700	Cruise Motor Truss	8
1800	Cruise Motor Controller (CMC)	4

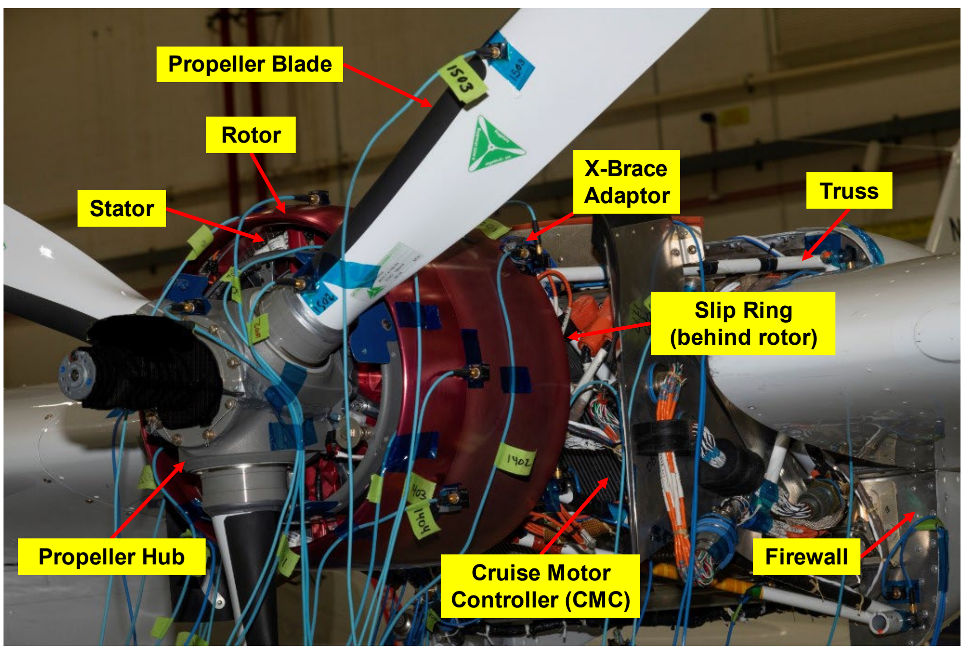


Figure 3: Cruise motor assembly GVT accelerometer group locations.

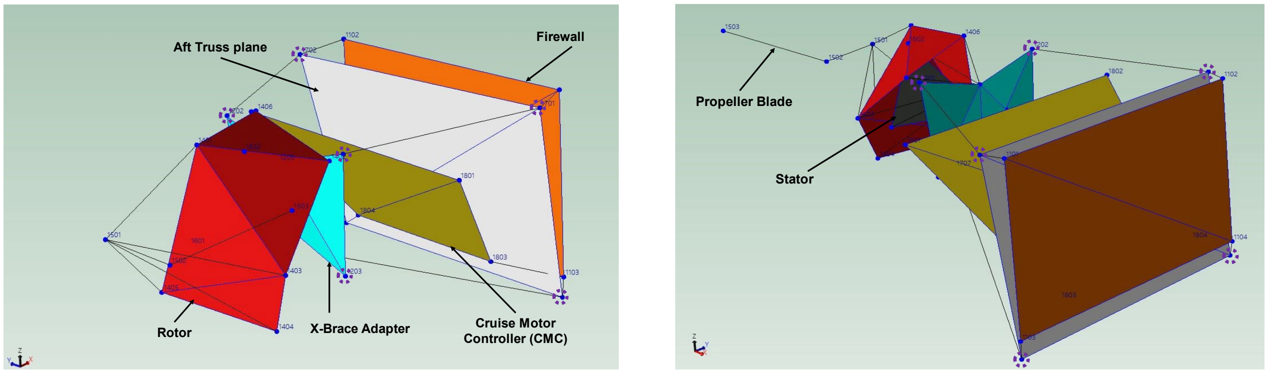
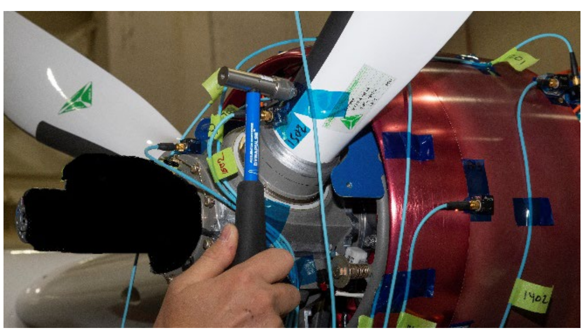


Figure 4: Test display model used for visualizing cruise motor GVT mode shapes; front Iso View (left) and back Iso View (right).

