Reliability Requirements and Research Strategies for Urban Air Mobility Propulsion

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Vertical Flight Society

Outline

1. Establishment of NASA RVLT Propulsion Technical Challenge
2. Relationships of configuration, power density, and reliability
3. A new approach to model the parametric distribution of gear surface fatigue failures
4. Multidiscipline research approach

Development of the NASA Aeronautics Research Mission Directorate (ARMD) Revolutionary Vertical Lift Technology (RVLT) Propulsion Technical Challenge

1. Guidance from ARMD vision and strategy
2. Planning workshops – idea generation and brainstorming
3. Initial research plan and internal white papers
4. Subject-matter-experts complete state-of-the-art evaluations of the research literature and engineering standards – identify gaps
5. Hazard Analysis FMECA of RVLT concept vehicles
6. White Paper completed and Technical Challenge established

7. Communicate the result to a wider vertical lift community

NASA ARMD and RVLT Vision and Strategy

ARMD - Safe, Quiet, and Affordable Vertical Lift Air Vehicles

- Realize extensive use of vertical lift vehicles for transportation and services including new missions and markets

RVLT

Vision

- Enable next generation of vertical lift vehicles with aggressive goals for efficiency, noise, and emissions to expand current capabilities and develop new commercial markets

Scope

- Technologies that address noise, safety, speed, mobility, payload, efficiency, environment
- Conventional and non-conventional very light, light, and medium vertical lift configurations

Goals

- Develop & validate tools, technologies & concepts to overcome key barriers for vertical lift vehicles

RVLT Concept Vehicles

- Motor power requirements range from 16 kW to 480 kW
- Hazard analysis and FMECA study completed
- UAM missions require frequent, intense propulsion duty cycles

NASA/CR—2019-220217

Hazards Analysis and Failure Modes and Effects Criticality Analysis (FMECA) of Four Concept Vehicle Propulsion Systems

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The Boeing Company, Philadelphia, Pennsylvania

ABSTRACT

The primary objective of this research effort is to identify failure modes and hazards associated with the concept vehicles and to perform functional hazard analyses (FHA) and failure modes and effects criticality analyses (FMECA) for each.

Summary of 2019 RVLT-sponsored HA and FMECA Study

NASA/CR—2019-220217

Hazards Analysis and Failure Modes and Effects Criticality Analysis (FMECA) of Four Concept Vehicle Propulsion Systems

Table 15: FMECA and FTA Summary.

NASA RVLT Concept Vehicle	Propulsion System Description	Flight Control Description	Variable Pitch, Fixed Speed	Fixed Pitch, Variable Speed	Severity Code I Failures per Flight Hour: FMECA Criticality	Severity Code I Failures per Flight Hour: FTA Reliability	Percent Time in OEI/OMI Avoid Region
Tilt-Wing	Series Hybrid	Collective and 1-Axis Cyclic	X		4.92×10^{-4}	6.95×10^{-4}	20%
Quad-Rotor	All Electric	Collective Only	X		2.47×10^{-4}	2.10×10^{-4}	25%
Quad-Rotor (No Shafts)	All Electric	Collective Only	X		1.01×10^{-3}	7.97×10^{-4}	20%
Lateral-Twin	Parallel Hybrid	Full Cyclic and Collective	X		9.65×10^{-5}	1.91×10^{-4}	20%
Lift+Cruise	Series Hybrid	RPM Controlled		X	4.67×10^{-4}	2.88×10^{-4}	0%
EASA Draft SC-VTOL-01	Proposed Air-Vehicle Requirement				10^{-9} (1)	10^{-9} (1)	–

- Likely that the propulsion system would need to have 10^{-10} failure rates per flight hour, or less, in order to meet the EASA SCVTOL- 01 air vehicle requirement of 10^{-9} catastrophic failures per flight hour

- Tilt-wing, quadrotor, and lateral-twin criticality numbers were all driven by the applied failure rates of the motors and inverters. Lift+Cruise reliability was driven by the Category I loss of the turbo-generation unit.

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Hazards Analysis and Failure Modes and Effects Criticality Analysis (FMECA) of Four Concept Vehicle Propulsion Systems

Selected Observations
RVLT-sponsored HA and FMECA Study

- Processes and tools to perform the subject analyses were lacking
- Existing regulations and specifications in regards to the subject analyses, are inadequate and most especially true for rpm controlled / distributed propulsion
- Commercially available components for distributed and/or hybrid electric propulsion are not readily available with adequate reliability
- Modeling tools are lacking for the design process, specifically to assess reliability of components prior to extensive test programs
- Regarding the safety requirements of the market, no amount of improvement in component reliability can overcome poor choices for mission profiles and/or architectures

