Flight Dynamics and Control of an eVTOL Concept Aircraft with a Propeller-Driven Rotor

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Outline

- **Introduction**
  - Background
  - Motivation
  - Objectives
- **Methodology**
  - Simulation Model
  - Dynamic Stability
  - Flight Control Design
- **Results**
  - Flight Control Law Validation
  - Autorotation Performance
- **Conclusions**

PennState

Background

Georgia Tech

- Tip-driven rotors are a long-standing alternative to shaft-driven rotors
  - ❑ Eliminate transmission + anti-torque system
  - ❑ Can shorten tail boom
  - ❑ Decouples directional and heave dynamics
  - ❑ Reduction in rotating parts, weight, maintainance costs, (power req.)
- Approaches to tip-driven rotors
  - ❑ **Cold tip jets** (FIAT 7002, 1961)
  - ❑ **Hot tip jets** (Fairey Rotodyne, 1957)
  - ❑ **Ramjets** (Hiller YH-32 Hornet, 1950)
  - ❑ **Pulsejets** (XH-26 Jet Jeep)

FIAT 7002

Fairey Rotodyne

PennState

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Hiller YH-32 Hornet

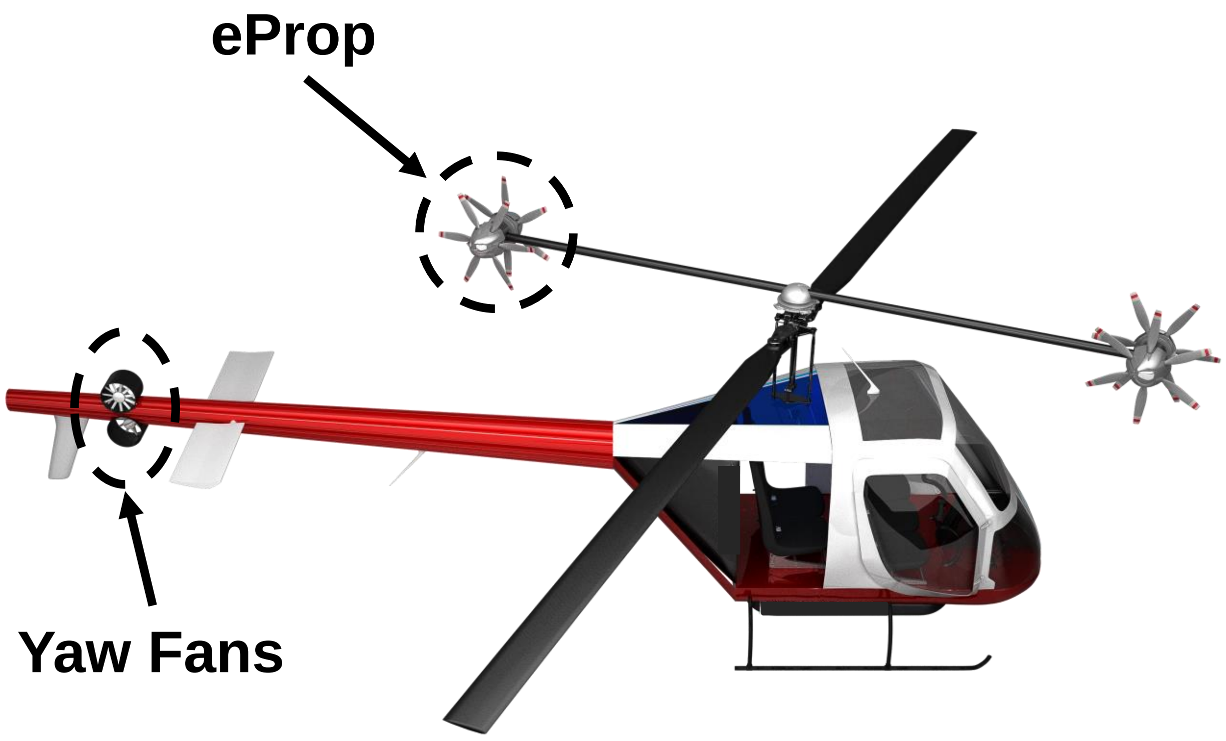
XH-26 Jet Jeep

Motivation

- Significant drawbacks as well
  - **Pressure losses** and **sealing challenges** for transporting compressed air or exhaust gasses to the blade tips
  - **High centrifugal loads** acting on the jet engines
  - **High noise levels** produced by the tip-jet
- New opportunities given by **distributed electric engines**
  - Main rotor driven by rotor-mounted propellers rather than tip jets
  - Eliminates difficulties with transporting compressed air or exhaust gasses
  - May relax disadvantages related to high noise levels
  - Increased main rotor inertia
  - Redundancy

F-Helix eVTOL Concept Aircraft

Motivation



F-Helix eVTOL Concept Aircraft

- Main rotor torque provided by two pairs of counter-rotating coaxial propellers (eProps)
- eProps powered by two electric engines each
- eProps mounted on a beam rigidly connected to the rotor hub
- eProps at a radial location of roughly half of the rotor radius [Saetti et al. 2019]
- Lift entirely generated by two-bladed rotor
- Fuselage based on Silvercraft SH-4
- Small ducted fans replace the tail rotor (Yaw Fans)

Objectives

- Previous investigations
  - ❑Design optimization
  - ❑Performance analysis
- Current investigation

1. **Assess dynamic stability**
   - ❑Hover
   - ❑Forward flight
2. **Develop Flight Control Design Methods**
   - ❑Automatic Flight Control System (AFCS)
   - ❑RPM Governor
3. **Verify the potential safety benefits of concept aircraft**
   - ❑Simulation of autorotation following total loss of power

Legacy F-Helix eVTOL Concept Aircraft

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Simulation Model

- **Fuselage and empenngage**
  - ❑ Lookup tables for fuselage aero coeffs.
  - ❑ Simple finite wing models for empennage
  - ❑ Simplified rotor to airframe interference model
- **Main rotor**
  - ❑ Quasi-steady tip path plane model
  - ❑ 3-state Pitt-Peters inflow model
  - ❑ Articulated rotor mode
- **eProps**
  - ❑ 1-state dynamic inflow model (per propeller)
  - ❑ Thrust coeff. calculated with BEPM
  - ❑ Aft propeller assumed fully in front propeller's wake
- **Yaw fans**
  - ❑ Blade element static model
  - ❑ Adjusted for ducted fans

