



A Preliminary Controllability and Dynamic Power Assessment of the Open eVTOL RAVEN Vehicle

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Acknowledgements

- The Open eVTOL RAVEN team
- Georgia Tech provided a preliminary but representative motor thermal model and thermal management system (TMS)
- NASA's FlightCODE developers
 - Contact: Carlos Malpica

Mission Need

There is an imminent need for publicly available flight test data relevant to:

- research
- development of design and analysis methods
- workforce competency

...to further U.S. leadership in technology development for safe, quiet, and efficient eVTOL aircraft for Advanced Air Mobility (AAM).

Open eVTOL

Establish NASA capability to perform open eVTOL flight research

RAVEN

Mid-scale eVTOL flight research platform



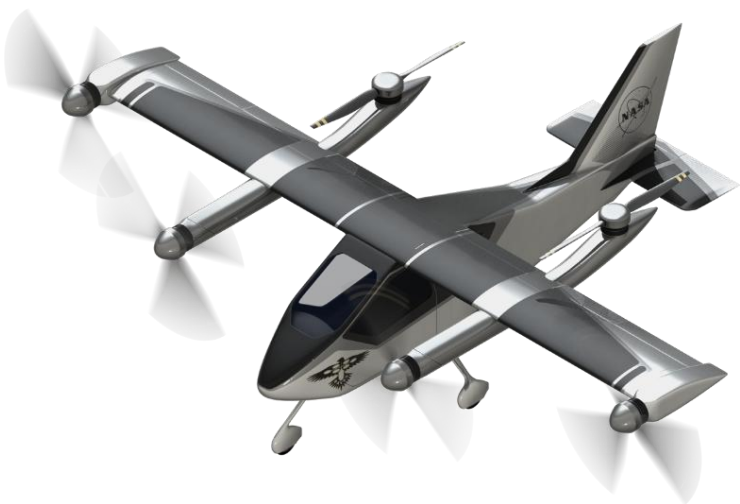


RAVEN: Research Aircraft for eVTOL Enabling techNologies

- 1000-lb class UAS
- Multi-tiltrotor aircraft with 6 proprotors
- All-electric custom powertrain
- Publishable parameters built on BD-6 airframe
- Onboard primary and research flight computers
- Building three (3) aircraft

Aircraft Characteristics

Wingspan	21 ft
Length	17 ft
Proprotor diameter	~6 ft
Hover disk loading	8 lb/ft ²
Tip speed: hover	Mach 0.35-0.5
Tip speed: cruise and conversion	≤ hover tip speed
Gross weight	≤ 1320 lb
Research payload	30 lb, 2 ft ³
Hover endurance	5 mins
VTOL, CTOL range	≥ 20 nmi



Wing-borne Configuration



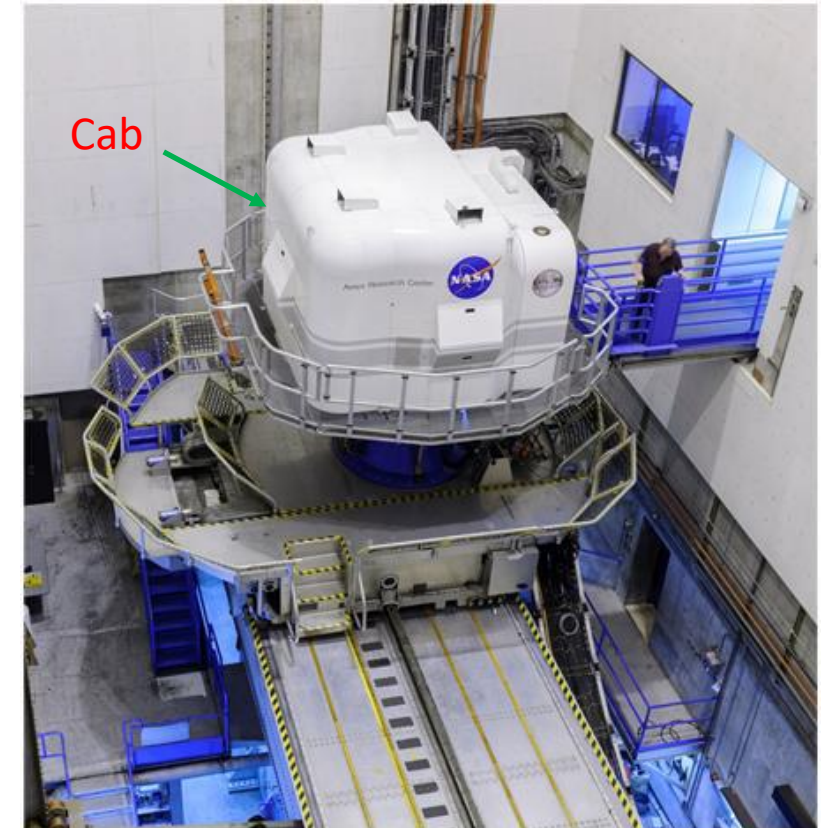
Rotor-borne Configuration



Presentation Context

- The Real-Time Powertrain Modeling (RTPM) tool under development by NASA has examined various hover/VTOL configurations in piloted and MDAO studies
- RAVEN required an initial controllability and power assessment
 - Required a first order approximate rotorcraft simulation to be developed for hover assessments with motor failures
 - Required forward flight corrections made to hover simulation to examine vehicle through transition and cruise
- Presentation Objectives
 - Show simulation development for the RAVEN Preliminary Design Review (PDR) simulation
 - *This is not the official D&C RAVEN simulation and all specific components are preliminary and not finalized*
 - Show rotor and aerodynamic verification approach
 - Show a sample of vehicle performance and trade studies

NASA Ames VMS





Codes Referred to in Presentation

- NDARC
 - NASA conceptual-design and performance analysis tool for sizing and evaluating rotorcraft and VTOL aircraft
- FlightCODE (In release process)
 - Develops fixed wing and rotorcraft models directly from NDARC files
 - Supports handling-qualities/control-system analysis at conceptual design level
- CAMRAD II
 - High-fidelity comprehensive rotorcraft aeromechanics tool for predicting rotor performance, loads, dynamics, vibration, and stability
- VSPAERO
 - OpenVSP's aerodynamic analysis solver for estimating aircraft forces, moments, stability derivatives, and control surface effects using potential-flow methods



Presentation Organization

- Nonlinear Simulation Development
- Powertrain Modeling
- Preliminary Nonlinear Simulation Assessment
- VTOL Mission
- Vehicle Controllability and Power Assessments
- Design Trade Study Example



Nonlinear Simulation Development



Nonlinear Simulation for Preliminary Assessment of Full-scale RAVEN

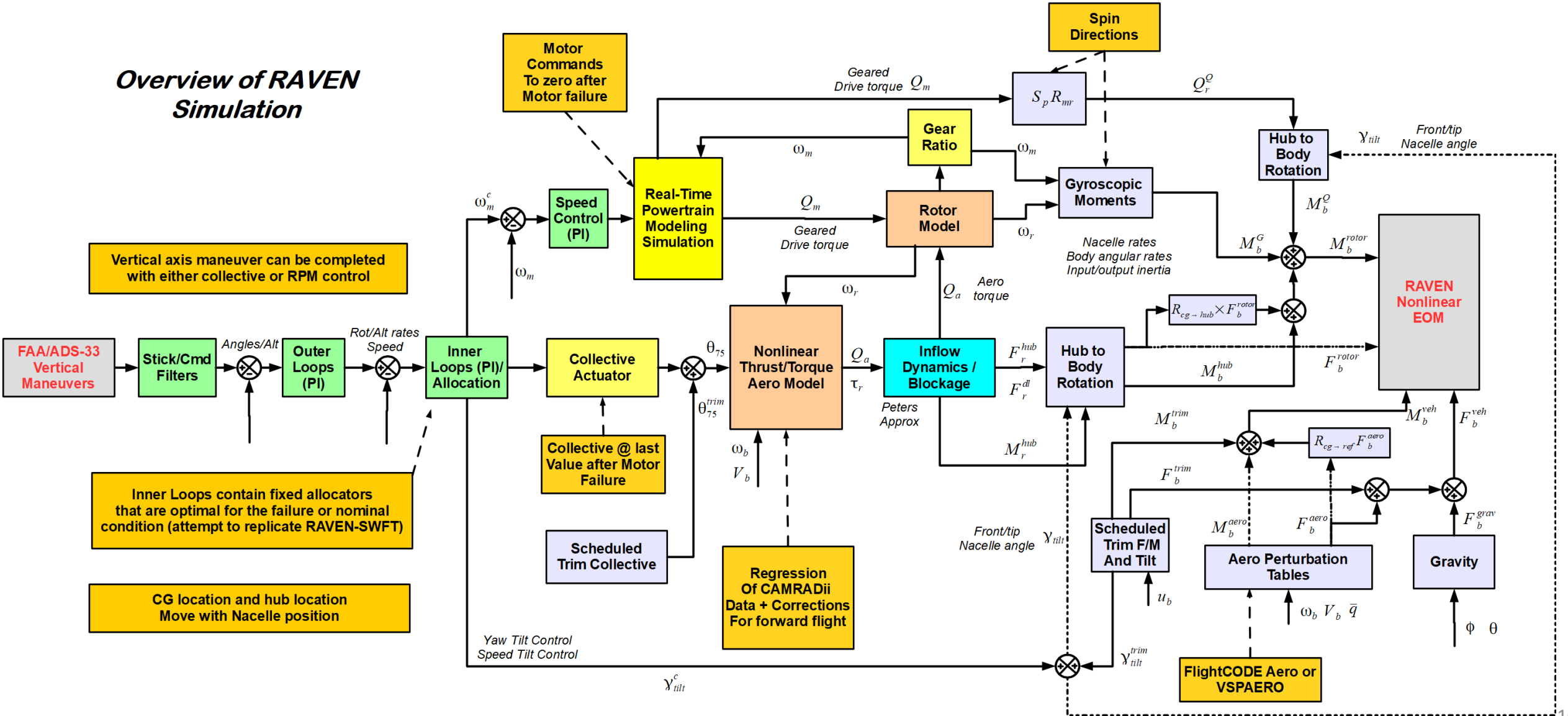
- Aero Characteristics
 - Rotor models developed with CAMRAD II data at hover and with corrections for forward flight
 - Nacelles Rotate
 - Fuselage and all aero surface aerodynamics provided by FlightCODE
 - No rotor-to-wing interactions explicitly modeled
- Powertrain Models in RTPM
 - All assumed powertrain component efficiencies
 - Motor
 - Battery
 - Gear
 - Thermal
- Wing, rotors and powertrain Integrated into a typical nonlinear simulation



Nonlinear Simulation for Preliminary Dynamics Assessments

- Preliminary Design Simulation inspired by previous VTOL VMS Piloted Studies

Overview of RAVEN Simulation

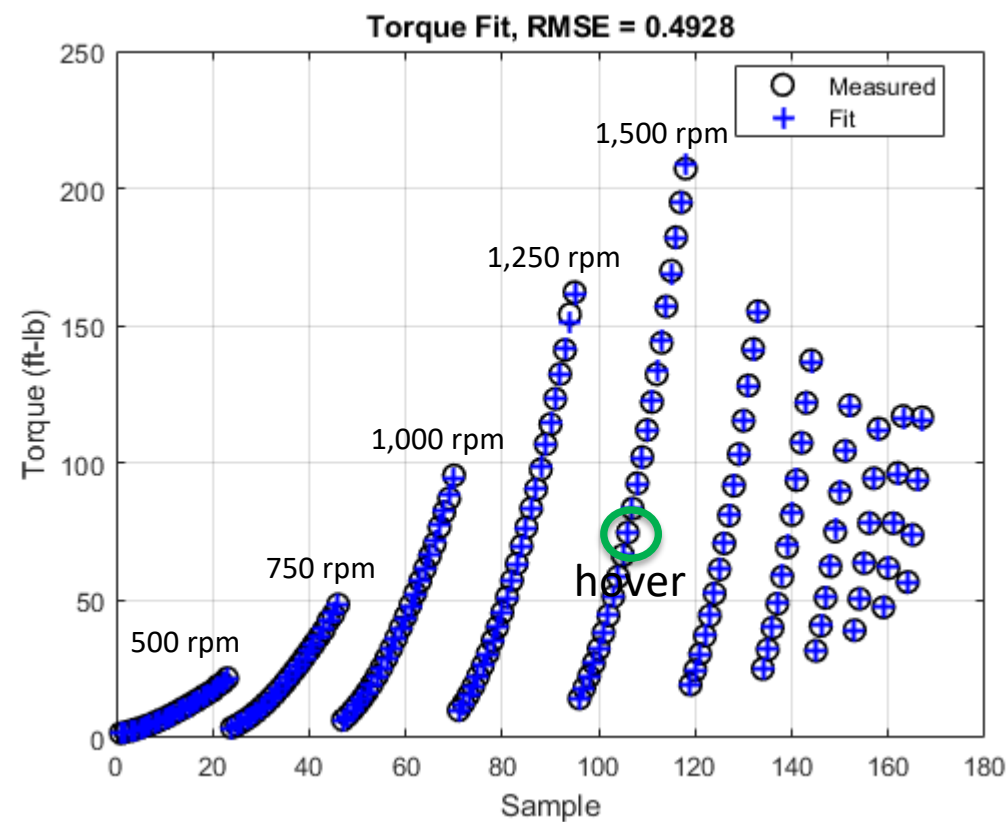
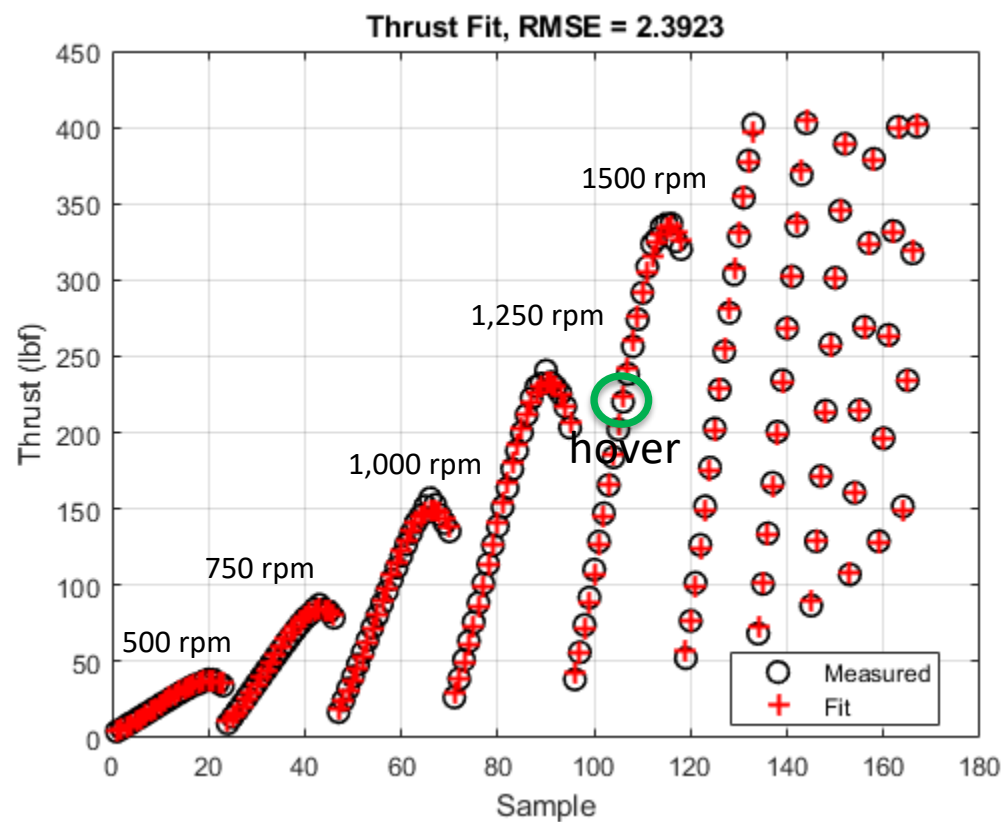




Rotor Model

- Rotor Models

- Hover CAMRAD II data used to fit thrust and torque for different speeds and collective
 - Regression equations with constant and linear rotor speed terms removed for better accuracy
 - Data used to fit the equation is limited based on a margin above a maximum expected thrust
 - For each RPM collective varies from 0 to some cutoff value after stall or below the thrust limit





General Strategy for Rotor Model Forward Flight Corrections

- The rotor aero data from CAMRAD II fit for hover condition and must be corrected for air-relative velocity, body and tilt rotations due to vehicle motion
- References for corrections: NDARC Vol3 Theory Manual (Hub forces/Torque correction), Leishman (TPP tilt visualization), and Prouty (Axial flow correction)
- First principles strategy
 - Compute the aerodynamic AoA (adjustment to collective angle at 75R) to interpolate from rotor torque and thrust response surfaces
 - Rotor speed assumed to be the same
 - Incorporate rotor tip path plane (TPP) tilt to model effect of in-plane velocity changes
 - 1st harmonic flapping

Key References:

Johnson, W. NDARC – NASA Design and Analysis of Rotorcraft: Theory, Vol. 3, NASA TP-2015-218751

Leishman, J. G., Principles of Helicopter Aerodynamics, 2nd ed. Cambridge University Press, 2006.

Prouty, R. W., Helicopter Performance, Stability, and Control, Krieger Publishing, 2002.



Key Equations and Definitions for Forward Flight Corrections

- Vehicle velocities and rotational rates and rotor tilt rates used to form the hub velocity in the body frame

$$V_b^{hub} = V_b + \omega_b \times R_{cg \rightarrow hub} + (\omega_b + \omega_b^{tilt}) \times R_{hinge \rightarrow hub}$$

Hub velocity in frame of body
(currently assuming negligible
distance between Nacelle
hinge center to rotor hub center)

- Rotate the body hub velocity into the rotor frame

$$V_r^{hub} = C_{b \rightarrow r} V_b^{hub} = \begin{bmatrix} u_r \\ v_r \\ w_r \end{bmatrix}$$

Hub velocity in frame of the
rotor after Nacelle rotations

- Rotor axes initially assumed to be identical to body axes before Nacelle rotation
- Axial flow seen by the rotor disk due to forward speed assuming no inflow
 - Used by Prouty in computation of axial disk velocity

$$V_c = -w_r$$



Axial Flow and Torque Correction

- The rotor inflow velocity (v_i) and the resultant flow-speed magnitude at the disk (v_{eff}) computed from generalized momentum theory as

$$v_h^2 = v_i v_{eff} = v_i \sqrt{u_r^2 + v_r^2 + (V_c + v_i)^2} \quad \text{where} \quad v_h = \sqrt{\frac{\tau_r}{2\rho A}} \quad \text{Is the hover induced velocity}$$

Axial disk velocity

- The inflow angle adjusts the effective collective (aerodynamic AoA) at the R_{75} station (CAMRAD II reference blade station)

$$\theta_{75}^{eff} = \theta_{75} - (\alpha_i - \alpha_h) k_{col} \quad \text{where} \quad \alpha_i = \text{atan2}(V_c + v_i, \omega_r R_{75})$$

$$\alpha_h = \text{atan2}(v_h, \omega_r R_{75})$$

k_{col} is a tuning coefficient

- Thrust (τ_r) and Hover torque (Q_h) computed from the hover thrust and torque regression equations with effective collective and rotor speed
- Torque adjusted for forward flight with inflow power relationship from NDARC

$$Q_r = Q_h + \frac{\Delta P_i}{\omega_r} = Q_h + \frac{(V_c + v_i - v_h) \tau_r}{\omega_r} \quad \text{where} \quad v_h \text{ subtracted from axial disk velocity to model change in axial disk velocity relative to hover}$$



Hub Forces

- The 1st harmonic flapping solution to the 2nd order flapping EOM is provided with a coning term, β_0 , lateral flapping angle, β_s , and longitudinal flapping angle, β_c , angles which define the TPP tilt

$$\beta(\psi_a) = \beta_0 + \beta_c \cos(\psi_a) + \beta_s \sin(\psi_a)$$

- NDARC theory manual provides an equation for in-plane lon/lat force coefficients (C_{H0} , C_{Y0})

$$\begin{bmatrix} C_{H0} \\ C_{Y0} \end{bmatrix} = \frac{\sigma}{8} c_{d,mean} F_H \begin{bmatrix} \mu_x/\mu \\ -\mu_y/\mu \end{bmatrix} \quad \text{where} \quad \mu_x = \frac{u_r}{\omega_r R} \quad \text{and} \quad \mu_y = \frac{v_r}{\omega_r R} \quad \text{and} \quad \mu = \sqrt{\mu_x^2 + \mu_y^2}$$

- Dividing through by C_T

$$\frac{C_{H0}}{C_T} = K_H \mu_x \quad \text{and} \quad \frac{C_{Y0}}{C_T} = -K_H \mu_y \quad \text{where} \quad K_H = \frac{\sigma c_{d,mean} F_H}{8 C_T \mu}$$

$$V_F = \frac{v_{eff}}{\omega_r R}$$

$$\mu_z = \frac{w_r}{\omega_r R}$$

$$\text{and} \quad F_H \cong \sqrt{1 + V_F^2} \left(3\mu + \frac{\mu^3}{4} \frac{(V_F^2 - 1)}{(1 + V_F^2)^2} \right) + \left(\mu \mu_z^2 + \frac{3}{4} \mu^3 \right) \ln \left(\frac{\sqrt{1 + V_F^2} + 1}{V_F} \right) \quad \text{and}$$

$$V_F = \frac{\sqrt{u_r^2 + v_r^2 + w_r^2}}{\omega_r R}$$



Hub Forces and Moments Implementation

- Assuming NCARC profile in-plane force ratios provide a surrogate for TPP tilt

$$\beta_c \cong \text{atan2}\left(\frac{C_{H0}}{C_T}, 1\right) = \text{atan2}(k_{lon}K_H\mu_x, 1)$$

$$\beta_s \cong \text{atan2}\left(\frac{C_{Y0}}{C_T}, 1\right) = -\text{atan2}(k_{lat}K_H\mu_y, 1)$$

- Assuming $K_H = 1$ ($H \approx \mu_x T, Y \approx -\mu_y T$)

$$\beta_c = \text{atan2}(k_{lon}u_r, \omega R) \quad \beta_s = -\text{atan2}(k_{lat}v_r, \omega R)$$

- Similar results with exact K_H and which also requires k factor (k_{lon}, k_{lat}) tuning
- Forces and moments are computed as

Hub Forces

$$F_r^{hub} = C_x(\beta_s)C_y(\beta_c) \begin{bmatrix} 0 \\ 0 \\ -\tau_r \end{bmatrix}$$

and

Rotor Hub Moments

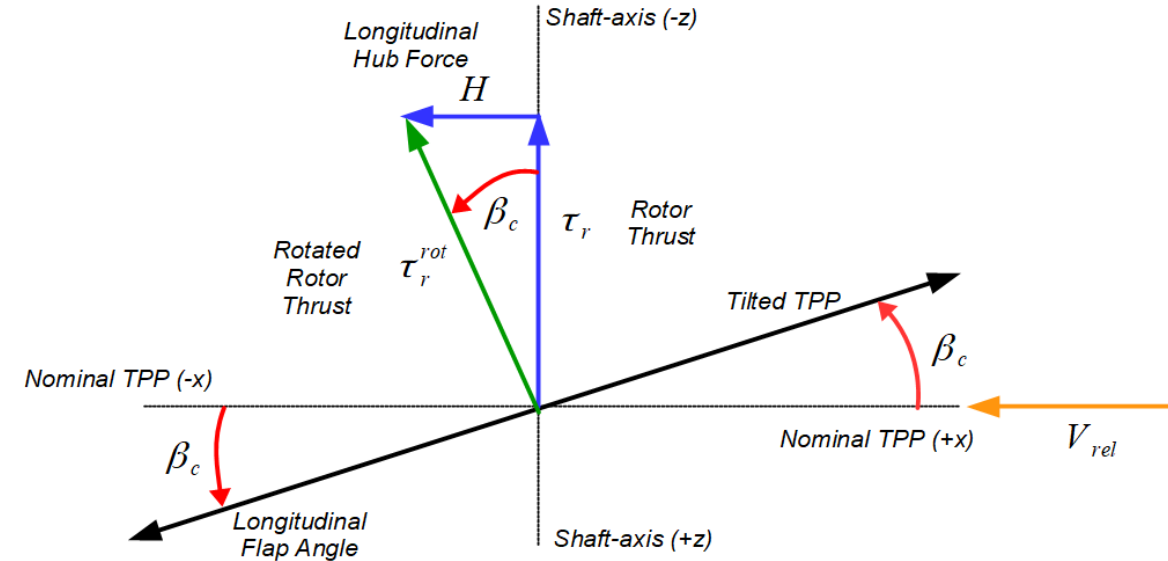
$$M_r^{hub} = R_{hub \rightarrow cg} \times F_r^{hub}$$

and

Body Frame Hub Moments

$$M_b^{hub} = M_c^{hub} + C_{r \rightarrow b} M_r^{hub}$$

Approximate Thrust-Vector Rotation from TPP Tilt



Currently assuming
Hub moment couples (M_c^{hub})
Negligible (but may not in future)



Inflow Dynamics First Order Approximation

- The rotor thrust and torque lagged using Peters uniform inflow (v_0) equation

$$K_M \dot{v}_0 + 2v v_0 = \tilde{C}_T \quad \text{Uniform inflow}$$

- The uniform inflow equation placed into first order DEQ form

$$\frac{K_M}{2v} \dot{v}_0 + v_0 = \frac{\tilde{C}_T}{2v}$$

- The non-dimensional thrust time constant can be determined to be

$$\tilde{\tau} = \frac{K_M}{2v} = \frac{4}{3\pi} \frac{1}{v} = \frac{4}{3\pi} \frac{\omega_r R}{v_{eff}} \quad \text{where} \quad v = \frac{v_{eff}}{\omega_r R} \quad \text{and} \quad K_M = \frac{8}{3\pi}$$

(A momentum theory solution
Peters suggests
but there are others)

- The thrust time constant is then determined as

$$\tau_{thrust} = \frac{\tilde{\tau}}{\omega_r} = \frac{4}{3\pi} \frac{R}{v_{eff}} \quad \text{and used in filter:} \quad A_{thrust} = \frac{1}{1 + \tau_{thrust} s}$$

- Torque assumes an average of 50% profile drag and 50% induced drag

$$\tau_{torque} = \frac{\tau_{thrust}}{2} \quad \text{and used in filter:} \quad A_{torque} = \frac{1}{1 + \tau_{torque} s}$$

Key Reference: Peters,
D. A. , “The
importance of steady
and dynamic inflow
On the stability of
rotor-body systems”

- Since thrust is rotated for
hub forces, may in the
future use separate time
constants derived in the
same way for pitch and roll
axis*



Download Force

- Download forces (modeled as blockage) caused by wake impingement on airframe from NDARC .acd file

- The download force (DL) is computed at hover as in Prouty

$$DL = \frac{1}{2} C_d A_{dl} \rho v_h^2 \quad \text{where} \quad v_h = \sqrt{\frac{\tau_r}{2\rho A}}$$

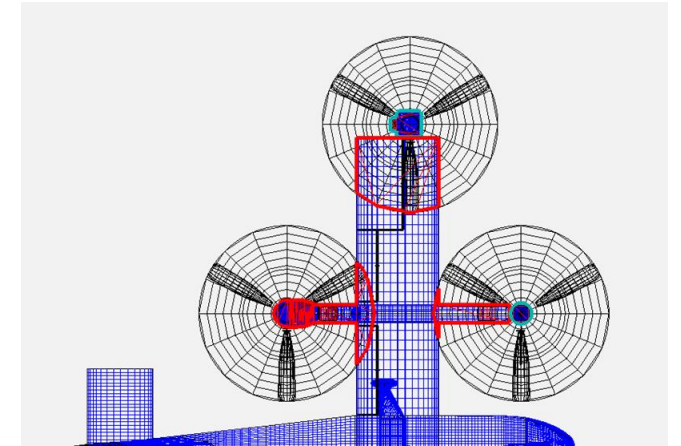
- The drag coefficient (C_{wi}) and area of wake impingement (A_{wi}) is solved for with thrust due to download (τ_r^{dl}) and isolated thrust (τ_r^{iso})

$$C_{wi} A_{wi} = \frac{2DL}{v_h^2 \rho} \quad \text{where} \quad DL = \tau_r^{iso} - \tau_r^{dl}$$

- The download force corrected for forward flight ($v_h \rightarrow v_i$) assumed reduced as Nacelles rotate approximating a reduction of opposing rotor wake force on the structure

$$F_{dl} = \frac{1}{2} C_{wi} A_{wi} \rho v_i^2 \cos\left(\frac{\pi}{2} - \gamma_{tilt}\right) \quad \text{And rotor frame download is} \quad F_r^{dl} = \begin{bmatrix} 0 \\ 0 \\ F_{dl} \end{bmatrix}$$

- Download forces higher for tip rotors (13% of thrust) than forward (6.1% of thrust) and aft rotors (7.1% of thrust)





Motor Torque Reaction Moments

- The motor hub torque assumed to cause reactionary moments on the body from
 - Aerodynamic torque on the rotors
 - Rotor acceleration due to flight control laws
- The motor hub torque is formed from motor torque after accounting for spin direction of the motor and relative spin directions of motor to rotor

$$Q_r^Q = \begin{bmatrix} 0 \\ 0 \\ Q_m S_p R_{mr} \end{bmatrix}$$

S_p Is a signed scalar for NDARC rotor spin in the rotor frame

R_{mr} Is a signed scalar for relative spin direction of motor to rotor spin direction

- Each motor torque is transferred to the body frame with a negative sign to account for the reaction effect on the body

$$M_b^Q = -C_{r \rightarrow b} Q_r^Q$$



Gyroscopic Moments for Tilting and non-Tilting Rotors

- The angular momentum of post gear box components at the rotor speed

$$H_b^{post} = C_{r \rightarrow b} \begin{bmatrix} 0 \\ 0 \\ I_{post} S_p \omega_r \end{bmatrix} \quad \text{where } S_p \text{ Is a signed scalar for NDARC rotor spin in the rotor frame}$$

- The body angular momentum of pre-gear box components at the motor speed

$$H_b^{pre} = C_{r \rightarrow b} \begin{bmatrix} 0 \\ 0 \\ I_{pre} S_p R_{mr} \omega_m \end{bmatrix} \quad \text{where } R_{mr} \text{ Is a signed scalar for relative spin direction of motor to rotor spin direction}$$

- Gyroscopic moments computed from cross product of the rotation rate of the body and relative Nacelle rates in body frame (ω_p) with angular momentum of moving post-gear and pre-gear components

$$M_b^G = -\omega_p \times (H_b^{post} + H_b^{pre}) \quad \text{where}$$

Body rates Nacelle tilt rates in body frame

$$\omega_p = \omega_b + \omega_b^{tilt} \quad \text{for tilting rotors}$$
$$\omega_p = \omega_b \quad \text{for non-tilting rotors}$$



Pre and Post Gear Inertia Determination

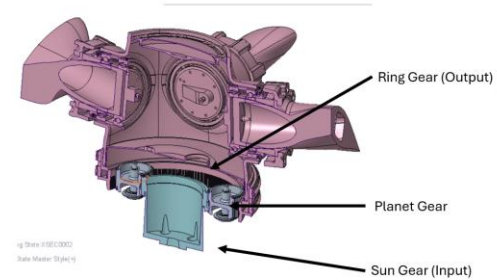
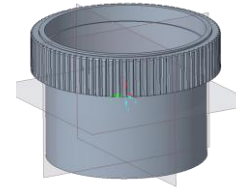
- The pre gear inertia (I_{pre}) was determined to be primarily motor inertia and sun gear inertia

$$I_{pre} = I_m + I_{sun} = 0.0204 \text{ slugft}^2$$

$$I_m = 0.0188 \text{ slugft}^2$$

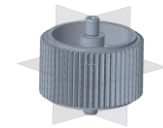


$$I_{sun} = 0.001585 \text{ slugft}^2$$



Assumptions:
Neglecting planet gear inertia
(will be added in future)

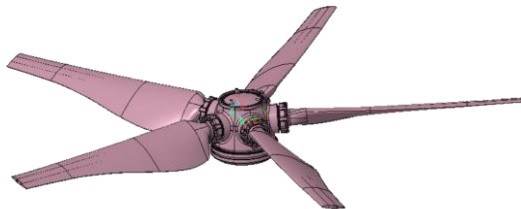
$$I_{pl} = 0.000051 \text{ slugft}^2$$



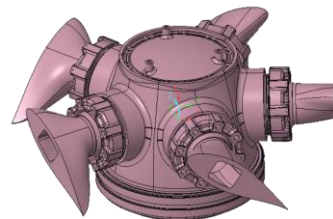
- The post gear inertia (I_{post}) was determined to be primarily rotor inertia, hub inertia and ring inertia

$$I_{post} = I_o + I_{ring} = I_r + I_h + I_{ring} = 0.4049 \text{ slugft}^2$$

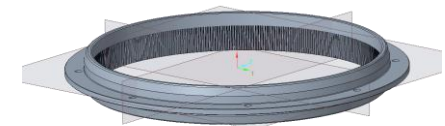
$$I_o = I_r + I_h = 0.3993 \text{ slugft}^2$$



$$I_h = 0.0807 \text{ slugft}^2$$



$$I_{ring} = 0.0056 \text{ slugft}^2$$





Trim forces and moments

- The trim vehicle forces and moments per rotor in body frame for a 0 deg pitch and bank trim with rotors set to VTOL mission rotor speed, collective and tilt schedule
 - Rotor speeds exact
 - Collective re-trimmed based on known rotor moment arms as NDARC trims to non-zero pitch angles
 - Tilt schedule exact

