X-57 Cruise Motor Controller Design and Testing

Jacob Terry, Susanah Kowalewski, David Avanesian, Sean Clarke
NASA Armstrong Flight Research Center (AFRC), NASA Glenn Research Center (GRC)

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Hello, my name is Jacob Terry from NASA Armstrong Flight Research Center and today I will be presenting

Cruise Motor Controller (CMC)

- The Mod II aircraft will have two 72 kW Cruise Motors (CM)
- Redundant Design: Each motor has two independent sets of windings, controlled by two Cruise Motor Controllers (CMC)
- The two isolated controllers each contribute half of the torque to the motor

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The X-57 Maxwell utilizes a Tecnam P2006T airframe to test a fully electric propulsion powertrain as a replacement for the original internal combustion engines. The MOD II configuration uses 2 electric motors that each contain two sets of windings for redundancy. There are two Cruise Motor Controllers, or CMCs, per motor each supplying half of the torque to the Cruise Motor.

CMC Design/Requirements

- 39kW Nominal Output with 55kW Emergency Overdrive
- Nominal Voltage 320-538 VDC
- 97% Efficient
- CAN/Ethernet Communication
- Current/Torque control
- Completely Air Cooled
- Must Pass Acceptance/Proto-qual Tests per X-57 Environmental Test Plan

The Cruise motor controllers were designed by a combination of NASA, Joby Aviation, and QDESYS. Controller testing was completed by NASA and NASA sub-contractor ES AERO. The key design features of the cruise motor controllers include:

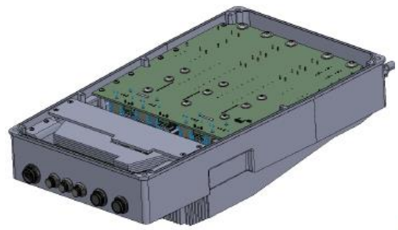
1. >50 kW DC power acceptance from the battery and conversion to 3-Phase AC output with nominal power of 39kW
2. Achieve a minimum of 97% efficiency at relevant speed, torque, and power settings utilizing a high power Silicon Carbide (SiC) (MOSFET) based motor drive
3. Provide torque control via current feedback loop to apply pilot-commanded torque independent of speed, battery voltage, and operating conditions utilizing CAN bus communication
4. The controller must survive the thermal environment within the X-57 Mod II nacelle with a passive air cooling approach
5. The controllers must also pass the acceptance and proto-qual test program developed by NASA and the X-57 project.

CMC Redesign

- Original design did not pass vibe nor close thermally
- Redesign updates included
  - MOSFET half-bridge module upgrade
  - Current sensor relocation and EMI/noise mitigations
  - Improved heat sink/enclosure and thermal mitigations

Original CMC Design

Redesigned CMC



The Original CMC design relied on Wolfspeed BM2 62mm half-bridge MOSFET modules. We found that these modules could not withstand the acceptance level vibration environment defined by the project. The project also found deficiencies in the internal current sense circuits, MOSFET gate drive design/quality, and heat sink/thermal design/considerations. The project elected for a CMC redesign and implemented fixes in the following areas:

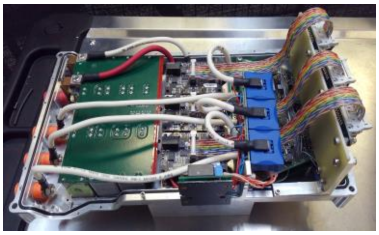
1. Replaced original MOSFET modules with Wolfspeed SiC 400 Amp XM3 modules. The updated modules had improved electrical and thermal performance, as well as a more robust packaging scheme.
2. LEM current sensor replacement, modified analog signal design on circuit boards to improve signal integrity, and changed packaging layout of CMC to better co-locate sensor and ADC without a noise source between. The goal being to improve SNR and reduce error in the current feedback control loop.
3. Aluminum case with integrated heat sink designed to fit 1-for-1 swap with the previous CMC design. Addresses the observed vibration testing shortfall of old design through internal support of the PCBs and overall stiffened design.
4. Improved CMC heat sink design to lower CMC enclosure-to-air temperature delta. The updated MOSFET package also included a higher junction temperature limit compared with the original.
5. Isolated low power PCBs from high power MOSFET sink, and cool via enclosure backplate – exposed to cooler (near-ambient temp) flow, either from aux inlet or natural circulation in nacelle.

