ARDUPILOT

Versatile, Trusted, Open

Traditional Helicopter Update

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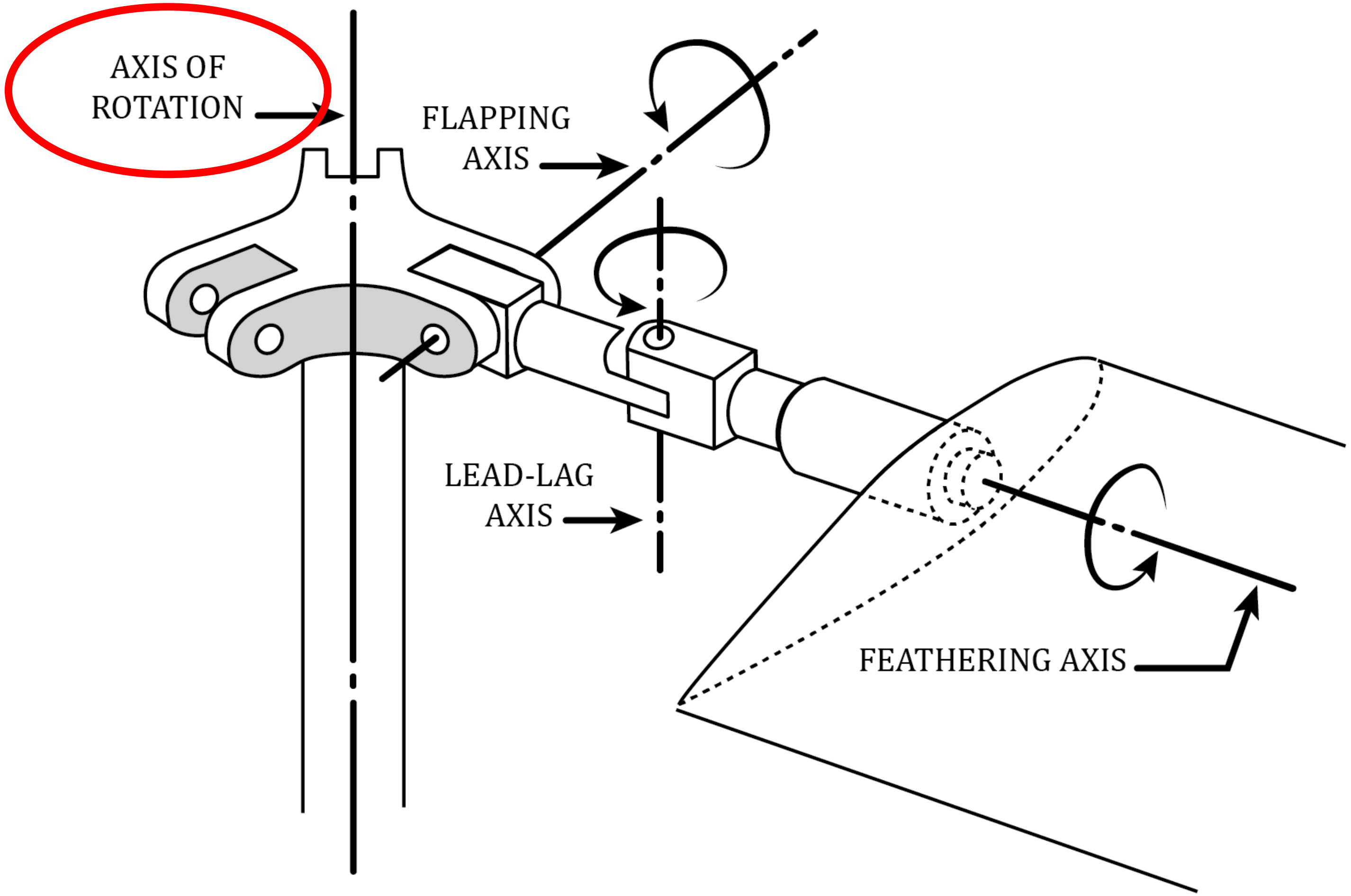
Tradheli Maintainer

Outline

- Introduction to Rotor Dynamics
- Current State of Tradheli Code
- Current Projects
  - Tuning Challenges
  - Harmonic Notch Impact on Tuning
  - Improved Command Model
  - Time Delay
  - Derivative Feedforward
- Future