F-Helix eVTOL Concept Aircraft

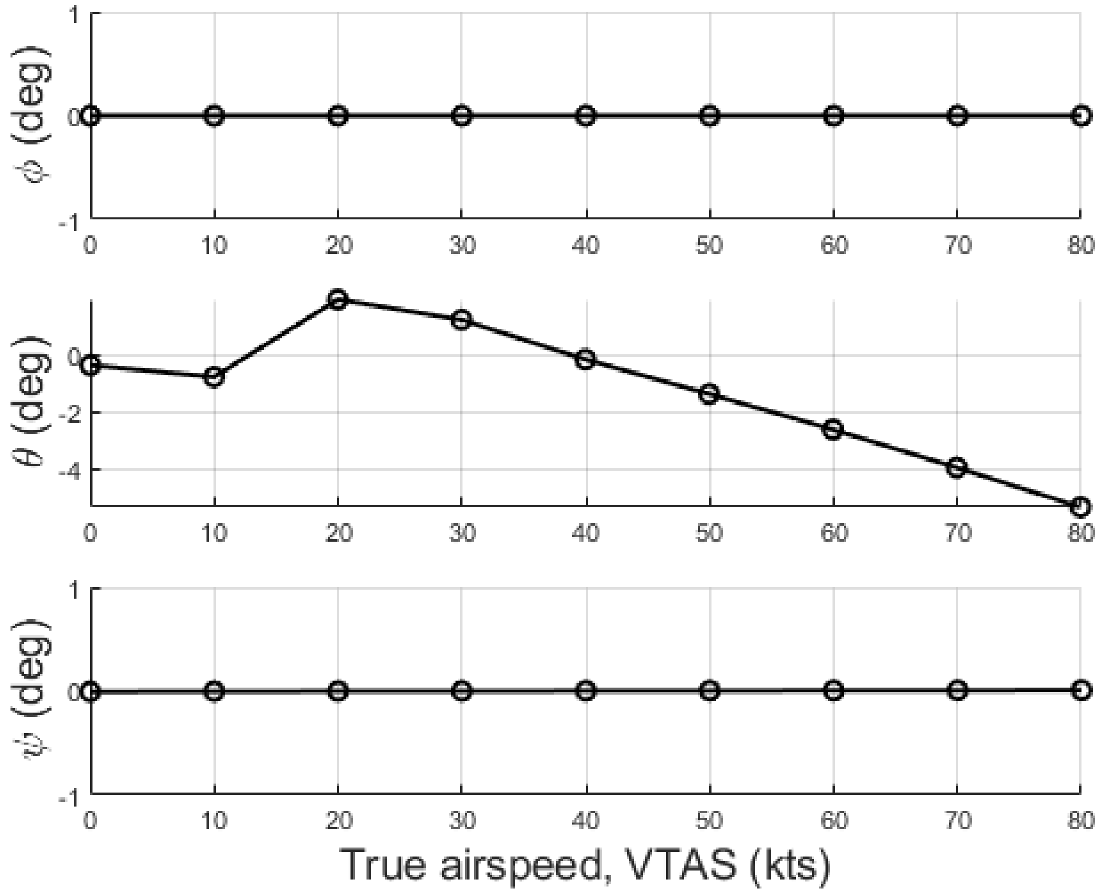
Simulation Model

- **Equations of motion**
  - Nonlinear system in first-order form
  - 18 states
  - 5 control inputs
- **States**
  - Body velocities (u, v, w)
  - Angular rates (p, q, r)
  - Euler angles (ϕ, θ, ψ)
  - MR inflow $(\lambda_0, \lambda_{1c}, \lambda_{1s})$
  - MR angular speed and azimuth $(\Omega_{\mathrm{MR}}, \psi_{\mathrm{MR}})$
  - Induced velocities of i^{th} eProp $(\lambda_u, \lambda_l)_{\mathrm{eProp}_i}$
- **Control Inputs**
  - Longitudinal and lateral sticks (A_{1c}, B_{1c})
  - Pedals (θ_{TR})
  - Collective stick (θ_0)
  - eProps angular speed $(\Omega_{\mathrm{eProp}})$

F-Helix eVTOL Concept Aircraft

Simulation Model

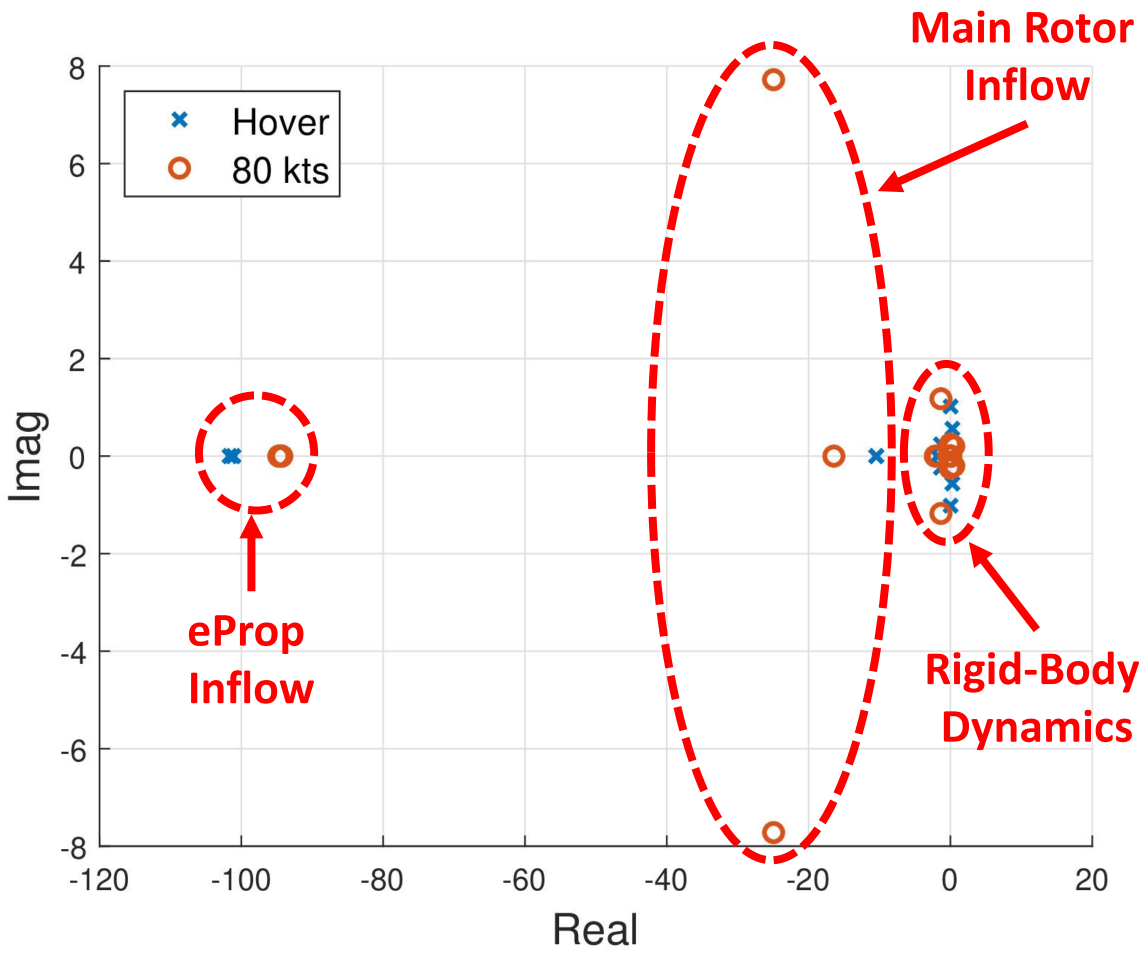
- Trim aircraft model at incremental speeds
  - ❑From hover to 80 kts (max. speed)
  - ❑Used Neton-Rhapson algorithm
  - ❑Maximum Take-Off Weight (1900 lbs)
- While rotorcraft trimmed w/ zero bank angle (ϕ), resulting sideslip angle (β) very small
- Because no torque exchanged between main rotor and fuselage, can trim simultaneously w/ zero bank and sideslip angle
- Different tendency w.r.t. standard helicopter configurations