2.3 Excitation Locations

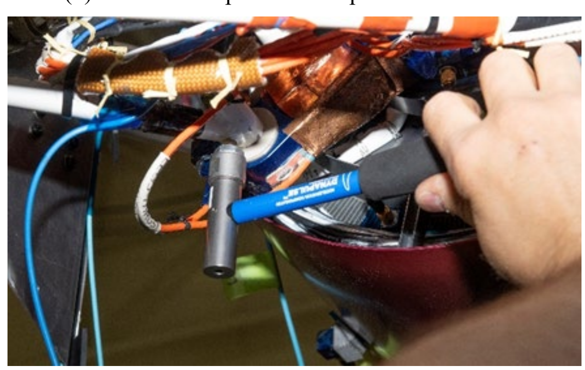
In addition to the ideal test article excitations typically required for GVT, to utilize the FBC technique additional excitation in 3-axes at each of the desired fixed-boundary candidate locations are required. Previously NASA AFRC had only used excitation from multiple shakers when applying the FBC technique. For this GVT, just a single impulse hammer was used. Many of the candidate fixed-boundary locations were in very tight confined spots and difficult to impact cleanly. However, connecting a shaker to those locations would have been nearly impossible to accomplish. For the X-57 cruise motor GVT, numerically fixed boundaries were attempted at two different interfaces of the motor assembly. These candidate points, shown by dashed-purple circles in Figure 4, were the four aft truss attachment points (Nodes 1701 – 1704), and the four corners of the X-brace adapter (Nodes 1201 – 1204). Impact excitations in all 3-axes at each of the candidate fixed points were performed, and necessary since no pretest analytical predictions were available to inform how many different DOF should be fixed to remove flexibility at the cruise motor/aircraft-wing interface. Figure 5 illustrates examples of test article and candidate fixed-boundary impact hammer excitations.



(a) Propeller Blade X-dir impact at Node 1502

(b) X-Brace Adapter Z-dir impact at Node 1202

(c) Aft Truss Y-dir impact at Node 1704



(d) X-Brace Adapter Z-dir impact at Node 1204

Figure 5: Impact excitation examples for the cruise motor GVT; test article tap (a), and candidate fixed-boundary taps (b,c,d).

3 RESULTS

Cruise motor system modes of interest were extracted using data from two typical test article impact taps: 1) in the Z-direction on top side of the rotor at Node 1401, and 2) in the X-direction near the root of a propeller blade at Node 1502. A complex mode indicator function (CMIF) using data from these two excitations is shown by the uncorrected blue line in Figure 6. In this uncorrected CMIF, strong response from the aircraft wing modes can been observed at lower frequencies. Additional aircraft response in the middle frequencies is also observed in the uncorrected CMIF. A CMIF corresponding to these same two test article taps but utilizing the FBC technique to numerically fix the aft truss attachment points (Nodes 1701 – 1704), is shown by the orange line in Figure 6. In this FBC CMIF, peaks corresponding to aircraft modes are no longer present. Verifying GVT mode shapes, like the example shown in Figure 7, confirms that the FBC technique was successful in removing the motion of the aircraft wing. The FBC CMIF shown in Figure 6 also better captures cruise motor system modes of interest occurring at higher frequencies. Some motor system modes, such as truss vertical bending, also shift slightly in frequency between the uncorrected and FBC modal measurements. The FEM developed by structural analysts for the cruise motor design can be simplified by not including the cruise motor/wing interface stiffness and rigidly fixing the FEM at the aft truss nodes. For validating such a model and having an apples-to-apples comparison of the fixed boundary conditions, the mode shapes and frequencies extracted from the FBC corrected data are the proper ones to use.