Rotor Dynamics – Degrees of Freedom

- Rotor has 4 degrees of freedom
- Rotational
  - Rotates about shaft



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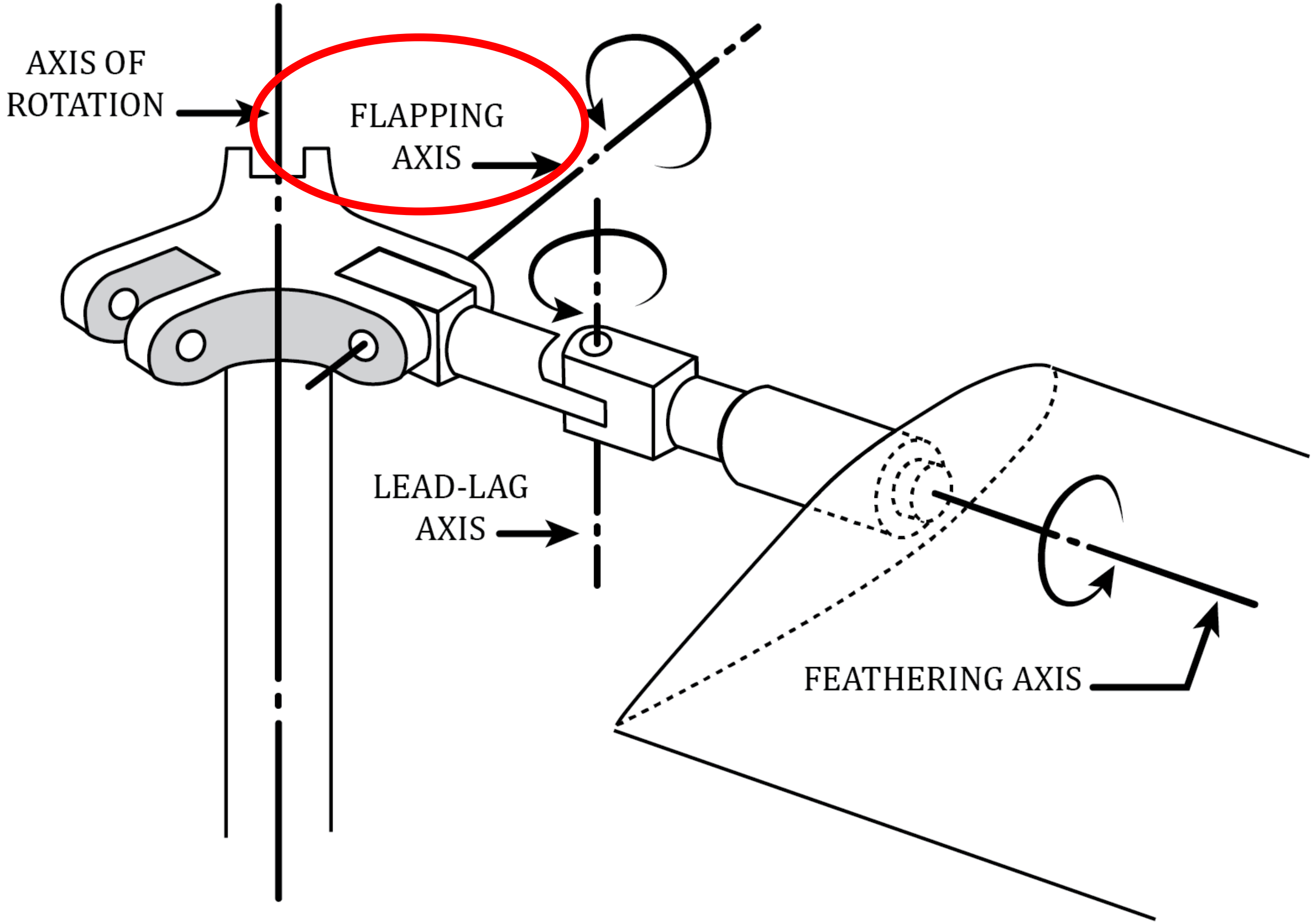
  - Blade vertical motion
  - Provides for helicopter control



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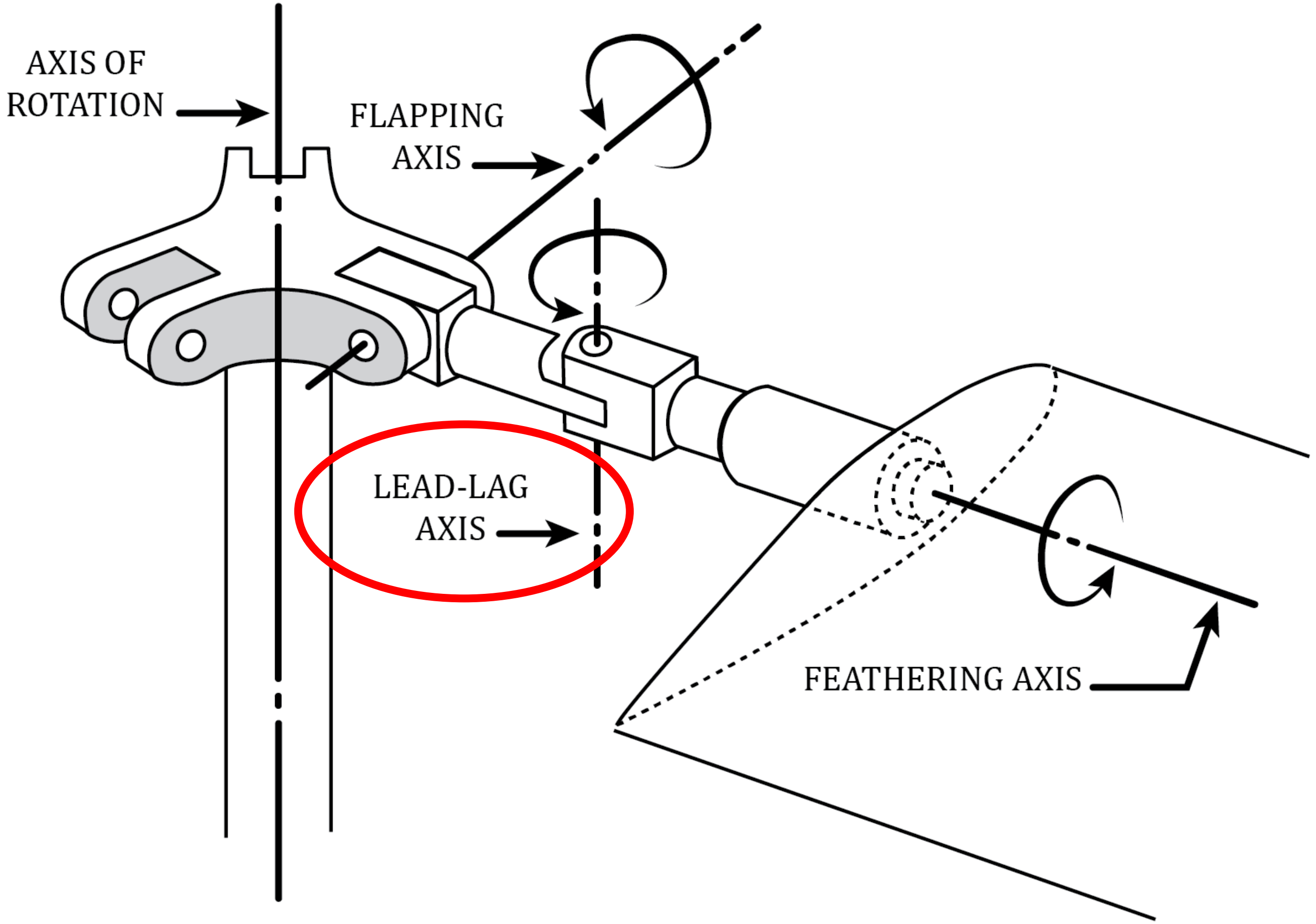
- Lead-Lag
  - Blade horizontal motion
  - Nuisance DOF with low damping