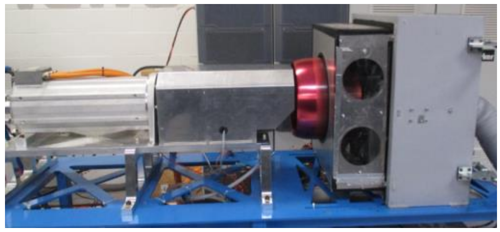
6. Redesigned and relocated with an optically isolated gate drive circuit, essentially on top of the MOSFET modules to reduce parasitics and improve drive quality. The drive also included a hardware desat fault circuit to protect the MOSFETs against over-current events.

7. The new design would also include Improved DC bus filtering with a cascading network of filter capacitors

Prototype Hardware Overview

- Prototype Inverter
  - Used to test circuits representative of new CMC design
- Rev A
  - 1st new build set of boards
  - Used to work integration and development issues
- Rev B
  - Incorporated updates from Rev A
  - Testing at ESAero and NASA GRC
- Rev C
  - Flight Boards built based off of Rev B testing

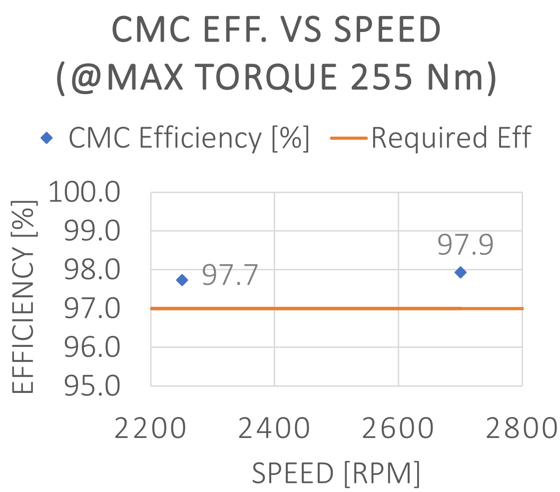




The XM3 CMC redesign included multiple prototypes and utilized a trial and error based testing approach to arrive at a flight worthy product. The first prototype was dubbed the "Frankinverter" and was built and tested at NASA sub-contractor, ES AEROs, facility in San Luis Obispo. The inverter was piecemealed together with parts from the original BM2 CMC along with upgraded parts including new Wolfspeed XM3 SiC MOSFET modules, Wolfspeed COTS gate drives, and updated LEM current sensors. The goal was to implement the new design features as fast as possible to get an idea of the performance improvements, and feasibility of making these changes before procuring any new hardware or PCBs. The Frankinverter was quite successful and from the lessons learned the project designed the next three revisions of the CMC based off of the dynamometer testing, pictured in the center of the slide, conducted at ES AERO. Rev C was the final design and 7 units have since gone on to pass our airworthiness acceptance test plan.

Initial CMC Dyno Performance Results

- Test points selected based off relevant speed, torque, and power requirements
- Achieved required eff. ≥97%
- 98% eff. @50kW = 1kW required heat rejection from heat sink
  - Allows for passive air-cooled design
- CMC power density ≈ 7kW/Kg



The dynamometer at ES AERO was the perfect testbed for rapid design iteration and high power testing of the redesigned Cruise Motor Controllers. The dynamometer consists of a Parker brake motor connected via shaft to an X-57 Cruise Motor which is then powered by 1 or 2 CMCs depending on the desired testing configuration. During rev B CMC prototype testing we were able to take the inverter up to the max power setting expected in a dual CMC configuration and, as shown in the plot above, achieve our 97% efficiency metric required for flight. The rev C “Flight” CMC has since performed multiple efficiency tests on the dynamometer at ES AERO with efficiencies in the 97%-98% range for relevant power settings.