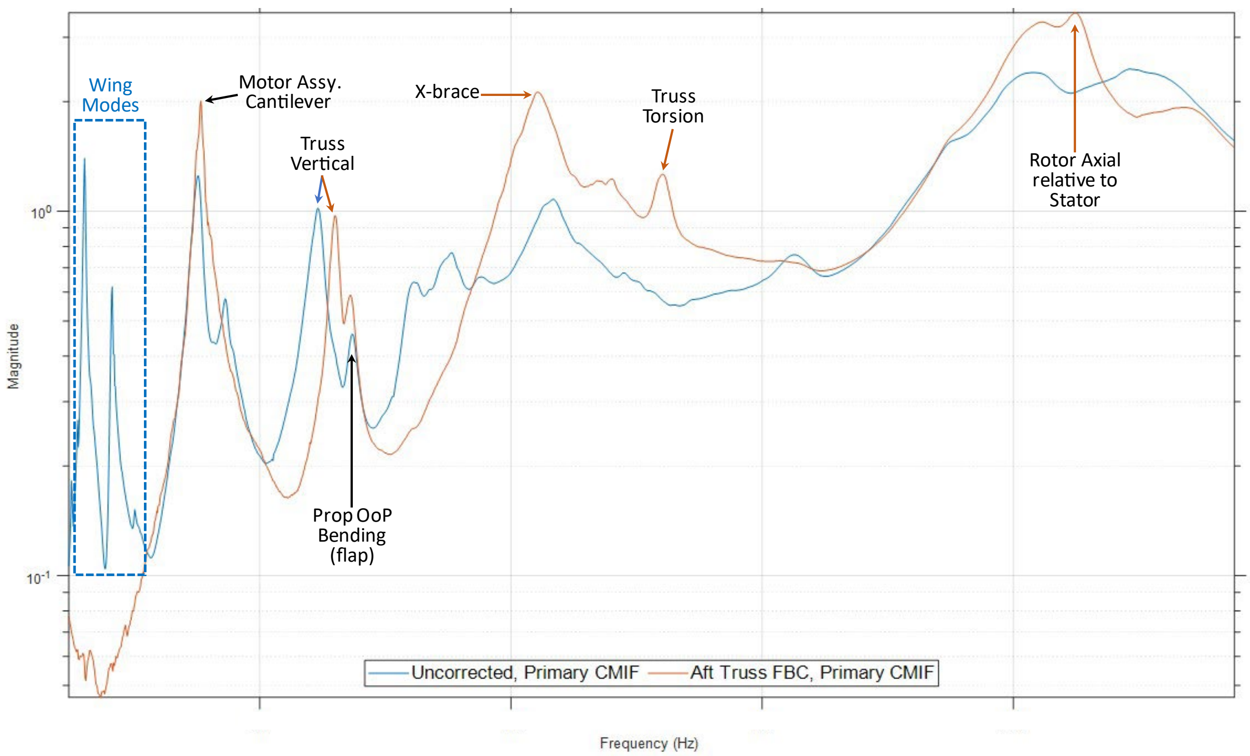
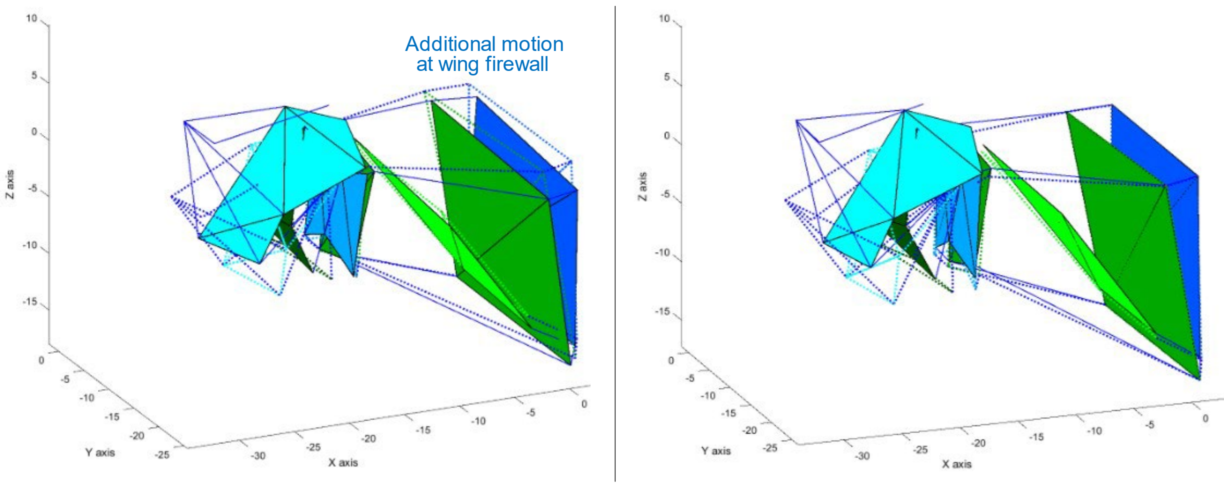