RVLT.TC.UAM.Electric.1 Reliable and Efficient Propulsion Components for UAM

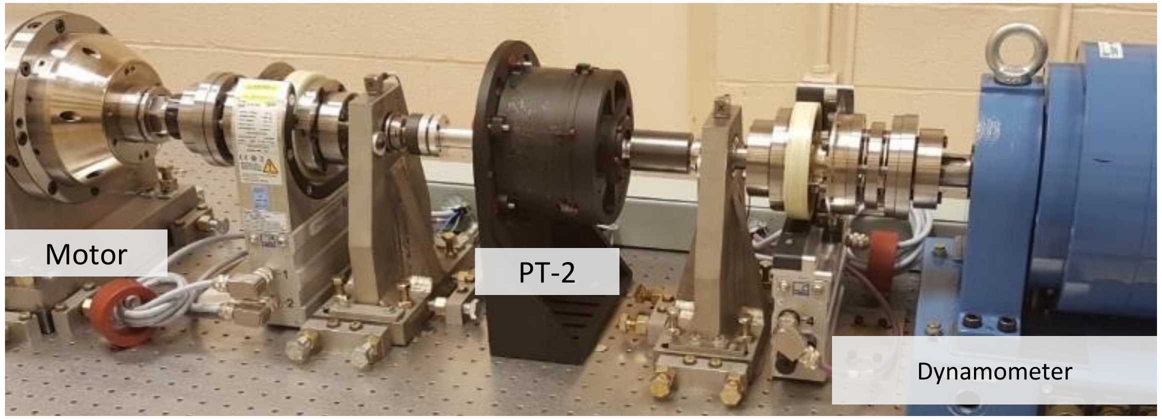
What is the problem/barrier being addressed by this Technical Challenge?
The rapidly emerging UAM market will require safe, reliable, low maintenance operations. New electric propulsion architectures do not have proven in-flight experience. In addition, the thermal management system integration within the eVTOL propulsion architecture has a significant impact on the safety, reliability, life, and weight of the system, and is not limited to one configuration or architecture. Lack of design standards, test standards, and validated tools to support certification will be significant barriers for expanding the eVTOL market

What are we trying to do?
Develop design and test guidelines, acquire data, and explore new concepts that improve propulsion system component reliability, culminating by demonstrating 2-4 orders of magnitude improvement in 100kW-class electric motor reliability.

What is the State of the Art (SOA) for predicting reliability of eVTOL propulsion architectures?
Existing integrated system design approaches are iterative in nature and cannot achieve an optimum design for current UAM systems. Recent assessments of reliability for eVTOL propulsion architectures range from 10E-4 to 10E-6 which is several orders of magnitude less than required for commercial operations.

Why is NASA uniquely suited for this Technical Challenge?

- NASA has the expertise and facilities to acquire validation data for tools
- NASA has extensive experience in:
  - Electrical power systems
  - Power trains
  - Structural reliability
  - Thermal management systems



Test setup in the E-Drives Rig at GRC

RVLT.TC.UAM.Electric.1 Reliable and Efficient Propulsion Components for UAM

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What are we t[illegible]
Develop design and test guidelines, acquire data, and explore new concepts that improve propulsion system component reliability by several orders of magnitude over state-of-the-art technology [illegible] electric VTOL vehicles.

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Existing integrated system design approaches are iterative in nature and cannot achieve an optimum design for current UAM systems. Recent assessments of relia[illegible] propulsi[illegible] E-4 to 10E-6 which is several orders of magnitude less than required for commercial operations.

Exit criteria:
Increased reliability of the electric motor component by 2-4 orders of magnitude over a baseline state-of-the-art with minimal weight penalty.

Completion date: Sept. 2023

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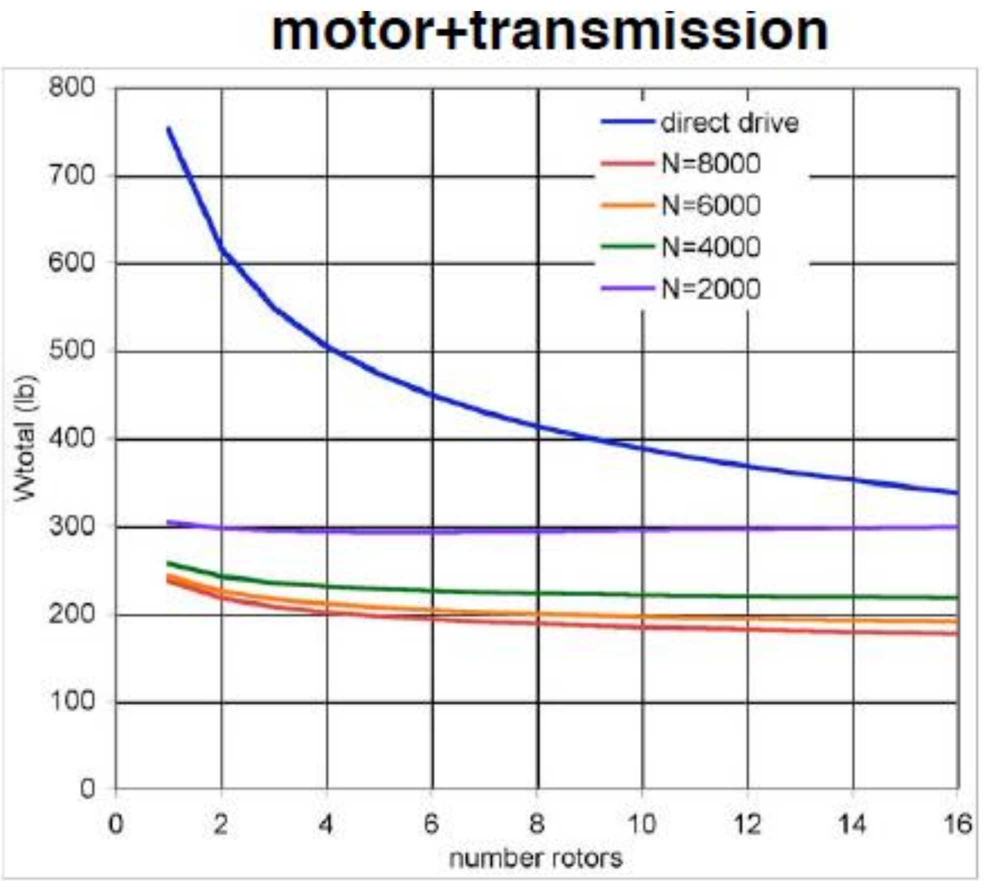
Electric Motor – Direct Drive vs. Geared Drive
(example #1)