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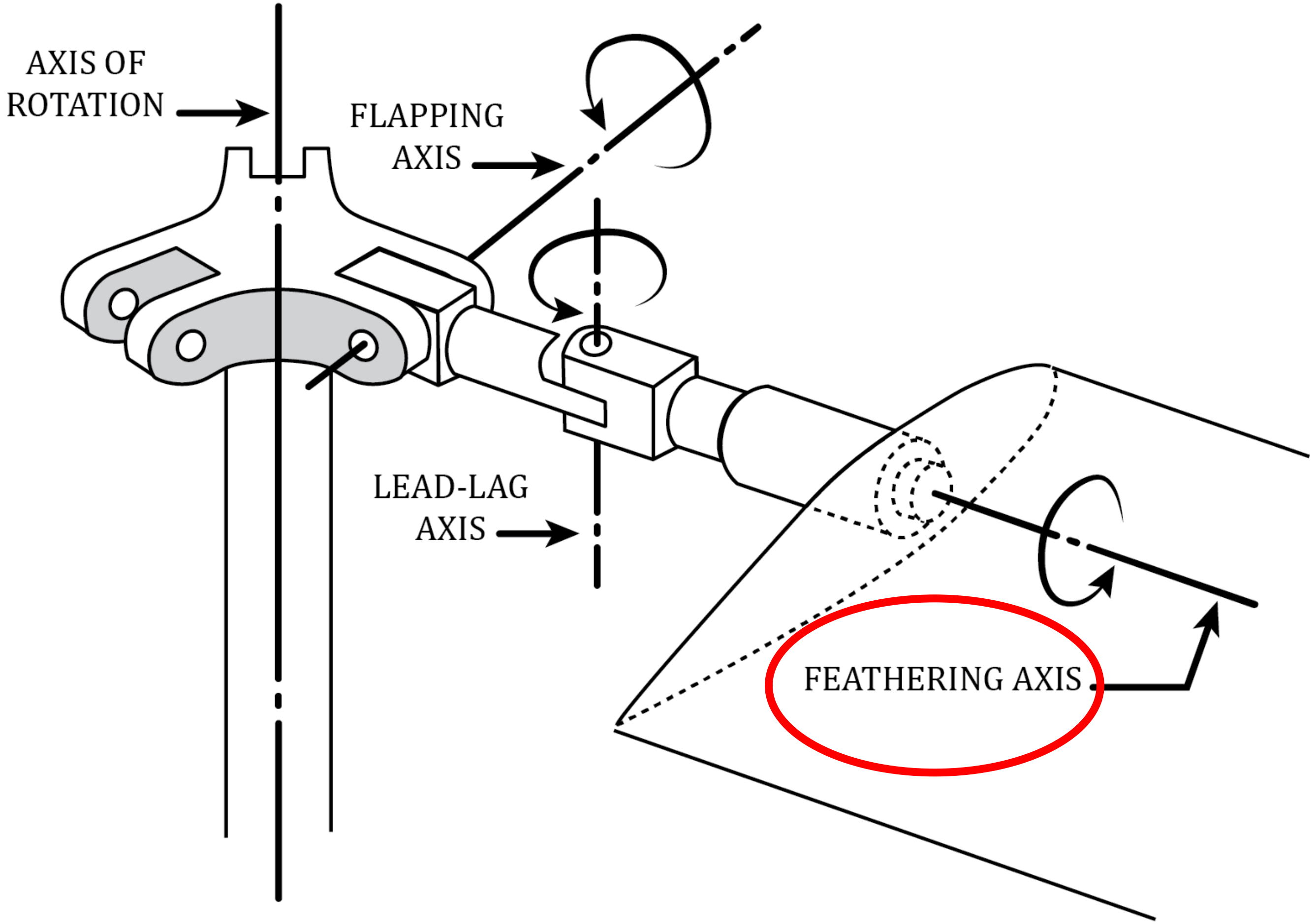
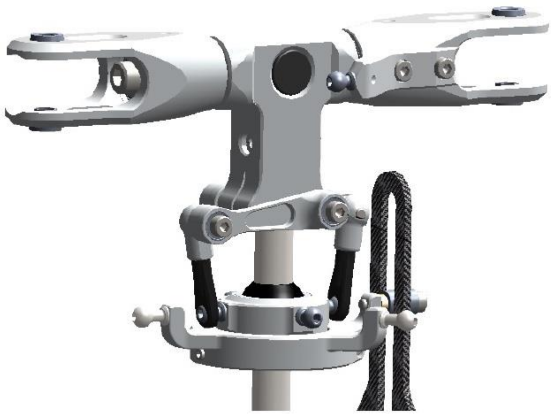
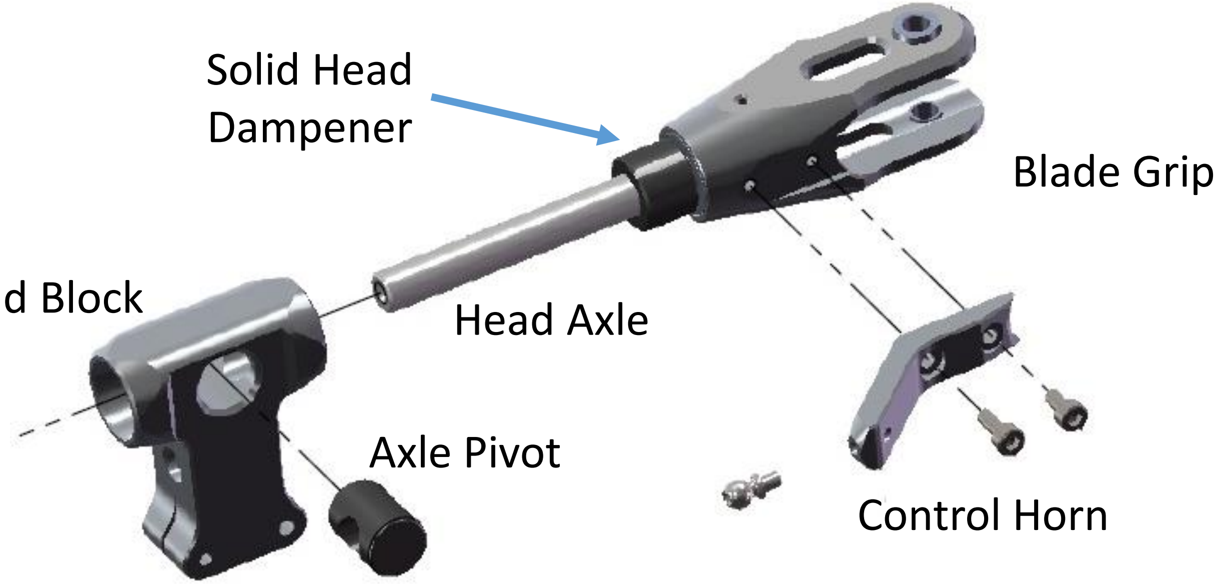
  - Nuisance DOF
- Feathering
  - Blade pitch controlled by swashplate