Figure 6: Primary CMIF comparison for uncorrected GVT data and GVT data with FBC technique applied (with significant cruise motor and aircraft modes labeled).



(a) Uncorrected mode shape

(b) Aft truss FBC mode shape

Figure 7: Uncorrected and FBC mode shape comparison; Motor Assembly Vertical Cantilever mode

CONCLUSION

X-57 Mod II Cruise Motor GVT results helped inform cruise motor redesign efforts. Utilizing the fixed-base correction (FBC) method provided many benefits: 1) enable testing without pre-test FEM predictions, 2) avoid the need to instrument significant portions of the wing and aircraft to separate and de-couple the cruise motor modes from aircraft modal response, 3) allow structural analysts to omit secondary components from their cruise motor system finite element model (FEM) and 4) save the project cost and schedule. Impact hammer data at two test article locations, the four corners of the X-brace and the four aft truss attachment points, were gathered to attempt the FBC technique. Flight hardware, wiring, and instrumentation already integrated into the cruise motor system made gathering FBC impact hammer data at the four X-brace corners difficult. FBC impact hammer data at the four aft truss attachment points was easier to gather, however the resulting model included modes from the motor truss and truss-attached hardware.

ACKNOWLEDGEMENTS

The authors would like to thank the X-57 flight operations crew for their assistance in setting up the aircraft for GVT. In addition, the authors would also like to thank Kevin Napolitano from ATA Engineering, and James Winkel from NASA Langley Research Center for their guidance on applying the impact hammer fixed base correction test technique.

REFERENCES

[1] NASA Armstrong Fact Sheet: NASA X-57 Maxwell, https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html, accessed August 2, 2023.

[2] Borer, N.K., Guether, S.C., Litherland, B.L., Kohlman, L., "Design and Performance of a Hybrid-Electric Fuel Cell Flight Demonstration Concept," Hampton, VA, June 2018. Available at: https://www.nasa.gov/X-57/technical/index.html, accessed August 2, 2023.

[3] Armstrong Flight Loads Laboratory, https://www.nasa.gov/centers/armstrong/research/Facilities/FLL, accessed August 2, 2023.

[4] Spivey, N., Truong, S., Truax, R., "All-Electric X-Plane, X-57 Mod II Ground Vibration Test," Edwards, CA, August 2020. Available at: https://www.nasa.gov/X-57/technical/index.html, accessed August 2, 2023.

[5] Papathakis, K.V., Sessions, A.M., Burkhardt, P.A., Ehmann, D.W., "A NASA Approach to Safety Considerations for Electric Propulsion Aircraft Testbeds," Edwards, CA, July 2017. Available at: https://www.nasa.gov/X-57/technical/index.html, accessed August 2, 2023

[6] Napolitano, Kevin L., and Nathanael C. Yoder, "Fixed Base FRF Using Boundary Measurements as References - Analytical Derivation," Proceedings of the SEM IMAC XXX Conference, Jacksonville, Florida, 2012.

[7] Napolitano, Kevin L. "Fixing Degrees of Freedom of an Aluminum Beam by Using Accelerometers as References," Topics in Modal Analysis I, Volume 5, Proceedings of the SEM IMAC XXX, A Conference on Structural Dynamics, Jacksonville, Florida, pp. 309-317, 2012.

[8] Spivey, N., Miller, K. Saltzman, R., and Napolitano, K., "Modal Testing of a Flexible Wing on a Dynamically Active Test Fixture Using the Fixed Base Correction Method," IFASD 2019-108, 2019.

[9] Spivey, N., Saltzman, R., Wieseman, C., Napolitano, K., and Smith, B., "Passive Aeroelastic Tailored Wing Modal Test Using the Fixed Base Correction Method" Proceedings of the SEM IMAC XXXVIII Conference, Houston, Texas, 2020.