Conceptual Design of eVTOL Aircraft

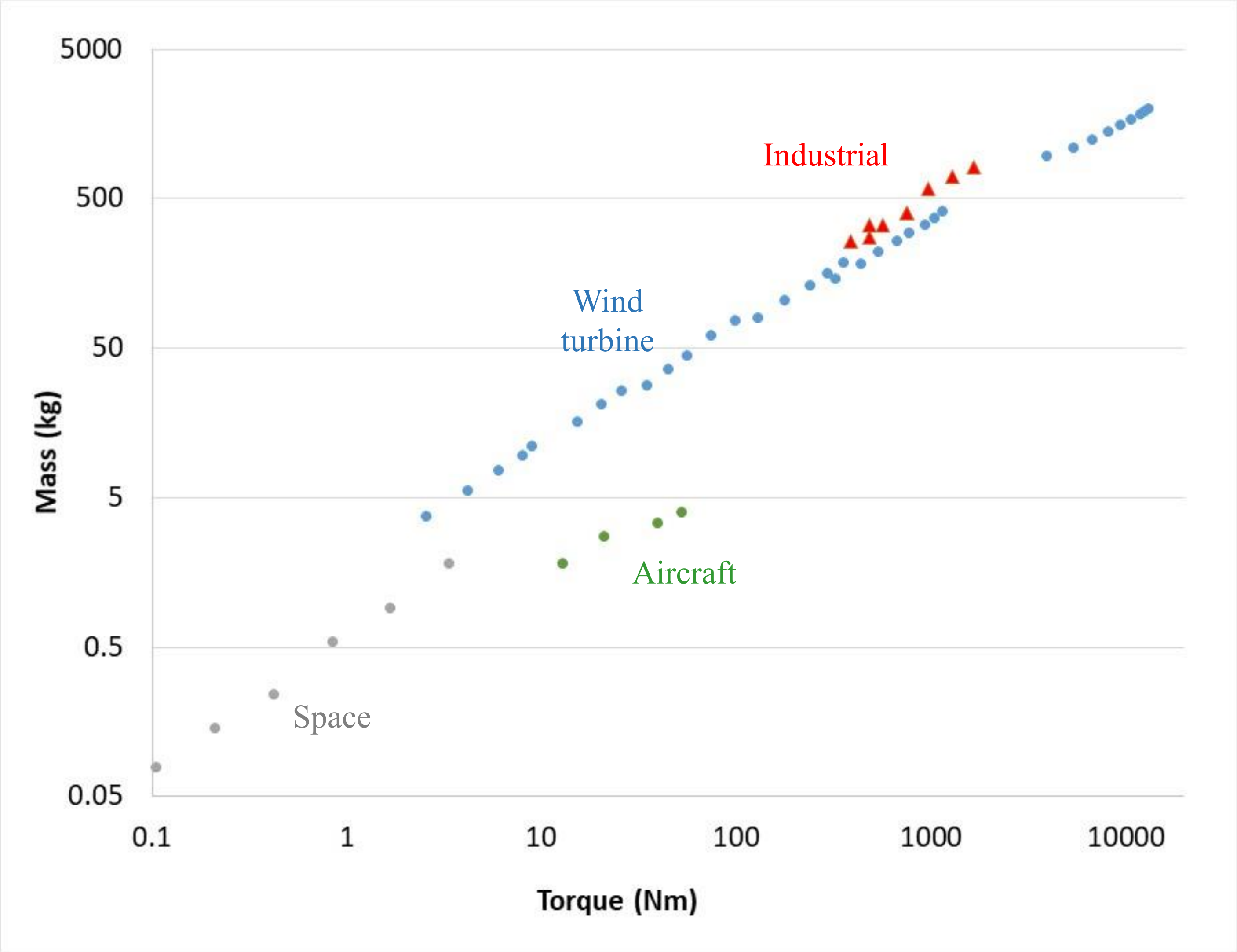
Wayne Johnson
Christopher Silva

NASA Ames Research Center

Short Course on Electric VTOL
AHS International's 74th Annual Forum and Technology Display
Phoenix, Arizona
May 14, 2018