Rotor Dynamics – Teetering

- Flapping hinge over shaft
  - Full scale in most cases don't have dampener
  - Model scale uses dampener to provide faster aircraft response
- Lead-lag pinned at blade grip
  - Full scale restrain lead-lag



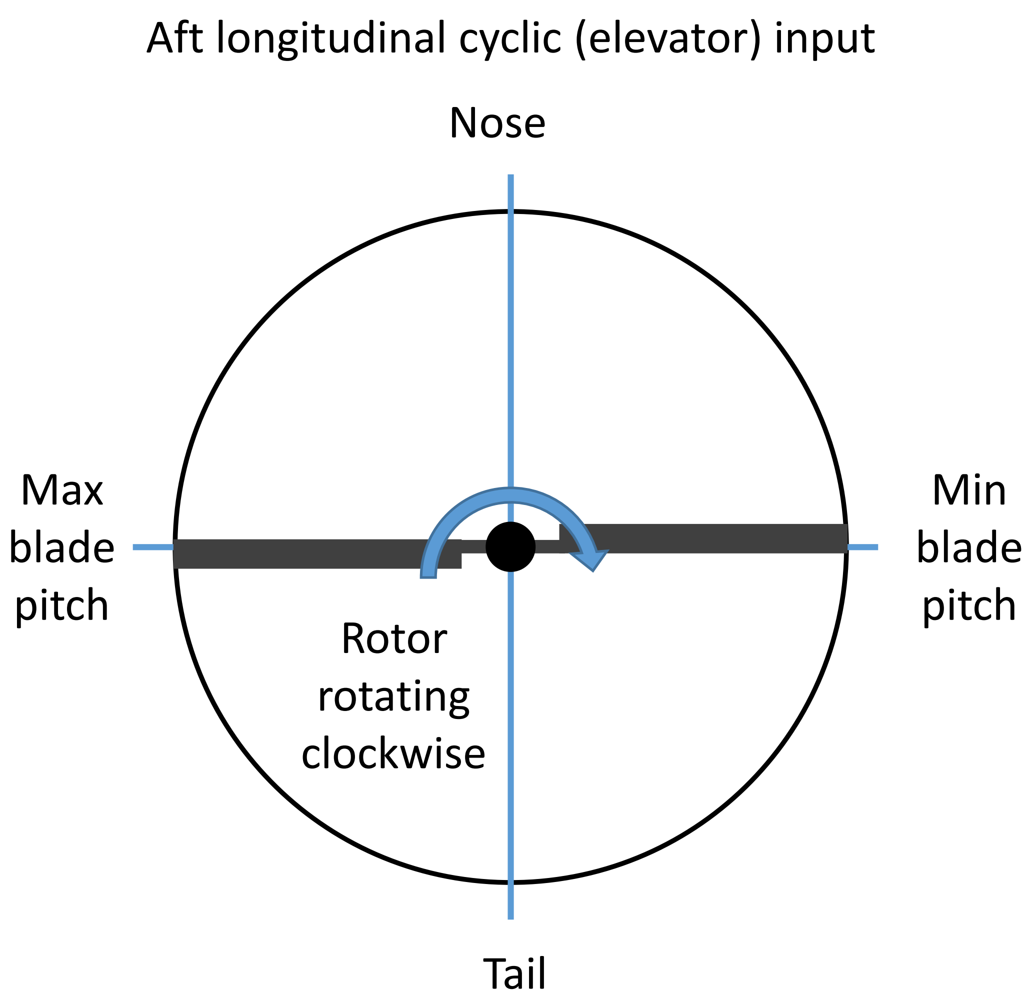


Rotor Dynamics – Hingeless

- Flapping accomplished thru flexible blade
  - Provides faster aircraft response
- Lead-lag pinned at blade grip

Rotor Dynamics – Rotor Phase Lag