Trim attitude vs. true airspeed

Dynamic Stability

- Rotorcraft dynamics linearized
  - ❑ Hover and 80 kts
  - ❑ Maximum Take-Off Weight (1900 lbs)
- eProp inflow dynamics stable and faster than rigid-body and main rotor dynamics
- Two unstable modes at hover
  - ❑ Phugoid
  - ❑ Roll-pitch oscillation
  - ❑ Typical of helicopters in hover
- Stable main rotor angular speed dynamics
  - ❑ Freq. doubled from hover to 80 kts
  - ❑ "More" stable than standard rotor due to eProp inflow
- Dutch roll mode unstable at 80 kts
  - ❑ Does not achieve Level 3 lateral-directional oscillatory HQ (ADS-33)
  - ❑ Lack of yaw damping from missing tail rotor
  - ❑ Provide yaw damping via feedback control or increased size of vertical tail



Eigenvalues

Dynamic Stability

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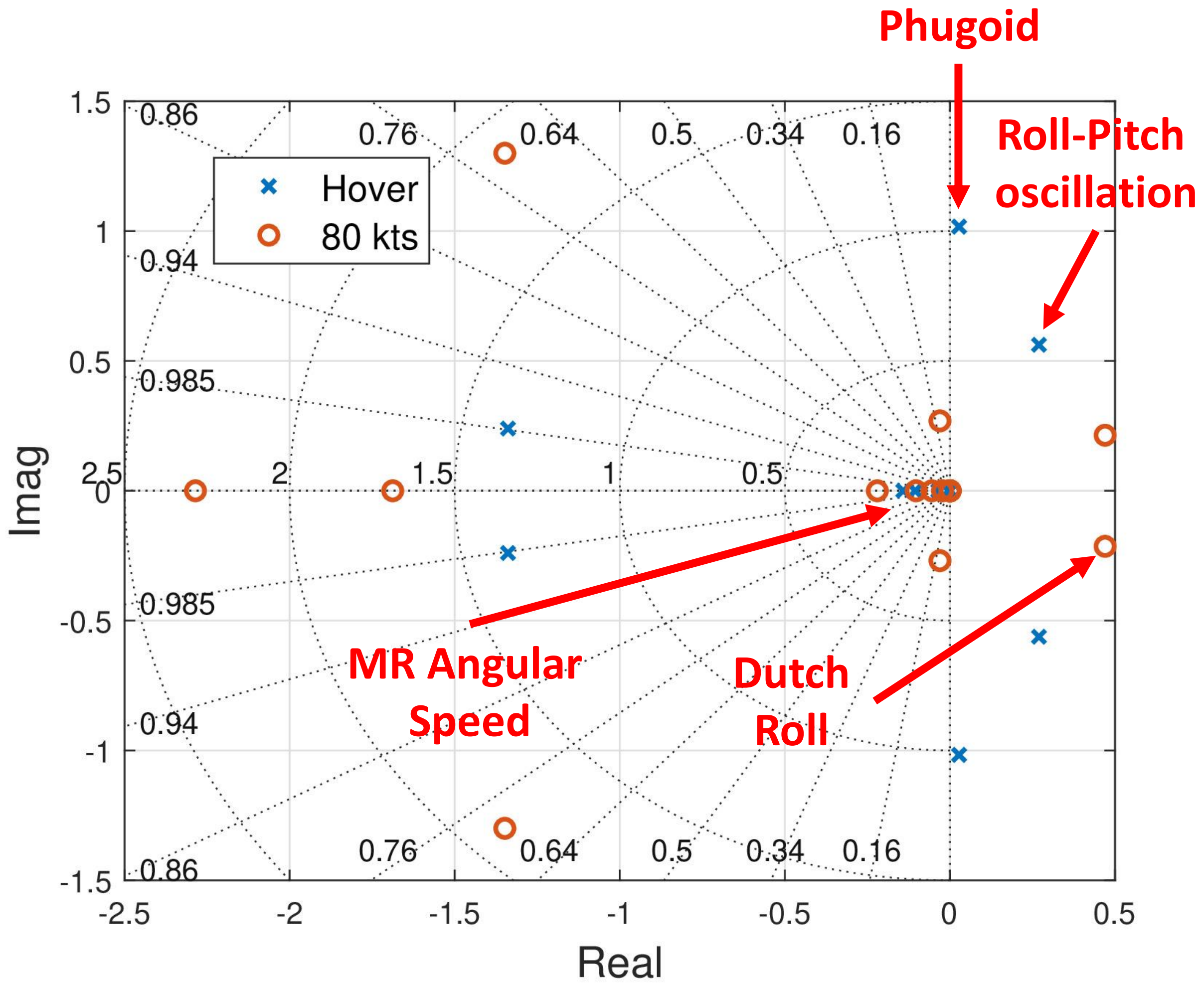


Rigid-body eigenvalues

Dynamic Stability

Eigenvalues at Hover

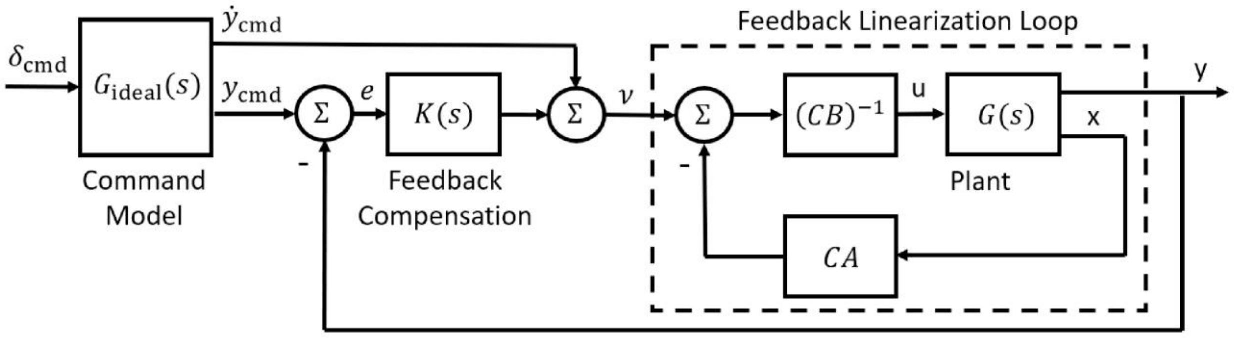
Mode	Eigenvalue
Roll-Pitch Oscillations	$-1.3387 \pm 0.2397i$
Roll-Pitch Oscillations	$0.2697 \pm 0.5620i$
Phugoid	$0.0276 \pm 1.0171i$
Heave Subsidence	-0.1053
Yaw Subsidence	-0.0045
Main Rotor Angular Speed	-0.1416
Main Rotor Collective Inflow	-1.8445
Main Rotor Cyclic Inflow (2x)	-10.4566
eProp Inflow	-101.6494
eProp Inflow	-101.1208
eProp Inflow	-101.1476
eProp Inflow	-101.6137