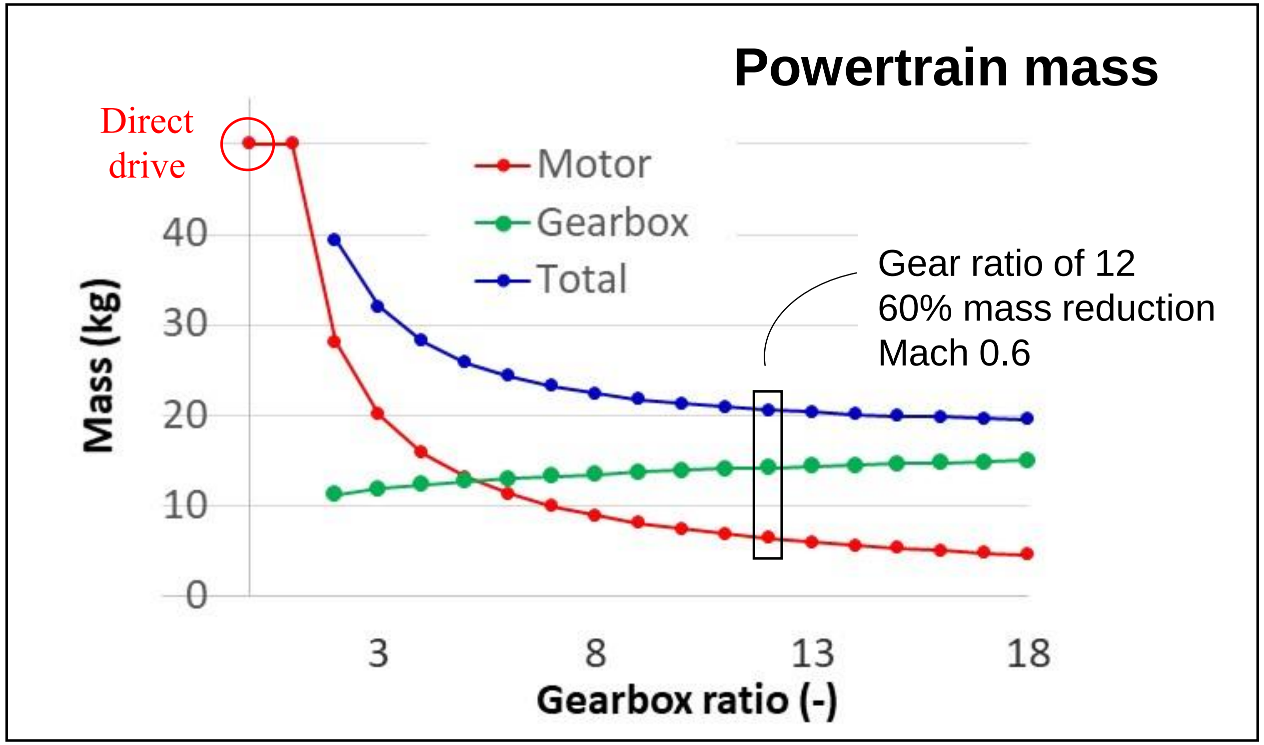
Background: Motor mass trends



- Mass vs. torque is shown for a variety of synchronous permanent magnet electric machines.
- Machines with common design are shown by color, and labeled according to application.
- Industrial machines are the heaviest and aircraft lightest at a given torque level. This represents different levels of motor optimization (magnetic, electrical, structural, and thermal loading).
- The data trends show that for a given design-type machine mass is directly related to torque. This reinforces the idea that gearing can reduce mass by scaling down machine torque.

Internal NASA study: Asnani, V. and Delgado, I.