- Assume per rotor that to trim that rotor, the following relationships hold:

$$F_{x,i}^{trim} = -F_{x,i}^{rotor}(\theta_0 = 0, \phi_0 = 0)$$

$$M_{y,i}^{trim} = -M_{y,i}^{rotor}(\theta_0 = 0, \phi_0 = 0)$$

And for all rotors aerodynamic
vertical trim computed as

$$F_z^{trim} = -\left(W + \sum F_{z,i}^{rotor}(\theta_0 = 0, \phi_0 = 0)\right)$$

- The body forces and moments to cancel the scheduled rotor trim forces maintained in the body frame since rotors move with body during turns or pitching

$$F_b^{trim} = \begin{bmatrix} \sum F_{x,i}^{trim} \\ 0 \\ F_z^{trim} \end{bmatrix} T_\alpha$$

$$M_b^{trim} = \begin{bmatrix} 0 \\ \sum M_{y,i}^{trim} \\ 0 \end{bmatrix} T_\alpha$$

where

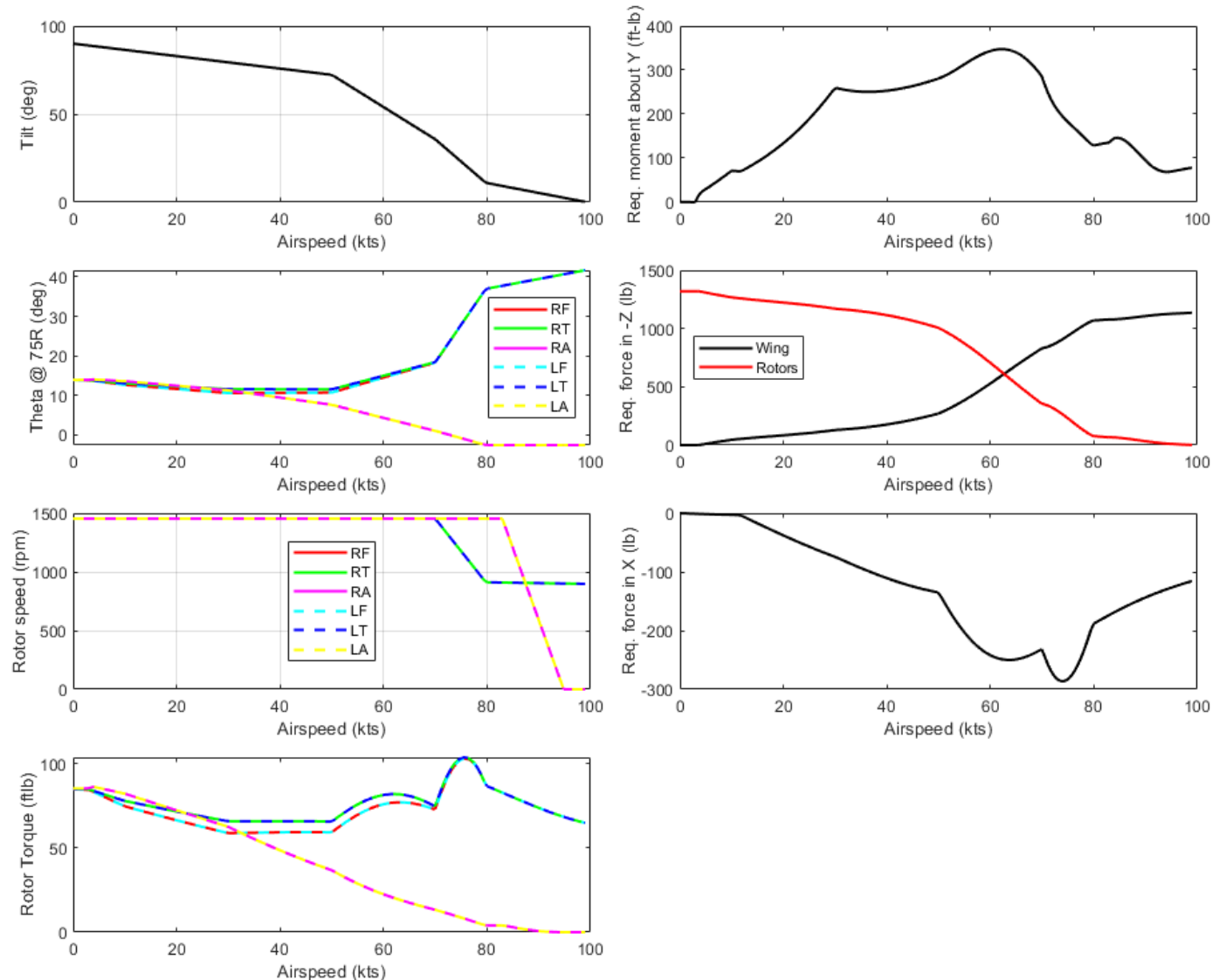
T_α is a tuning coefficient
Used to adjust away from
0 pitch trim to align with
NDARC trim AoA at cruise



Trim Forces & Moments Example for VTOL mission

- A scheduled forces & moments approach is used to trim the vehicle to any tilting configuration
 - Set the rotor tilts, max collective, rotor speeds for any particular speed as received from NDARC or directly from CAMRAD II
- Benefits of the scheduled forces & moments approach
 - First order dynamic assessments
 - Transition schedule change assessments
 - Energy and power assessments
 - Aerodynamic assessments

Example for Required 0 pitch and bank Trim Forces and Moments





Aero Forces and Moments

- Aero data incorporated assumes existing longitudinal trim forces and moment exist
 - Incorporates only perturbation aero data
- Two data sources provided
 - FlightCODE perturbation aero tables for hover to transition through cruise
 - Component (c) wing, horizontal tail, vertical tail, fuselage
 - Perturbation forces and moments provided for p, q, r, u, v, w
 - Control delta forces and moments
 - $\delta_{ail}, \delta_{stab}, \delta_{rud}$
 - Scheduled with exact tilt and velocity schedule used for the NDARC VTOL mission
 - VSPAERO perturbation aero tables for comparisons
 - Whole vehicle sources (e_s)
 - $p, q, r, \alpha, \beta, V, \delta_{flap1}, \delta_{flaps2-5}, \delta_{flap6}, \delta_{stab}, \delta_{rud}$
 - Flaps 1 and 6 are tip surfaces typically used as an aileron
 - Flaps 2-5 ganged together and treated as a single flap
 - Scheduled with a close but not exact tilt/velocity schedule used for the NDARC VTOL mission

FlightCODE Aero

$$F_b^{aero} = \sum_i^{n_c} F_b^i(u, v, w, p, q, r, \delta)$$

$$M_{bc}^{aero} = \sum_i^{n_c} M_b^i(u, v, w, p, q, r, \delta)$$

$$M_b^{aero} = M_{bc}^{aero} + R_{ref \rightarrow cg} \times F_b^{aero}$$

VSPAERO

$$F_b^{aero} = \sum_i^{n_s} \frac{F_b^i}{e_s} [\alpha, \beta, V, p, q, r, \delta]^T$$

$$M_b^{aero} = \sum_i^{n_s} \frac{M_b^i}{e_s} [\alpha, \beta, V, p, q, r, \delta]^T$$

$$M_b^{aero} = M_{bc}^{aero} + R_{ref \rightarrow cg} \times F_b^{aero}$$

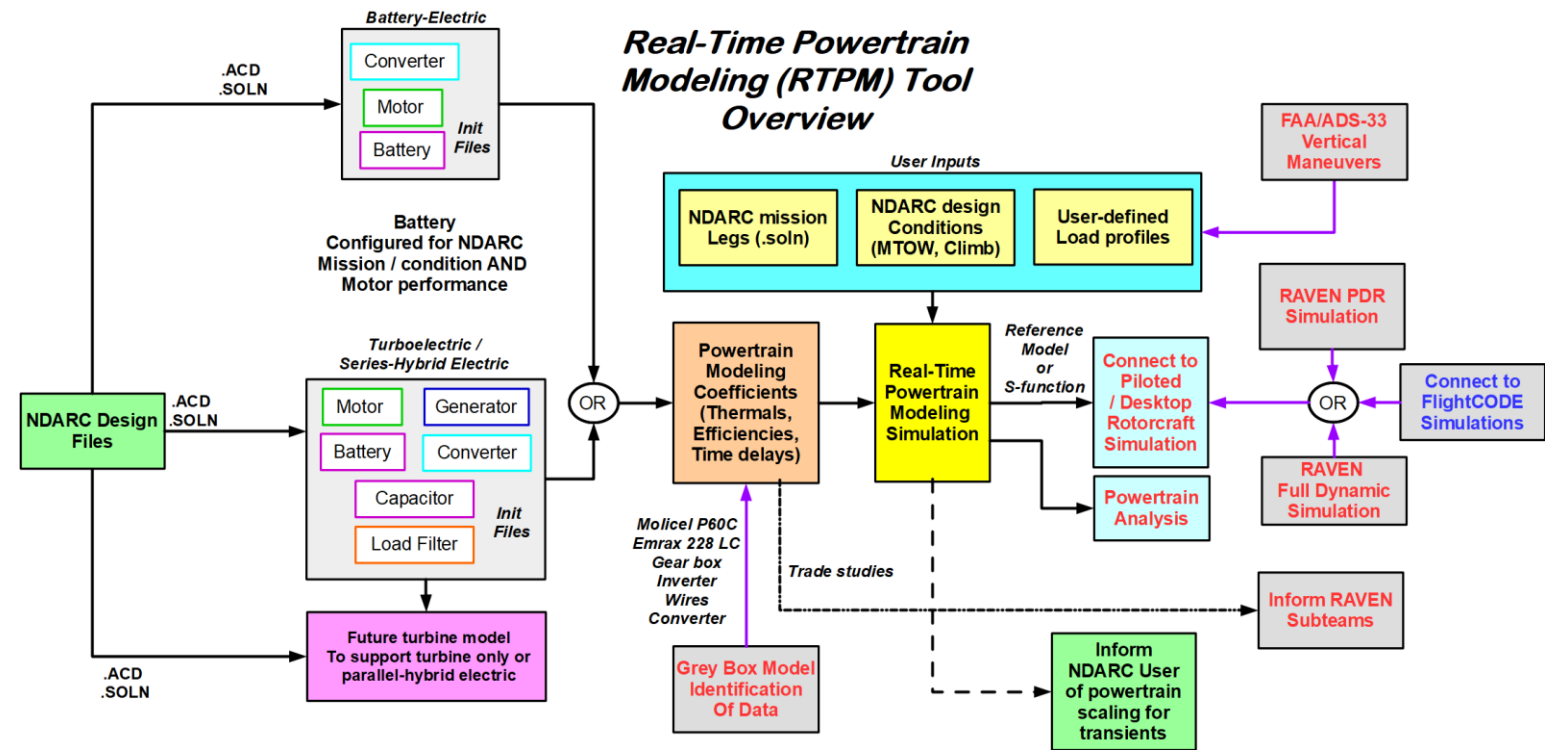


Powertrain Modeling

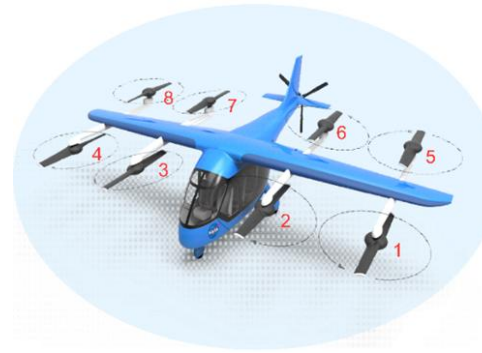


Overview of Real-Time Powertrain Modeling (In-Development)

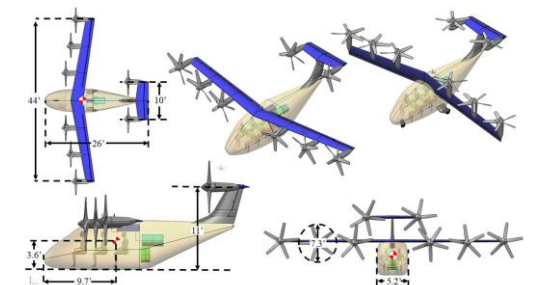
- The real-time powertrain modeling (RTPM) tool
 - Builds up full powertrain simulations directly from NDARC acd/soln files
 - Series hybrid electric/all electric lift + cruise, turbo-electric tiltwing, hexacopter, quadcopter, conceptual Joby powertrain, now RAVEN
 - Capable of integrating into any Simulink nonlinear simulation with a reference model
 - Currently integrated partially into NASA's FlightCODE tool
 - Has supported
 - Several ACGSC presentations
 - 7 VFS publications (5 simulation, 2 MDAO)
 - Various handling qualities experiments at AFRC and ARC



**Lift + Cruise
Concept Vehicle Design**



**Tiltwing
Concept Vehicle Design**

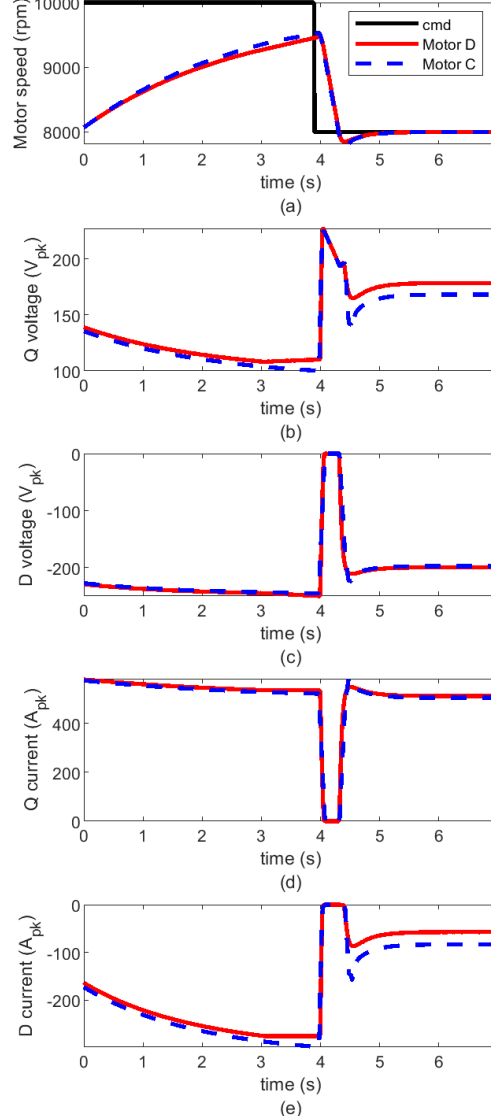




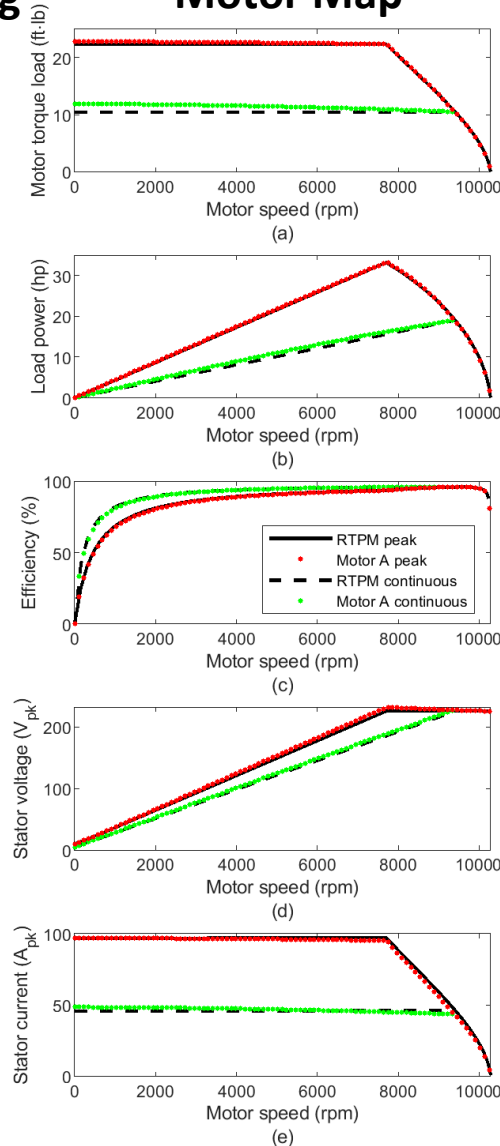
Prior RTPM Verification & Validation Work

- First figure shows comparison of simplified RTPM to full Mathworks Simscape (equivalent to PSIM) model with field weakening control
- Second figure compares simplified RTPM predictions to Manufacturer's motor data showing peak and continuous overlay limitations
- Third figure shows comparison of simplified RTPM time history to Advanced Reconfigurable Electrified Aircraft Lab (AREAL) Emrax Motor data collected by GRC's former RVLT Electric Propulsion Team

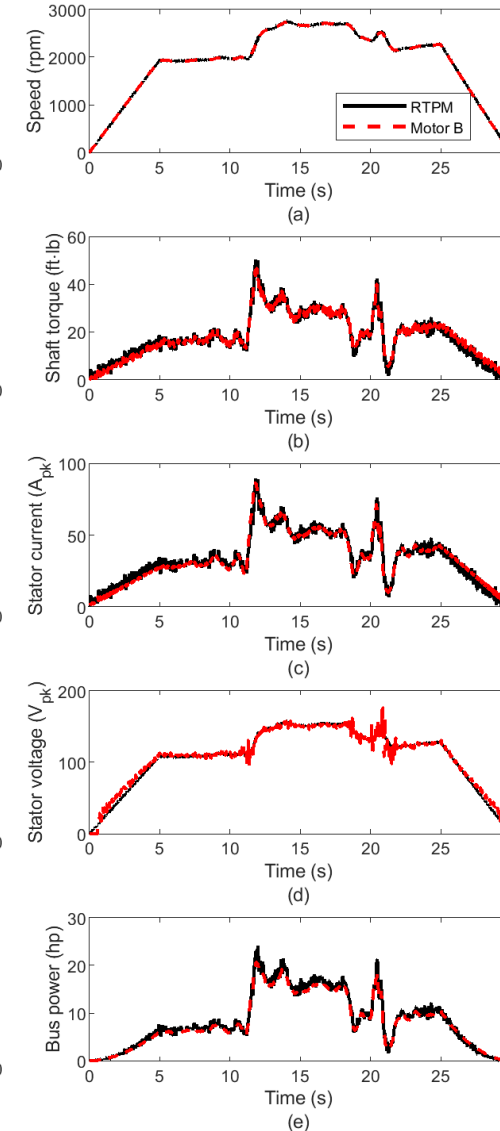
**RTPM to Simscape
PMSM in Field Weakening**



**RTPM to
Motor Map**



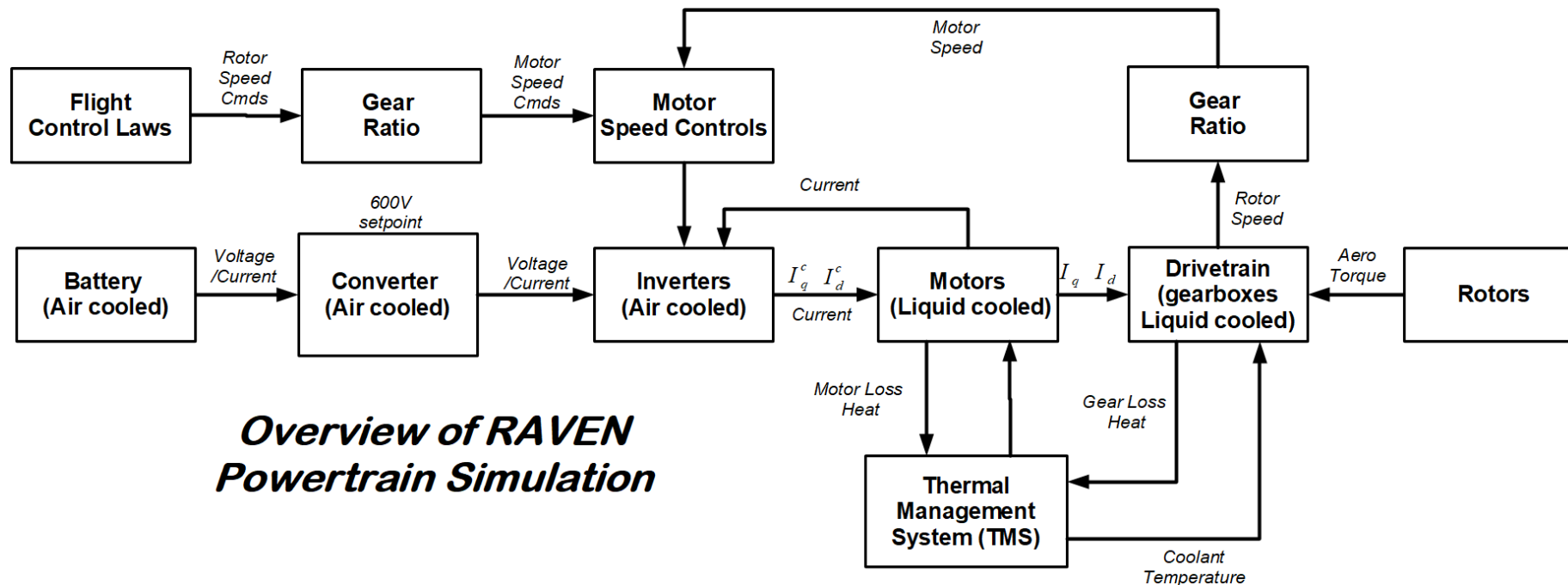
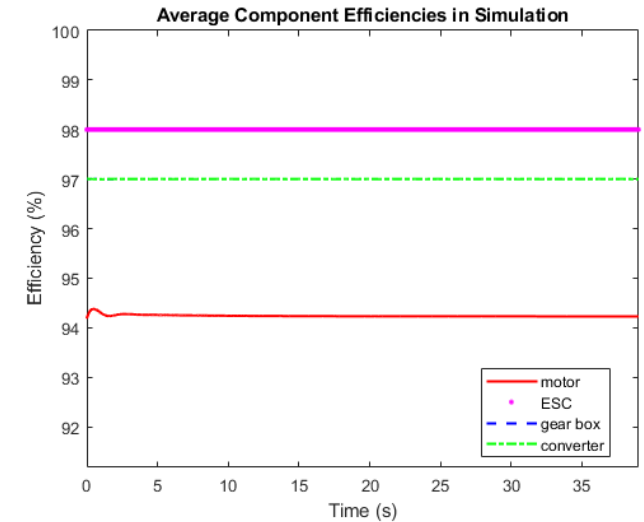
**RTPM to AREAL
Motor data**





Powertrain Modeling for Dynamic Simulation

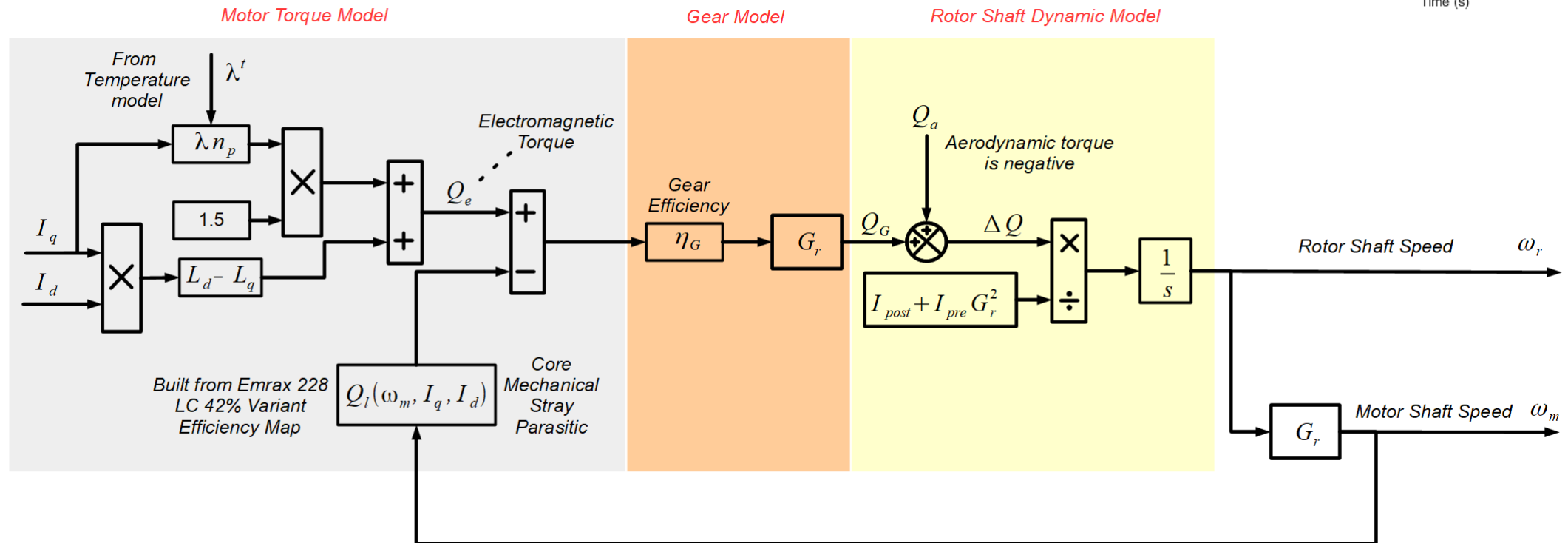
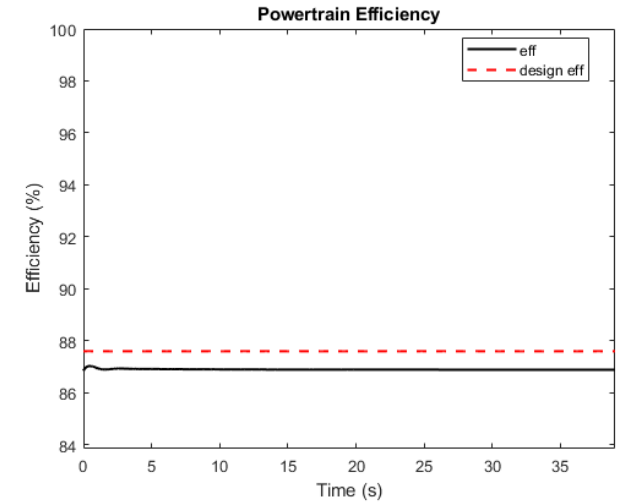
- The power models consists of
 - Battery with 5 strings of 222 Molicel P60C battery cells (1110 cells)
 - Custom DC-DC converter with a setpoint of 600V and an assumed efficiency of 97%
 - Six custom inverters with an assumed efficiency of 98%
- The motors modeled
 - Emrax 228 LC HV 42% using model-based efficiency





RAVEN Rotor Drivetrain

- Each rotor drivetrain modeled based on a
 - Motor Torque Model
 - Gear Model with an assumed efficiency of 97%
 - Rotor Shaft Dynamic Model
- The torque loss map adjusts depending on the operating point of the motor

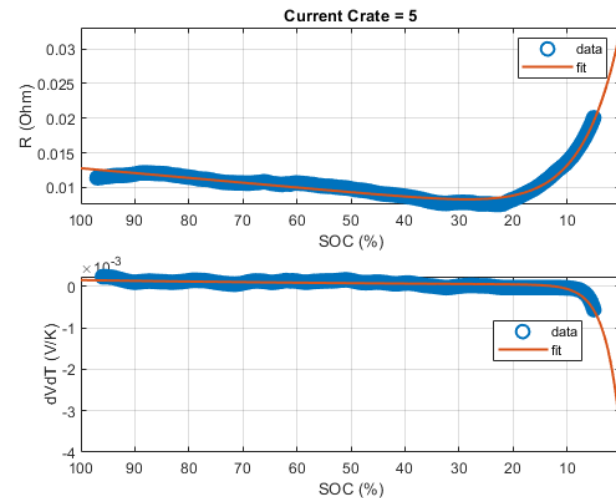
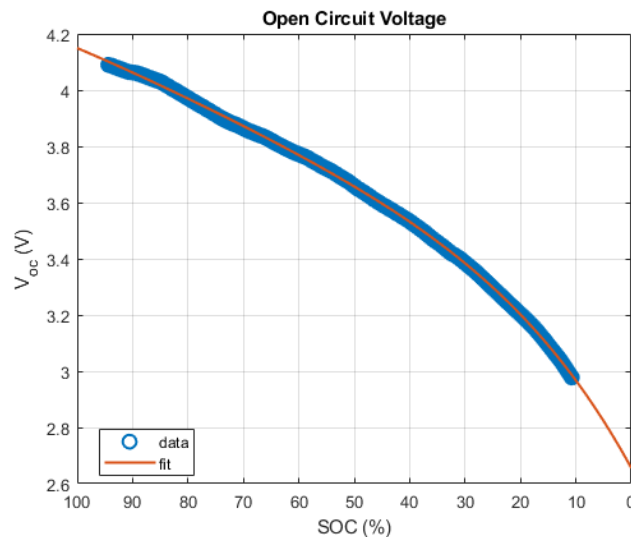




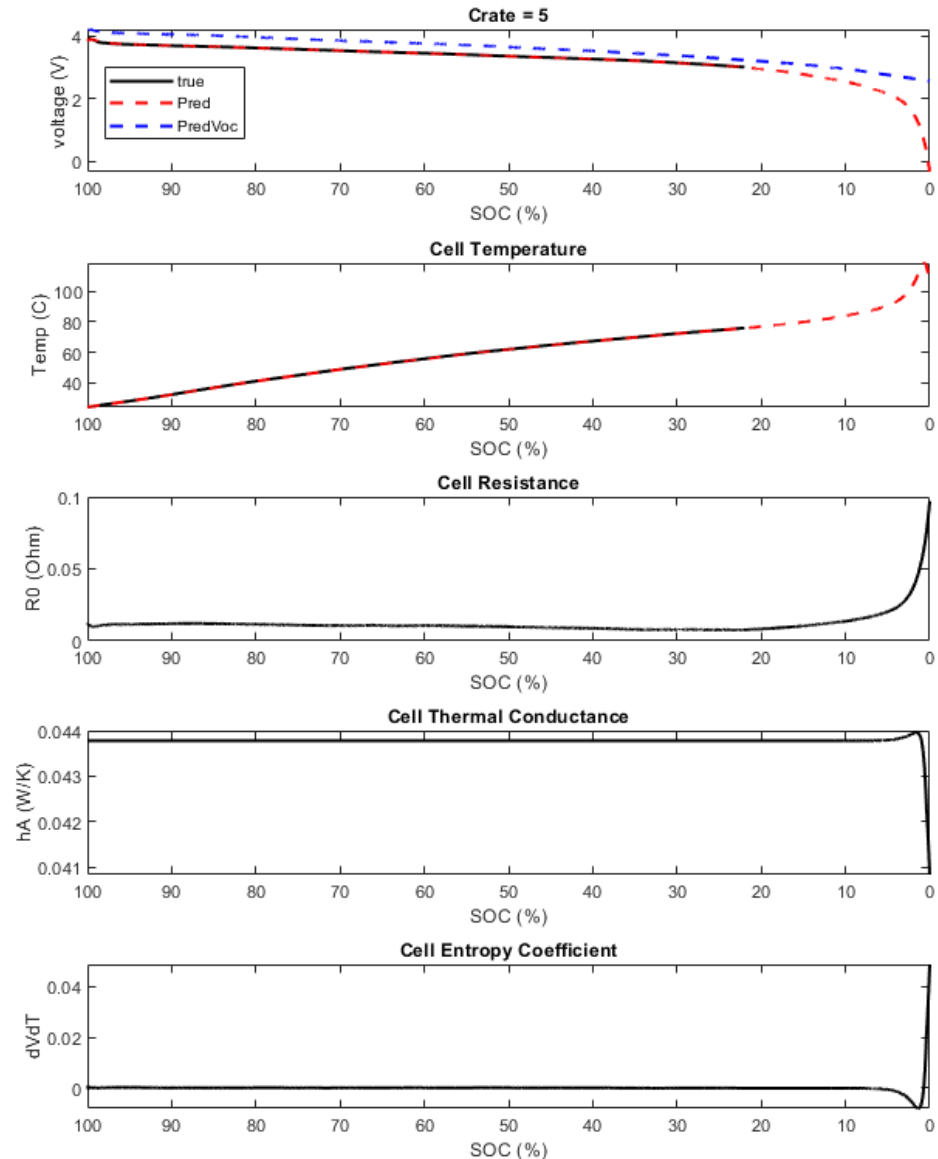
Battery Model

- The battery voltage and temperature model formed by NASA's grey-box physics-based network (GBPBN) with public Molice P60C battery data
- The GBPBN determined the physics-based coefficients
 - Using 0.5C, 1C, 5C, 10C and 12C datasets
 - Predictions from GBPBN required to complete data sets
- Resulting battery open circuit voltage, resistance, and temperature coefficients fit as a function of a limited range of state of charge