Eigenvalues at 80 kts

Mode	Eigenvalue
Short Period	$-1.3377 \pm 1.1845i$
Phugoid	$-0.0386 \pm 0.2476i$
Dutch Roll	$0.4672 \pm 0.2049i$
Coupled Subsidence/Spiral Mode	-2.1776
Coupled Subsidence/Spiral Mode	-1.7793
Main Rotor Angular Speed	-0.2209
Main Rotor Collective Inflow	-16.4377
Main Rotor Cyclic Inflow (2x)	$-24.935 \pm 7.7208i$
eProp Inflow	-94.7127
eProp Inflow	-94.2907
eProp Inflow	-94.6667
eProp Inflow	-94.3279

Flight Control Design

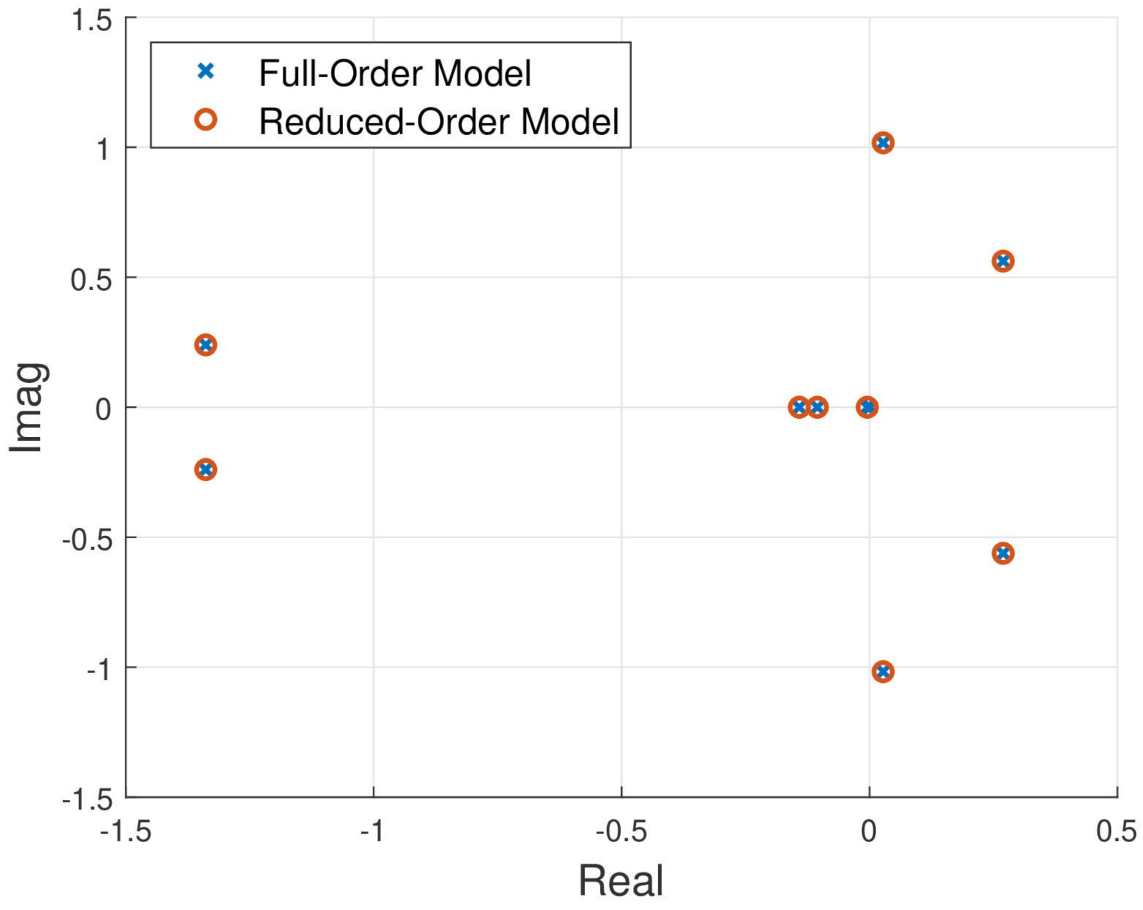
- Non-Linear Dynamic Inversion (NLDI)
  - ❑ Model-following scheme
  - ❑ Extensively studied in rotorcraft community
  - ❑ Popular among aircraft/rotorcraft manufacturers
- NLDI key components
  - ❑ **Command model** to specify desired response to pilot cmds
  - ❑ **Feedback compensation** on tracking error
  - ❑ **Feedback linearization loop** to achieve model inversion
- Automatic Flight Control System (AFCS)
  - ❑ Based on NLDI
  - ❑ Provides **stability**, **disturbance rejection**, and **RCAH response** about roll, pitch, and yaw axes
  - ❑ RCAH response could potentially be implemented as partial-authority flight control system
  - ❑ Vertical speed command in heave axis
  - ❑ NLDI-based governor to hold MR angular speed constant