Electric Motor – Direct Drive vs. Geared Drive
(example #2 – propeller aircraft)

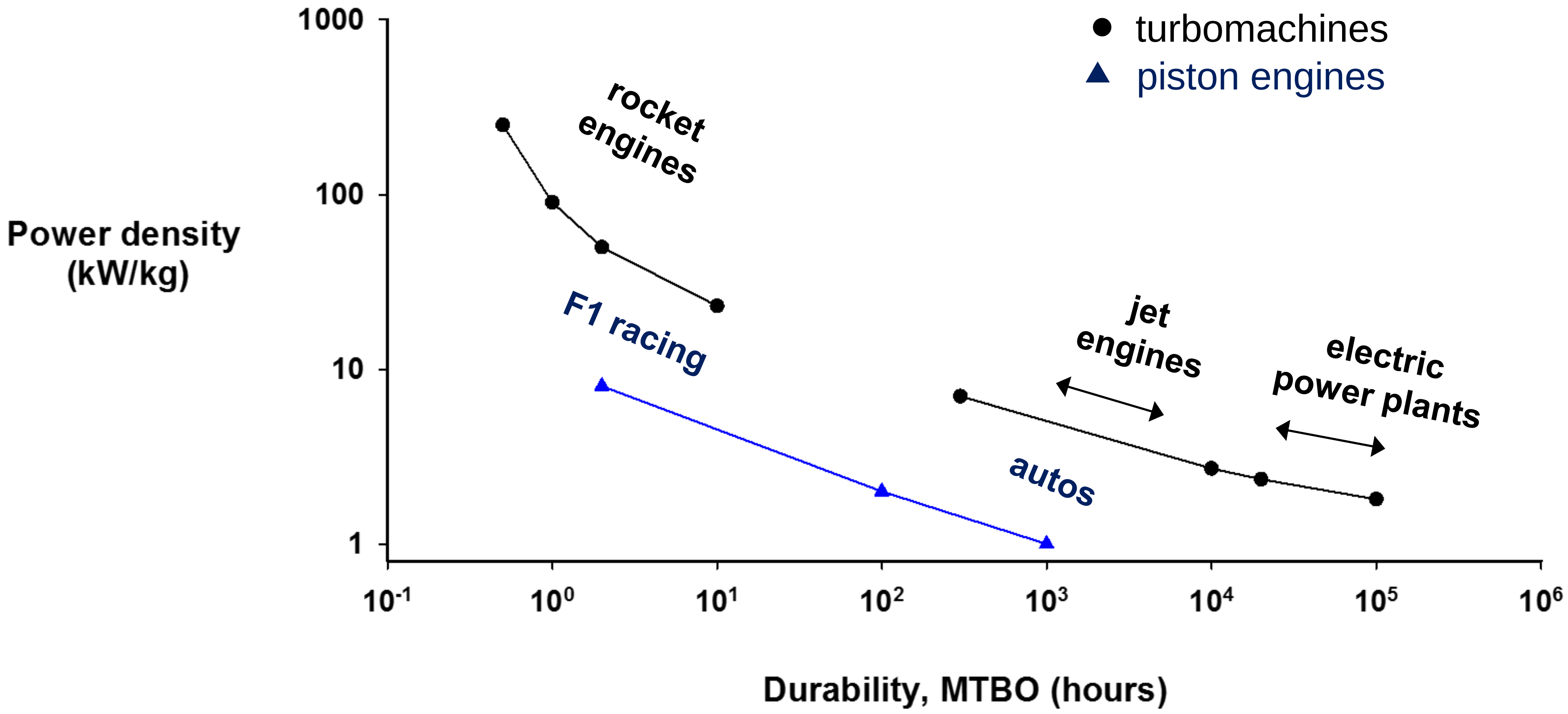


Internal NASA study: Asnani, V. and Delgado, I.

- The aircraft motor design was scaled according to empirical mass-torque relationship
- The gearbox mass was estimated using empirical relationship from [1] based on derived requirement for speed ratio and output torque
- The total mass (gearbox + motor) is reported vs. the gearbox ratio.
- Savings of motor mass far exceeds the added mass of the gearbox.
- At moderate gear ratio (12:1), the motor speed is within reason (Mach 0.6, 30,000 rpm), and the **total driveline mass is reduced by 60%.**