- Rotor phase lag is the change in azimuth angle from when max cyclic pitch is made to when max rotor flapping is seen
- Phase lag is 90 deg for teetering rotor system with no dampener



Rotor Dynamics – Rotor Phase Lag

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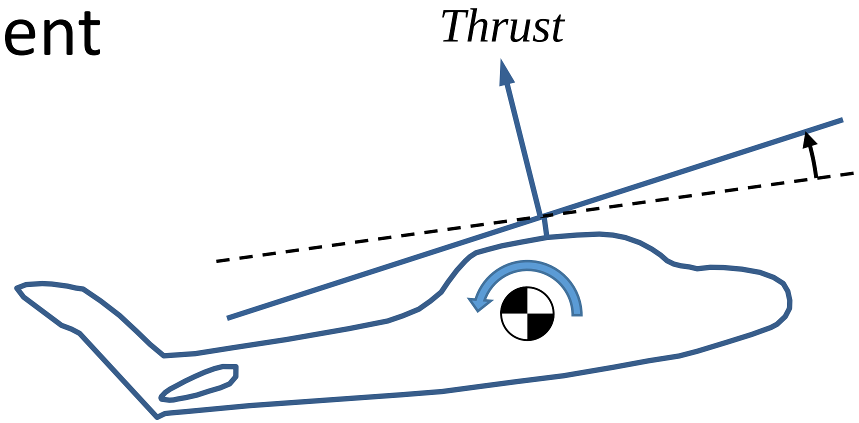
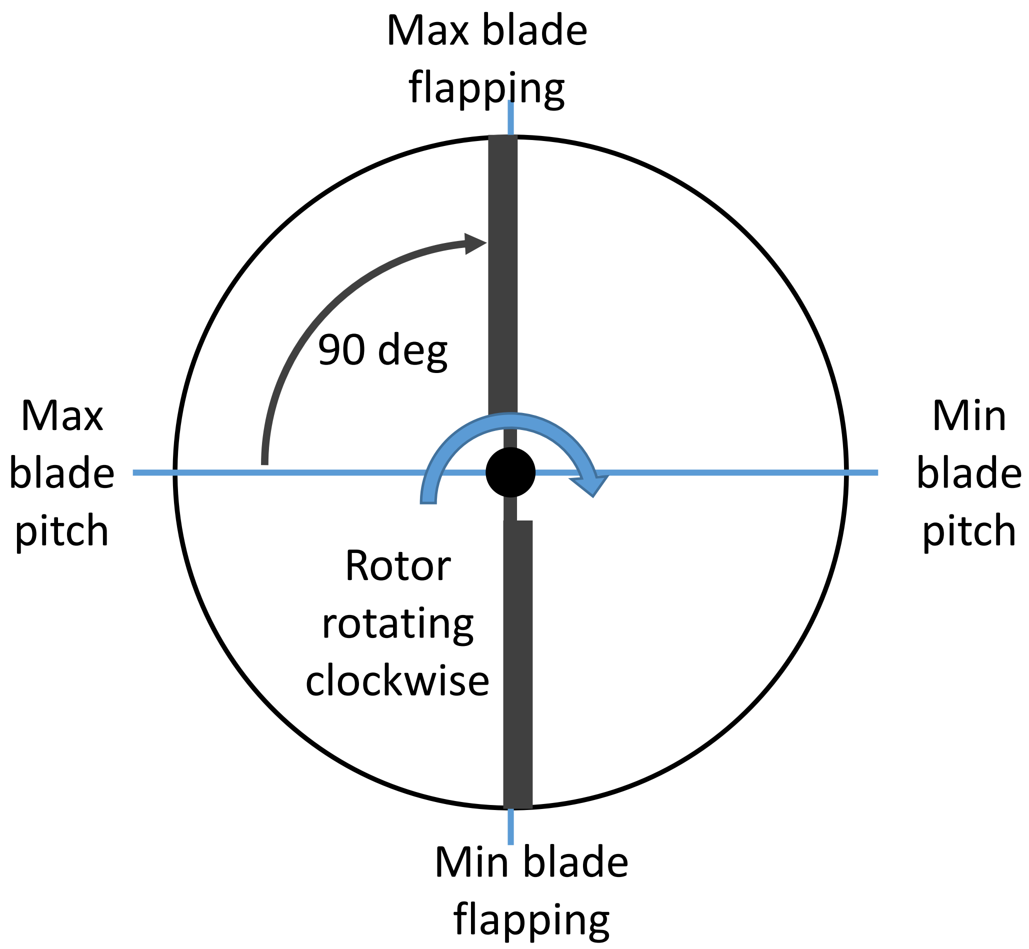
- Phase lag is 90 deg for teetering rotor system with no dampener
- Tip path plane tilts creating pitching moment