DI controller applied to linear system

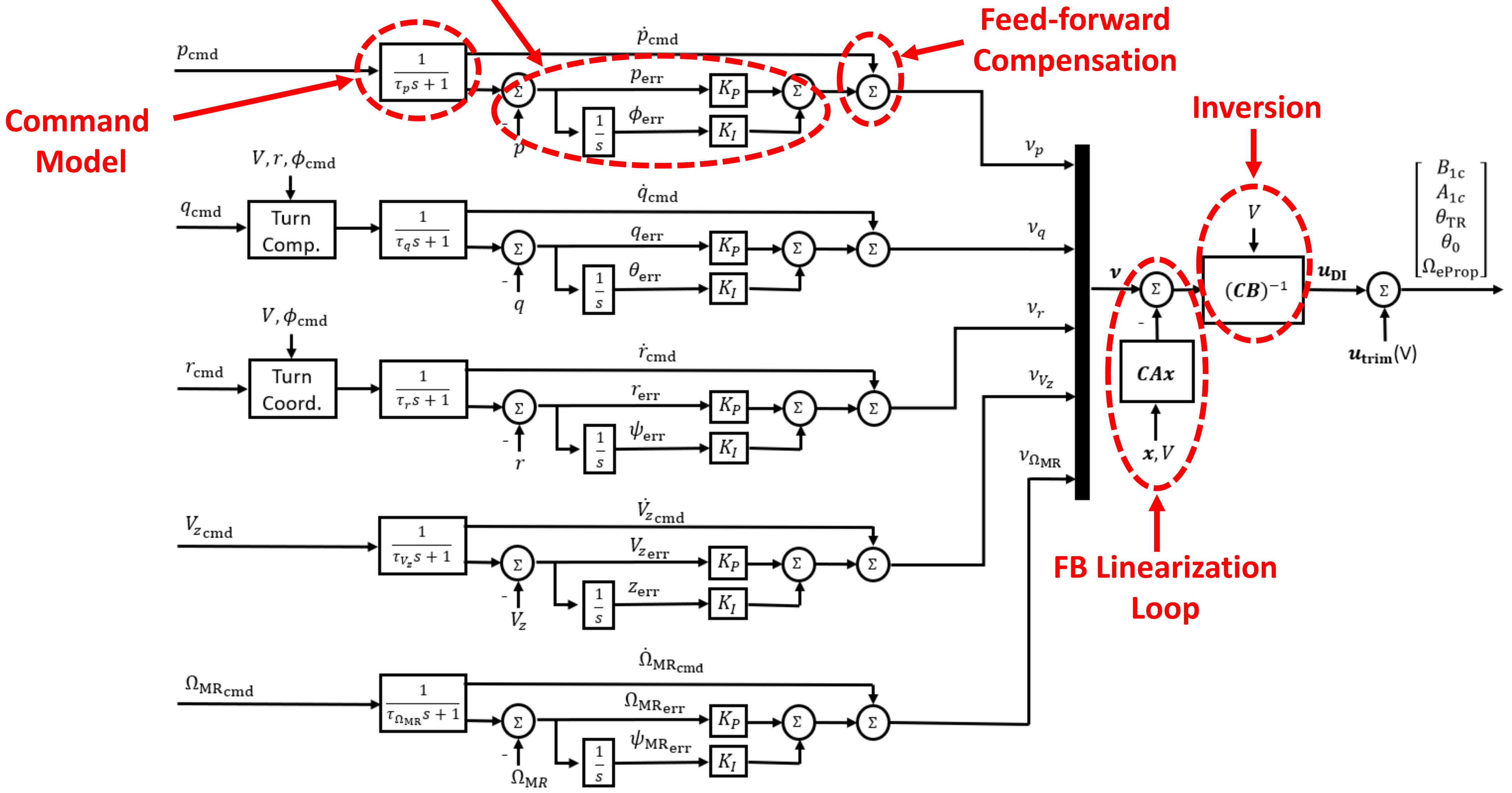
Flight Control Design

- Reduced-order models
  - NLDI requires full-state FB
  - Low-order models make design more tractable
- Residualization (singular perturbation theory)
  - **Slow states**: rigid-body states + angular speed dynamics (8 states)
  - **Fast states**: main rotor + eProps inflow
  - Low-order eigs overlap full-order eigs
- NLDI design
  - Based on reduced-order models
  - Control law: $\boldsymbol{u} = \left(\boldsymbol{C}\widehat{\boldsymbol{B}}\right)^{-1}\left(\boldsymbol{v} - \boldsymbol{C}\widehat{\boldsymbol{A}}\boldsymbol{x}_s\right)$
  - $\widehat{\boldsymbol{A}}$, $\widehat{\boldsymbol{B}}$, and $\boldsymbol{C}$ matrices scheduled with speed
  - Feedback gains chosen so that error dynamics is of same order of command models



Reduced-order vs full-order eigenvalues at hover

Flight Control Design



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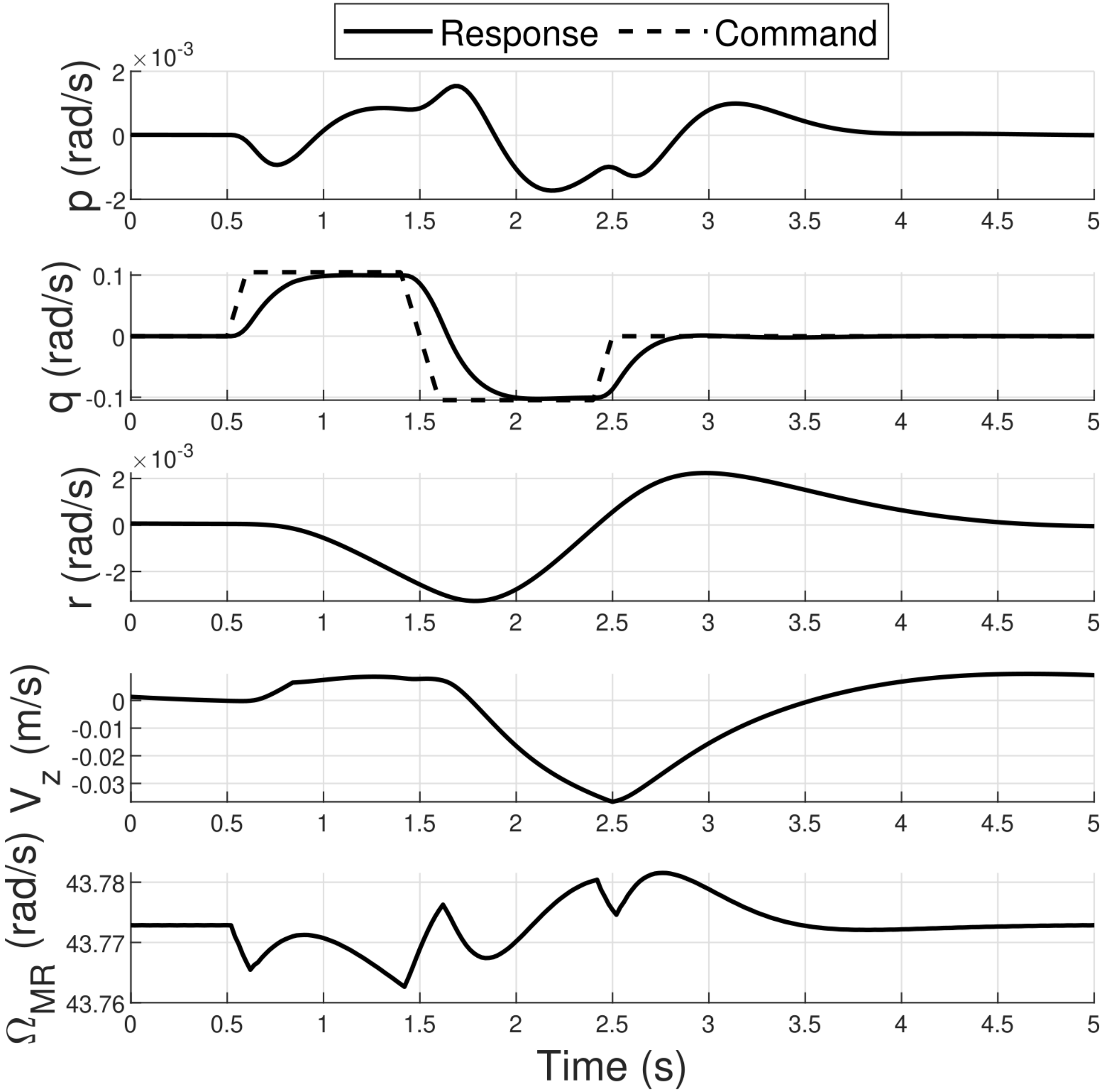
Flight Control Law Validatior

- NLDI control law implemented on nonlinear aircraft dynamics
- Test case 65 kts level flight (speed for max range)
- Response to 20% long. stick doublet
  - ❑Closed-loop systems tracks commanded pitch rate
  - ❑Off-axis response very well-contained
  - ❑MR angular speed held approx. constat by governor
- eProp inflow ratio
  - ❑Amplitude of oscillation of upper (front) rotor greater than lower (aft) rotor
  - ❑Front rotor of each eProp acts as filter to inflow of aft rotor
- NLDI control law successful in stabilizing aircraft while providing desired response