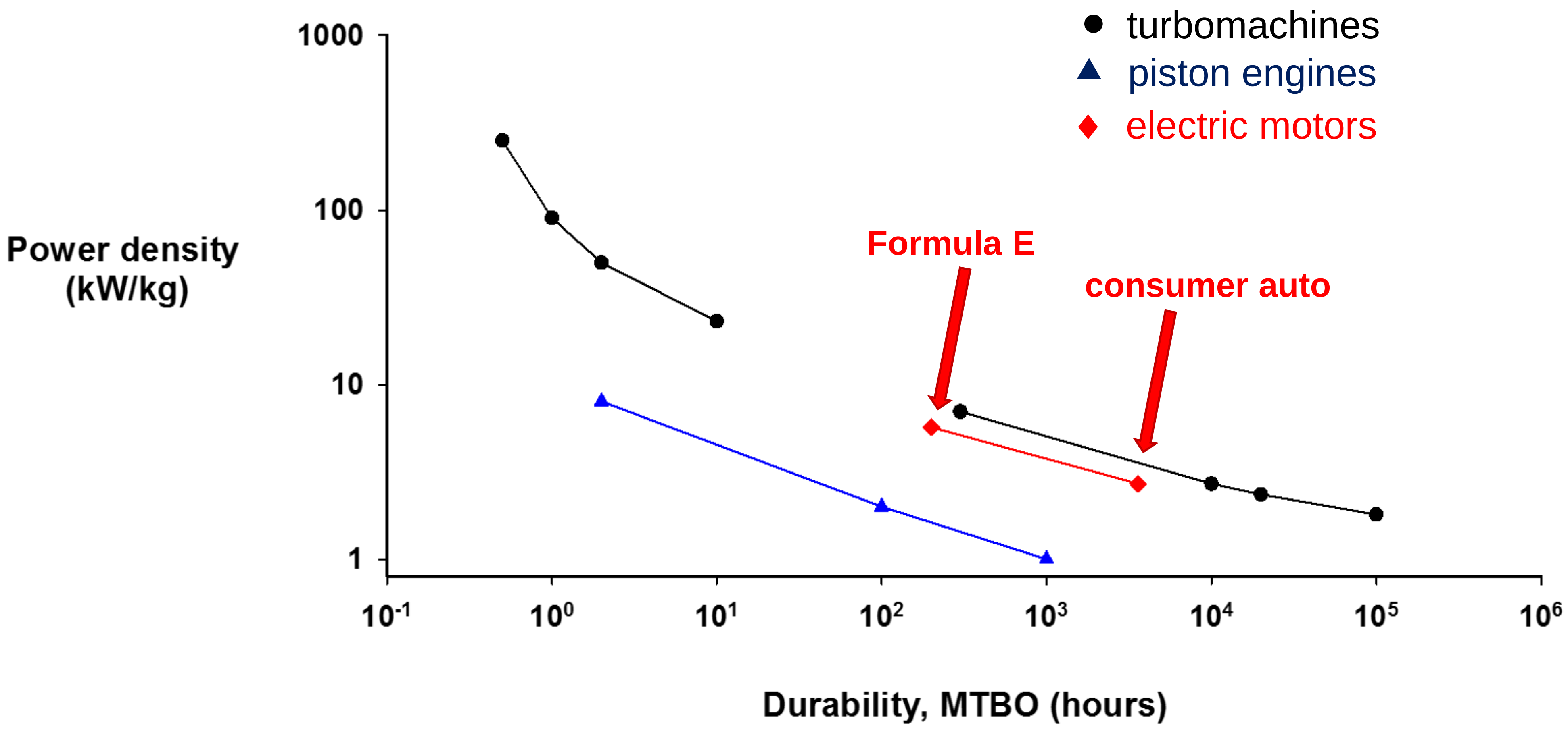
1. Brown, G. V., Kascak, A. F., Ebihara, B., Johnson, D., Choi, B., Siebert, M., and Buccieri, C., “NASA Glenn Research Center Program in High Power Density Motors for Aeropropulsion,” NASA TM 213800, 2005.

Power Density – Reliability Relationship



Data from and in manner of: Preclik, D., et al. "Reusability aspects for space transportation rocket engines: programmatic status and outlook." CEAS Space Journal 1.1-4 (2011): 71.

Power Density – Reliability Relationship



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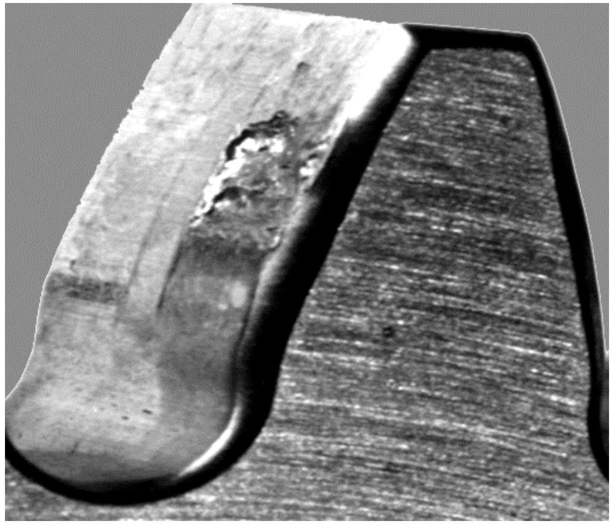
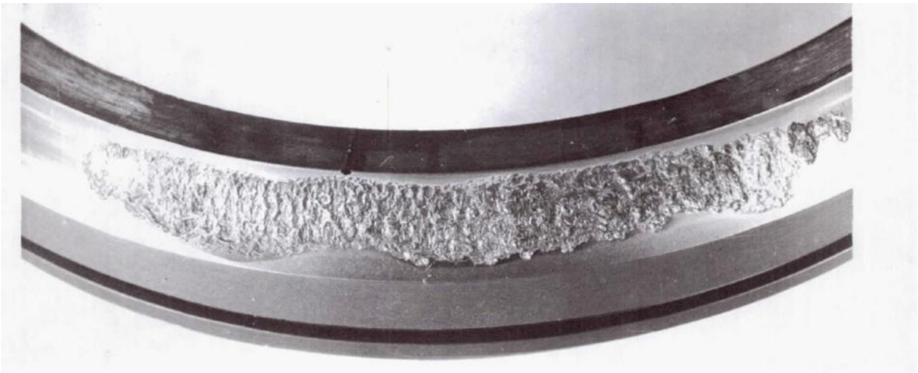
A new approach to model the parametric distribution of gear surface fatigue failures