PINN predicted data fit for implementation into RAVEN simulation



Molice P60C public data versus GBPBN predictions

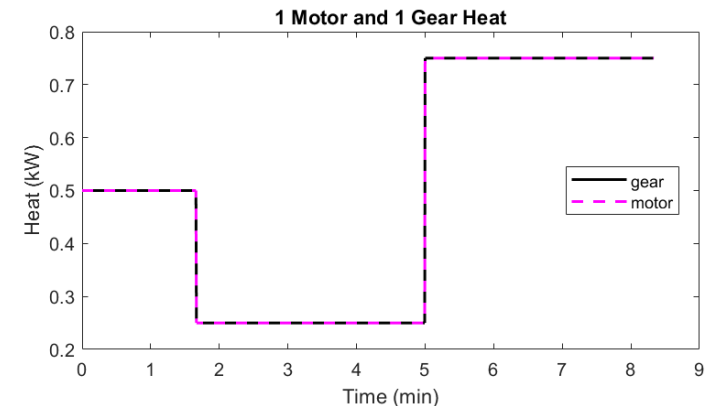
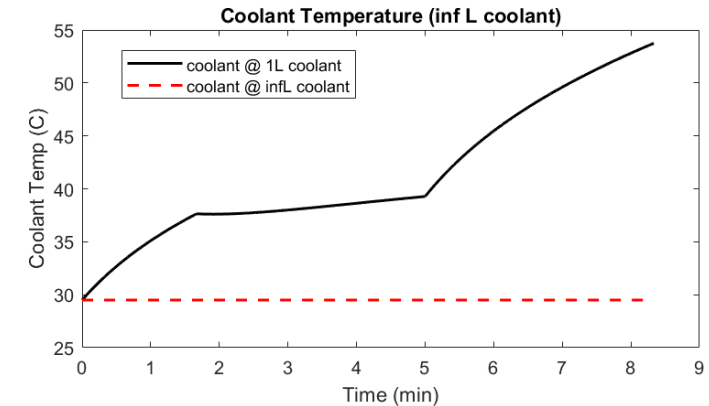
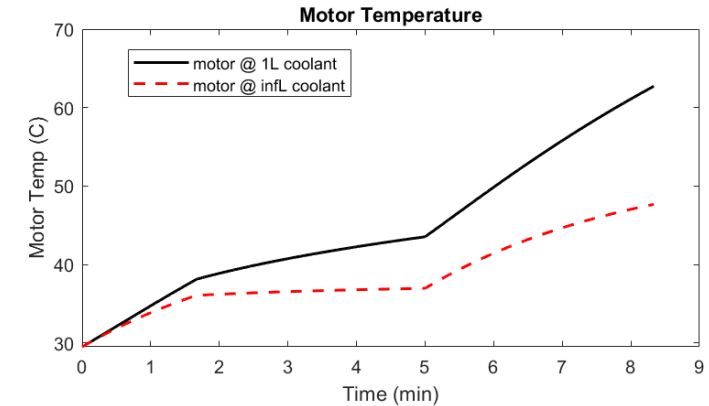




Motor and Thermal Management System (TMS)

- An initial low order lumped mass motor and thermal management system (TMS) has been provided by GT
 - Uses expected design coolant loop with heat exchanger
 - Coolant reservoir affected from gear heat and motor heat
 - Coolant temperature varies
 - Coolant reservoir contains 1L of coolant for 1 gear box and 1 motor
 - Ambient temperature assumed to be 29.5 deg C

GT Motor + TMS Thermal Model





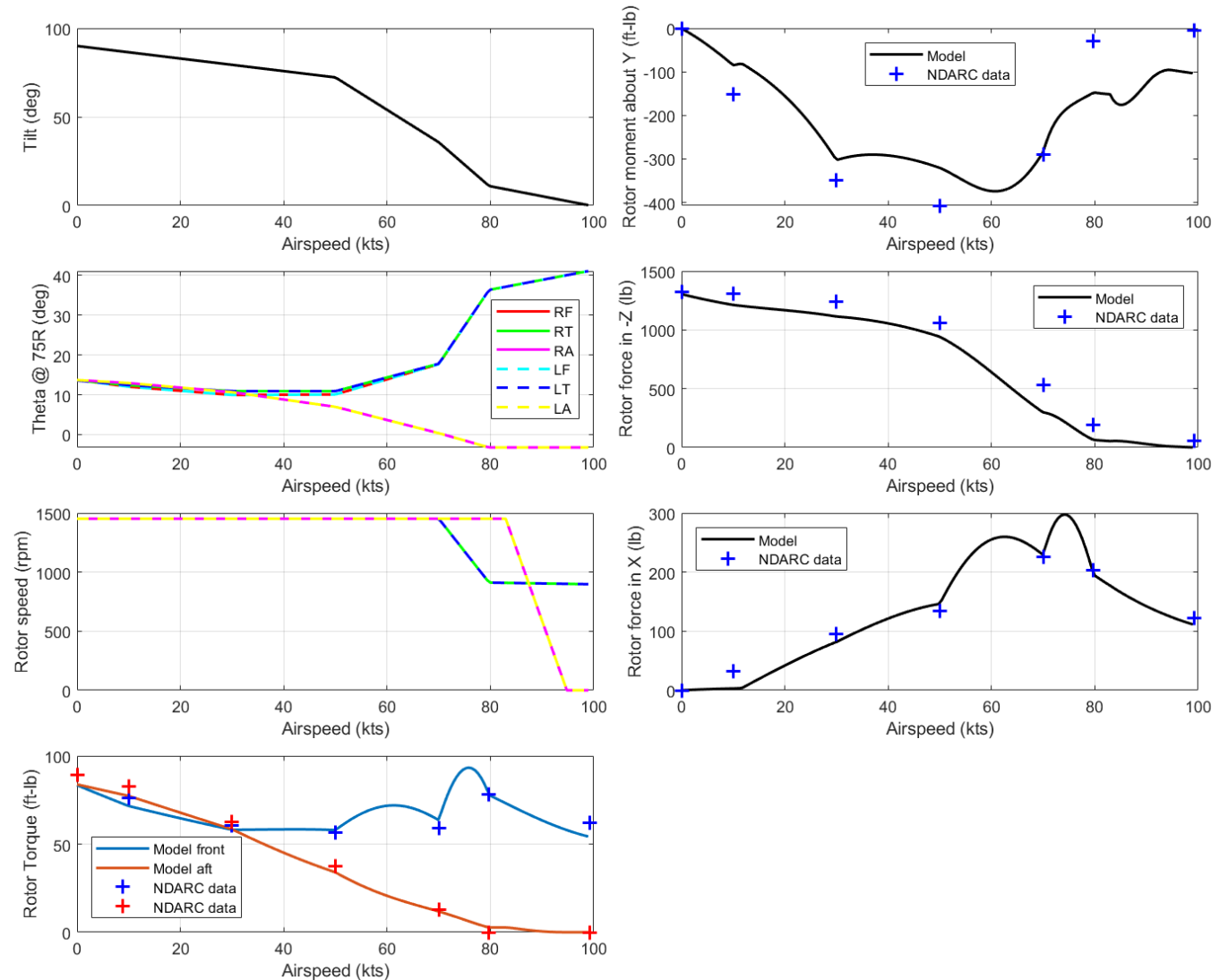
Preliminary Nonlinear Simulation Assessment



CAMRADii-adjusted Rotor Performance versus NDARC

- The rotor-only performance was compared to NDARC design file (.soln) for the VTOL mission
 - Aerodynamic data for the rotors informed by CAMRAD II at forward flight conditions
- Results show CAMRADii-adjusted model rotors can approximate forward flight operations
 - Nacelle tilt changes
 - Rotor torques
 - Important for power
- Lateral axis not yet directly compared to NDARC

Verifying CAMRADii-adjusted models for forward flight operations

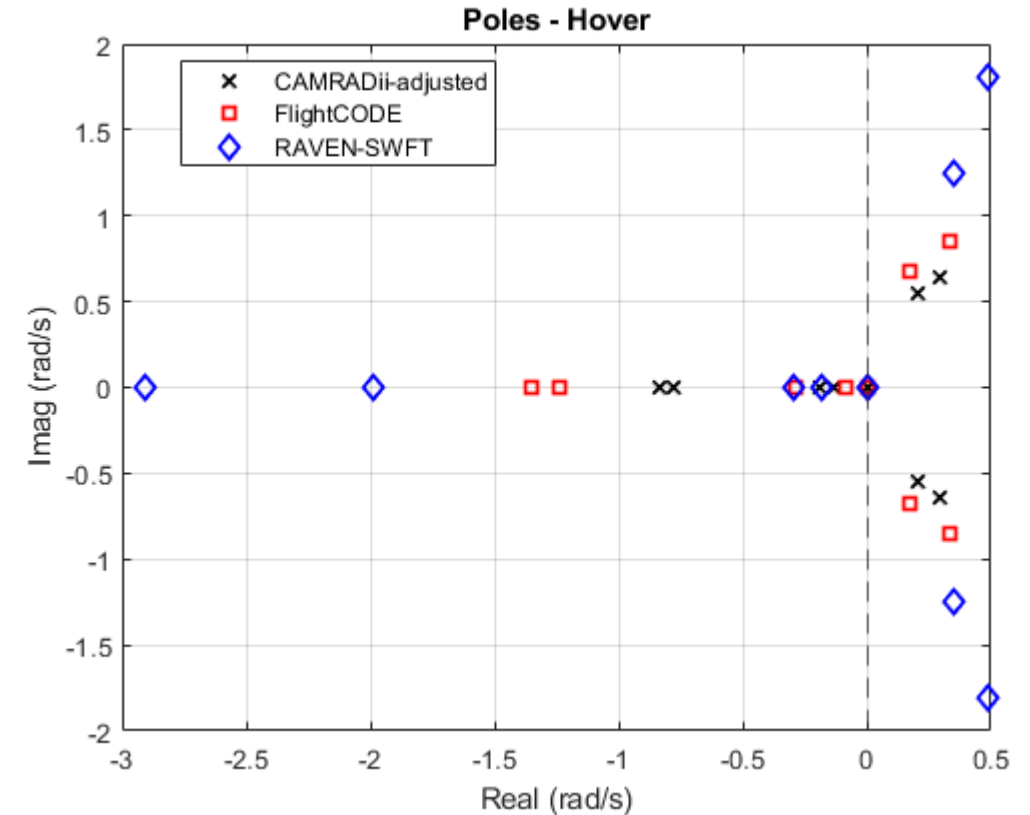




Hover Model Comparisons

- CAMRADii-adjusted
 - State space model of RAVEN vehicle developed from CAMRAD II hover data with adjustments for forward flight
- FlightCODE
 - State space model, originally produced from NDARC .acd/.soln files
 - Poles observed are after reduction of full order model to rigid body states
- RAVEN-SWFT
 - State space model identified by wind tunnel and flight test data
- Tests @ Hover speed
 - Check pitch, roll and vertical axis comparisons
 - Time domain
 - Frequency domain
- Observed significant similarities in the poles/trends among all models at hover
 - Tuning factors set to 1, but can be used to shift CAMRADii-adjusted closer to FlightCODE

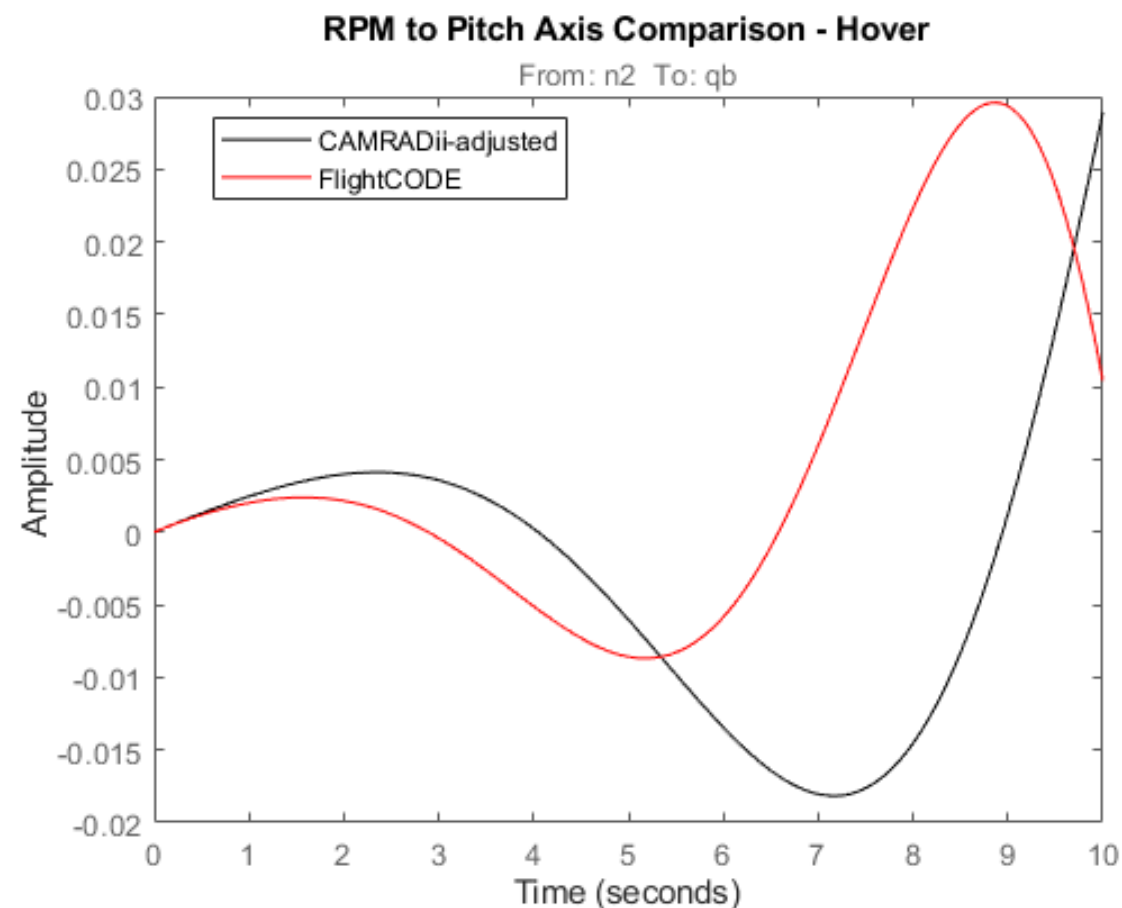
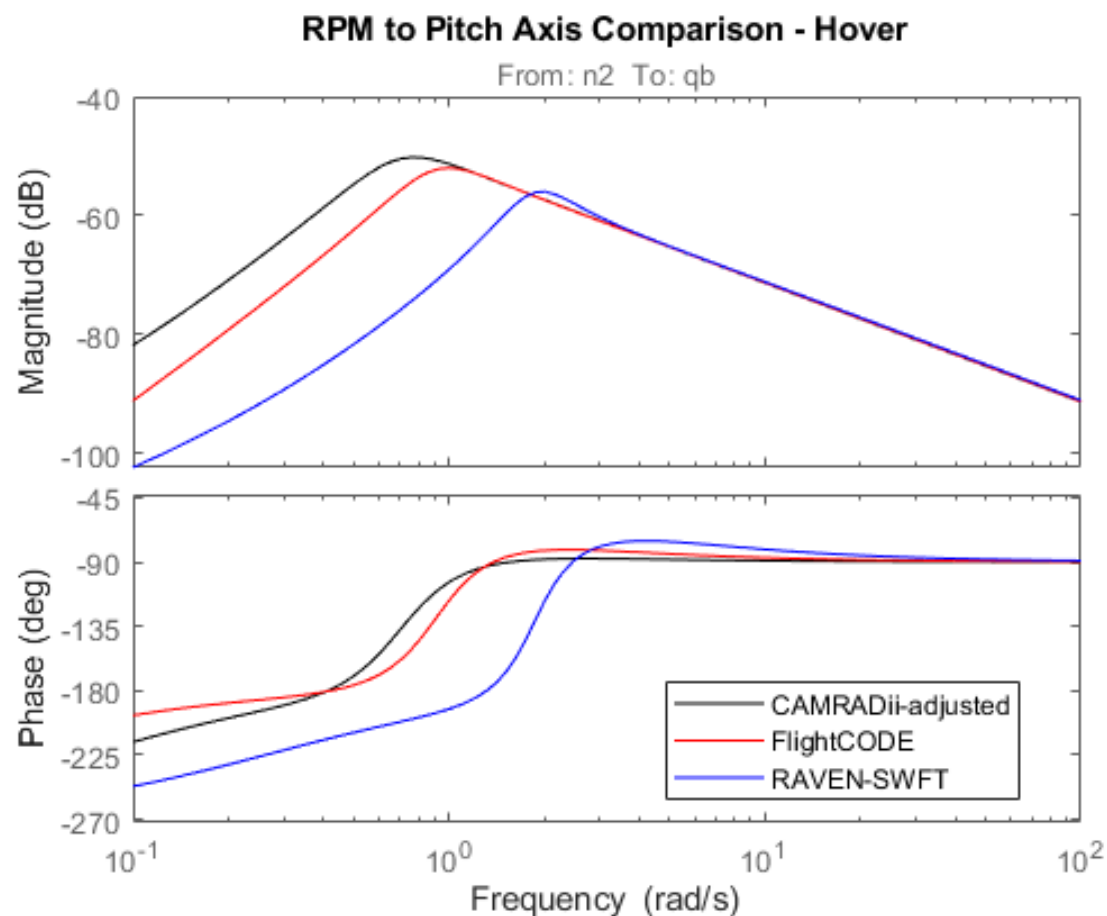
Hover Pole Comparisons





Pitch axis – RPM control

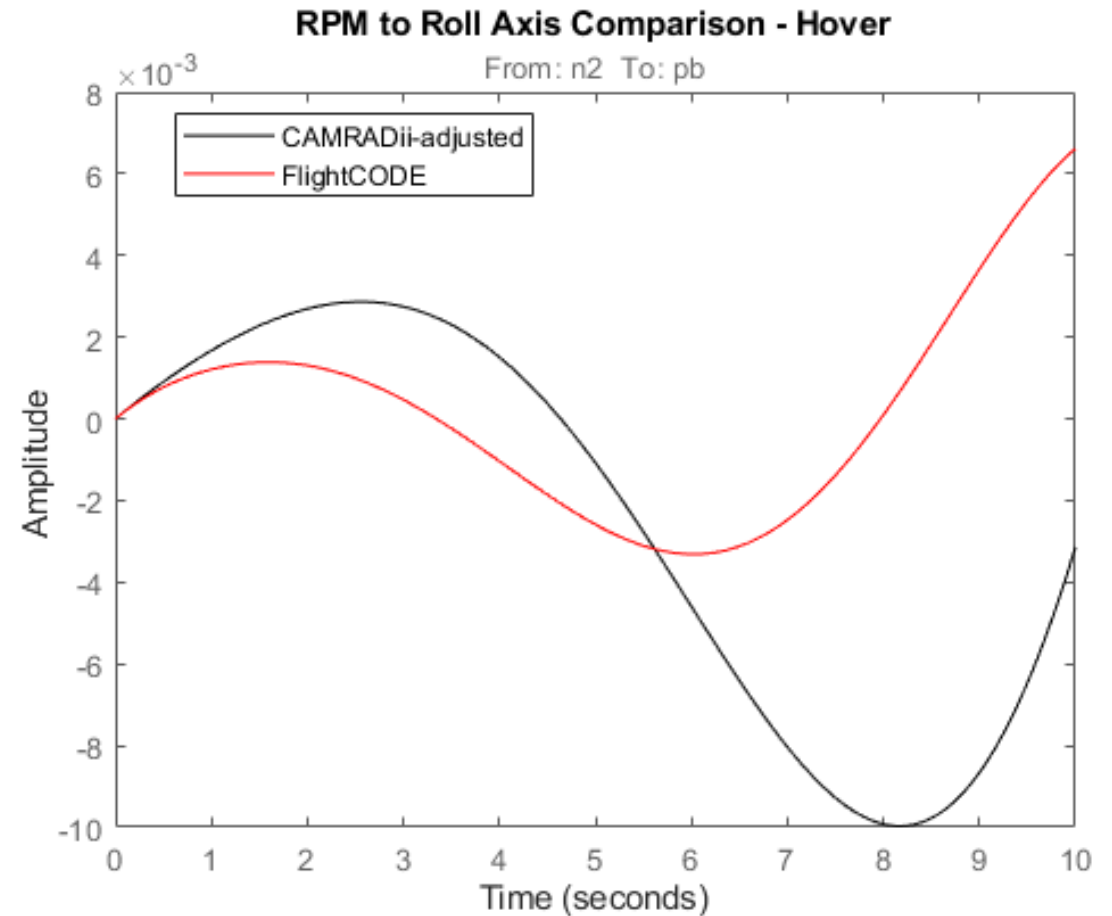
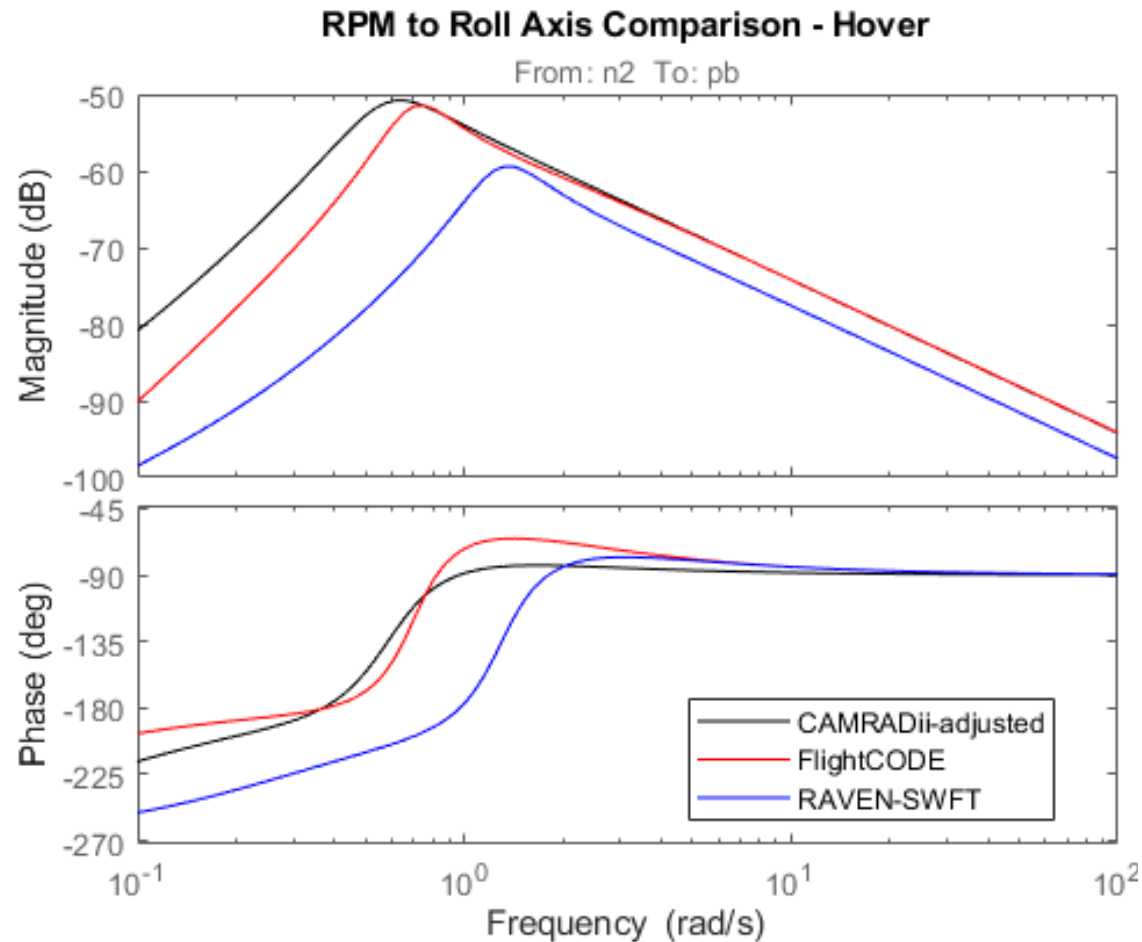
- FlightCODE and CAMRADii-adjusted model are frequency shifted from RAVEN-SWFT
- The time domain response is more integrated for CAMRADii-adjusted than FlightCODE





Roll axis – RPM control

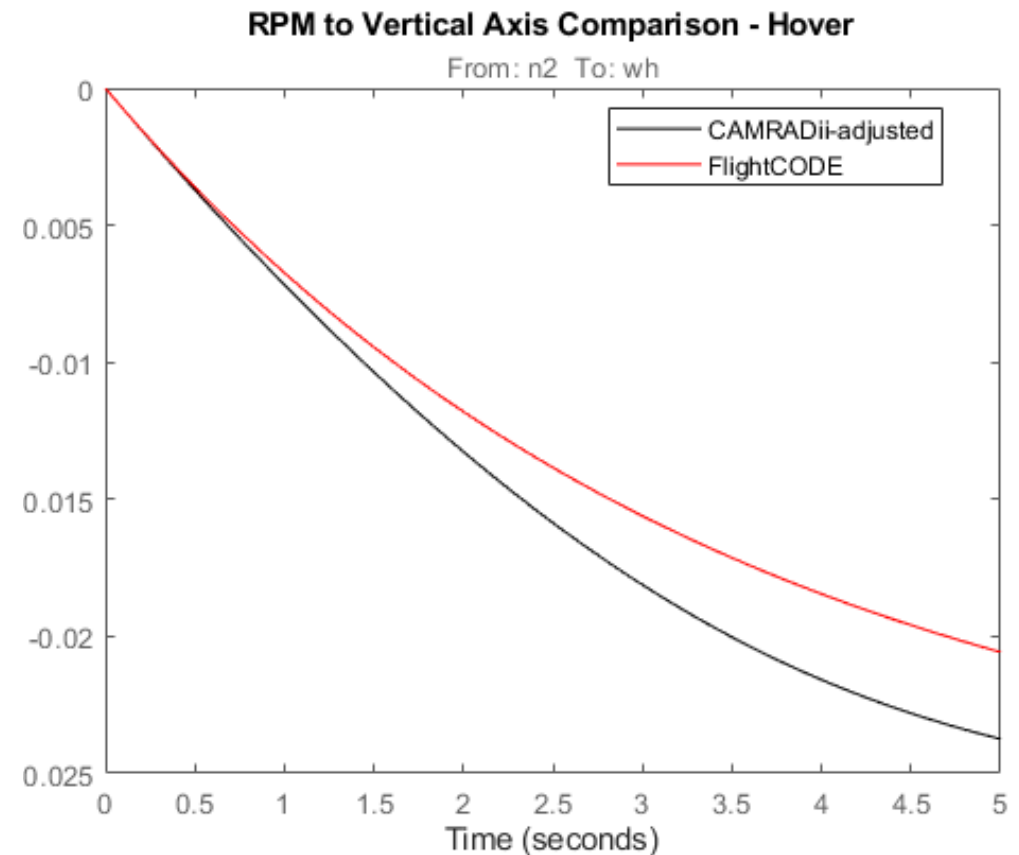
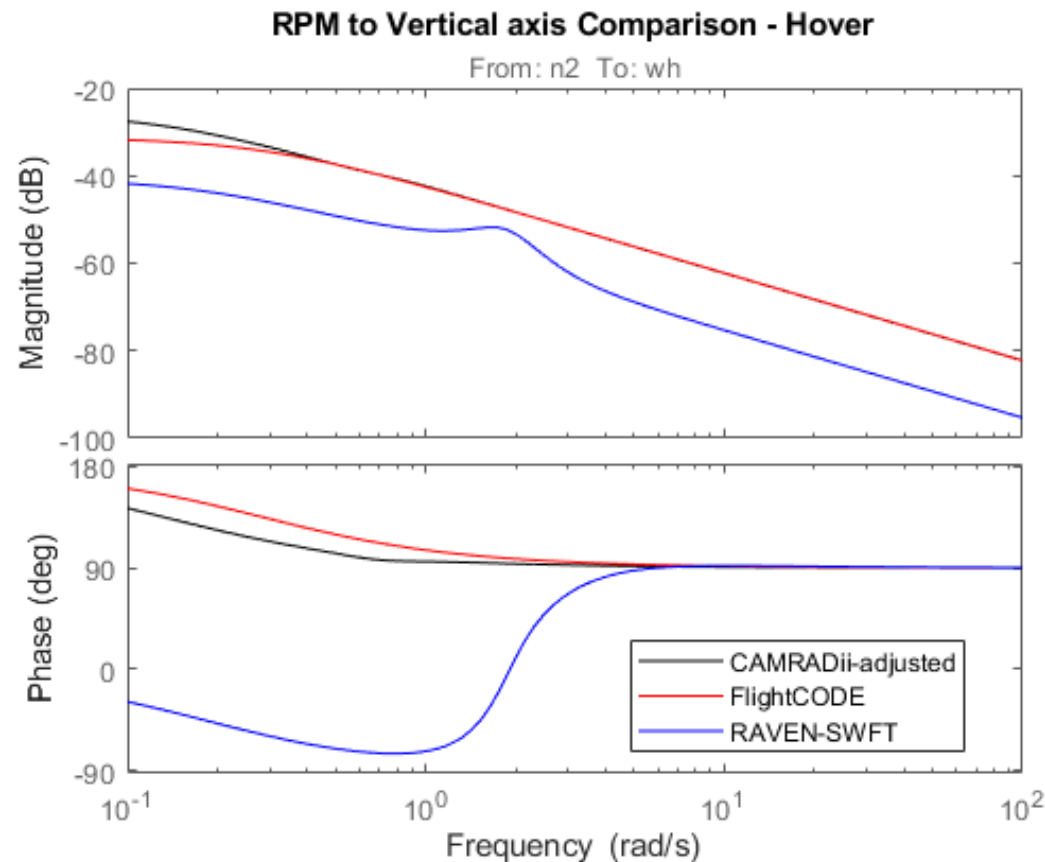
- FlightCODE shows a similar lag for RPM control as for collective control
- The time domain response is more integrated for CAMRADii-adjusted than FlightCODE





Vertical Axis – RPM control

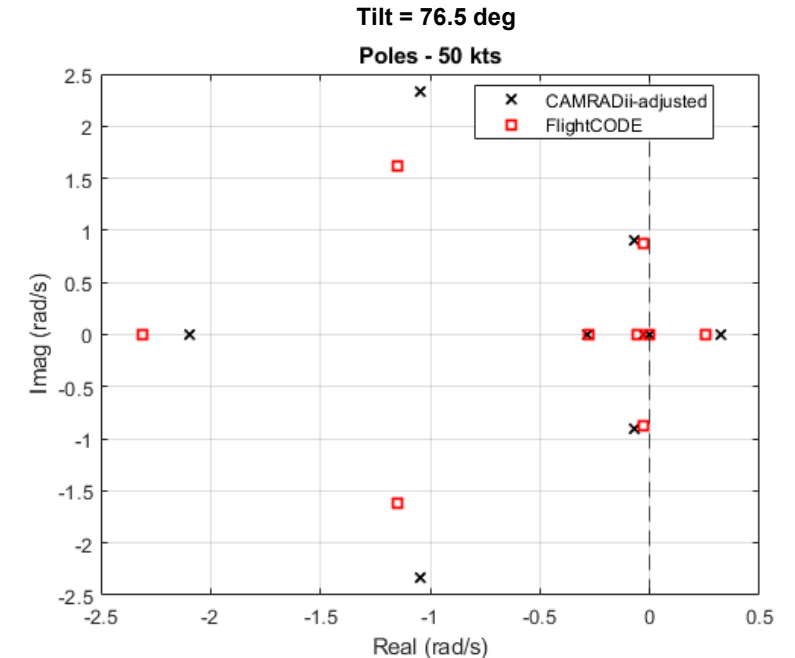
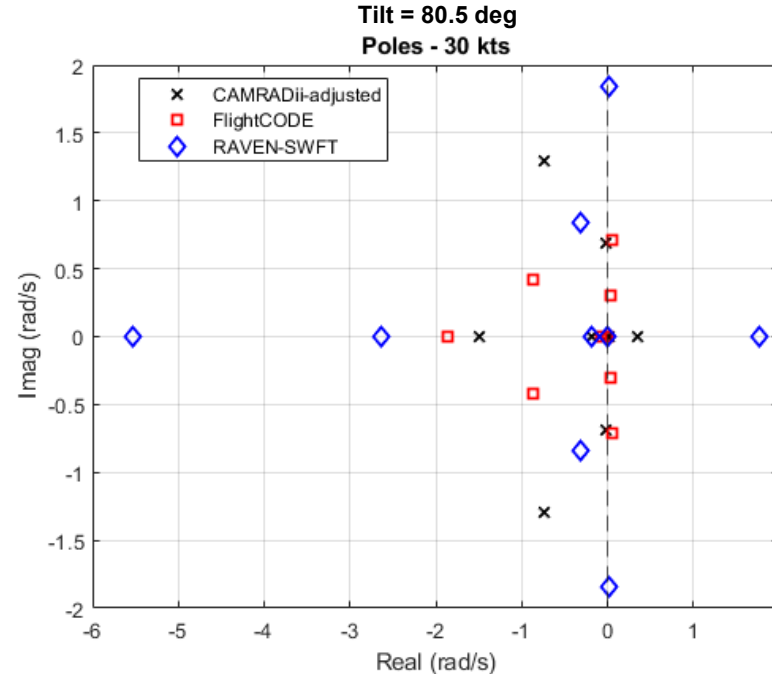
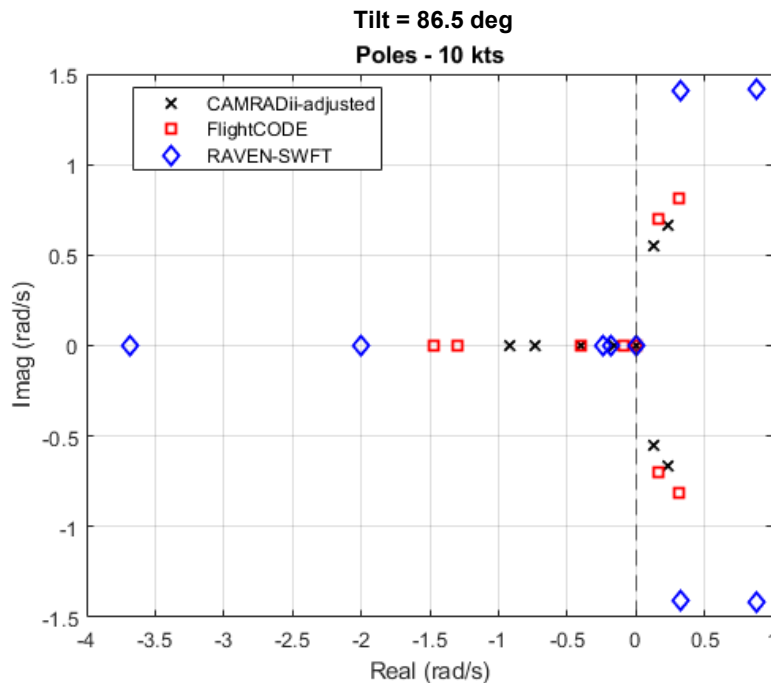
- CAMRADii-adjusted model shows similar RPM performance on the vertical axis as FlightCODE
 - RAVEN-SWFT gain is shifted lower but follows a similar slope
 - Same phase loss at very low frequency