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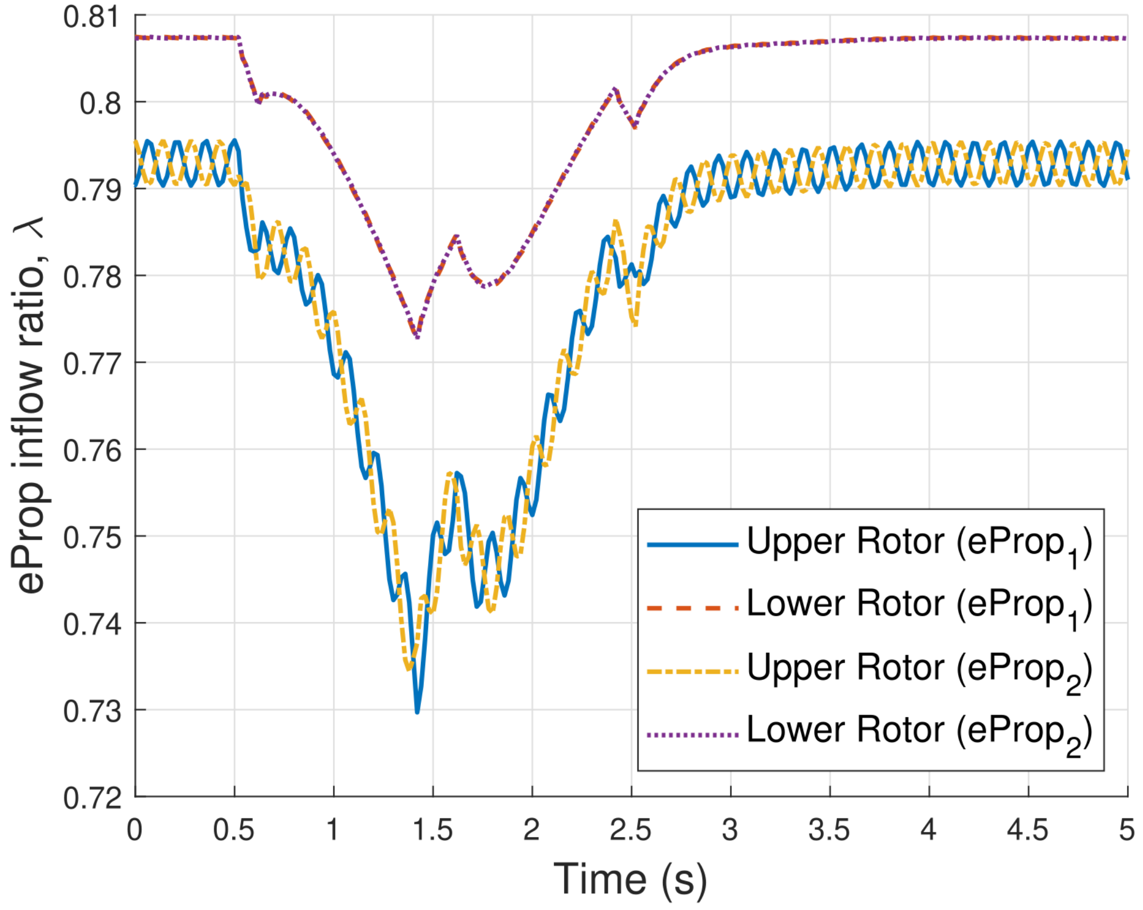
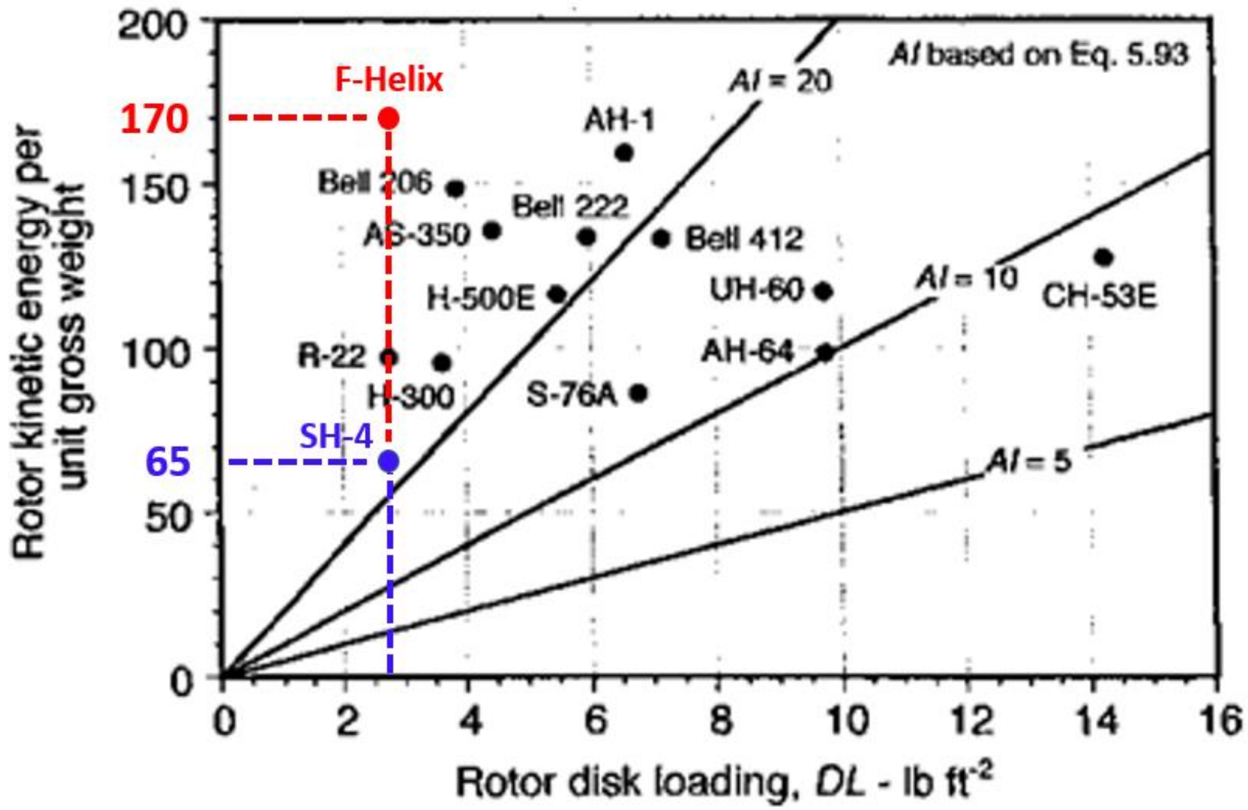