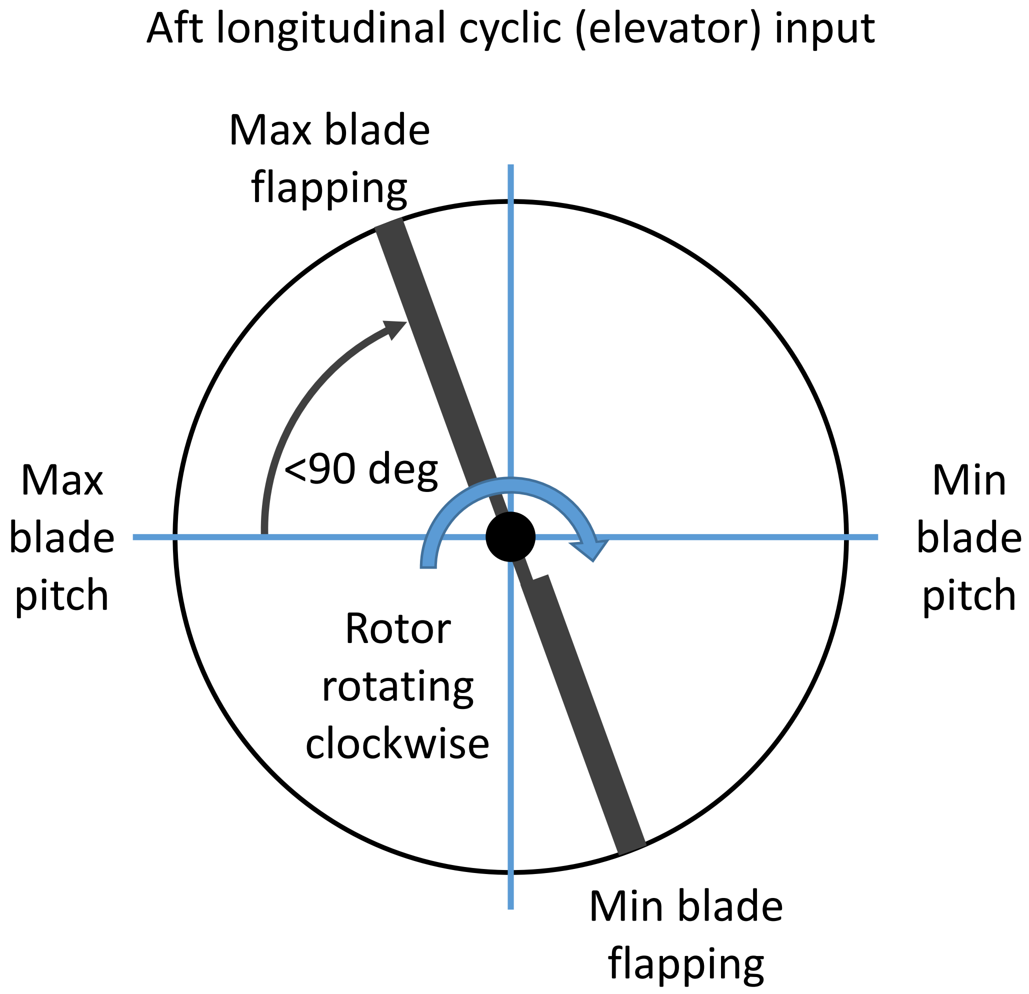


Aft longitudinal cyclic (elevator) input



Rotor Dynamics – Rotor Phase Lag

- Rotor phase lag is the change in azimuth angle from when max cyclic pitch is made to when max rotor flapping is seen
- Phase lag is less than 90 deg for teetering rotors with dampeners or hingeless rotors
- Rotor tilts aft and to the right causing roll coupling