CMC Acceptance Test Program

HW Assy.	HW Check	Dyno Accept.	Vibe Env.	Therm. Env.	Aircraft V&V	Flight Ops
• AFRC Fab • Insp. points and Hi-pot	• Unloaded functional tests	• Sensor gains cal. • Full power and high operating temps	• X, Y, Z, 20 min/axis	• 7 thermal cycles (~18 hrs)	• Exercise powertrain • Exercise flight interfaces in EMI and power quality env.	• Combined Systems Test (CST) • Taxi Test

This slide details the acceptance test program all CMCs must pass before being declared flight worthy. Upon delivery each PCB must pass an individual board test developed to screen for workmanship defects. All necessary parts are then provided to our instrumentation fabrication shop at NASA AFRC for CMC assembly. A detailed assembly document was written by engineers along with our techs to ensure each build is assembled with the same approach. There are multiple engineer inspection points throughout the build process and some of these include hi-pot isolation checks to reduce the likelihood of high voltage isolation failures, as well as a need to reopen an assembled CMC.

After assembly the CMCs must pass a HW checkout test where an unloaded motor is spun at low power so that CMC performance and output waveforms can be monitored for errors.

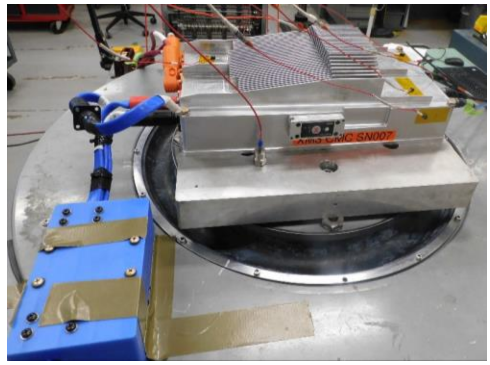
If the HW checkout is passed the CMC must be electrically tested at high power and high MOSFET temperatures on the dynamometer to ensure it meets all performance metrics required for flight. Additionally, two CMCs are tested at higher levels, or proto-qual levels, to ensure there is margin in design. The CMCs must also complete the environmental screening tests including vibration and thermal testing. The order of CMCs put through Dyno acceptance, Vibe, and Thermal testing was allowed to change due to project priorities and schedule.

Lastly, the CMCs are put onto the aircraft for V&V and Flight Operations testing of the entire powertrain and all flight interfaces within the X57 aircraft.

6 CMCs (4 flight units plus 2 spares) have made it passed thermal testing, and the project is currently awaiting approval to begin V&V testing.

CMC Vibration Testing

- Initial vibration test profile insufficient
- Sine on Random Profile Adopted
  - Random vibration spec:
    - 0.008 g^2/Hz at 15 Hz and 0.008 g^2/Hz at 2000 Hz
  - 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
- Sine Sweep before and after test to test for UUT dynamics shifts



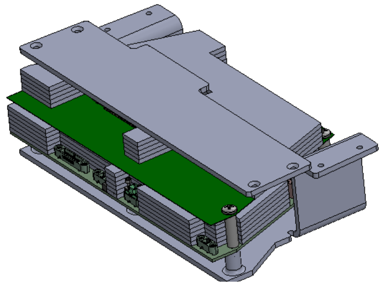
Highlighting the environmental screening portion of our airworthiness acceptance test program; our initial vibe testing approach only included a random vibration component at 7.7 Grms for acceptance, and 10.9 Grms for proto-qual levels. Upon further analysis of the MOD II nacelle environment and the flight environment (measured on the original Tecnam with ICE's), a Sine on Random vibration testing approach was adopted to include both the random and sinusoidal modes generated on the CMC mounting structure. Pictured here is XM3 CMC SN007, instrumented with multiple accelerometers, during a z-axis vibration test.

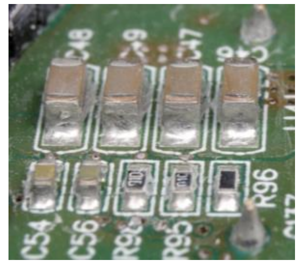
Each CMC must pass an acceptance level vibration test in all 3 axes and 20 minutes per axis, total test time of 1 hour, to be considered flight worthy.

7 units have now passed our vibration test program.