Model Comparisons (Tuning gains set to 1)

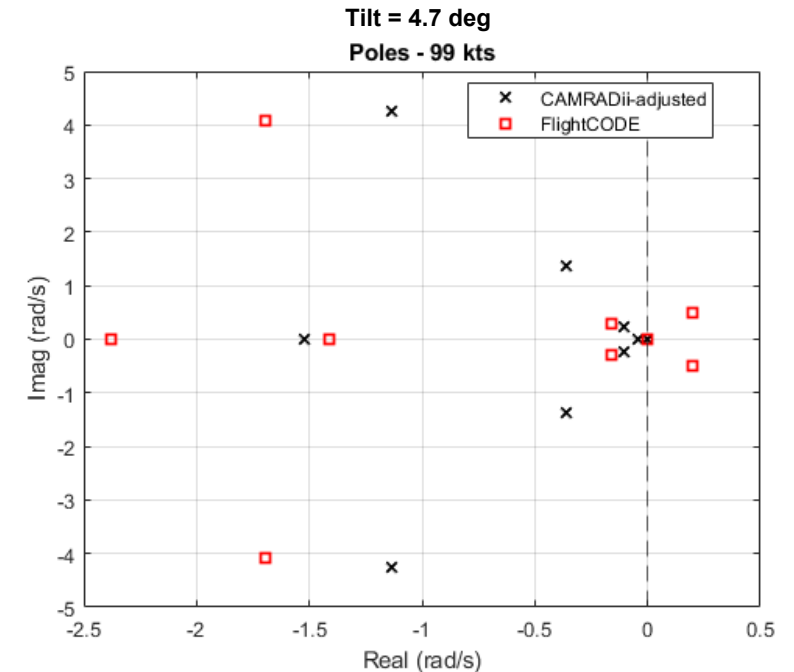
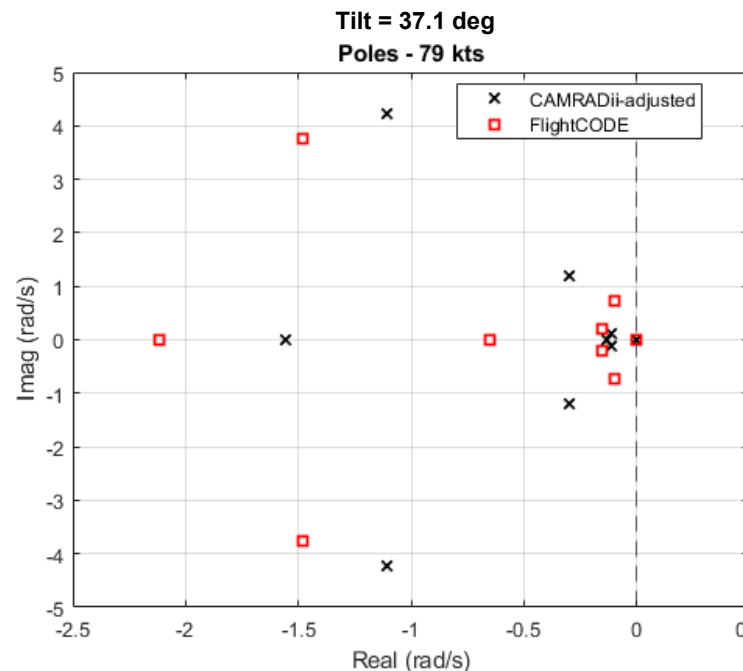
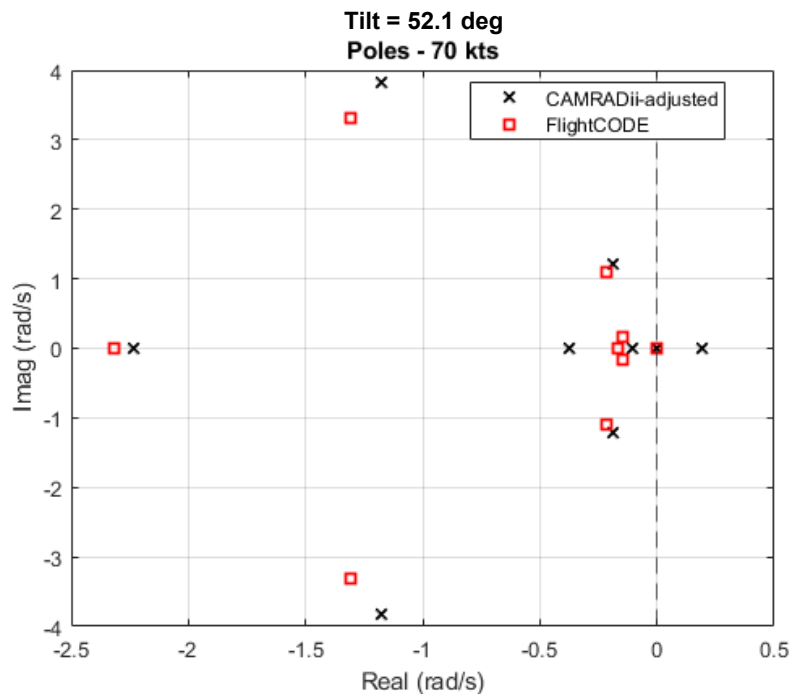
- Sample comparisons show pole locations vary considerably with rising speed
 - At 10 kts, the variation of the poles of all systems tend to have similar performance
 - At 30 kts, RAVEN-SWFT and CAMRADii-adjusted showed an unstable real axis pole, but FlightCODE did not
 - At 50 kts, FlightCODE and CAMRAD II showed a slightly unstable real axis pole
 - Unclear which RAVEN-SWFT model to compare at this condition
 - No SWFT windtunnel data past 5 psf
 - k tuning factors can be used to move poles closer than shown





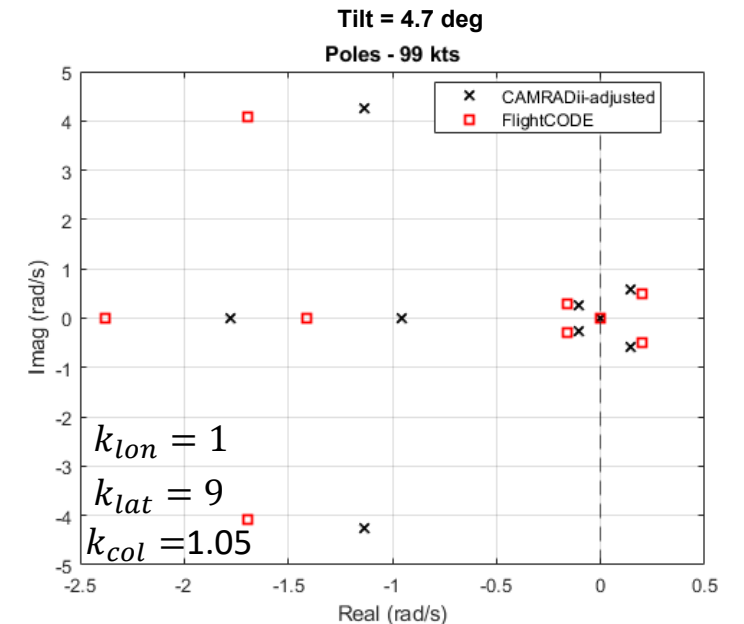
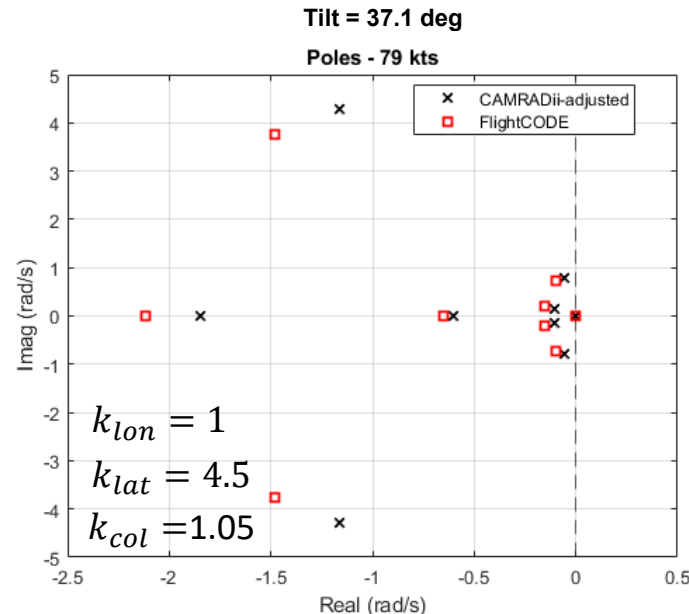
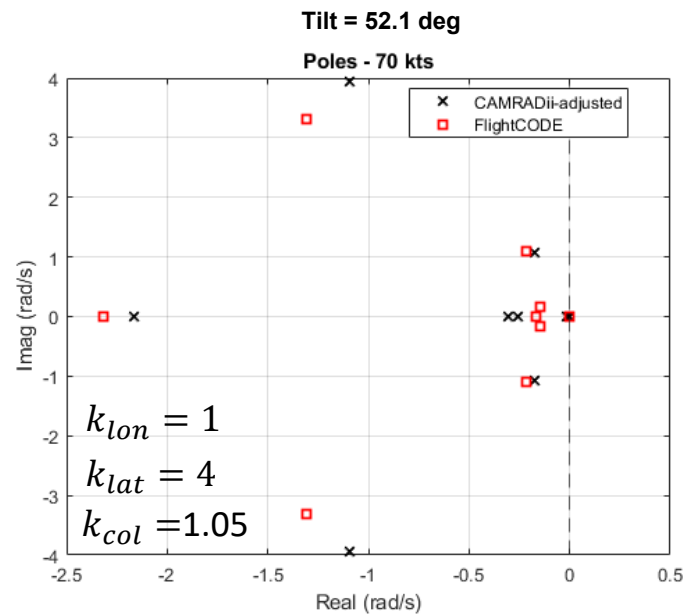
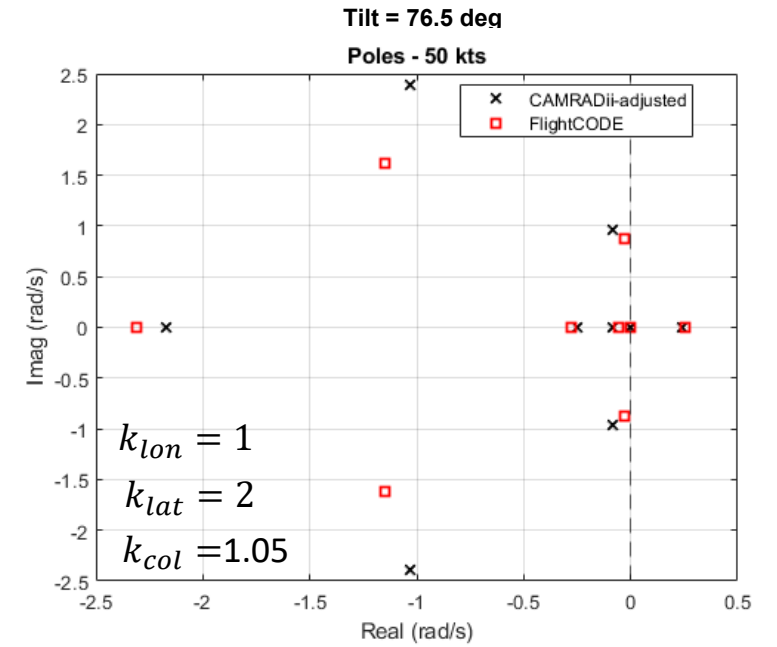
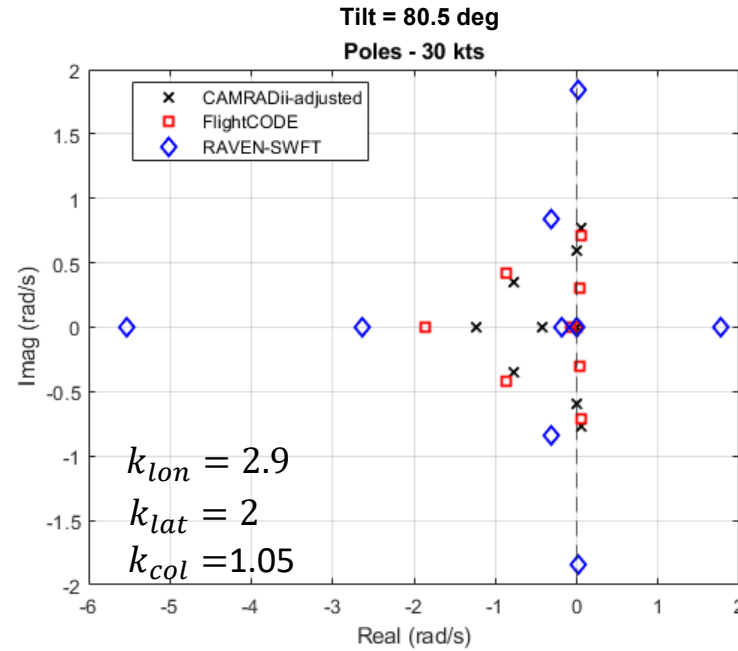
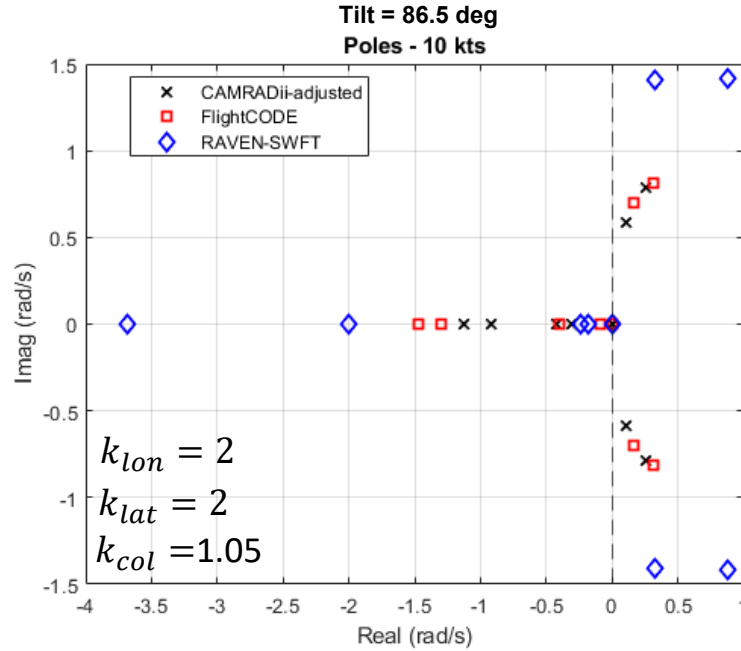
Model Comparisons (Tuning gains set to 1)

- Sample comparisons show pole locations vary considerably with rising speed
 - At 70 kts, pole locations are similar, but a real unstable pole appears in CAMRADii-adjusted model
 - At 79 kts, Similar pattern of poles but higher frequency poles starting to shift further away
 - At 99 kts, FlightCODE suggests an unstable Phugoid, but CAMRADii-adjusted did not
- k tuning factors can be used to move poles closer than shown
- Takeaway: the CAMRADii-adjusted models are capturing key dynamics for control design, but expect damping differences between models





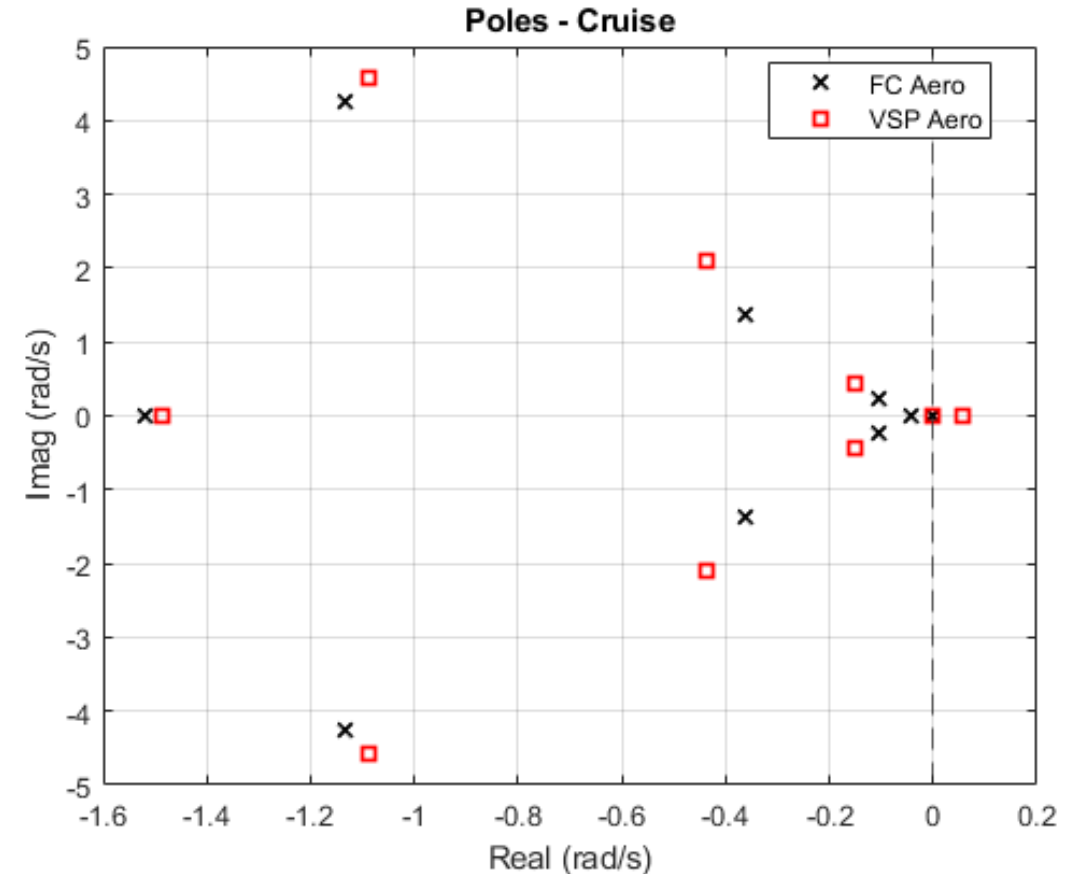
Model Comparisons (Tuned) – But tuning gains not used in PDR





Comparison of VSPAERO and FC Aero State Space Models at Cruise

- Generated state space models using VSPAERO and FlightCODE Aero
 - Near cruise both show similar sets of poles
 - VSPAERO has wing interference on
 - FlightCODE has wing interference off
 - Difference may be primarily interference effects
- Differences may originate from rotor dynamic modeling differences
 - Noted that FlightCODE models appeared to be higher frequency at hover and at cruise
- Useful to use different sets of aerodynamics to make trade studies

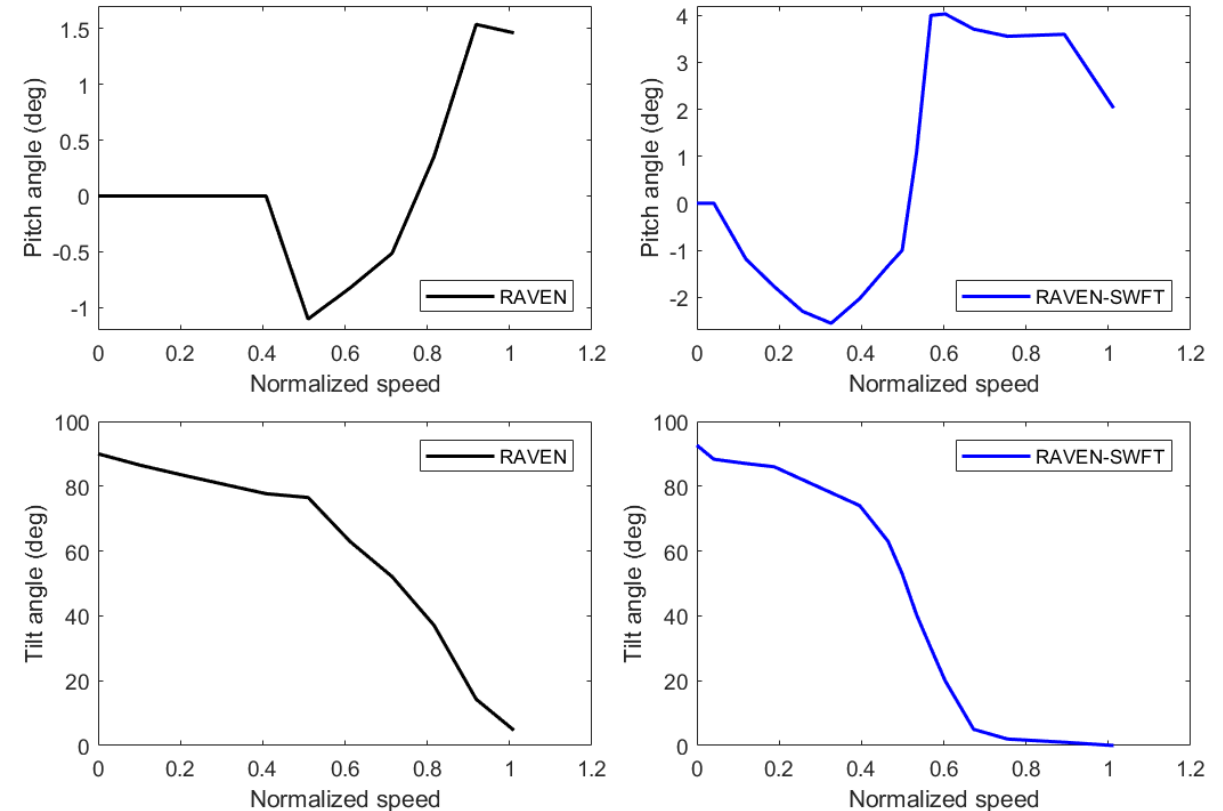




Example Simulation Pitch Angle Trims

- Representative pitch trim as compared to RAVEN-SWFT
 - The RAVEN pitch trim looks shifted to the right for full-scale RAVEN
- Useful to D&C for assessing outer loop controllability with various control architectures
- Pitch trim in the simulation is determined by
 - Steady forces and moments predicted to be required by rotors
 - Interaction of specific speed and pitch controllers

Representative RAVEN and RAVEN-SWFT Pitch Trim Angle / Tilt Comparisons



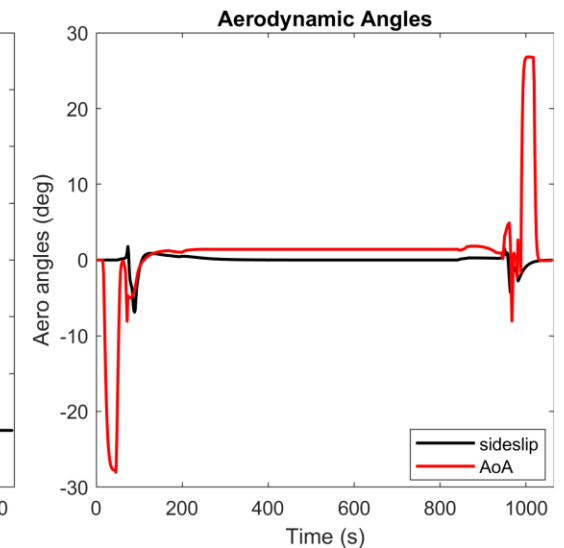
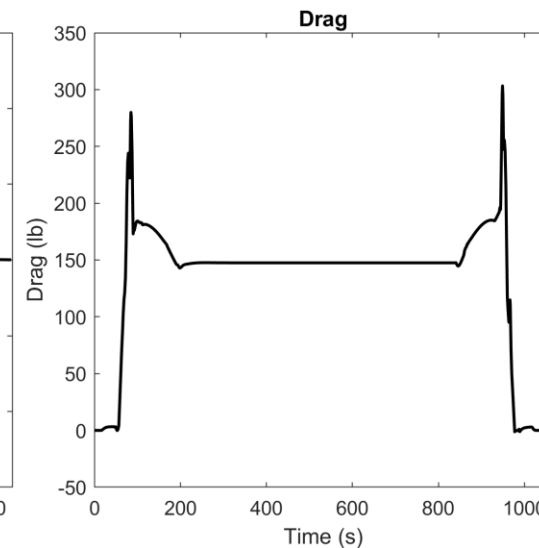
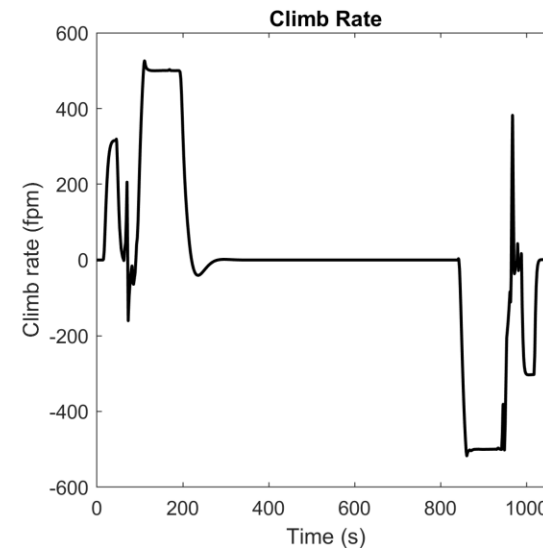
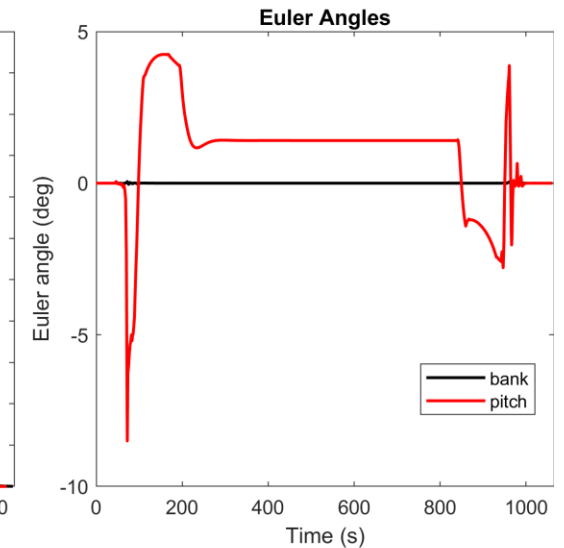
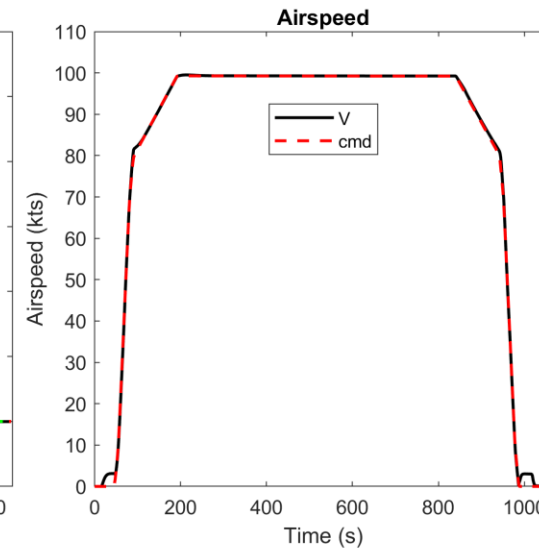
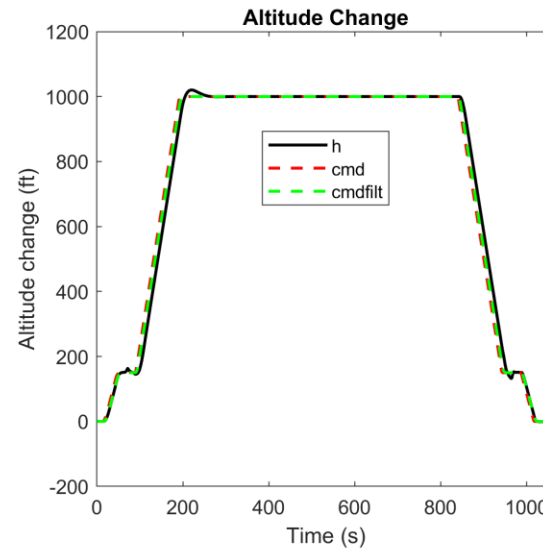


VTOL Mission



VTOL Mission + Reserve Mission (Controllability)

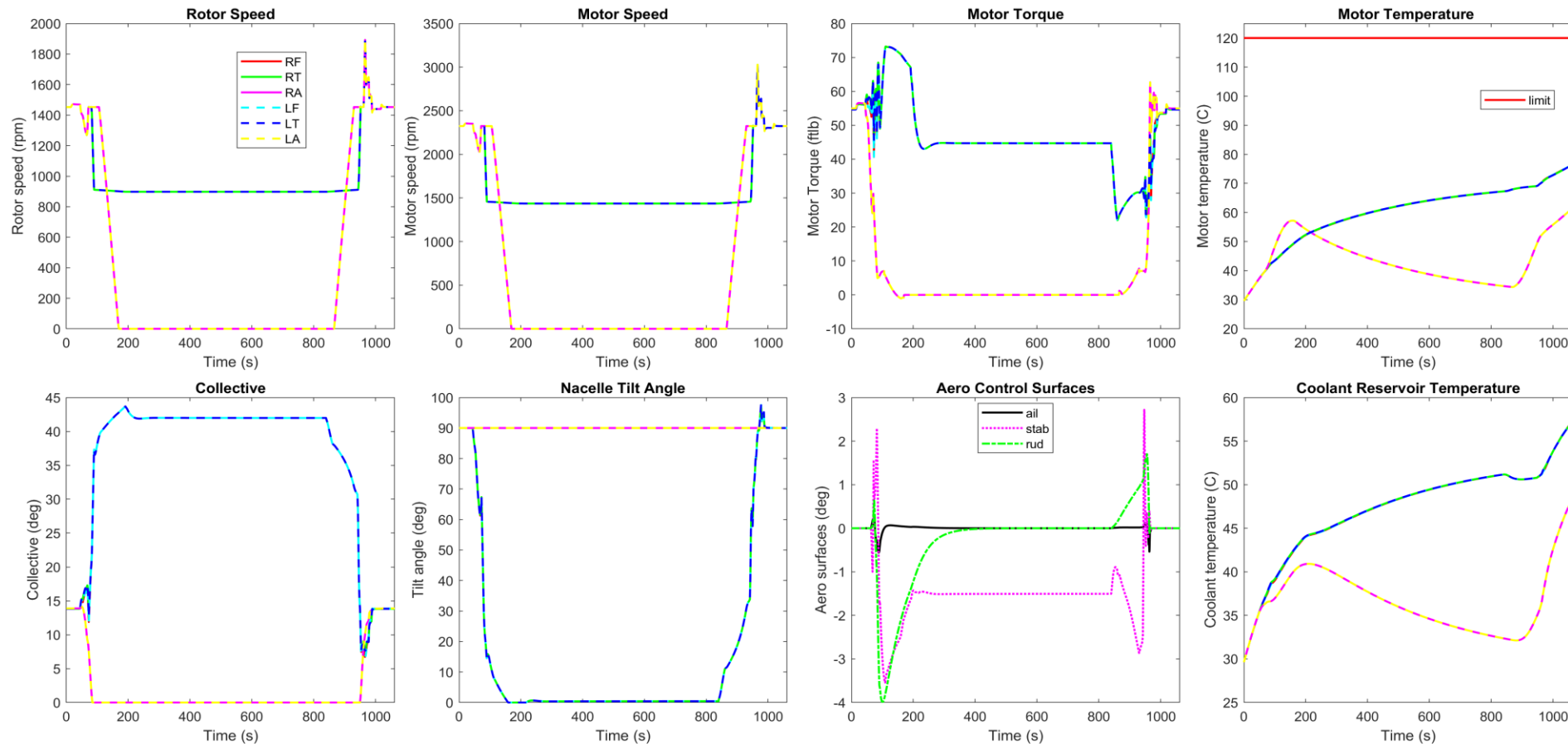
- Altitude and airspeed are tracked fairly well
- Drag increases during certain maneuvers from expected at cruise
 - Cruise speed slightly higher than most recent cruise speed for the same drag for power assessment
- Speed and pitch control coupling will present challenges without a sophisticated solution from D&C



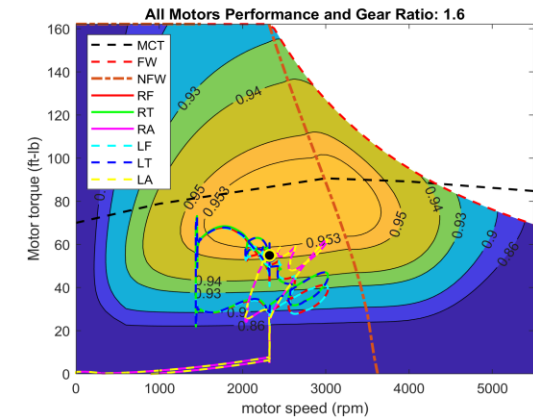


VTOL Mission + Reserve Mission (Controllability)

- Motor torque highest near the beginning of the mission
- Front and tip motor temperatures end at 75C
 - Well under Emrax 228 LC HV motor spec sheet continuous torque limit
- Control surfaces have reasonable deflections (< 4 deg)