Current State of Tradheli

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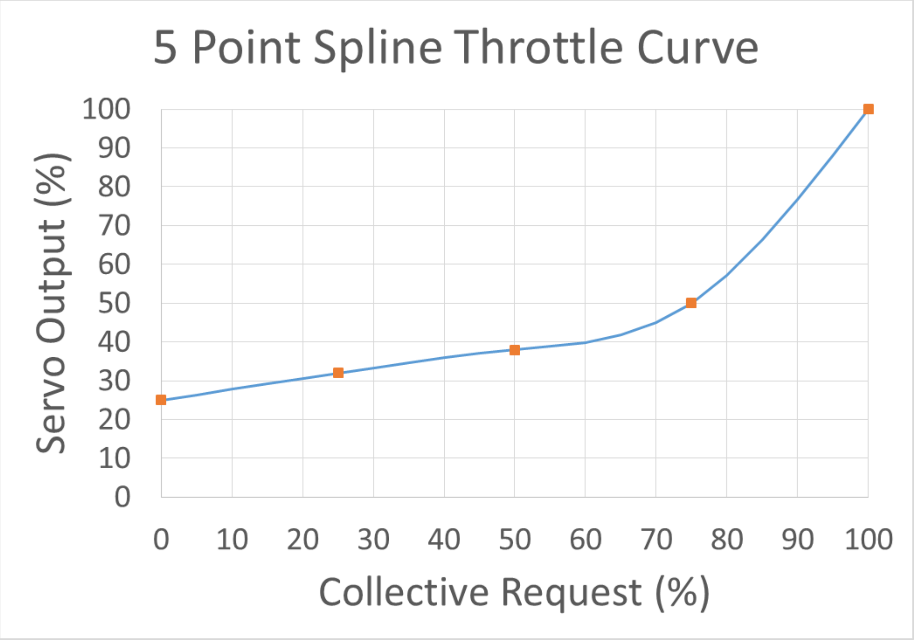
- Maintenance
  - Servo library
  - Spool Logic
- Improvements/enhancements since AC 3.3.3
  - 5 point spline throttle curve
  - Wiki updates to include setup videos
  - Heli setup page in QGC and Mission Planner
  - Rotor governor
  - Swashplate library
  - Linearize swashplate servo output
  - Virtual Flybar
  - Autonomous Autorotation in SITL (Matt Kear)



New Universal Heli Setup Page

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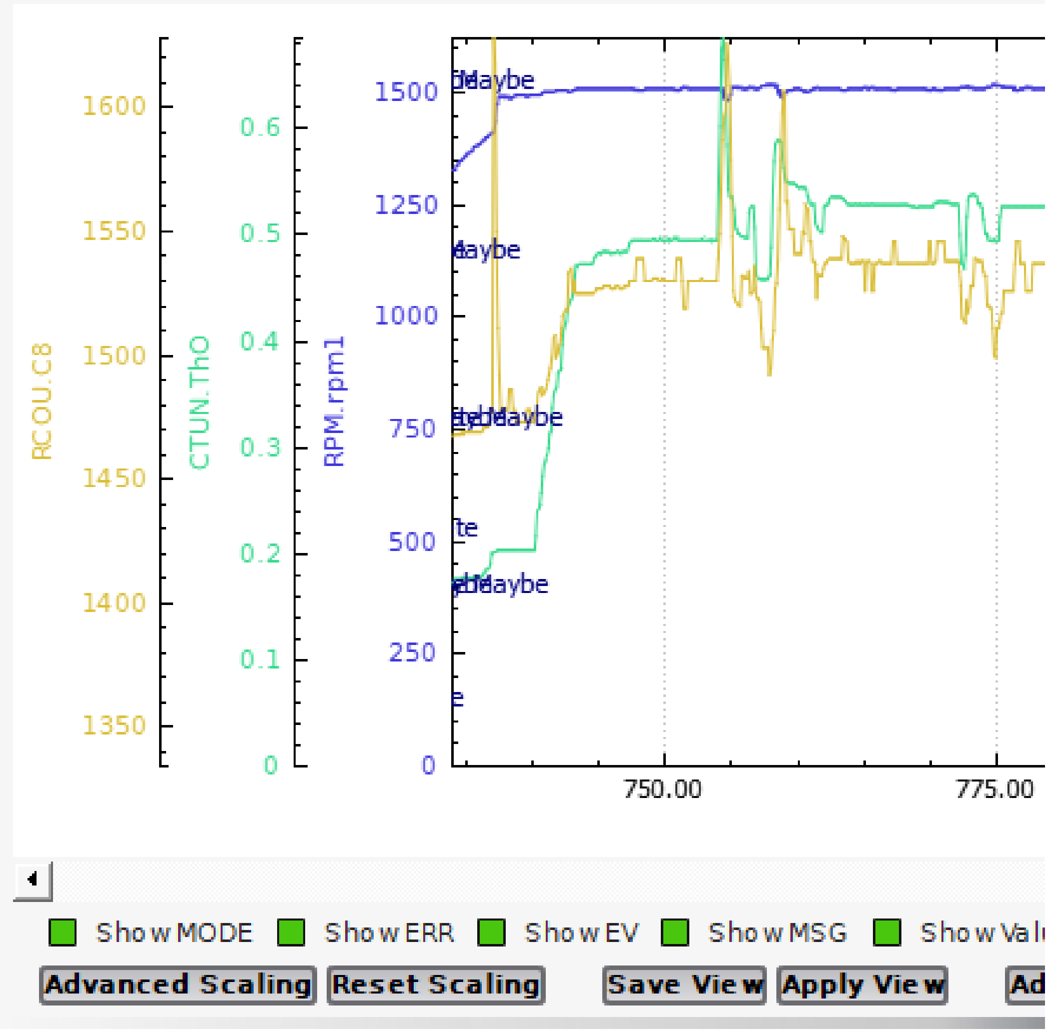
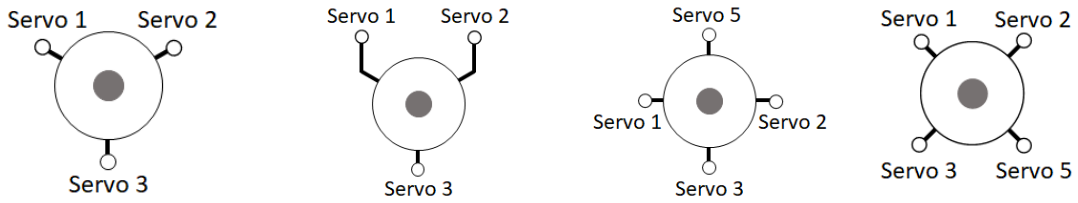
Rotor Governor