Autorotation Performance

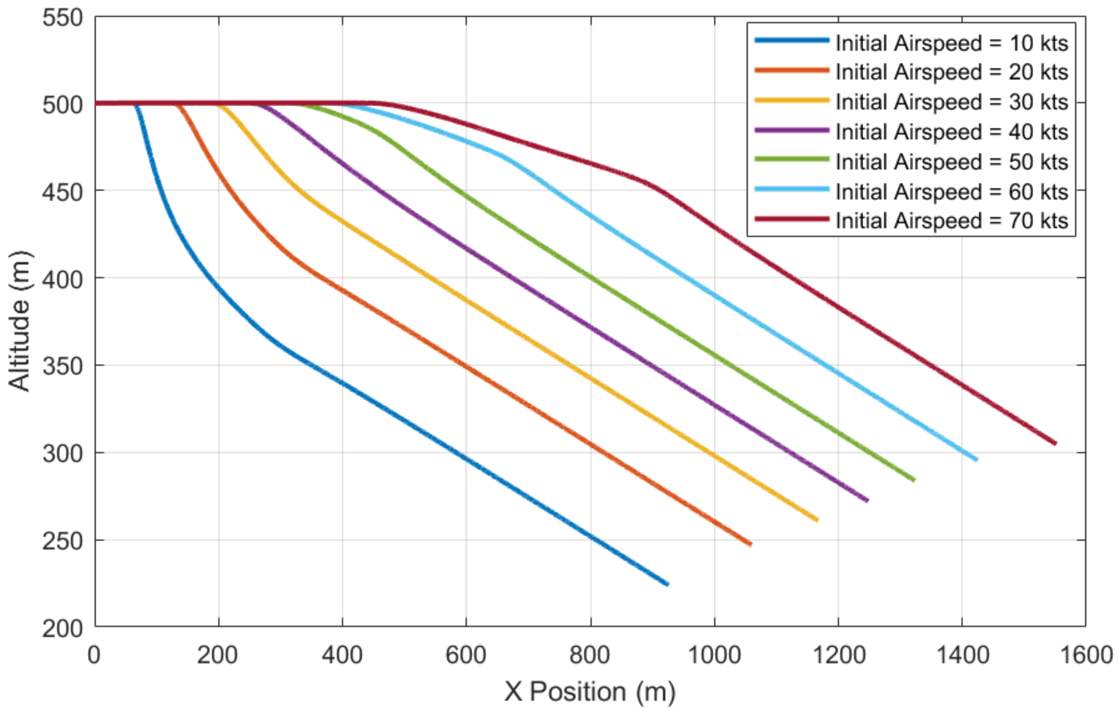
- High main rotor inertia
  - ❑Rotor inertia increased by ≈ 162%
- Potential safety benefits
  - ❑Decreased RPM decay rate
  - ❑Increased pilot reaction time
  - ❑No need to disengage clutch (no clutch)
- Autorotation Index (AI)
  - ❑Measure of autorotation performance
  - ❑Ratio of total kinetic energy to rotorcraft weight
  - ❑AI index higher than legacy and fielded rotorcraft



Autorotation index (recreated from Leishman)

Autorotation Performance

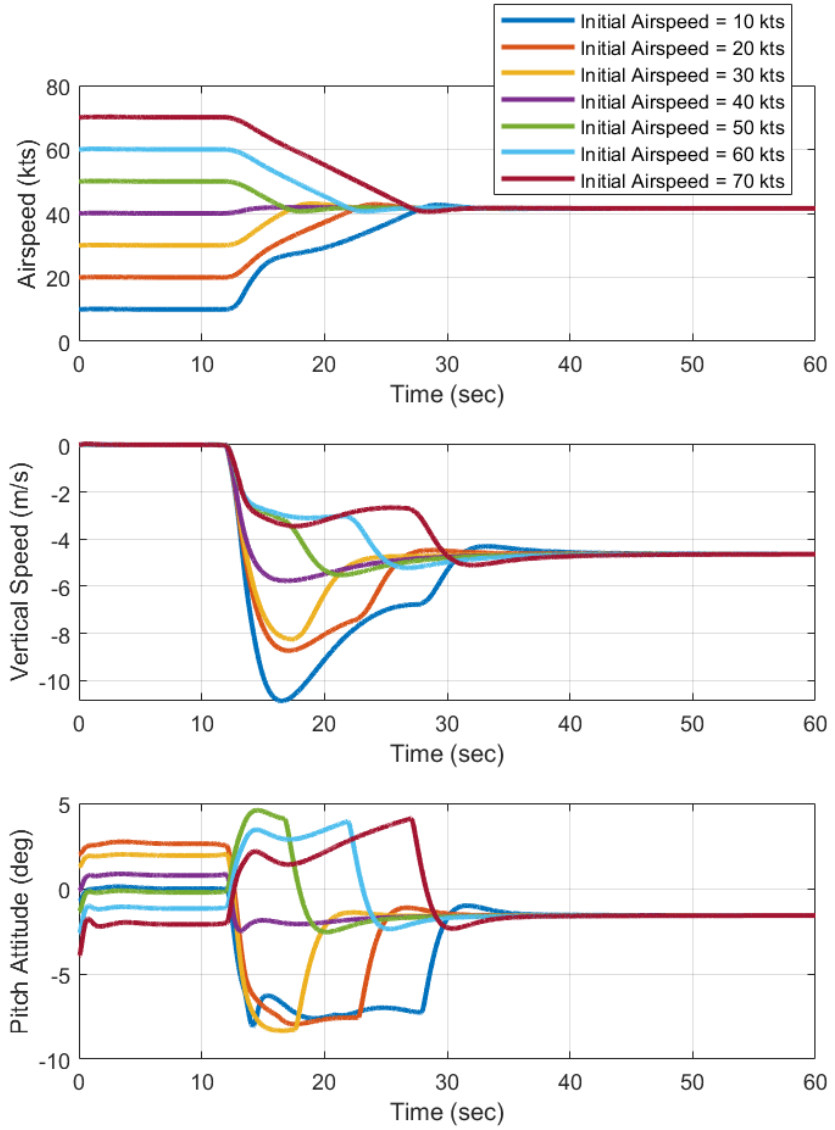
- Simulation performed following loss of power
  - ❑ Analyze autorotation performance
  - ❑ Verify potential safety benefits
- Following power loss, NLDI controller switches to **autorotation mode**
  - ❑ Added ACAH and airspeed hold
  - ❑ Vertical axis NLDI controller disabled
  - ❑ Collective moved to fixed position (≈ 4 deg)
  - ❑ Governor disabled
  - ❑ Airspeed controller commands 41 kts fwd speed (corresponds to min. descent rate of ≈ 4.5 m/s)
- Autorotation simulations
  - ❑ Power failure simulated by ramping down eProp RPM to zero over 1 sec
  - ❑ 2 sec pilot response time
  - ❑ Start at 500 m altitude
  - ❑ 50 sec duration
  - ❑ Initial speeds ranging 10-70 kts



Flight trajectories for autorotation simulation

Autorotation Performance

- No successful autorotations below 10 kts
  - ❑ Numerical instability when near vortex ring state
  - ❑ Possible issue with Pitt-Peters implementation
  - ❑ Not a limitation of configuration
- In all cases (10-70 kts) rotorcraft reaches steady-state autorotative descent
  - ❑ 41 kts fwd speed, 4.5 m/s descent rate
  - ❑ Higher initial speeds (50-70 kts) → deceleration so that initial desscent rate < 4.5 m/s
  - ❑ Slower initial speeds (10-40 kts) → acceleration so that initial desscent rate > 4.5 m/s
- Because of delay in power failure detection
  - ❑ Vertical axis controller initially tries to increase collective to maintain altitute
  - ❑ Delays descent but increases main rotor speed droop (11.5% due to high rotor inertia)
  - ❑ 2 sec pilot response time conservative