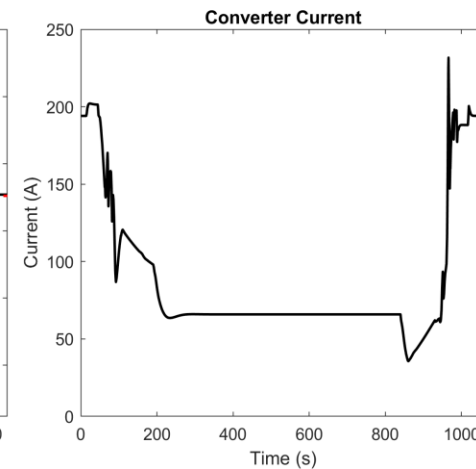
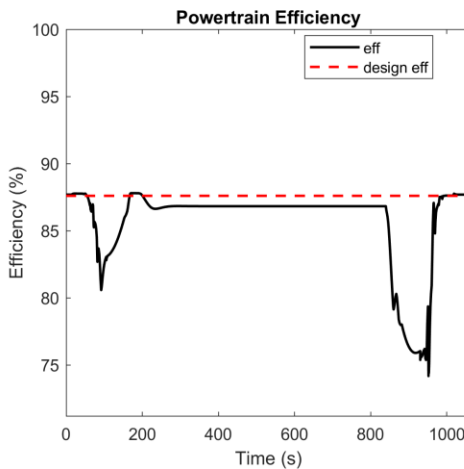
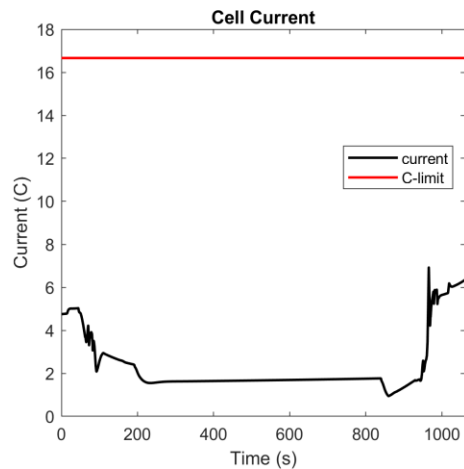
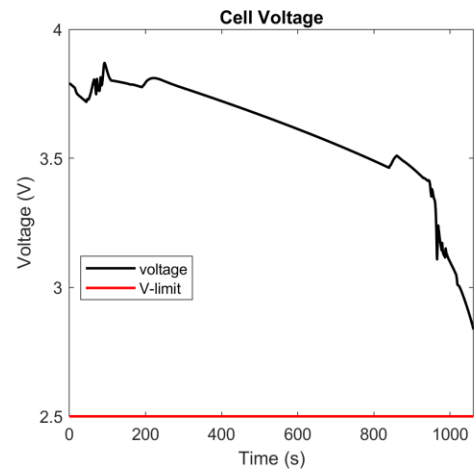
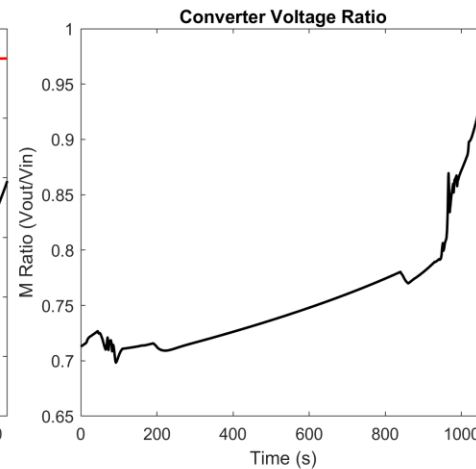
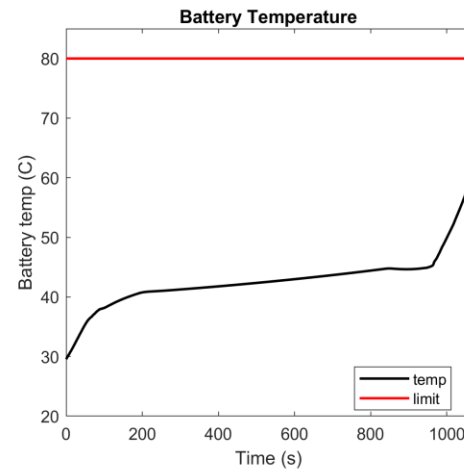
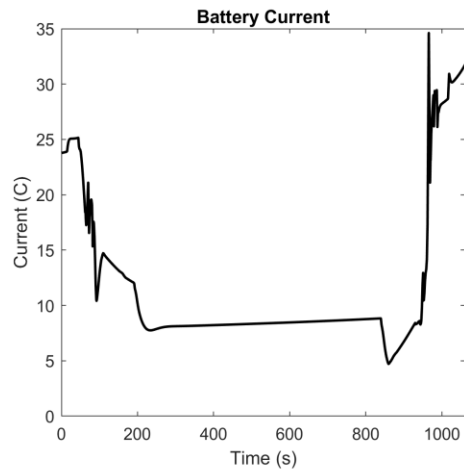
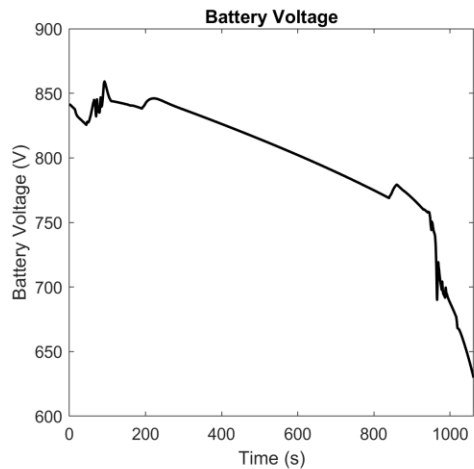
All motors operating
Under MCT leaving
Room for maneuvers



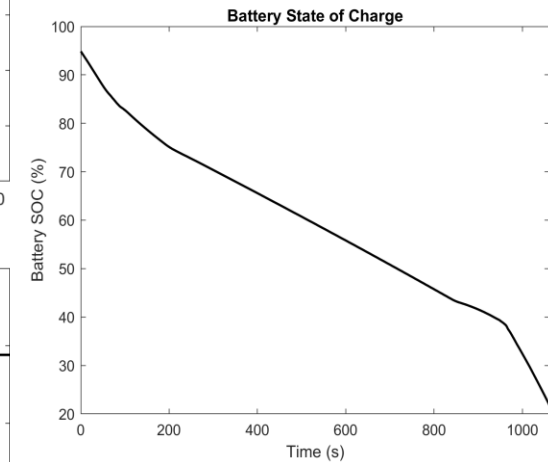


VTOL Mission + Reserve Mission (Power)

- Cell voltage stays above 2.5C cell limit
- Power efficiency significantly lower at end of mission
 - Possible that D&C can optimize performance during slowdown
- Battery temperature finish at 60C well under 80C limit
- Air cooling reduces the rise rate of battery temperature
- Battery state of charge finishes mission plus reserve mission at 22%, above the 20% limit



Battery SOC As a Key Sizing Metric

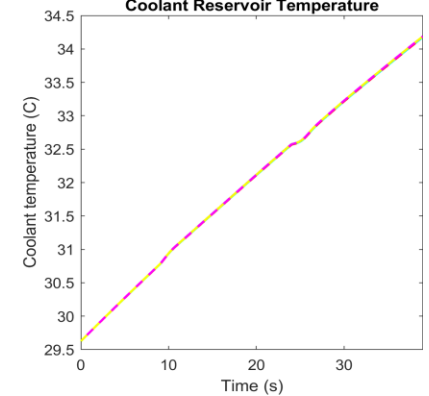
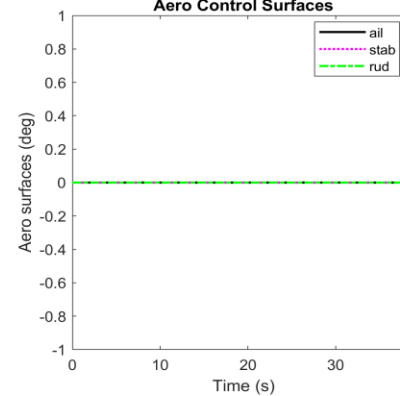
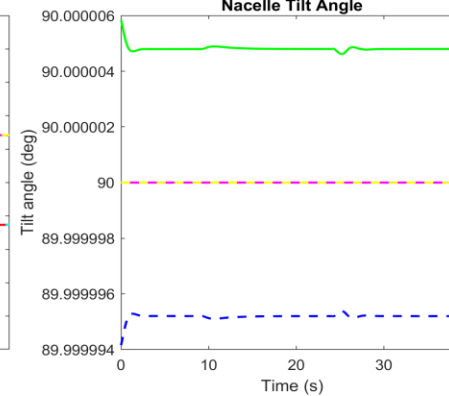
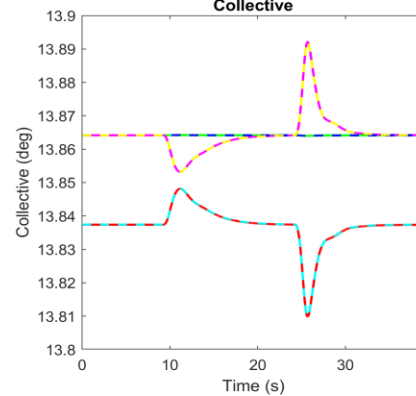
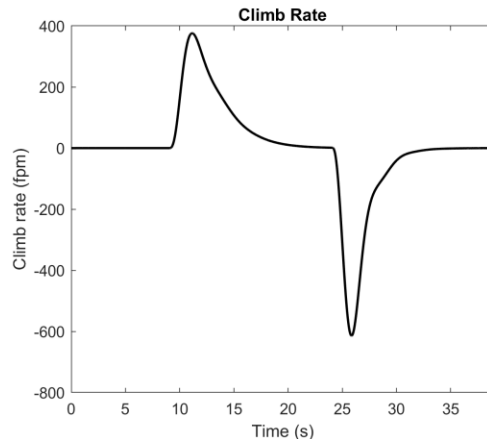
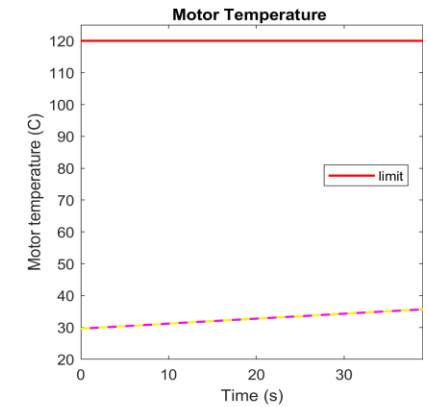
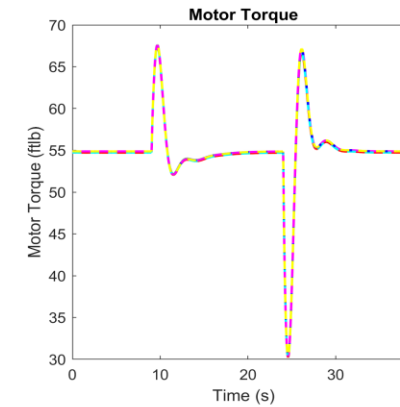
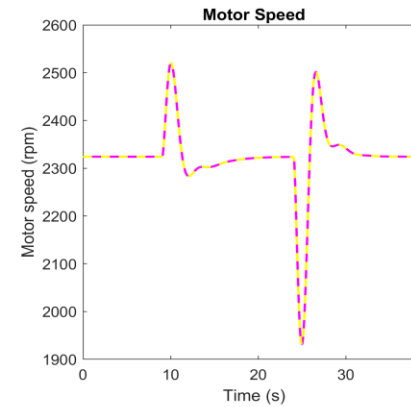
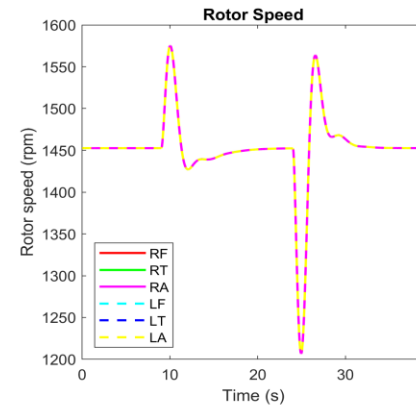
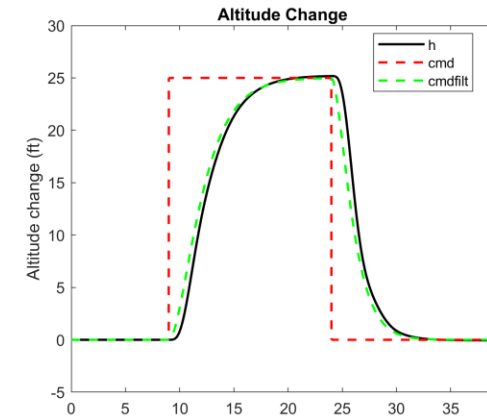
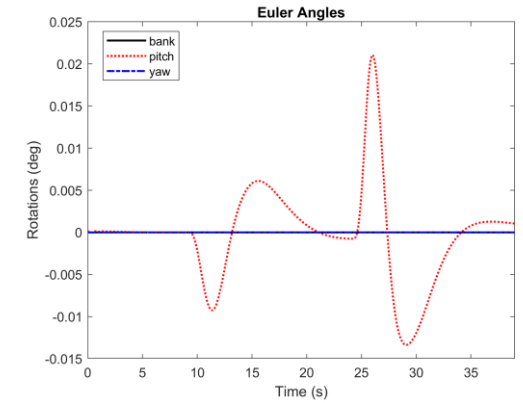
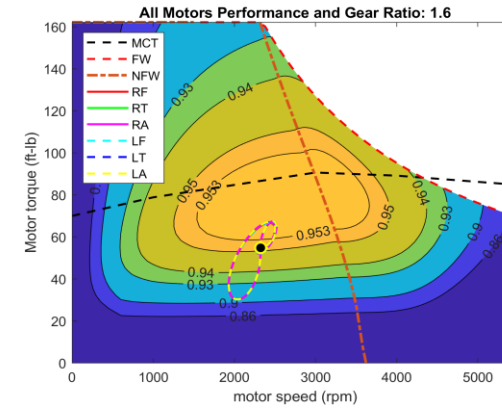




Vehicle Controllability and Power Assessments

Hover Vertical Reposition + RPM Control (Controllability)

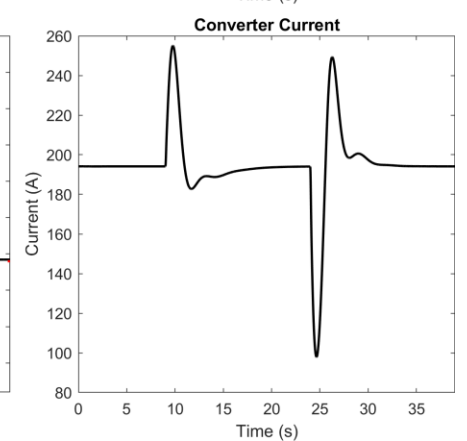
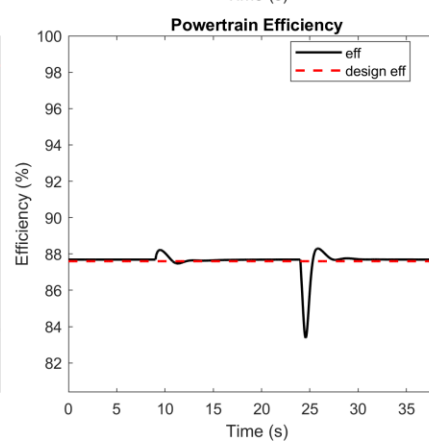
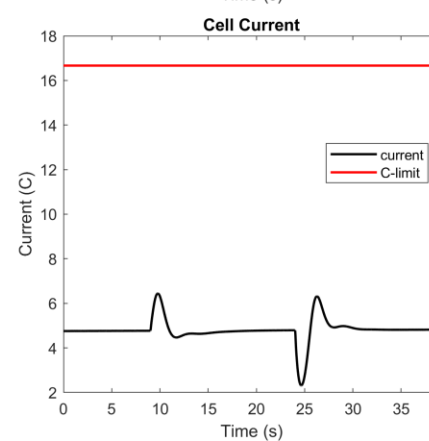
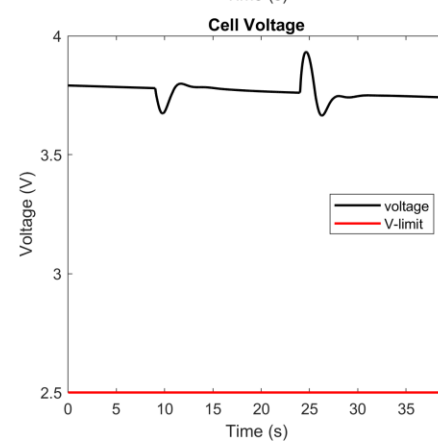
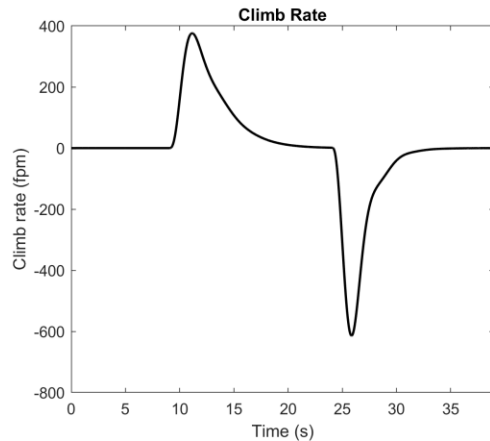
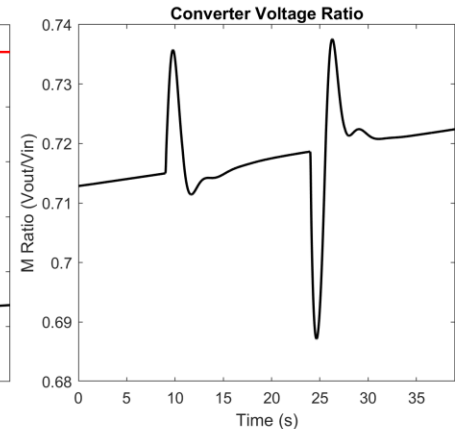
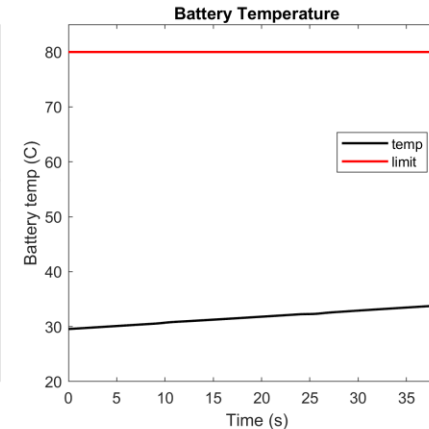
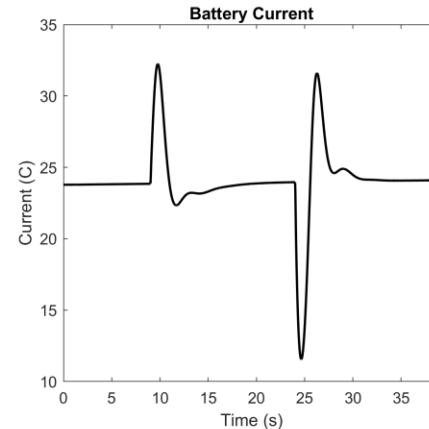
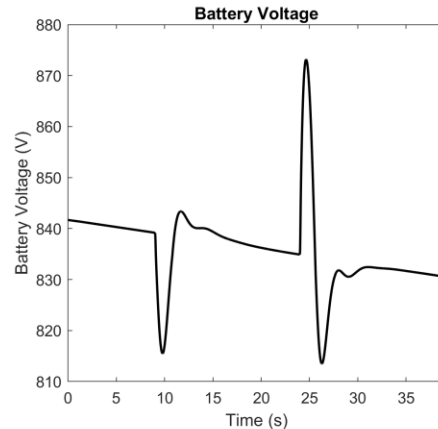
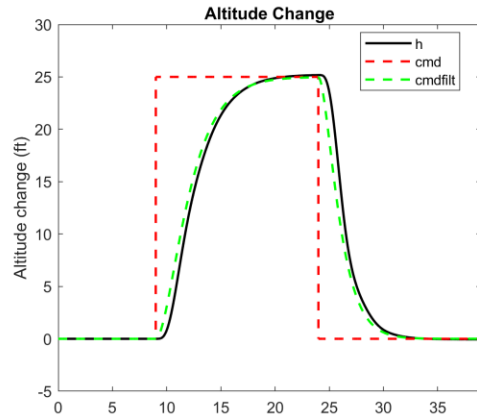
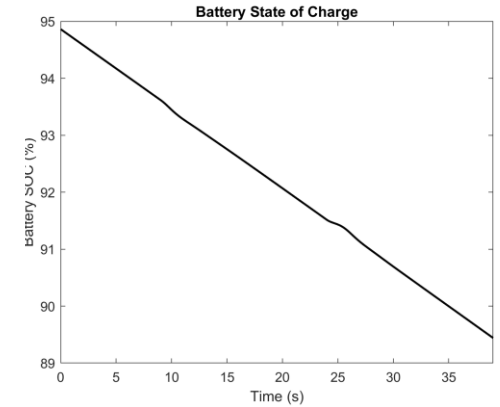
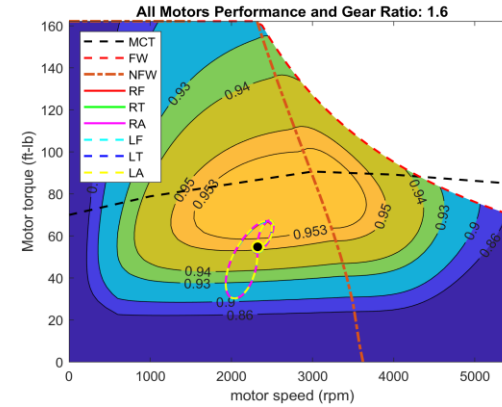
- Controllable
- Motors operate well under MCT
- No significant cross axis coupling





Hover Vertical Reposition + RPM Control (Power)

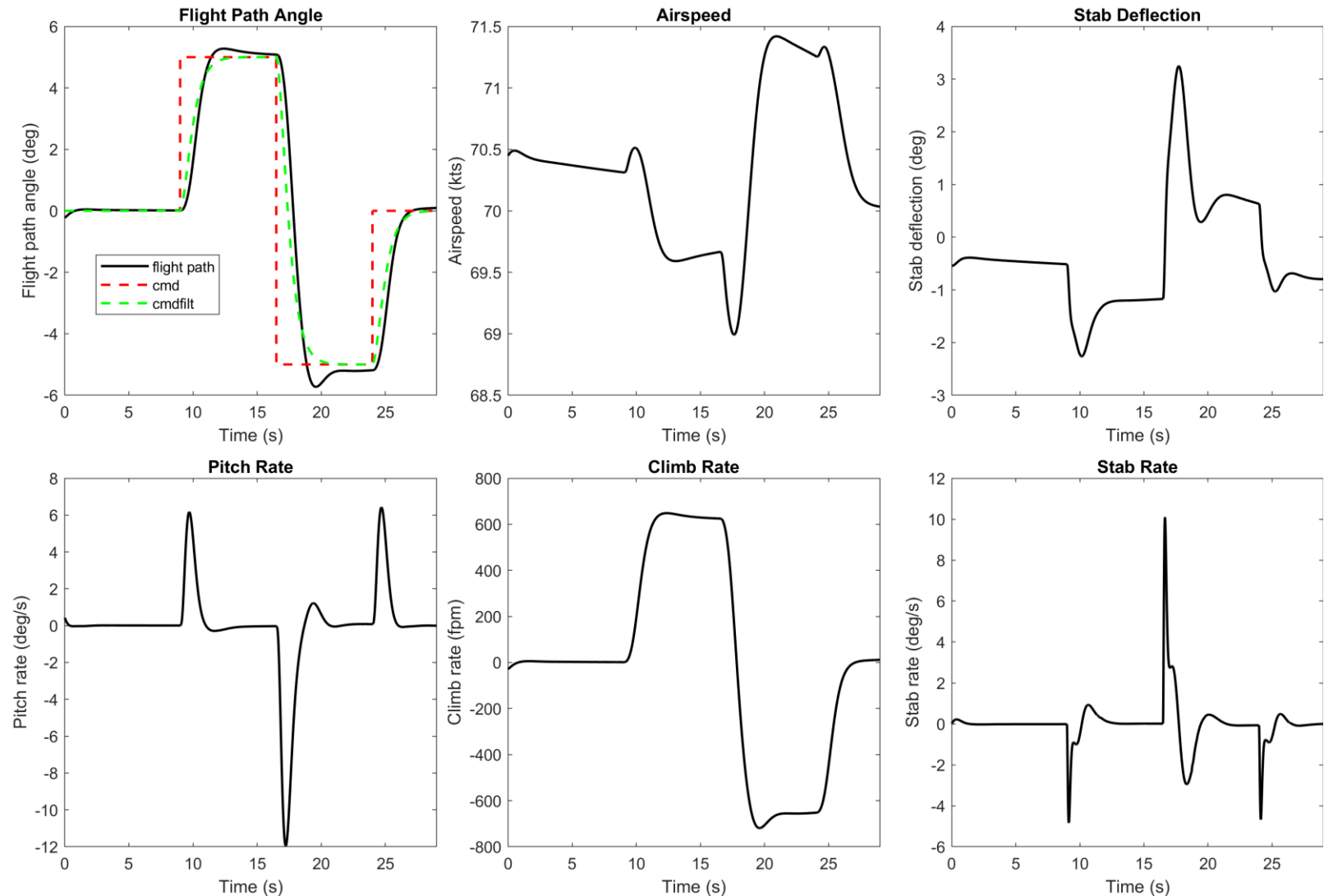
- Converter operating entirely within Buck mode
- Cell currents well under peak C-limit
- Cell voltage drop very reasonable during maneuver





10 deg Flight Path Angle Change @ 70 kts

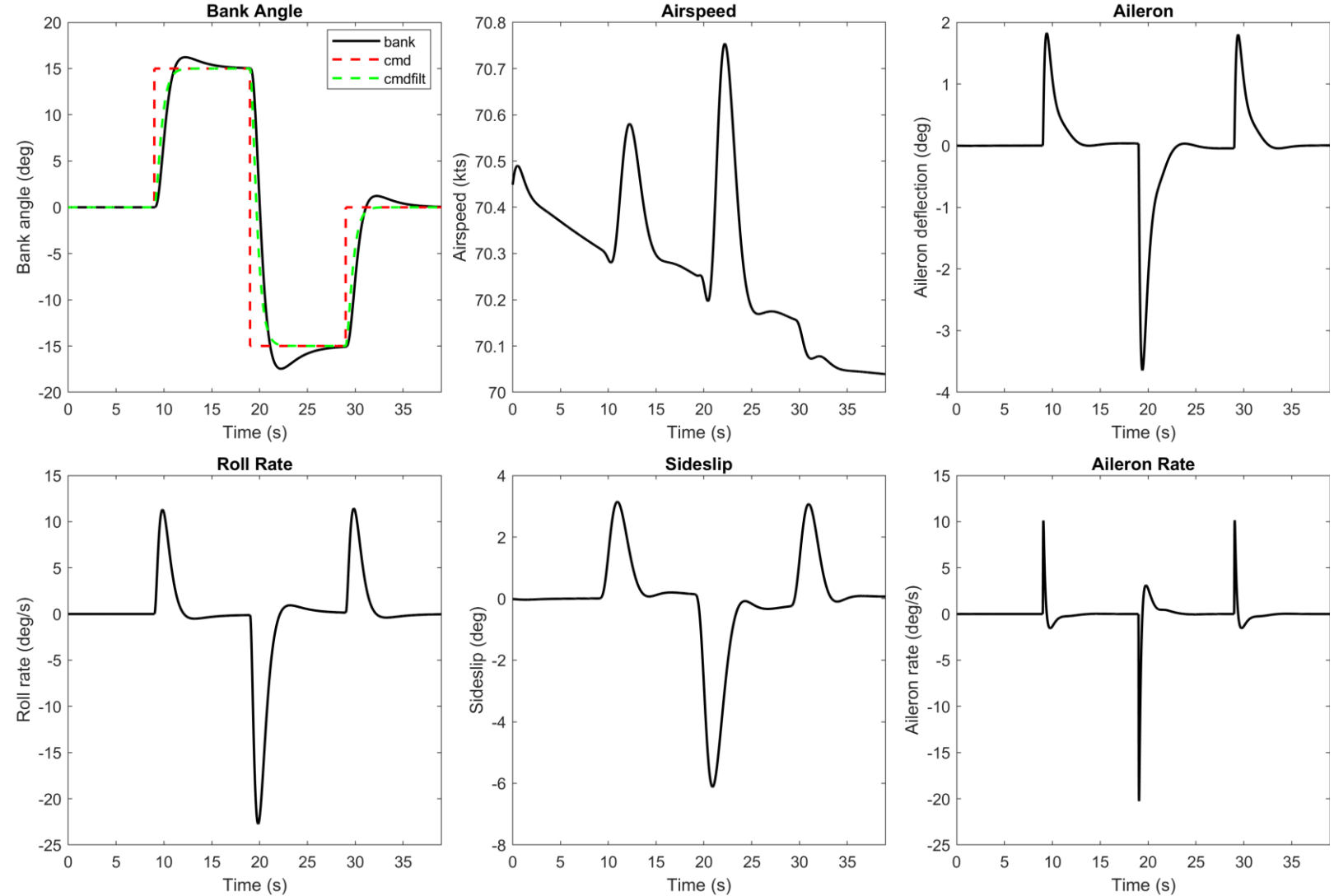
- Significantly higher participation of stab than at 30 kts once pitch collective no longer participates
 - Stab rate peaks at 10 deg/s
 - Stab deflection peaks at -2.2 deg





30 deg bank angle change at 70 kts

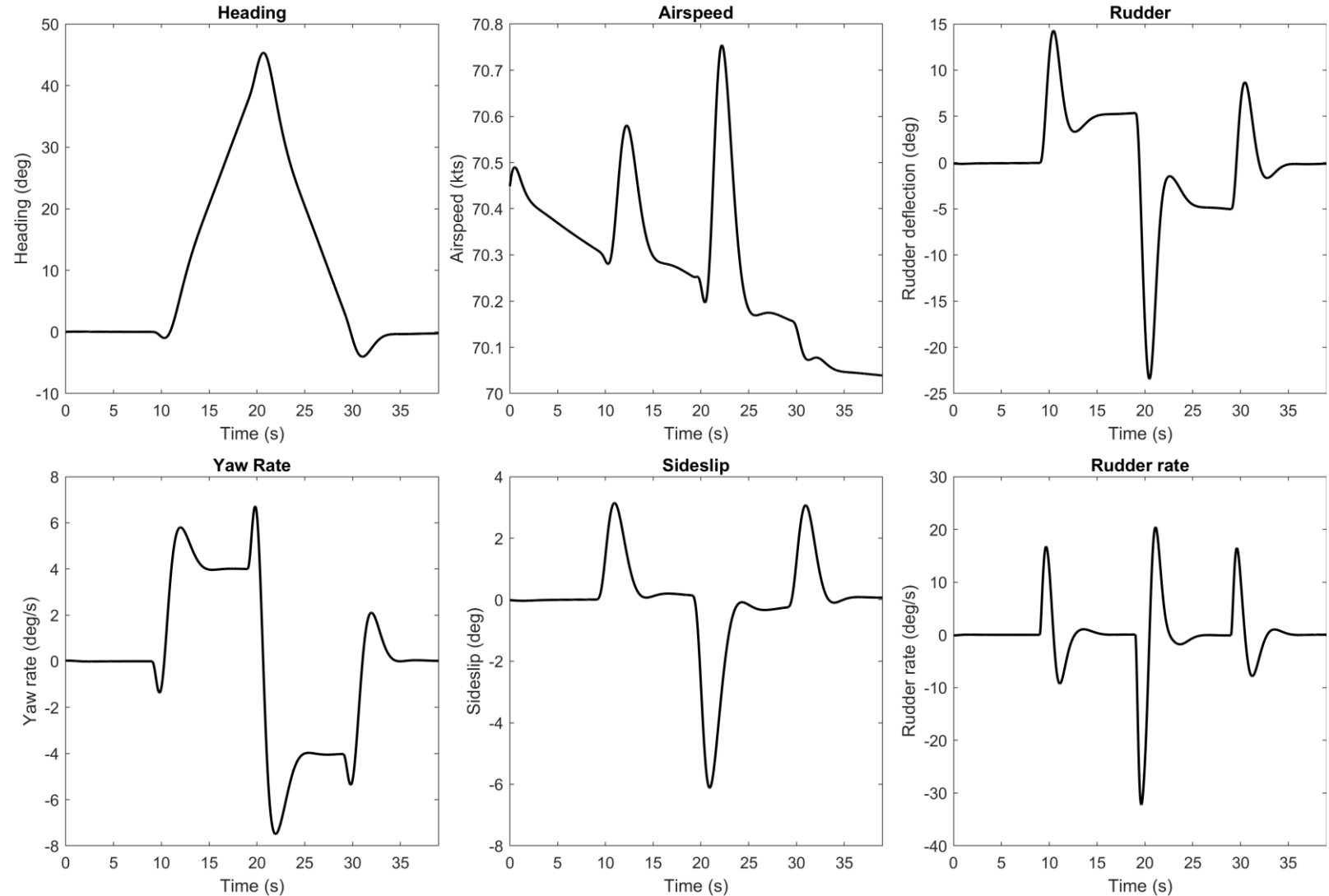
- Aileron rate peaks at -20 deg/s
- Aileron deflection peaks at -3.7 deg
- Sideslip goes to 0 once turn is in steady state





30 deg bank angle change at 70 kts (Yaw)

- Rudder tuned just enough to suppress a lightly damped Dutch Roll
- Rudder rate peaks at -32 deg/s
- Rudder deflection peaks at -24 deg
- During turn
 - Yaw rate moves to steady state around 4 deg/s
 - Sideslip trends to 0 deg

