X-57 60kW Permanent Magnet Synchronous Cruise Motor
Finite Element Electromagnetic Modeling

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Abstract

The X-57 60kW Permanent Magnet Synchronous Motor for cruise applications was modeled utilizing a two-dimensional electromagnetics simulation software called Finite Element Method Magnets (FEMM, D. Meeker). Through FEMM, the simulated induction and torque characteristics of the X-57 PMSM were obtained. These parameters and other values were compared to actual static laboratory measurements. A three-dimensional electromagnetic model of the X-57 cruise motor was created utilizing OperaFEA (Dassault Systemes SE, Velizy-Villacoublay, France). Torque, RPM, power, resistance, and inductance characteristics were examined along with establishing work to begin examining heat flow and heat dissipation for efficiency purposes.

Background

As reported by NASA's Armstrong Factsheet for the X-57 Maxwell [1], the X-57 is the agency's first all-electric experimental aircraft and is being used as a "design driver", which is a technical challenge that aims for a 500 percent increase in high-speed cruise efficiency, zero in-flight carbon emissions, and flight that is much quieter for the community on the ground.

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Specifications [1]

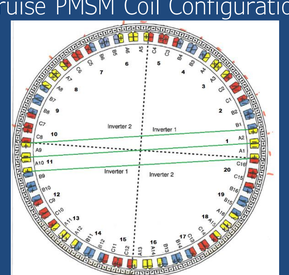
Batteries:
- Lithium ion
- 860 pounds
- 69.1 kilowatt hours (47 useable)

Cruise Motors and Propellers (2):
- 60 kilowatts.
- Air-cooled.
- 5-foot diameter propeller.
- Out-runner, 14-inch diameter.
- 117 pounds each, combined weight.

High-Lift Motors and Propellers (12):
- 5-blade, folding propeller.
- 10.5 kilowatts.
- Air-cooled.
- 1.9 foot diameter propeller.
- 15 pounds each, combined weight.

Aircraft Weight – Approximately 3,000 pounds.
Maximum Operational Altitude – 14,000 feet.
Cruise Speed – 172 mph (at 8,000 feet)
Critical Takeoff Speed – 58 knots (67 mph).

Cruise PMSM Coil Configuration



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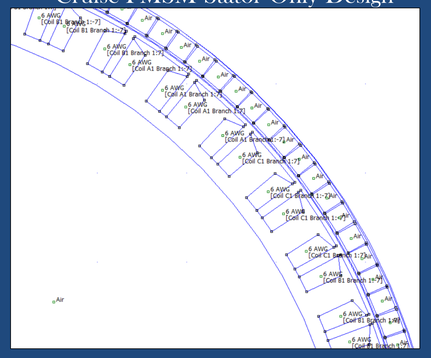
Finite Element Method Magnetics

The X-57 PMSM was first modeled in FEMM to examine torque, power, and induction characteristics. Two FEMM models were designed for comparison with lab models and measurements – one being a design with the stator only and the second being the full PMSM design.

Cruise PMSM Stator Only Design



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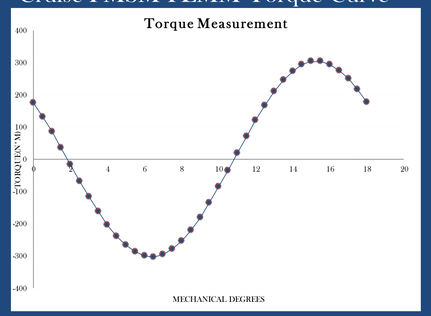
From the full FEMM PMSM model, torque data was derived.

The torque curve behaved as expected, with FEMM calculating a maximum of 303 Nm of torque compared to a measured 295 Nm of torque from a laboratory setting [2].

Cruise PMSM FEMM Torque Curve



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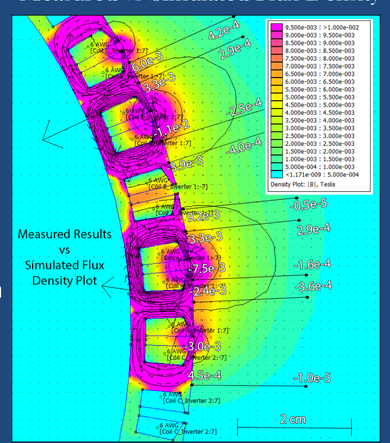
Model Verification

In order to verify measurements from FEMM, Laboratory measurements were conducted to compare both magnetic flux density values and inductance values.

In both cases, comparisons are given for the stator-only PMSM model.

Magnetic flux density was measured by feeding 1A of current into the PMSM and then utilizing a gaussmeter to take a flux reading. Then, a magnetic flux density gradient diagram was drawn from the FEMM model and values were crudely compared as a sanity check, of which can be seen by the diagram to the right.

Measured vs Simulated Flux Density



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Phase Inductance

An inductance meter was used to measure and verify inductance values of each phase.

After measuring each inductance between the three different phases of the PMSM, these values were compared to the results from FEMM simulations.

Both experimental and simulated measurements were done with 1A of current and a frequency of 1kHz.

As reported below in the table, the experimental and simulated measurements experimental error ranged from 8% to 17%.

Experimental vs. Simulated Results

Phase (Motor 1)	FEMM Inductance	Meas. Inductance	Exp.. Error Inductance
A	88 µH	74 µH	**-16%**
B	88 µH	81 µH	**-8%**
C	88 µH	73 µH	**-17%**

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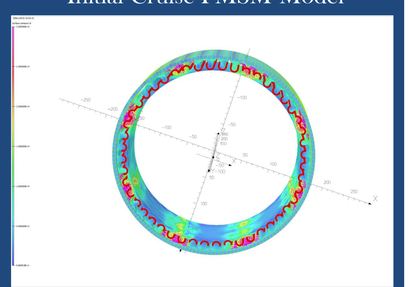
Opera 3D Modeling

The full X-57 Cruise PMSM has been initially modeled on OperaFEA, where future work will be done to examine heat characteristics.

Initial Cruise PMSM Model



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References

1. Connor, E. (2019, Oct 28th). *NASA Armstrong Fact Sheet: NASA X-57 Maxwell.* Retrieved from nasa.gov
2. Montalvo, K. (2019, June). *NASA Armstrong Summer 2019 Intern Exit Presentation.*

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