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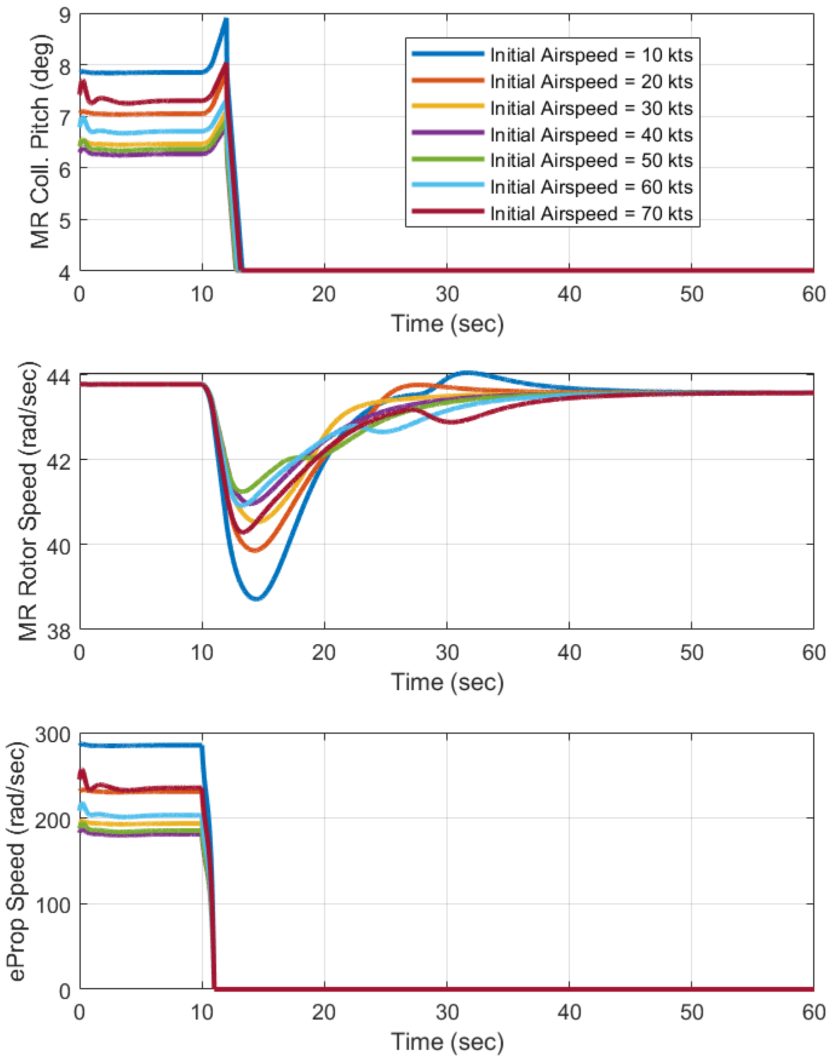
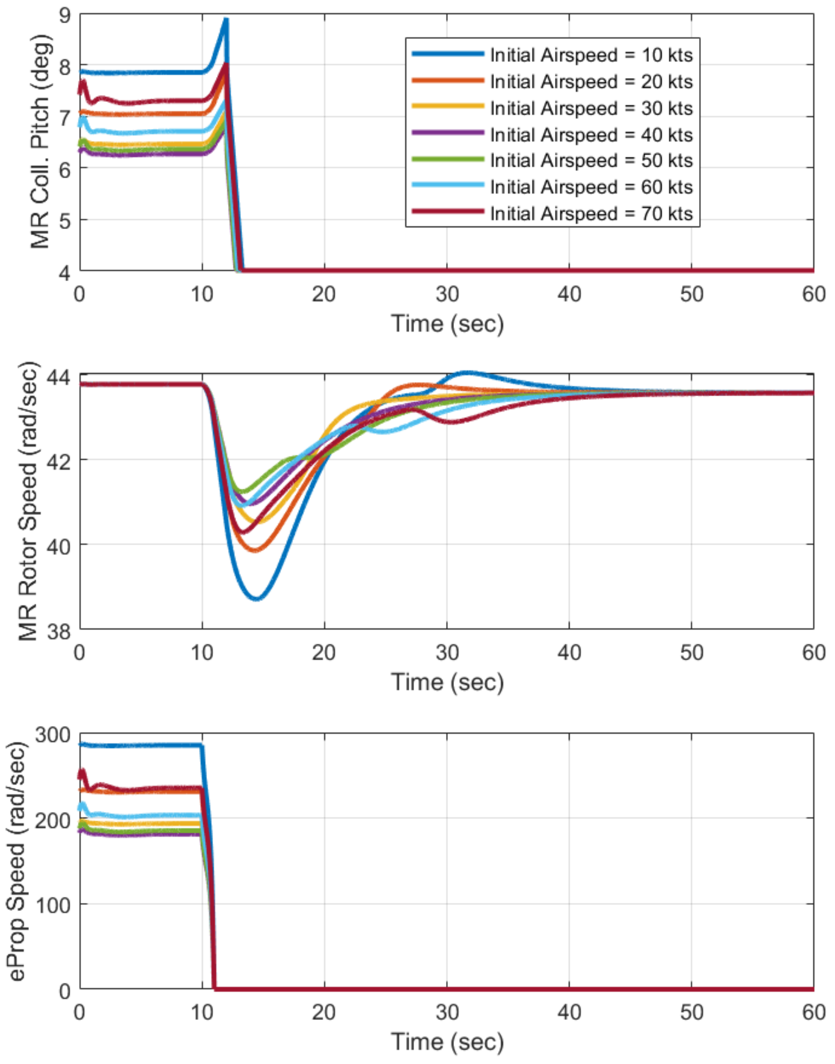


Autorotation Performance

- **Height-Velocity envelope**
  - ❑First steps towards prediction of **H-V diagram** for safe autorotation
  - ❑Can only predict **entry phase** where rotorcraft reaches steady-state
  - ❑In emergency autorotations at low altitude helicopter may not reach steady descent rate
  - ❑Need for more complex dynamic maneuver
- Overall, rotorcraft reaches steady descent with small transient droop in rotor RPM
- High-inertia rotor would also benefits
  - ❑Final flare maneuver
  - ❑Collective breaking maneuver to land rotorcraft



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Conclusion

1. **Aircraft trimmed with zero sideslip and roll angle simultaneously**
   - ❑No torque exchanged between main rotor and fuselage
   - ❑Not possible for standard helicopter configs.
2. **Dutch roll mode is unstable at high speeds**
   - ❑Lack of yaw damping from tail rotor
   - ❑Can add yaw damping with feedback control or increased vertical tail size
3. **Main rotor angular speed mode stable at hover and high-speed flight**
4. **Dynamics of the heave and yaw axes are decoupled**
   - ❑No torque exchanged between the main rotor and fuselage
   - ❑Favorable response characteristic when comparing to standard helicopter configs.
5. **Front rotor of each eProp acts as a filter for the lower rotor inflow**
6. **Small transient droop in rotor RPM following total loss of power**
   - ❑High-inertia rotor

Acknowledgements

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The End

Thank you

Questions?