- Gear surface fatigue is fatigue of material from repeated applications of contact forces
- Typical gear design practice calculates 1% probability of failure, then design is supplemented by additional safety/application factors for higher reliability requirements
- The statistical parametric distribution used in practice is either a Normal or a 2-parameter Weibull distribution

- The bearing community has adopted an empirical based correction factor for similar failure modes
- For very high reliability requirements (>99.5%), the correction factor is based on work of Tallian (1962)



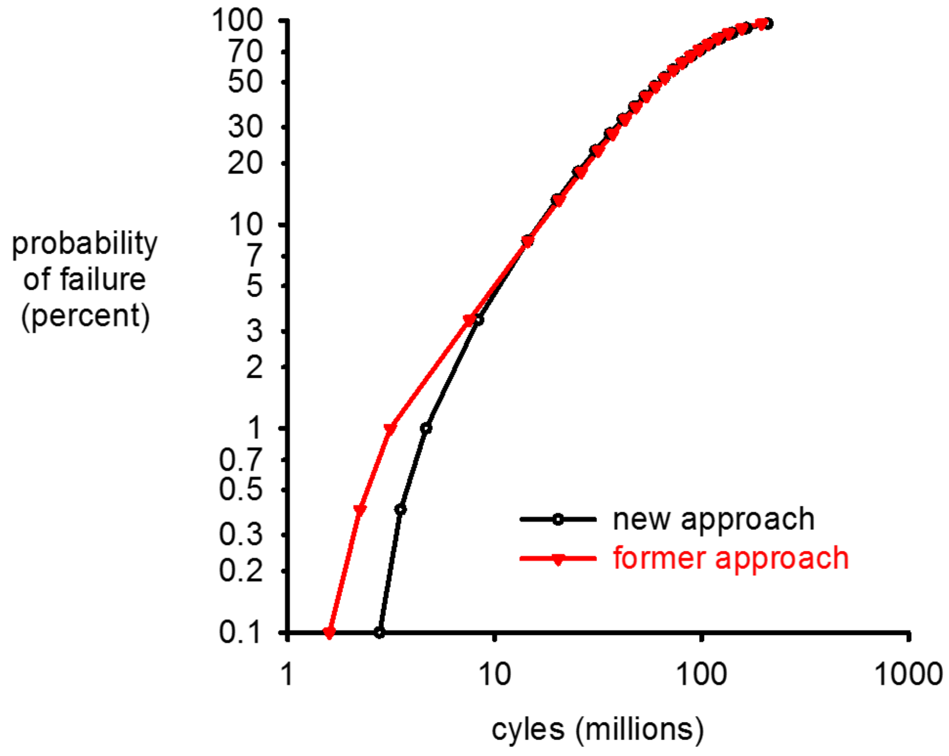


gear and bearing fatigue

A new approach to model the parametric distribution of gear surface fatigue failures

- The approach to statistical model of gear surface fatigue was critically re-examined
- Data from decades of gear fatigue testing at NASA were collected and properly normalized to allow for “statistical pooling” as one large dataset of 950 tests
- The 3-parameter Weibull distribution is proposed as a new model for gear surface fatigue
- Modern statistical fitting methods were extended and applied to the gear dataset
- An example highlighting the differences of the former and new models are depicted in the figure

- for a reliability requirement of 99.99%, the predicted lifetimes differ by factor of 4.5X !!



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Temperature – Motor Reliability

Databases for motor reliability, representing a wide class of applications, document two failure categories as large contributors to the overall failure rates

1. motor winding life
2. bearing life

Both failure modes are highly influenced by operating temperatures / thermal effects

The RVLT Propulsion team is approaching the technical challenge using as a multidiscipline research approach including thermal management

Why is NASA uniquely suited for this Technical Challenge?