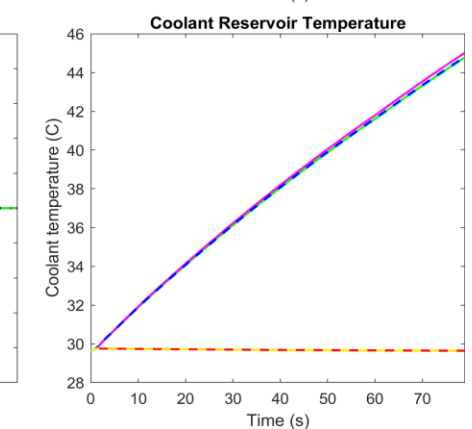
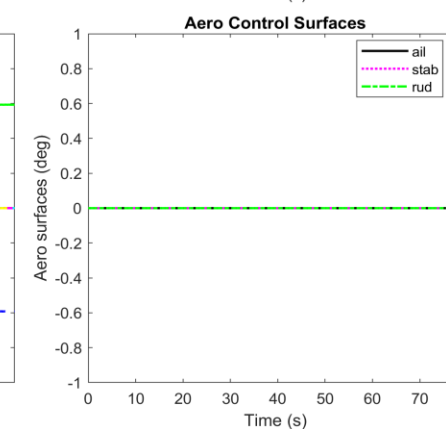
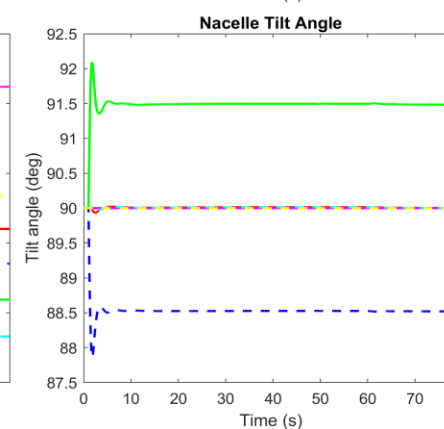
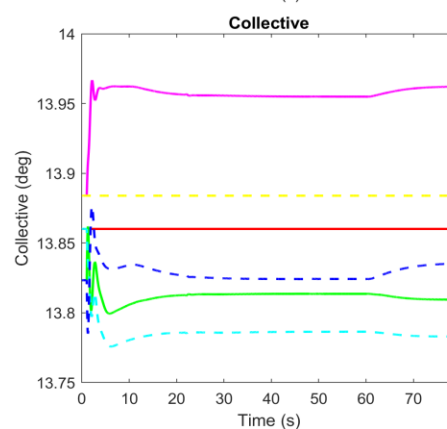
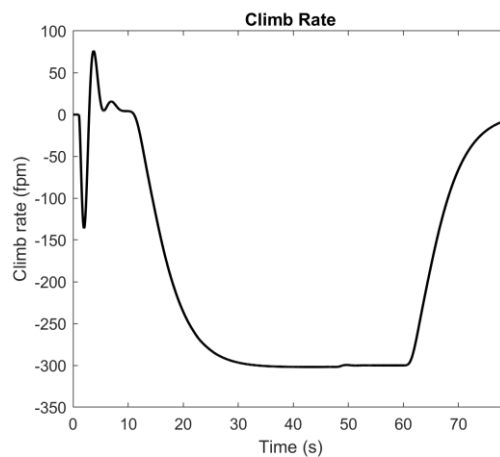
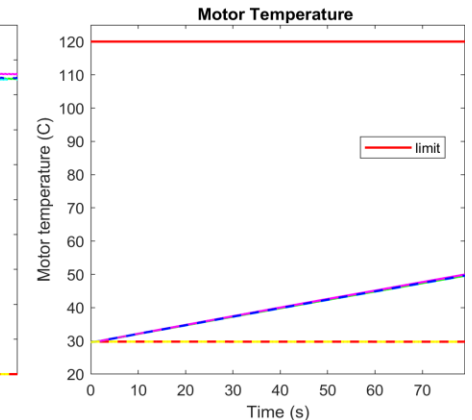
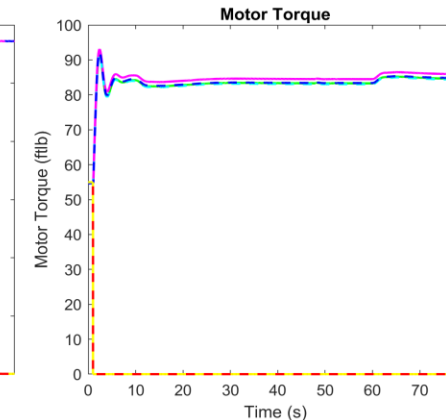
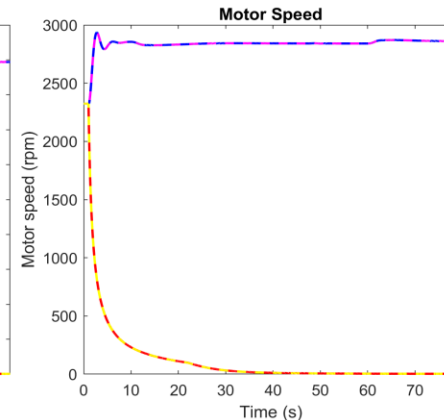
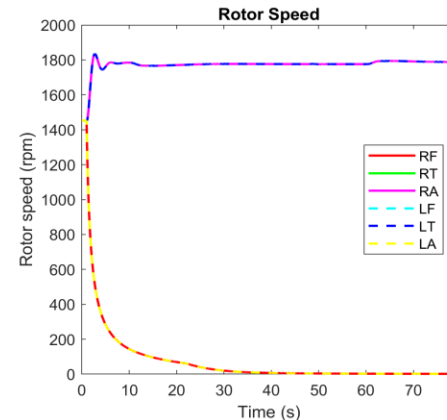
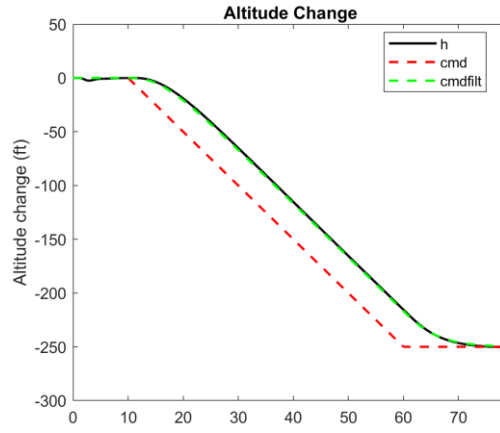
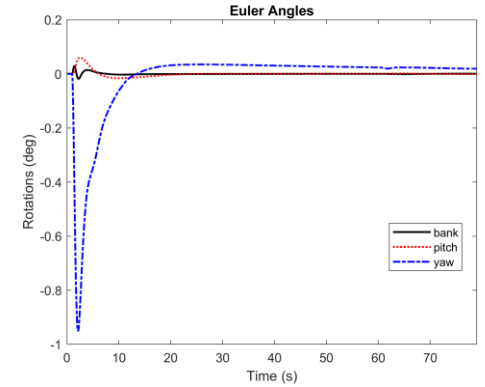
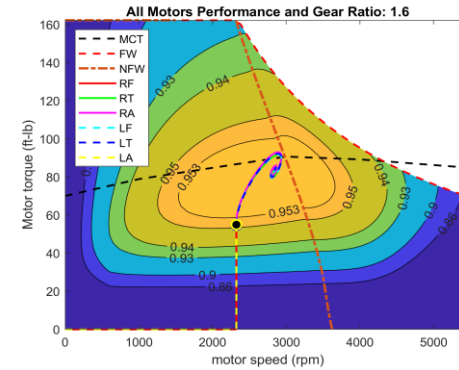




Design Trade Study Example

Hover Motor Failure + Land Immediately (Controllability)

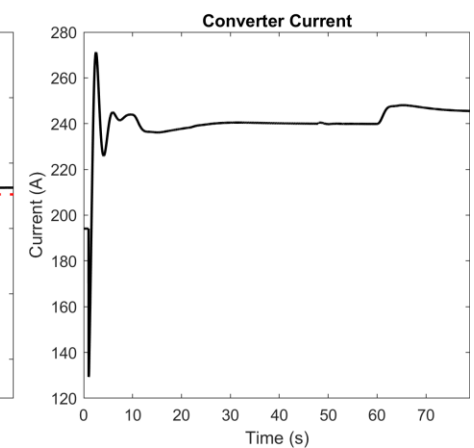
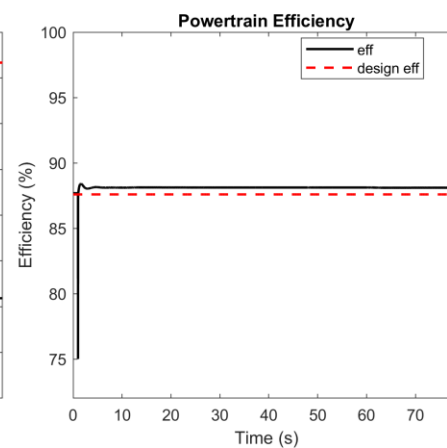
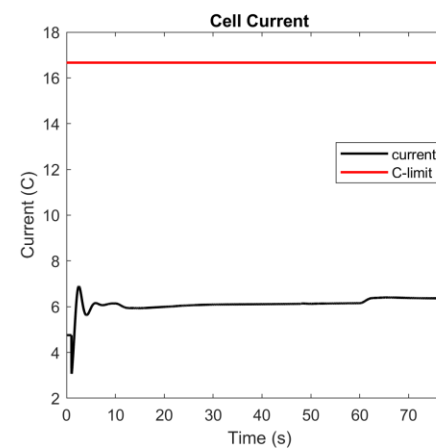
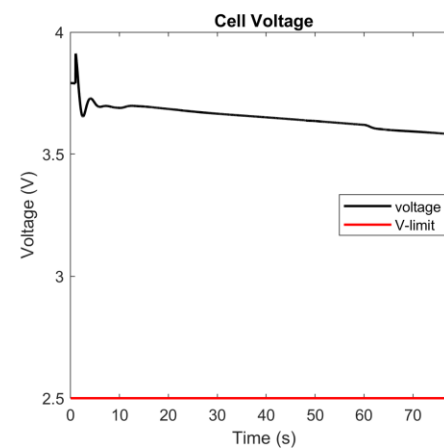
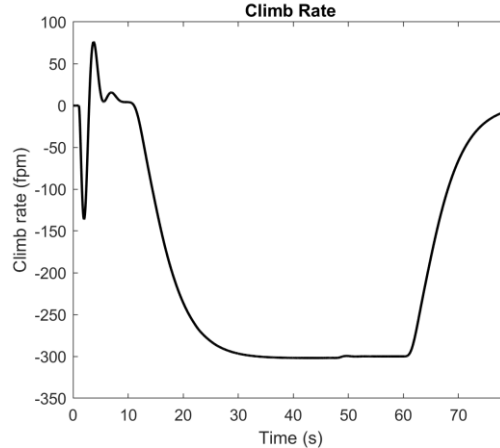
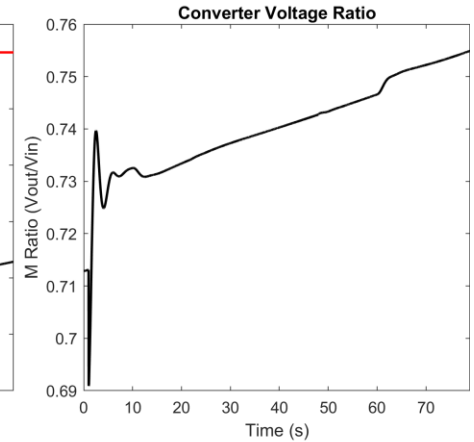
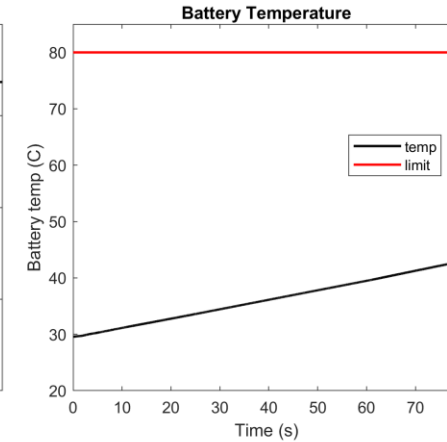
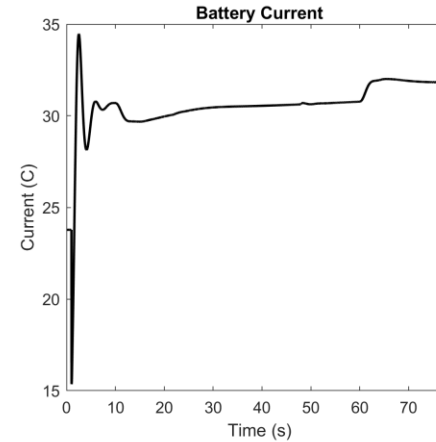
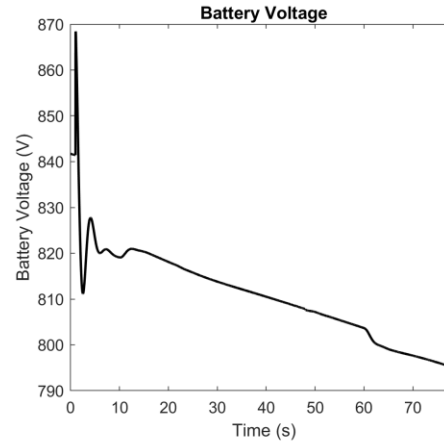
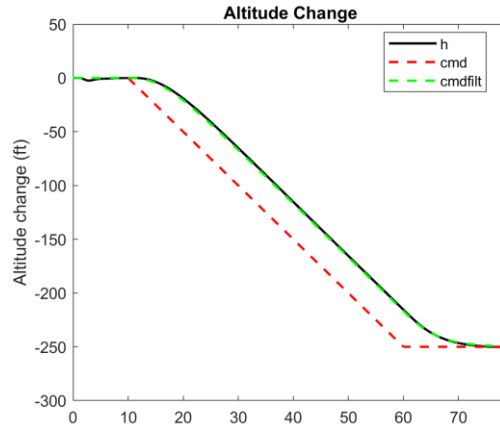
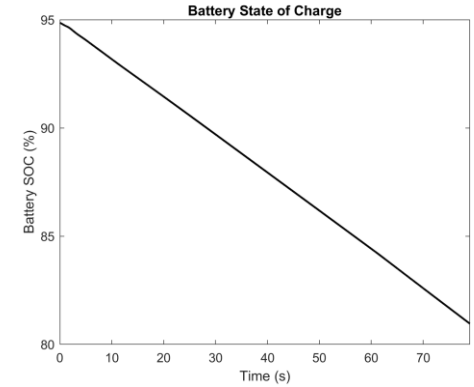
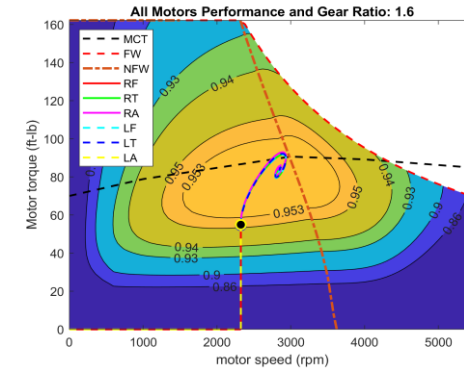
- Vehicle experiences right front motor failure, stabilizes in 9 seconds and descends within 60 seconds
- No large vehicle attitude changes and motors do not saturate





Hover Motor Failure + Land Immediately (Power)

- Converter swings from 130A to 270A during failure
- Cell current swings from 3C to 7C during failure
- State of charge falls 15% from failure to landing





Concluding Remarks

- The nonlinear simulation provided a way to assess & characterize future RAVEN performance
 - Rotors compared well with predictions from NDARC and FlightCODE
 - Suggests rotor dynamics will be capable of supporting RAVEN project
 - k tuning factors will probably be used in the future
- The initial controllability & power assessment suggests the initial RAVEN design
 - Is controllable on all axes
 - Has enough power capability for dynamic maneuvers
 - Has enough energy for the hover and VTOL mission
- Vehicle assessments
 - Various trade studies proved useful to Engineering Leadership before design decisions
 - Motor failures were key to sizing the motors
- The powertrain modeling will continue to improve with project direction



Sample of Key References

- **RAVEN-SWFT Modeling and Flight Controls**

- Simmons, B. M., Ackerman, K. A., Asper, G. D., Gray, M. N., Snyder, S. M., Axten, R. M., Geuther, S. C., and Chan, R., “Subscale Tiltrotor eVTOL Aircraft Dynamic Modeling and Flight Control Software Development,” *Proceedings of the Vertical Flight Society 81st Annual Forum & Technology Display*, Virginia Beach, VA, May 20–22, 2025.

- **FlightCODE Demonstration**

- Malpica, C., Silva, C., and Suh, P. M., “Flight Dynamics Conceptual Design Exploration of Multirotor eVTOL,” *Proceedings of the Vertical Flight Society 80th Annual Forum & Technology Display*, Montréal, Québec, May 7–9, 2024.

- **Amex Vertical Motion Simulator (VMS) Handling Qualities Testing with Real-Time Powertrain Modeling (RTPM)**

- Suh, P. M., Barnes, K., Hanson, C., and Kloesel, K., “Real-Time Powertrain Development and Sizing for the RVLT Lift Plus Cruise Concept Vehicle,” *Aerospace Control and Guidance Systems Committee (ACGSC), Meeting 130*, Missoula, MT, March 22–24, 2023.
- Barnes, K., Suh, P. M., and Hanson, C., “Vertical Motion Simulator Handling Qualities Testing of a Piloted eVTOL Vehicle Having a Degraded Powertrain,” *Proceedings of the Vertical Flight Society 81st Annual Forum & Technology Display*, Virginia Beach, VA, May 20–22, 2025.

- **RTPM Conceptual Development**

- Suh, P. M., Barnes, K., Hanson, C., and Kloesel, K., “Real-Time Powertrain Development and Sizing for the RVLT Lift Plus Cruise Concept Vehicle,” *Aerospace Control and Guidance Systems Committee (ACGSC), Meeting 130*, Missoula, MT, March 22–24, 2023.
- Suh, P. M., Hanlon, P. A., Hunker, K. R., Barnes, K., Collazo Fernandez, X., Sadey, D. J., Trevino, J., Valco, M. J., Tallerico, T., and Malpica, C., “Real-Time eVTOL Powertrain Modeling for the NASA Vertical Flight Simulator,” *Proceedings of the Vertical Flight Society 81st Annual Forum & Technology Display*, Virginia Beach, VA, May 20–22, 2025.

- **RTPM Application to Tiltwing for upcoming VMS test**

- Caudle, D., Singh, R., Nadell, S. J., Berger, T., Malpica, C., and Suh, P. M., “Development and Integration of Flight Dynamics Models for Study of eVTOL Aircraft in the NASA Vertical Motion Simulator,” *Proceedings of the Vertical Flight Society 81st Annual Forum & Technology Display*, Virginia Beach, VA, May 20–22, 2025.



Questions?



Backup



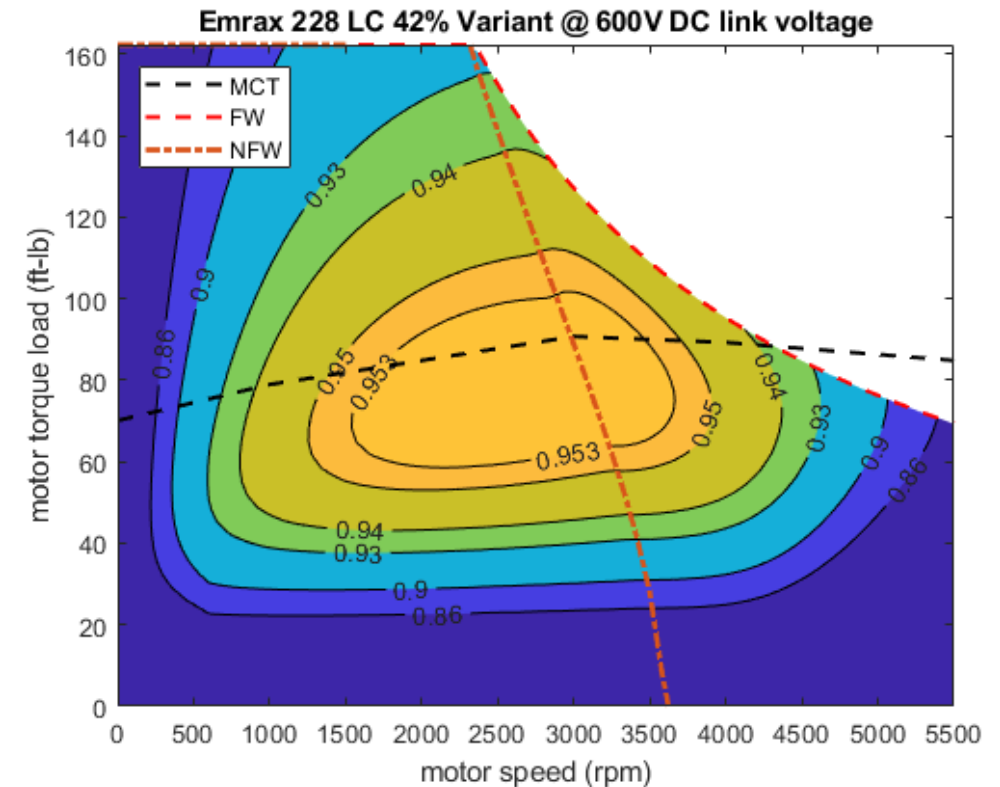
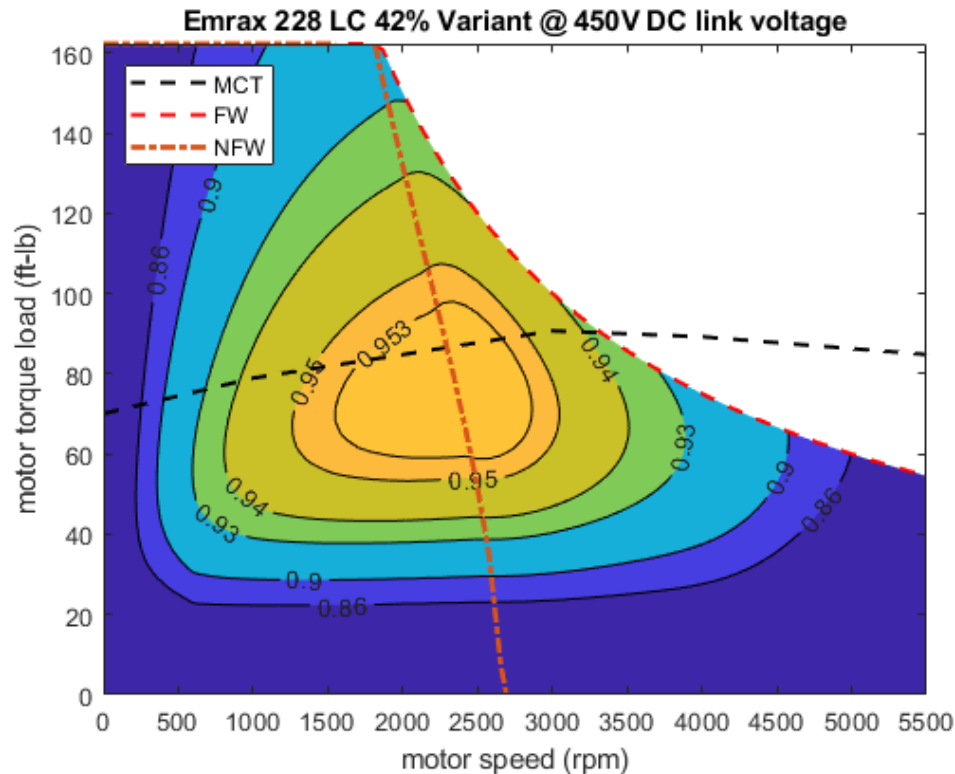
Control Laws for Performance Assessment

- Proportional-Integral (PI/PID) control laws created to trim and assess basic performance of the vehicle
 - Low speed (0-26 kts)
 - Vertical axis PI control at low speed with a fixed optimal rpm allocator
 - Pitch axis control (PID) at low speed with a fixed optimal pitch allocator
 - Roll axis PI control at low speed with a fixed optimal roll allocator
 - Yaw axis PI control at low speed with antisymmetric Nacelle tilt
 - Low speed control is blended linearly into high-speed control from 26 kts to 47 kts and used up to 100 kts
 - Vertical axis PI control blends to zero effect with integrators held to avoid windup
 - Pitch axis outer PI control blends to outer PID flight path angle control, with stab and equal collective allocation to front and tip Nacelle collectives replacing optimal pitch allocator
 - Roll axis PI control blends in aileron to hover-based optimal roll collective allocator
 - Yaw axis PI control blends to yaw rate control with rudder and augmented with traditional turn coordination and sideslip control
 - Speed control
 - PI control to forward and tip Nacelle collectives equally and a small allocation to Nacelle tilt
 - Some attempts were made to check robustness such as gain changes to control loops, but not thorough (will not be flight CLAWs)



Example Emrax 228 LC + 42% Motor Map at Different Voltages

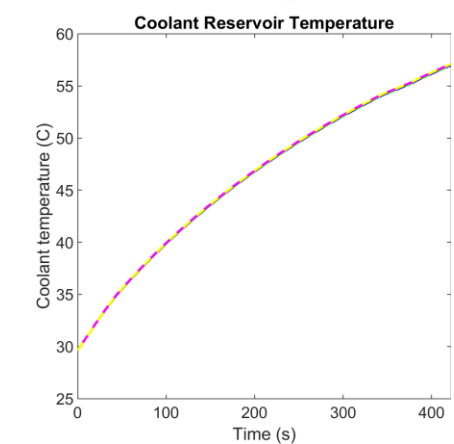
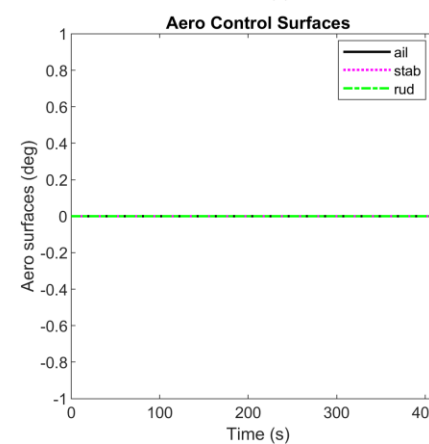
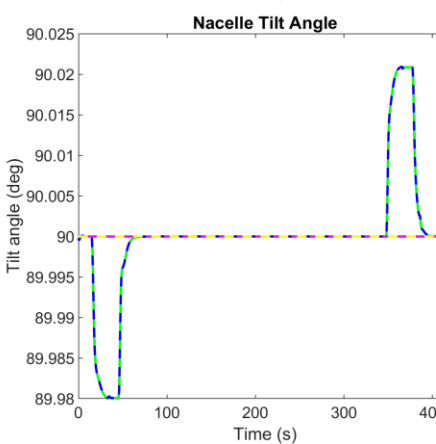
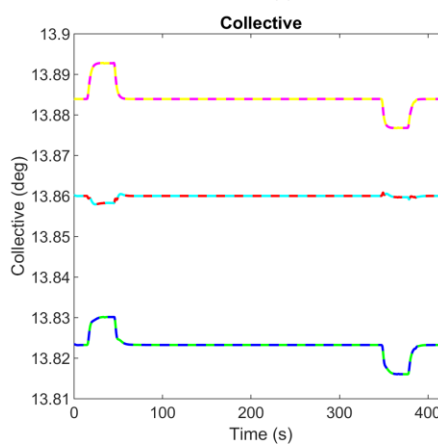
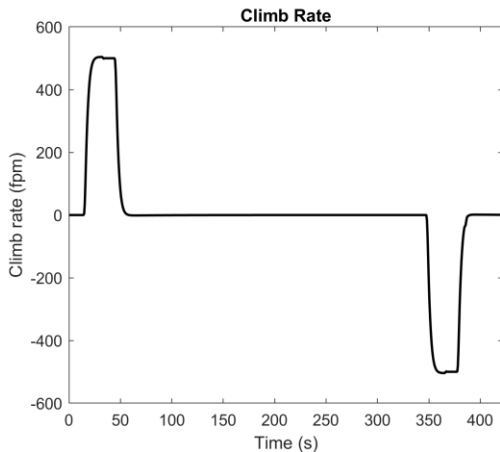
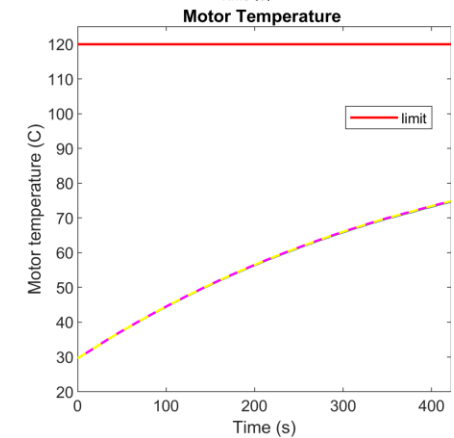
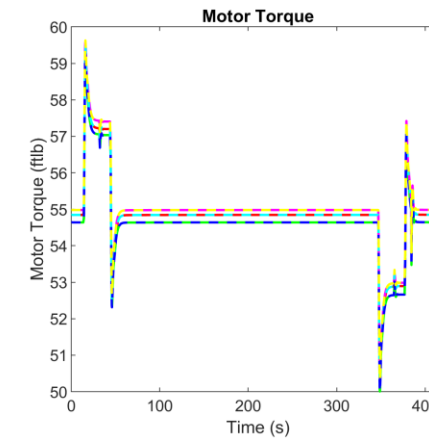
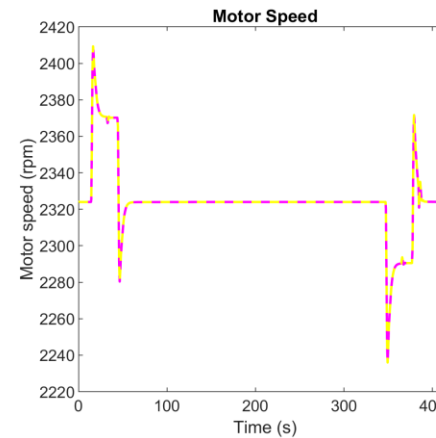
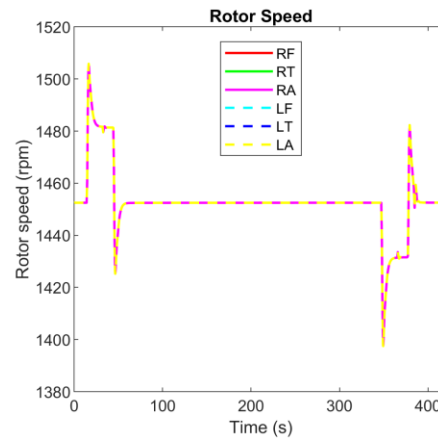
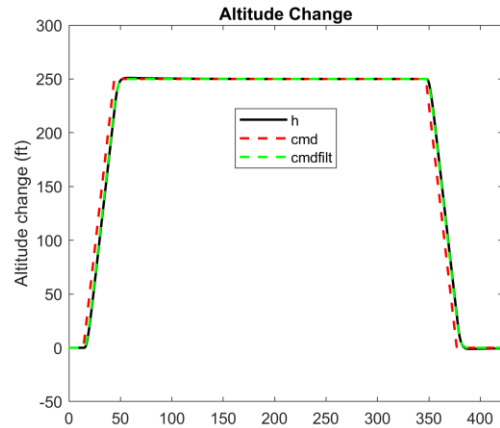
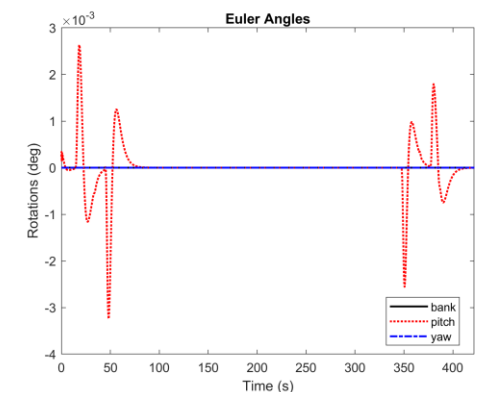
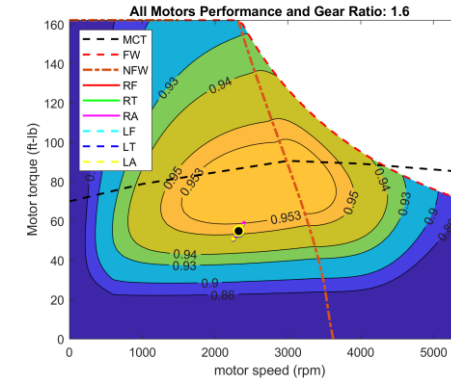
- Maps developed completely from open-source specification sheets
- The voltage available to inverters governs the available map usage
 - Possible use of 450V during certain conditions or 600V during other conditions
 - The max continuous torque (MCT) line is a manufacturer determined line of continuous performance
 - The Non-flux weakening (NFW) line is peak motor performance *without* flux weakening control
 - The Flux weakening (FW) line is the peak motor performance *with* flux weakening control





Hover Mission + Reserve Mission (Controllability)