CMC Vibration Testing

- Thermal gap pads used to transfer heat from low power boards to the enclosure
- Thermal pad migration and wear on components during vibe





In this slide I wanted to highlight an interesting problem we had to face during the development of our vibration test program. For some background: The XM3 CMC utilizes thermal gap filler pads to reduce airgaps between the low power boards, and to also transfer heat away form the boards and into the heatsinks/enclosure. During some of our initial vibration tests at the original random vibe only acceptance levels, this gap filler material, which was much more abrasive than originally thought, was able to migrate and rub on the boards, acting a bit like sandpaper. The result was that the PCBs of one XM3 CMC unit was permanently damaged due to abrasion of the components on the boards.

Improvements in our assembly procedures and extensive vibration testing have shown that the gap filler material has a very low likelihood of migrating or damaging components with the updated Sine on Random vibration curves. It is something to take into consideration, though, if you are looking to use a gap filler material directly on top of a PCB.

CMC Thermal Testing

- Seven total cycles (~18 hours)
- 1st cycle includes unpowered "survival" temperatures -24ºC to 64ºC
- No altitude testing (low operating ceiling in flight)
- Max temp of -17.3ºC to 53.3ºC (while powered) provides 10ºC margin over expected environment

The second part of our environmental screening process is to test the CMCs in a relevant temperature environment to what they'd see on the hottest or coldest days out at NASA AFRC on Edwards AFB. The temperature ranges are listed here.

The intent of the environmental tests is to confirm CMC performance in the possible worst case environments they'd see in flight. The tests are not as effective at screening for workmanship defects. The project relies on the culmination of all tests within the CMC airworthiness acceptance program to ensure each unit is performing as expected and prepared for flight on X-57.

So far 6 units have successfully undergone our thermal test profile with one more unit awaiting testing. Once that final unit passes the thermal test the X-57 project will have 4 flight CMCs plus 3 spares that can be used for the upcoming flight campaign.

Design/Assembly Lessons

- Avoid stacking multiple layers of thermal gap filler material by packaging the boards with dedicated heat rejection paths and using rigid heat distribution parts
- Improve internal isolation between LV and HV components by establishing separate ground planes with single-point interfaces
- Choose high precision parts for applicable circuits (desat, current sensing, voltage sensing, temp sensing, etc)
- Test DC bus filter quality with full powertrain and avionics to avoid future EMI troubleshooting
- Perform hi-pot isolation checks throughout the assembly process
- Take the time to perform HW functional checks at intermediate stages during the assembly process to avoid unnecessary disassembly/troubleshooting

So now I'll speak to a few of the lessons learned I have listed here. An interesting one we found during the prototyping stage of the CMC design was that capacitive coupling between our HV, LV, thermal, and ground planes caused problems with the MOSFET gate drive quality, as well as our current sense feedback. Isolating HV and LV and eliminating copper from all layers in isolation gaps allowed us to move forward with the design.

An issue that we discovered after the CMC design was finalized was that we designed for the minimum DC Link filtering required to provide voltage stability, but did not arrest all switching transients from back-propagating to the battery system. An external Pi filter with inductive chokes and capacitors was added to avoid signal corruption of the battery sense lines. Simultaneously developing the CMC on the dyno while separately developing our avionics and battery systems on the aircraft lead to a disconnect once the two were integrated. If possible EMI mitigations for battery and avionics systems should be integrated into the inverter before closing out the flight design.

Conclusions

- NASA X-57 project has developed and tested a flight worthy motor controller utilized to power 3-phase 72kW PMSM Cruise Motors
- The project has developed an acceptance/qualification process for electric propulsion powertrains
- The knowledge gained through this integrated approach to electronic power train design has been used as a guide for ongoing new electric power train component development.

Contact Info

- jacob.r.terry@nasa.gov
- sean.clarke@nasa.gov
- susanah.r.kowalewski@nasa.gov
- david.avanesian@nasa.gov

Thank you all for your time, and also thank you to the folks at NASA GRC, LRC, AFRC, and ES AERO for supporting this work on developing and testing the Cruise Motor Controllers. Here is a list of contact information if you are looking to get ahold of us, and thank you again for your time.

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