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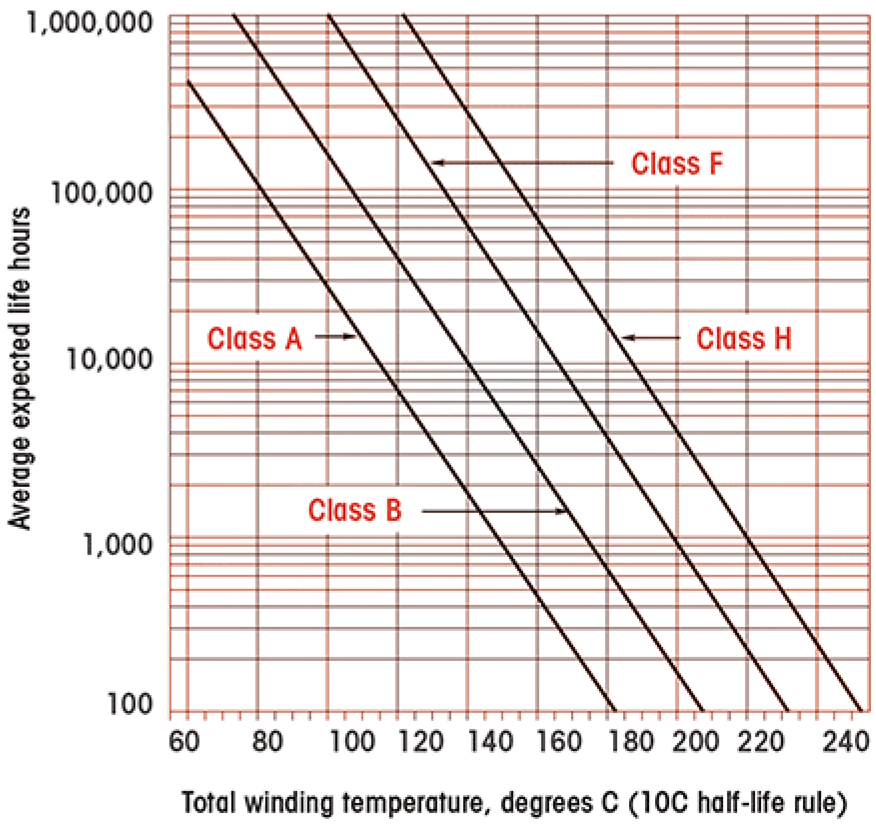
Electric motor windings
(expected life vs. temperature)



RVLT FY19 Accomplishment - Tool Developments for UAM Electric Propulsion

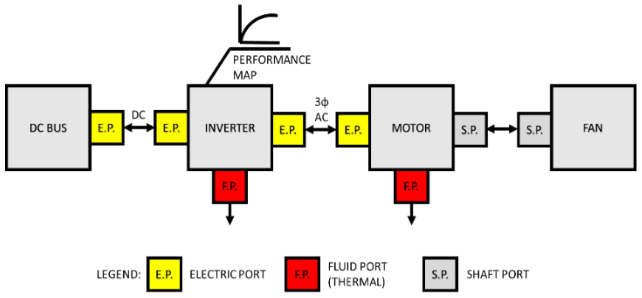
PROBLEM Software analysis packages, such as Numerical Propulsion System Simulation (NPSS) used by many in the aero field to size and integrate combustion based propulsion and thermal systems, have gaps for modeling the needed electrical system components.

OBJECTIVE The objective this year was to develop or modify modeling tools to address the needs of electrical systems for propulsion.

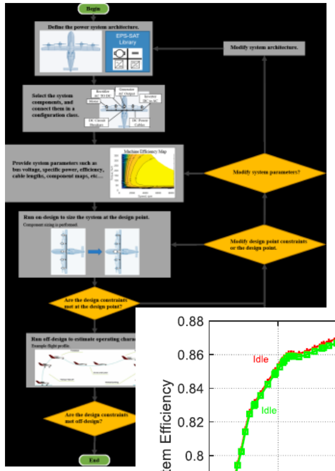
APPROACH The approach was to: (1) develop an electrical port and toolbox for the Numerical Propulsion System Simulation (NPSS) software, and (2) develop an Electrical Power System Sizing and Analysis Toolbox (EPS-SAT) for MATLAB.

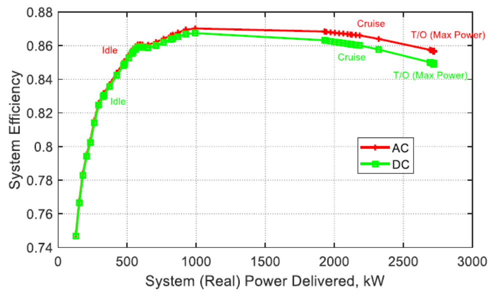
ACCOMPLISHMENTS
- Completed toolbox and electrical port for NPSS
  - Accepted by NPSS Consortium for incorporation in future versions of SW for international use
  - Development team honored with GRC Steven Szabo award
- Completed EPS-SAT toolbox for MATLAB, including recently added thermal port
  - Allows for high-level electrical system analysis
  - Two papers completed and presented at the 2019 AIAA P&E/EATS
  - New Technology Report submitted

SIGNIFICANCE
- The development tools allow for a common basis from which to evaluate electrical power systems for EP, both within NASA and by the wider aerospace community.



NPSS Building Blocks with Thermal Port





POC: Dave Sadey, Jeff Csank, George Thomas, Pat Hanlon, Tom Lavelle GRC

MATLAB EPS-SAT Flow Diagram and Sample Results

Summary

The NASA Revolutionary Vertical Lift Project has defined a technical challenge that provides a research focus for propulsion for FY20-23.

We welcome feedback and collaboration discussions.

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