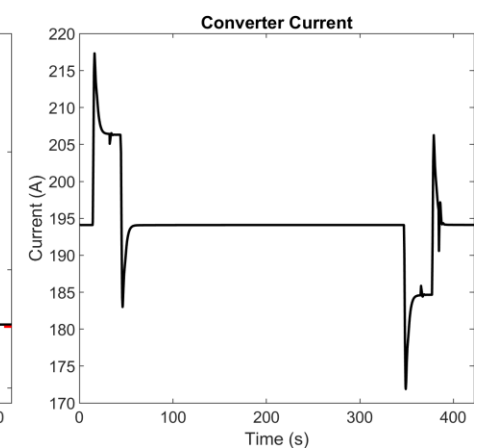
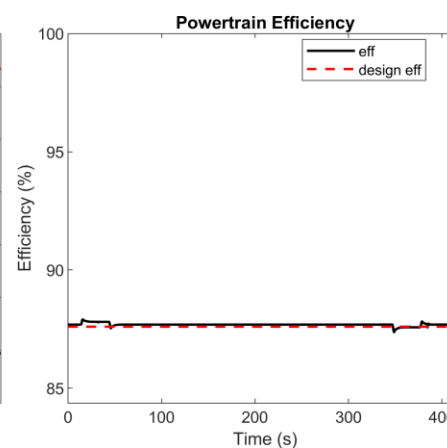
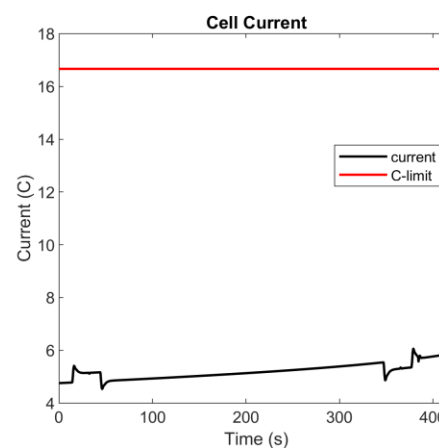
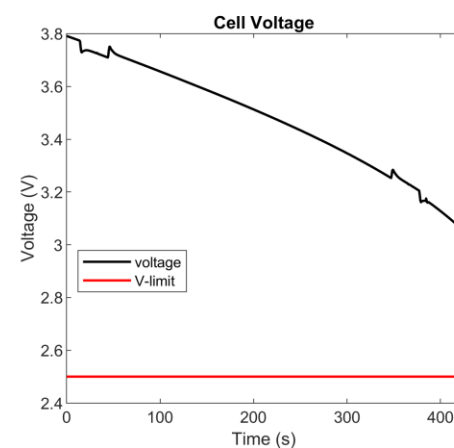
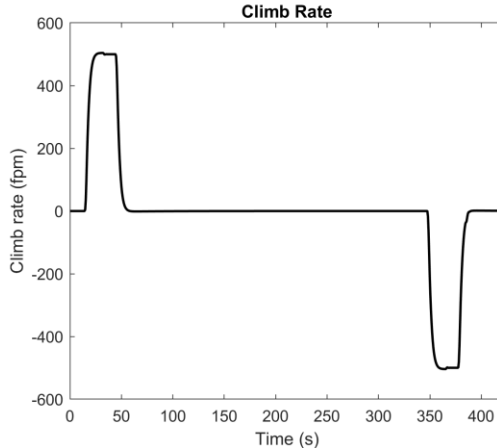
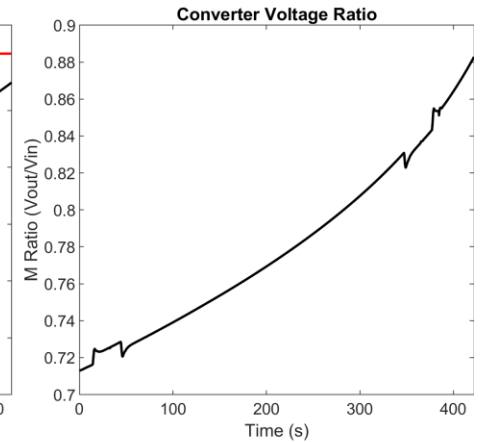
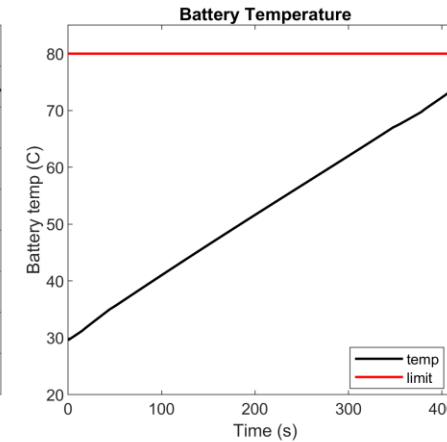
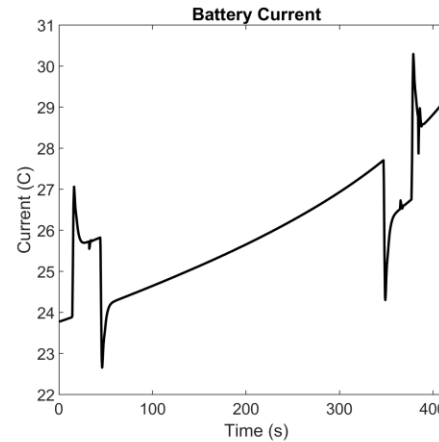
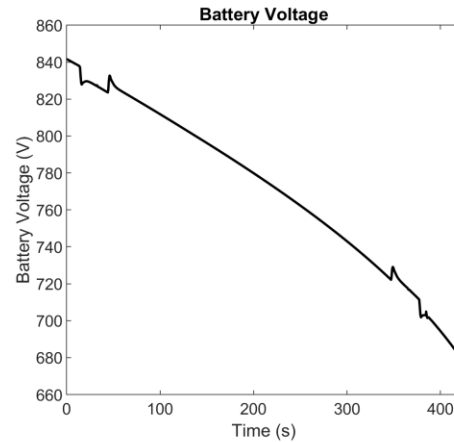
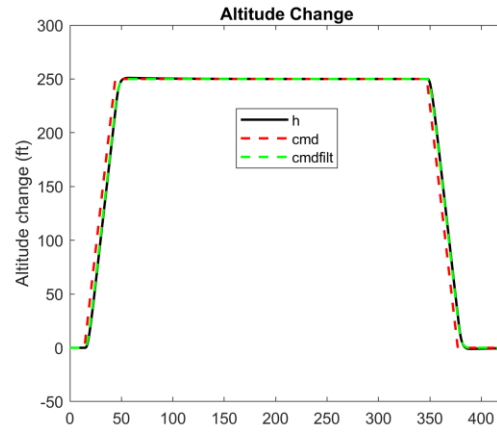
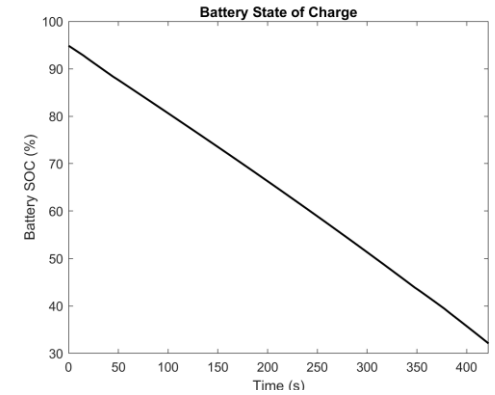
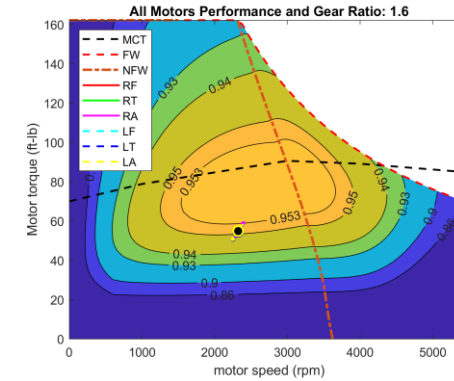
- Vehicle tracks filtered altitude command closely
- Motor temperature stays well under limit finishing at 75C
- Vertical axis is controllable





Hover Mission + Reserve Mission (Power)

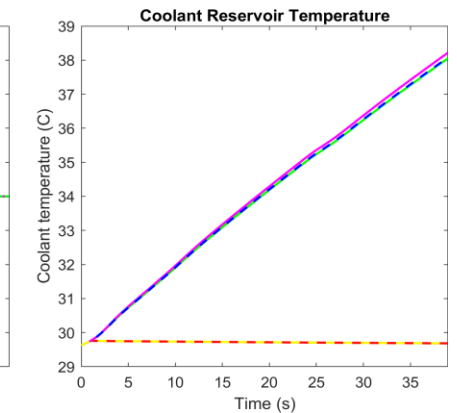
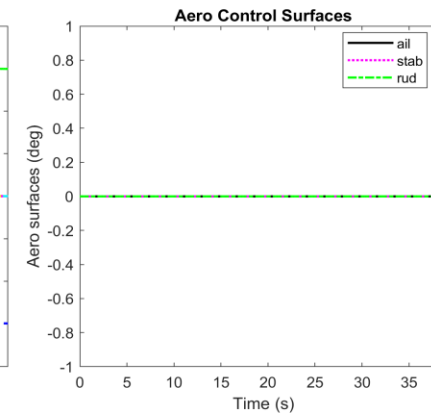
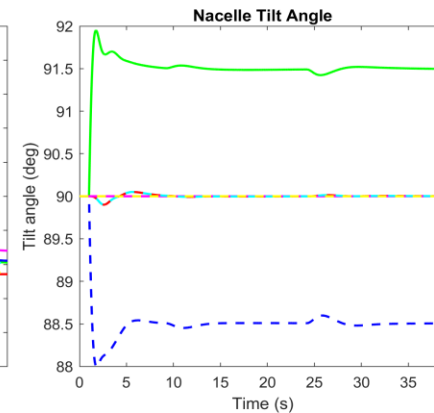
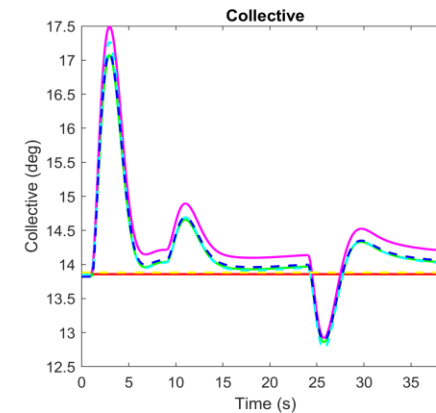
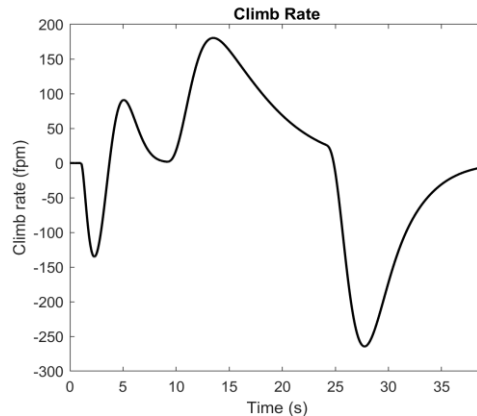
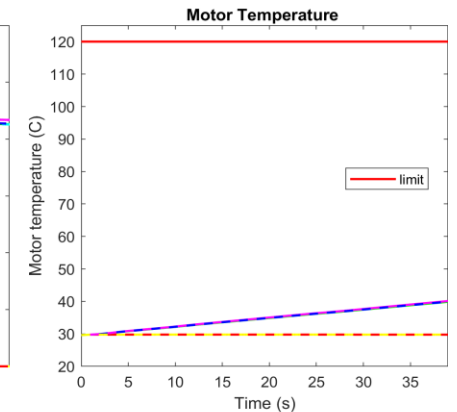
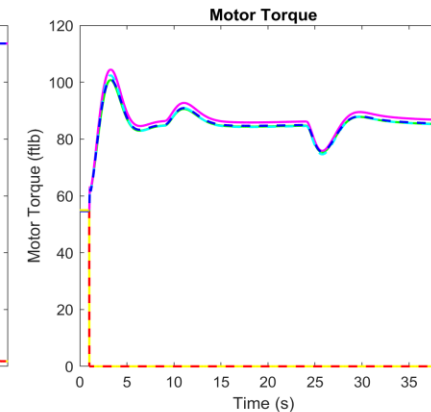
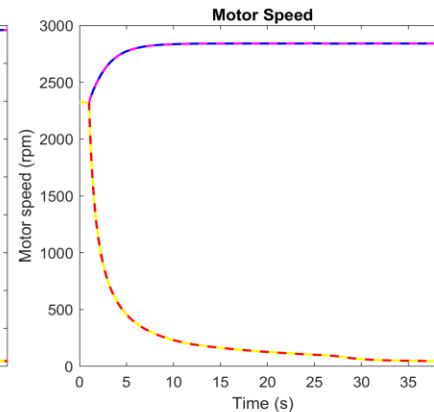
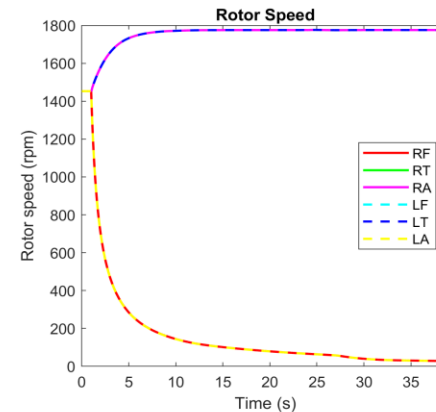
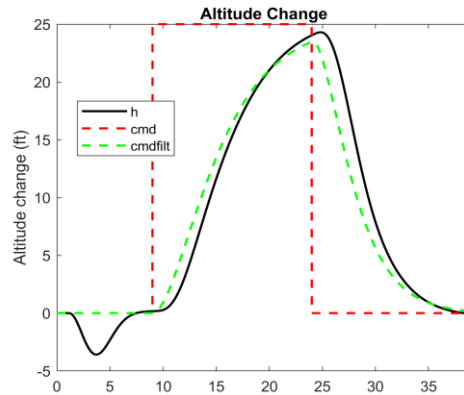
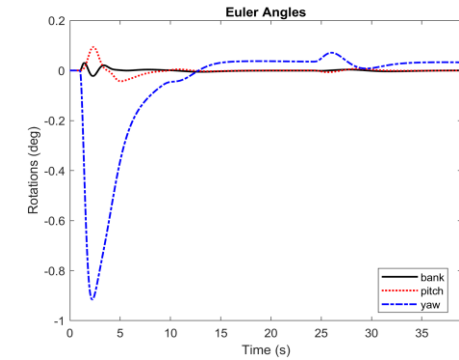
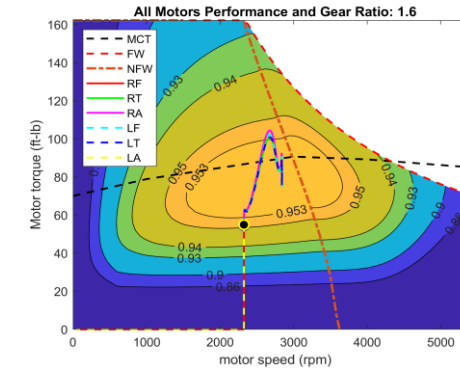
- State of charge after reserve mission remains above 32% SOC
 - Excess energy for hover mission task elements (MTEs)
- Battery temperature at 75C below limit of 80C.
- Converter remains in buck mode





Hover Vertical Reposition + Collective Control + Right Front Motor Failure (Controllability)

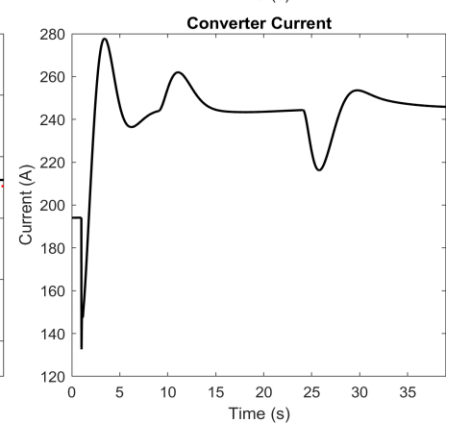
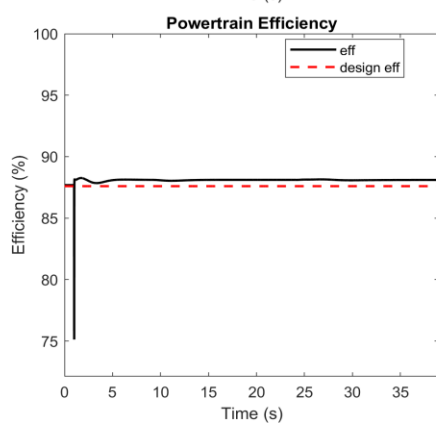
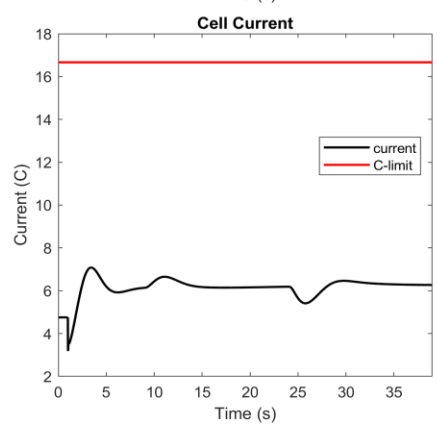
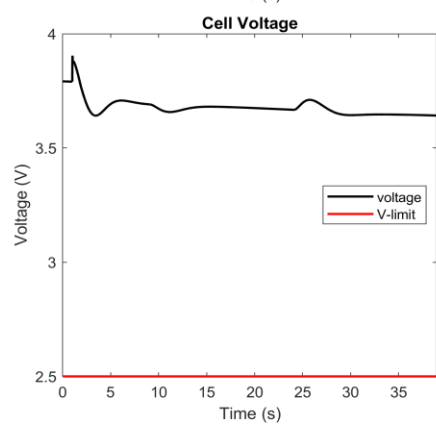
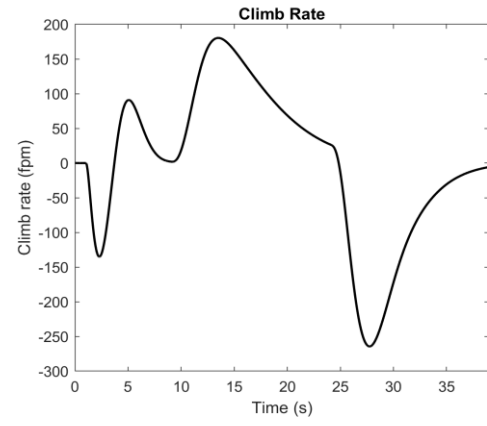
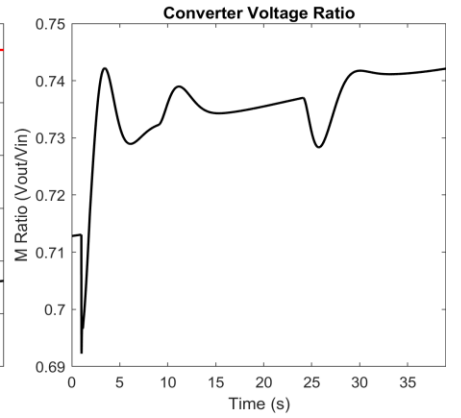
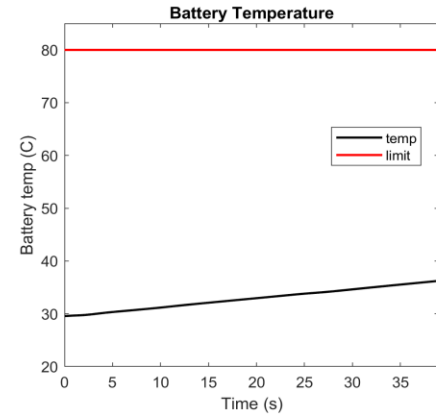
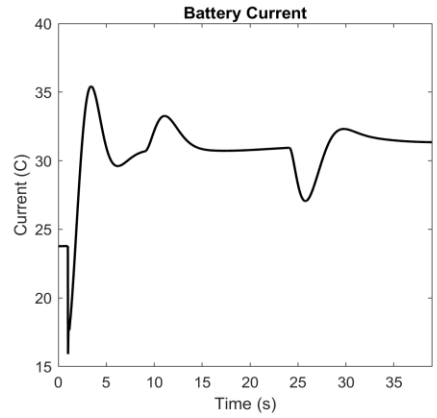
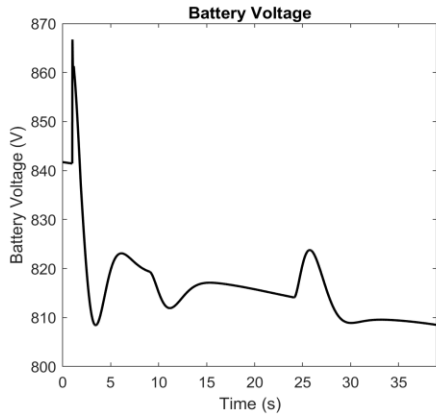
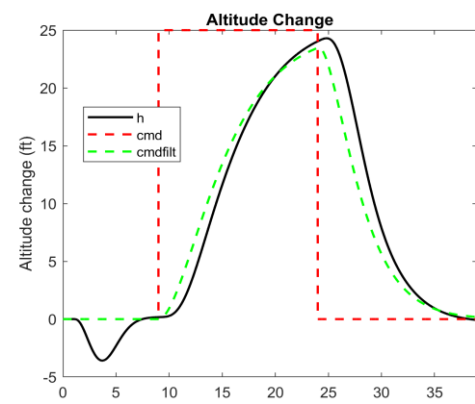
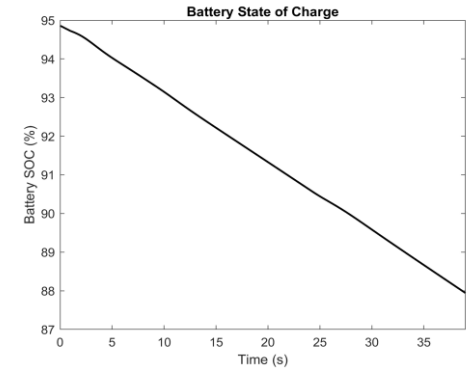
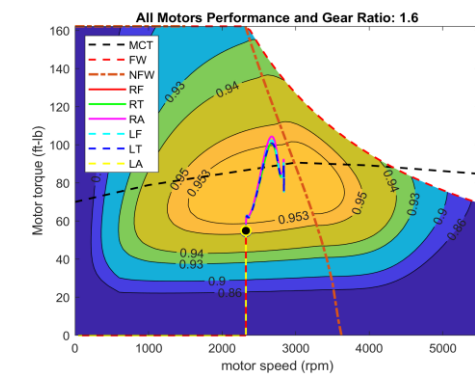
- Motors do not saturate but much closer to NFW
- Collectives initially rise from 13.8 deg to 17.5 deg during failure
- Rotor speed increased to avoid blade stall
- Altitude command is followed well





Hover Vertical Reposition + Collective Control + Right Front Motor Failure (Power)

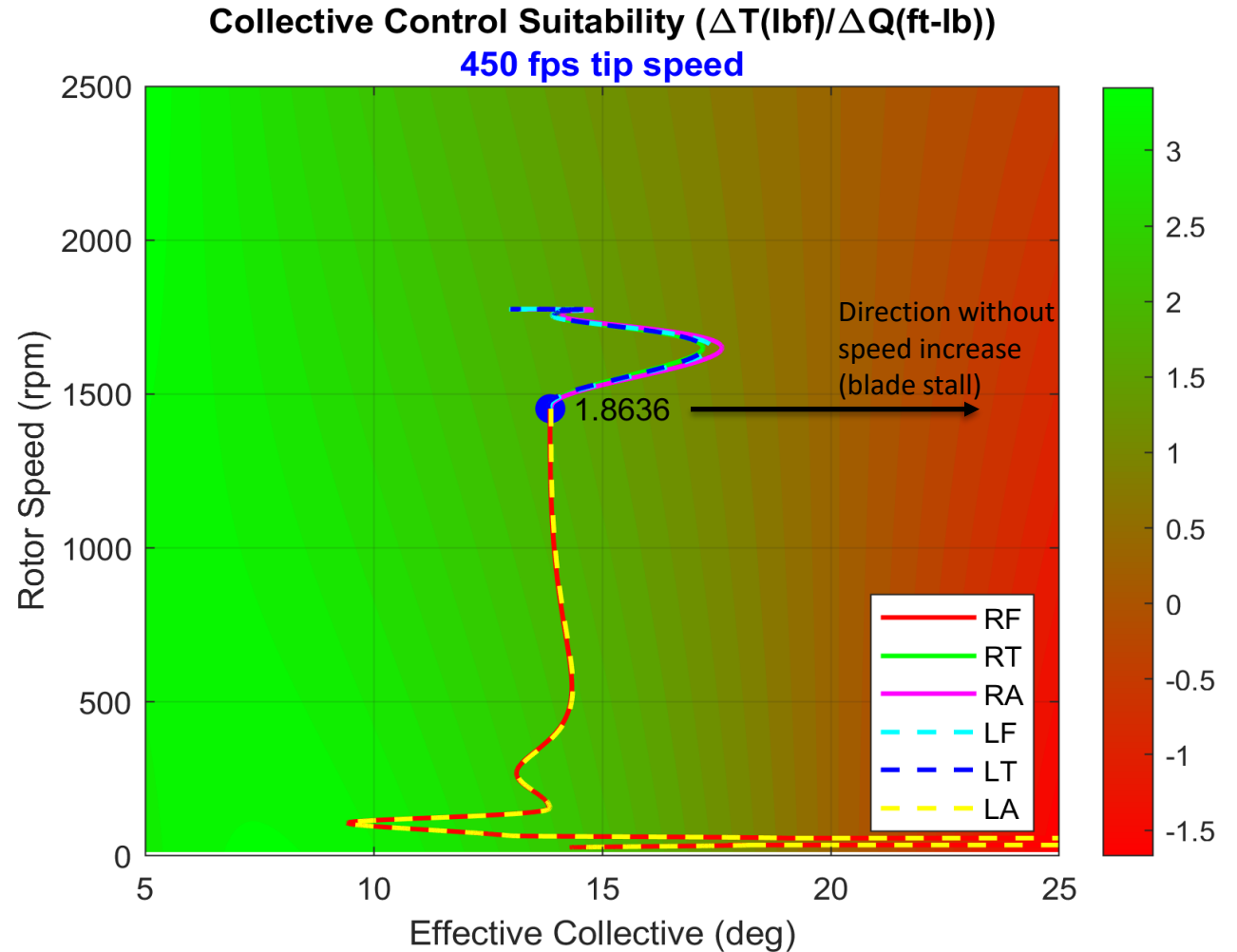
- Max cell current swing from 3C to 7C
- Max converter current swing from 135A to 280A
- State of charge decreases 7% during maneuver





Why Collective Control + Motor Failure Required Rotor Speed Increase for Remaining Rotors

- The collective moves to the right on the chart to the right to maintain thrust (ΔT) to support the vehicle during the failure
- If speed not increased collective moves further right to zero thrust produced per unit of torque
- Increasing speed of 4 remaining motors reduces need to move collective to the right to generate thrust
 - Significantly reduces torque requirements

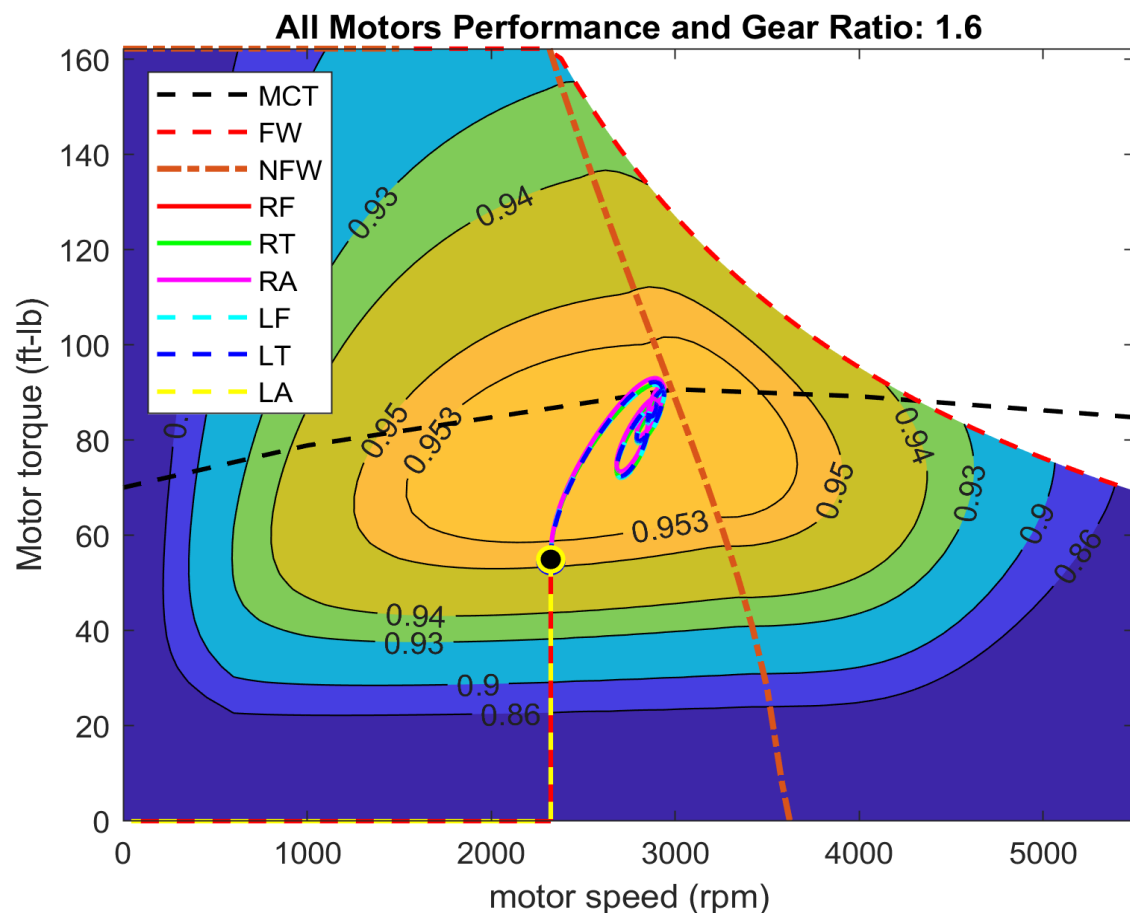




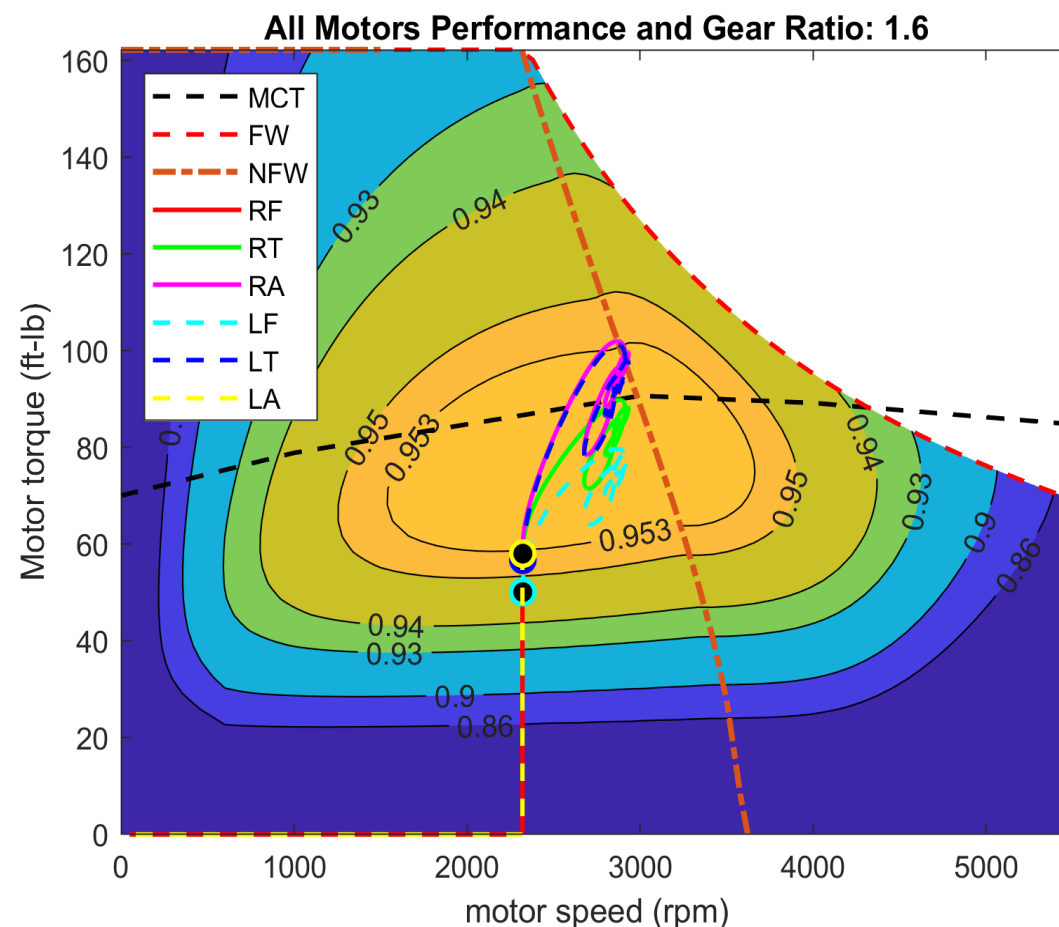
Vertical Reposition + Right Motor Failure + c.g. shift aft by 3.5 inches

- During a failure, if the c.g. is shifted away from the fore-aft rotor centerline, torque requirements go up for two motors and down for other motors
 - Motor temperatures will go up at different rates

c.g. centered on fore-aft rotor centerline



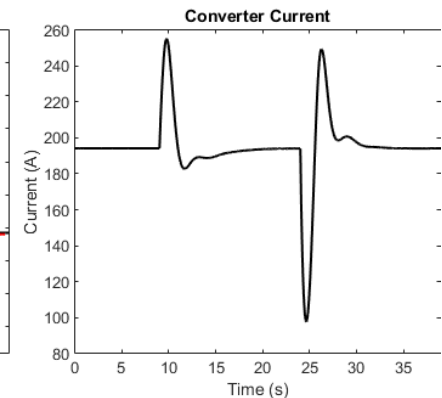
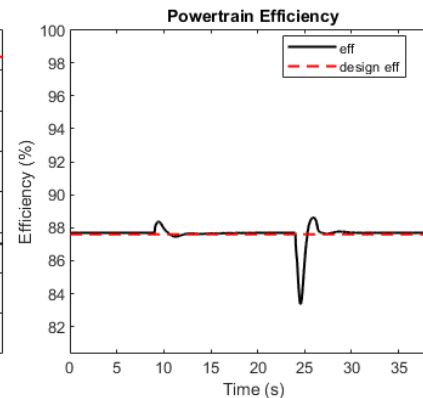
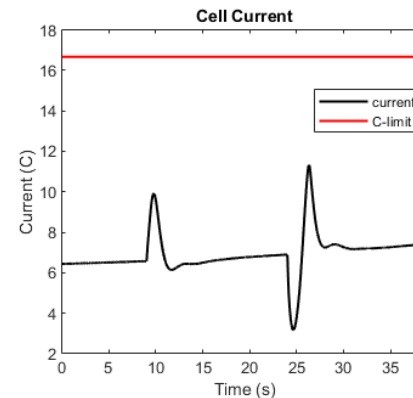
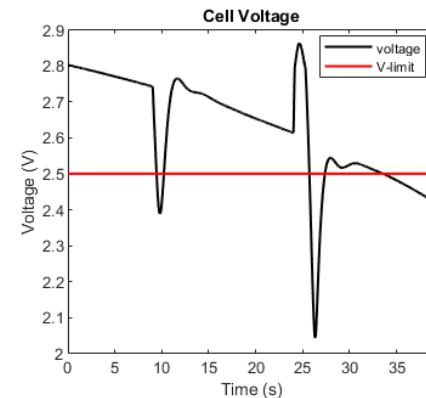
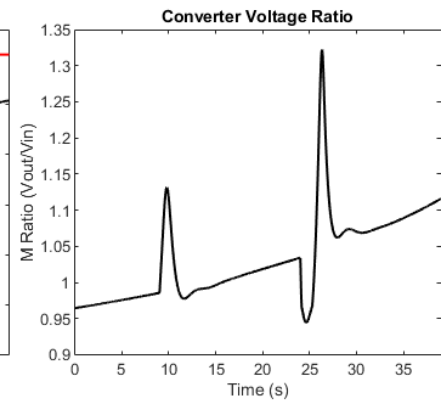
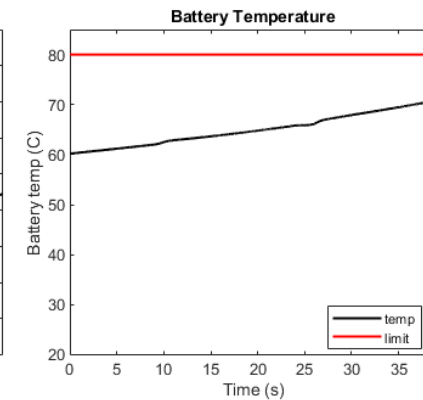
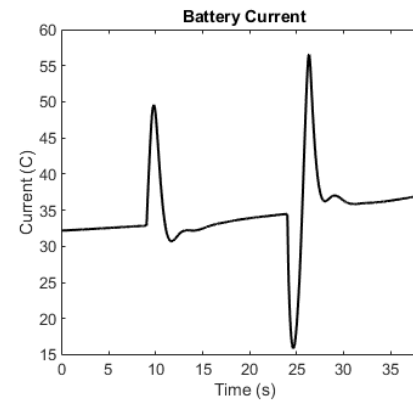
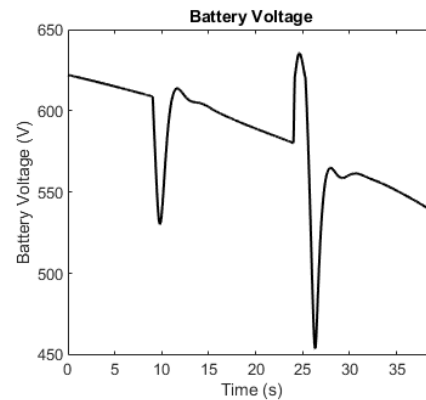
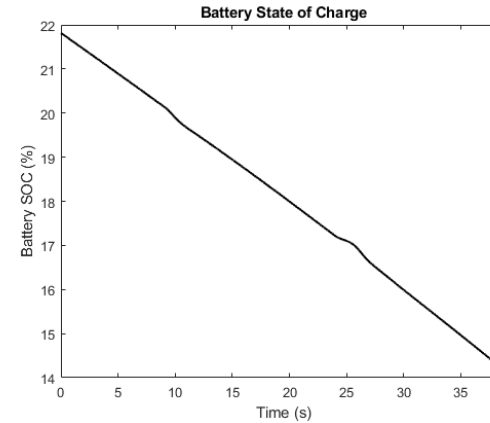
c.g. aft by 3.5 inches





Vertical Reposition + 22% SOC + 60 degC Battery

- Near the end of the VTOL mission + reserve mission
 - Battery SOC fell to approximately 22% SOC
 - Battery temperature was around 60 degC
- Maneuvers would be severely limited at 22% SOC due to cell voltage limitations
- Closer to cell current thresholds than before
- Converter operating almost entirely in boost mode

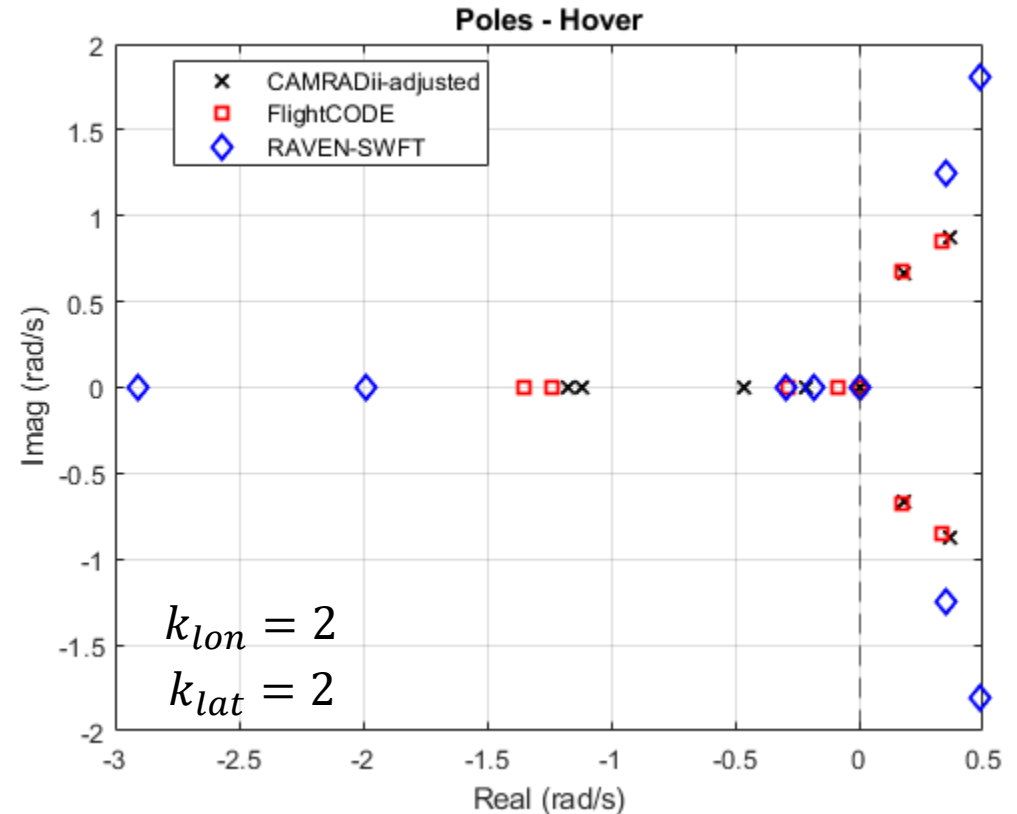




Tuned Hover Comparisons

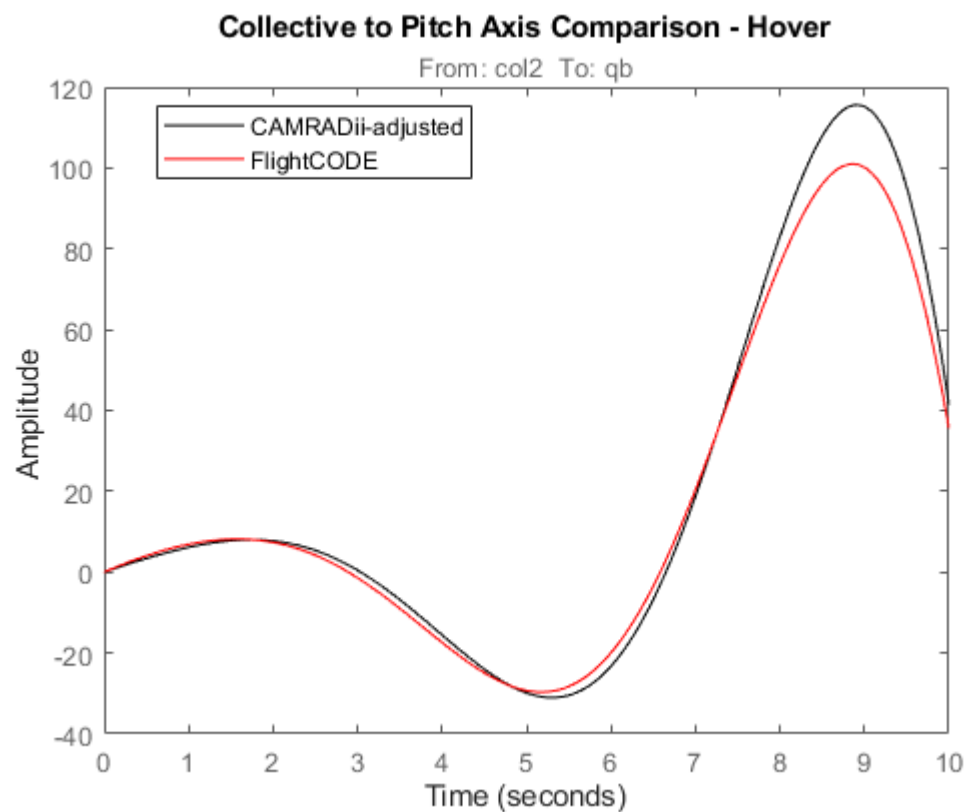
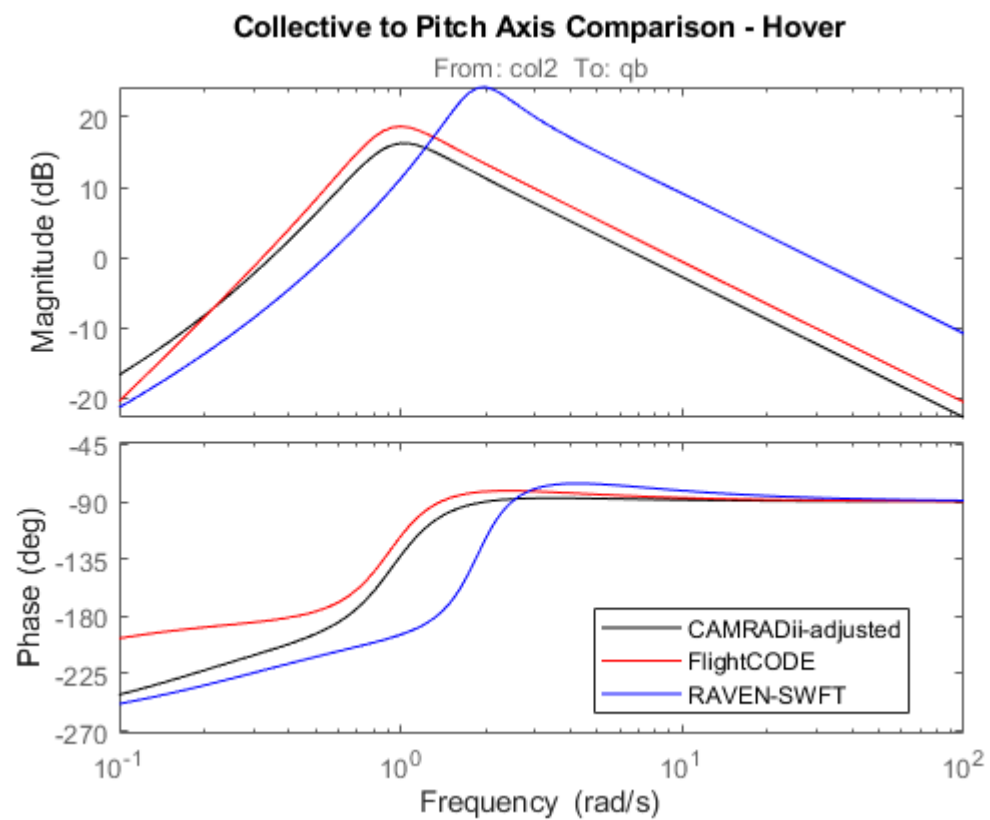
- CAMRADii-adjusted
 - State space model of RAVEN vehicle developed from CAMRAD II hover data with adjustments for forward flight
- FlightCODE
 - State space model, originally produced from NDARC .acd/.soln files
 - Poles observed are after reduction of full order model to rigid body states
- RAVEN-SWFT
 - State space model identified by wind tunnel and flight test data
- Tests @ Hover speed
 - Check pitch, roll and vertical axis comparisons
 - Time domain
 - Frequency domain
- Observed significant similarities in the poles/trends among all models at hover

Tuned Hover Pole Comparisons



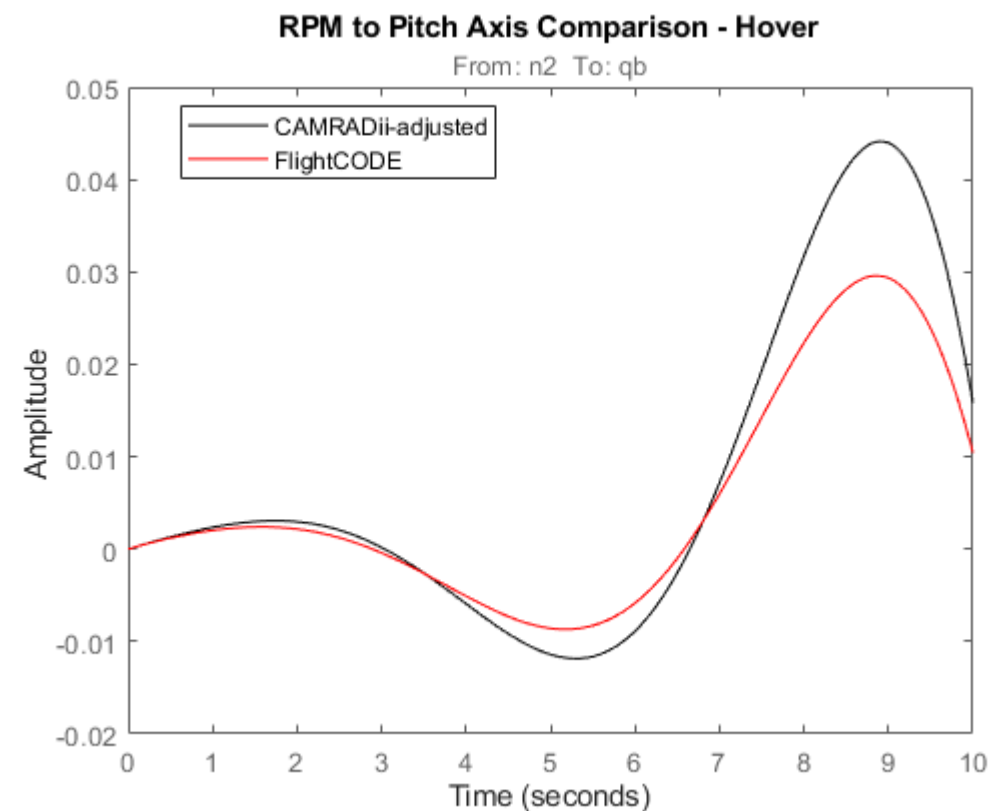
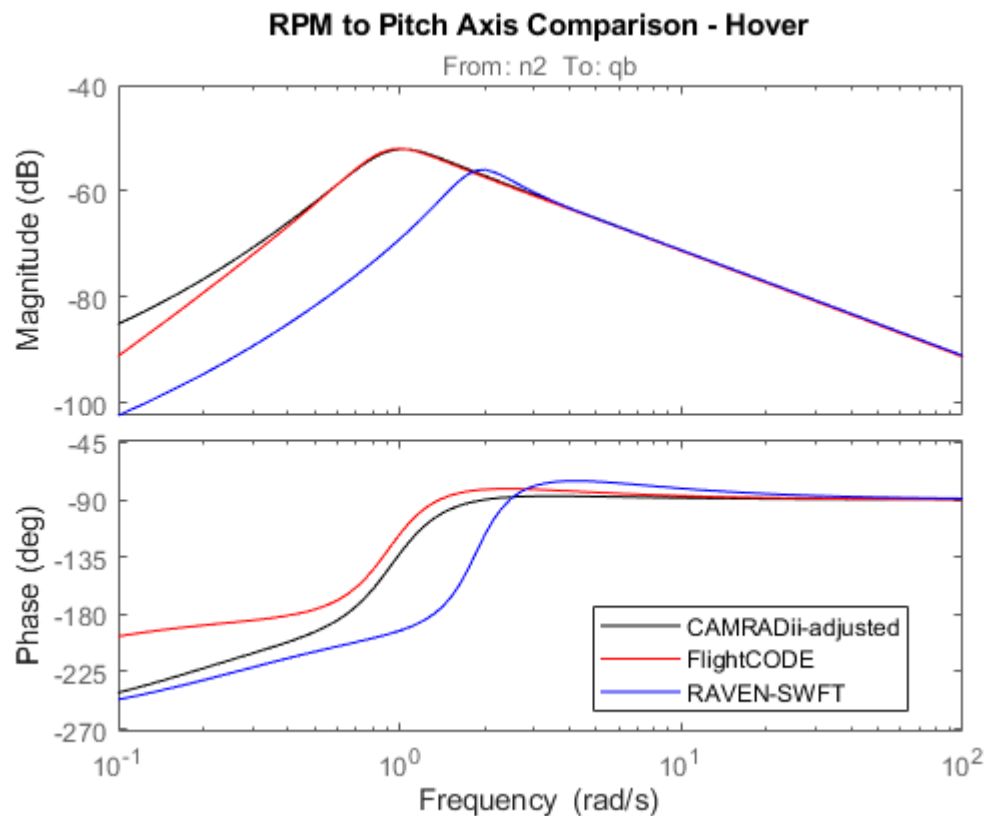


Pitch axis – Collective control (Tuned)



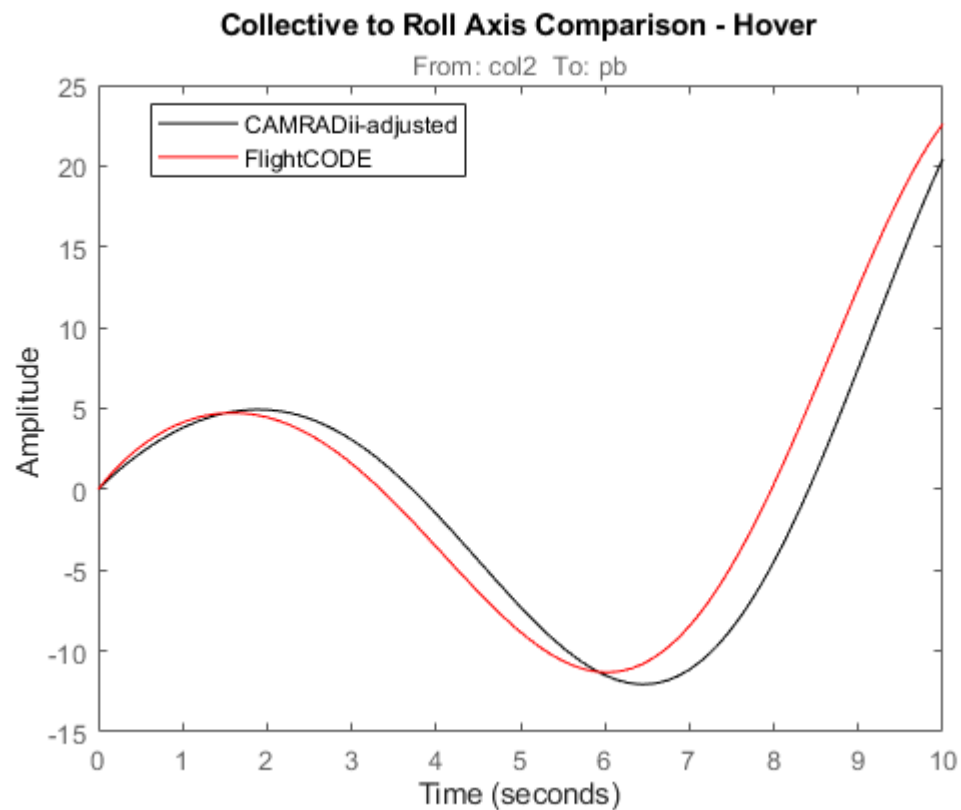
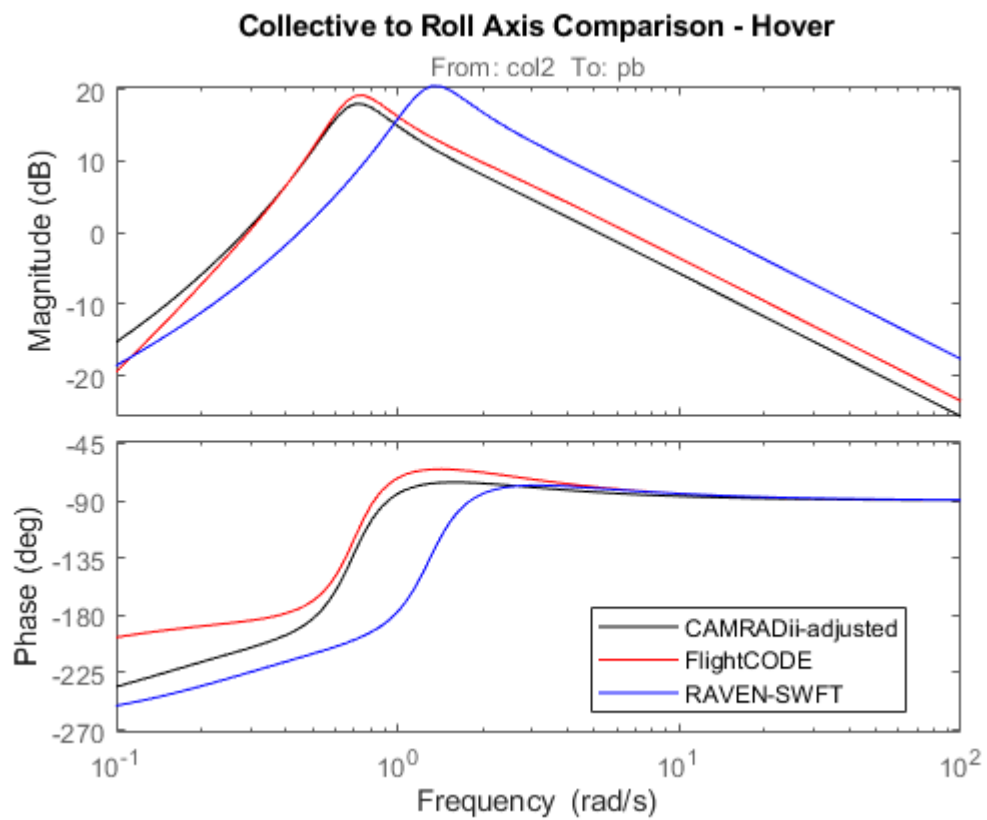


Pitch axis – RPM control (Tuned)



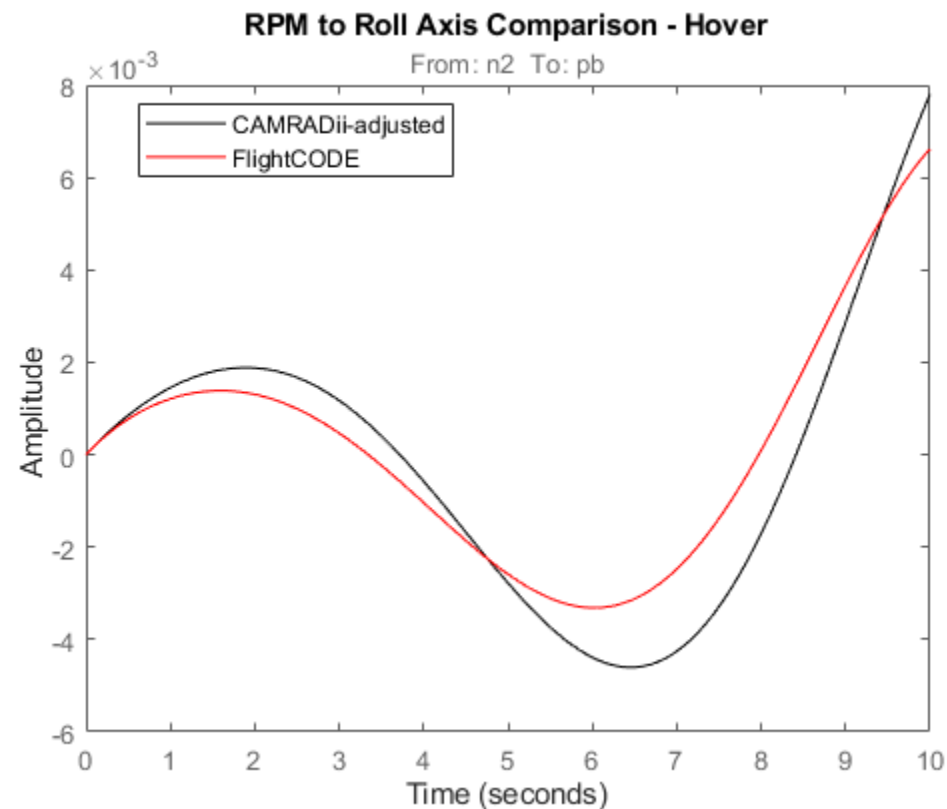
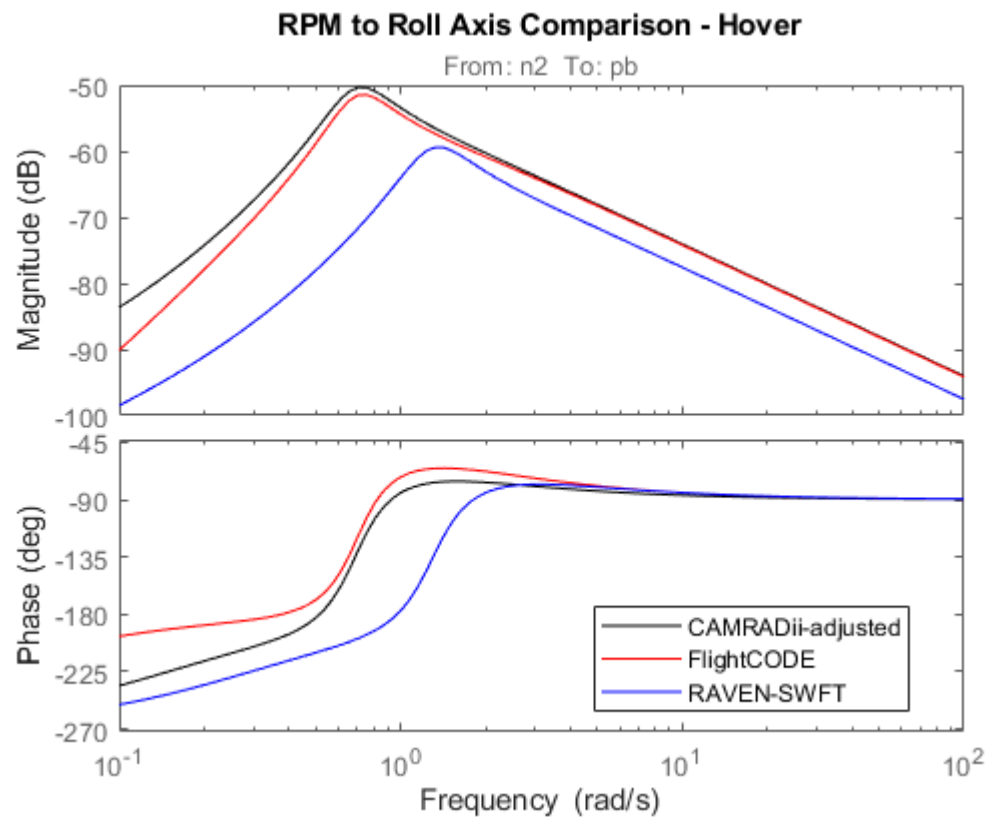


Roll axis – Collective control (Tuned)



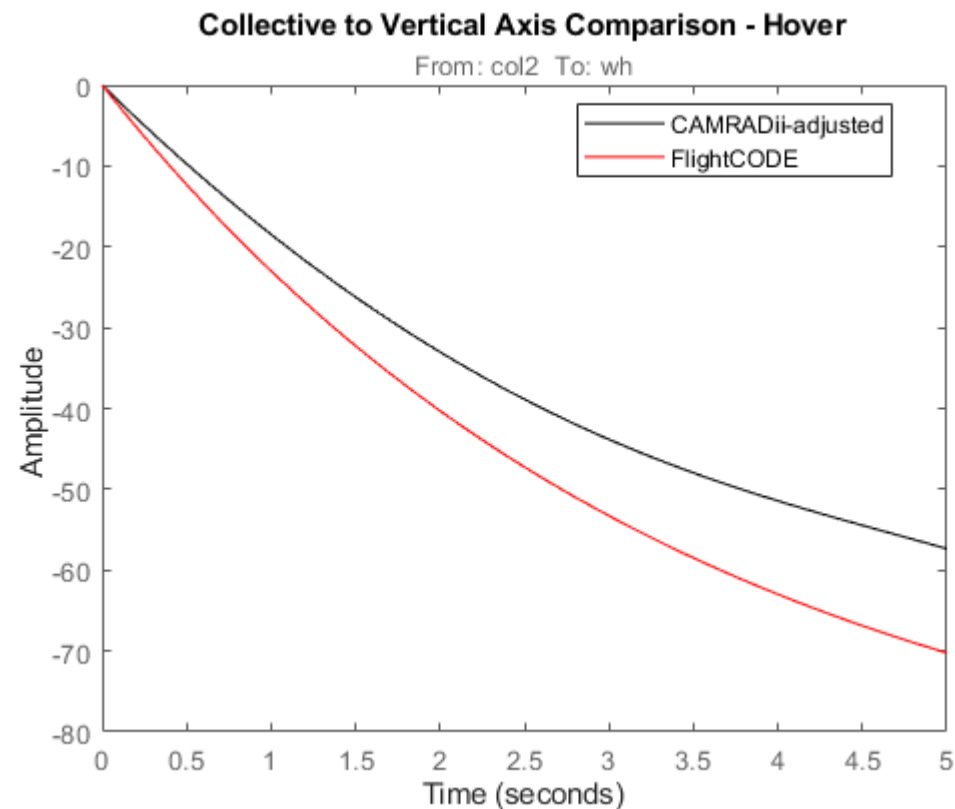
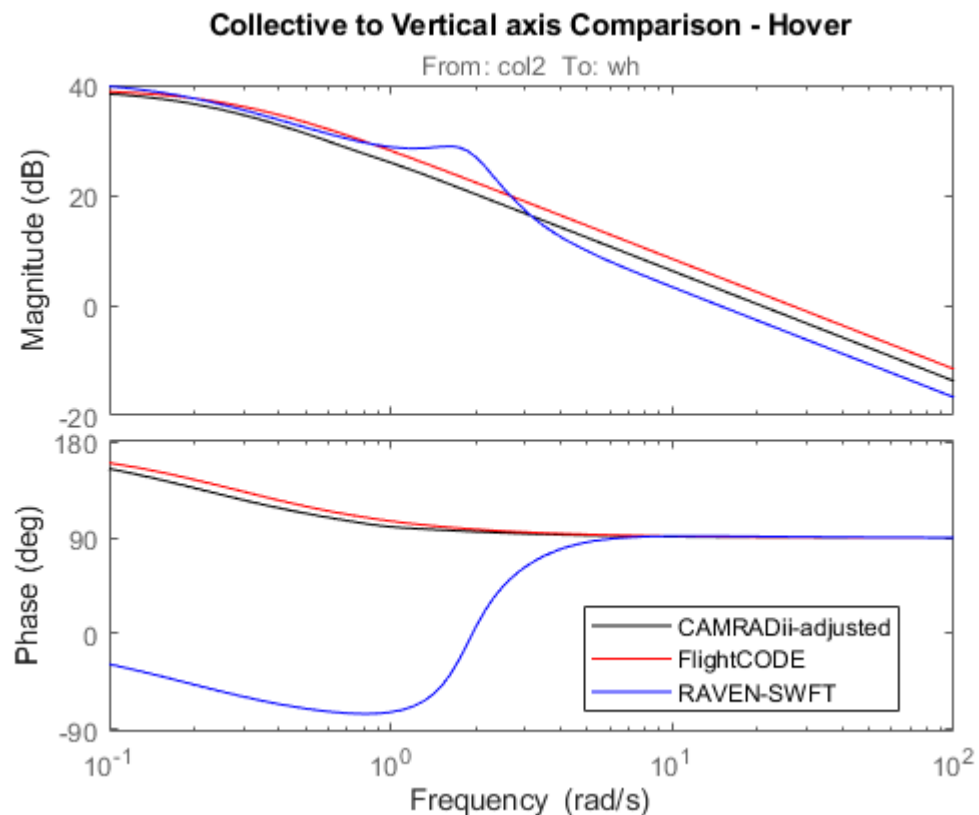


Roll axis – RPM control (Tuned)





Vertical axis – Collective Control (Tuned)





Vertical Axis – RPM control (Tuned)