- Developed within the Rotor Speed Controller
- Design
  - Based on mechanical governors
  - Uses only a proportional controller based on the rotor droop (rotor speed error)
  - Throttle curve used for feedforward input
- Requires an RPM sensor
- Overwhelmingly positive response from users on governor performance



Swashplate Library

- Supports all popular swashplate types
  - H1, H3-120, H3-140, H4-90, H4-45



- Available on Single and Dual heli
  - Dual can set individual swashplate types for each rotor
- Retained generic H3 swashplate
  - Enables virtual rigging adjustment through phase parameter

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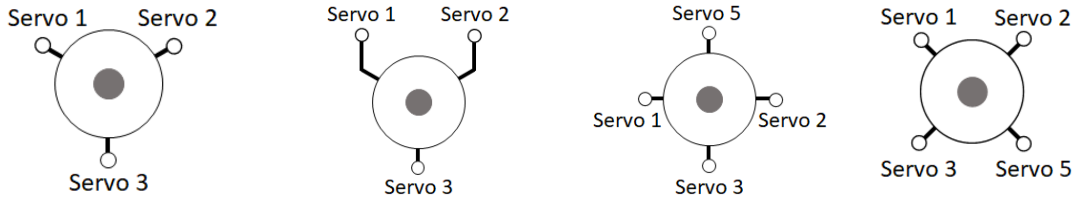
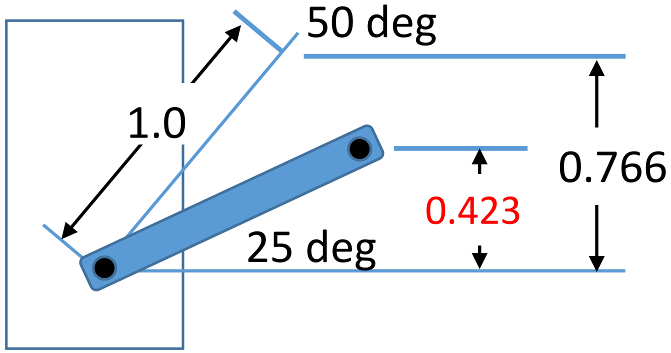


- Available on Single and Dual heli
  - Dual can set individual swashplate types for each rotor
- Retained generic H3 swashplate
  - Enables virtual rigging adjustment through phase parameter
- Linearized Servo Output
  - Modifies servo arm throw to remove nonlinear movement due to arm arc
  - Critical for 4 servo swashplate

Normal Servo
Servo request of 0.5



Linearized Servo
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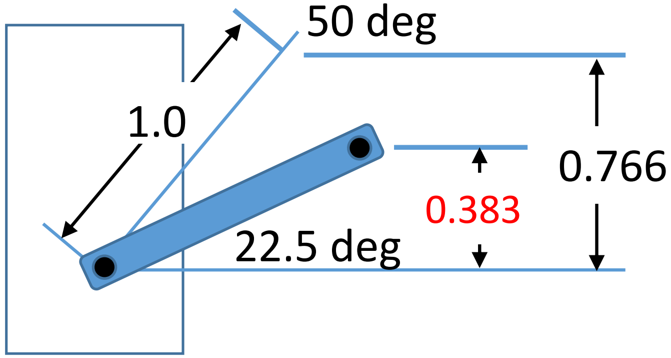

Virtual Flybar

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- Designed for Acro Flight Mode
- Issues with acro mode
  - Difficult to smoothly set and adjust attitude (attitude hold gives digital feel)
  - Not easy to judge requested attitude while on the ground
- Virtual Flybar provides the short term attitude retention of a real flybarred helicopter
- Attitude error in pitch and roll is leaked off
  - On the ground, allows pilot to center the swashplate by centering the stick
  - During flight, provides a softer feel similar to a trim follow up.
- Set by having non zero ACRO_BAL_PITCH and ACRO_BAL_ROLL with ACRO_TRAINER disabled.

Tuning Challenges

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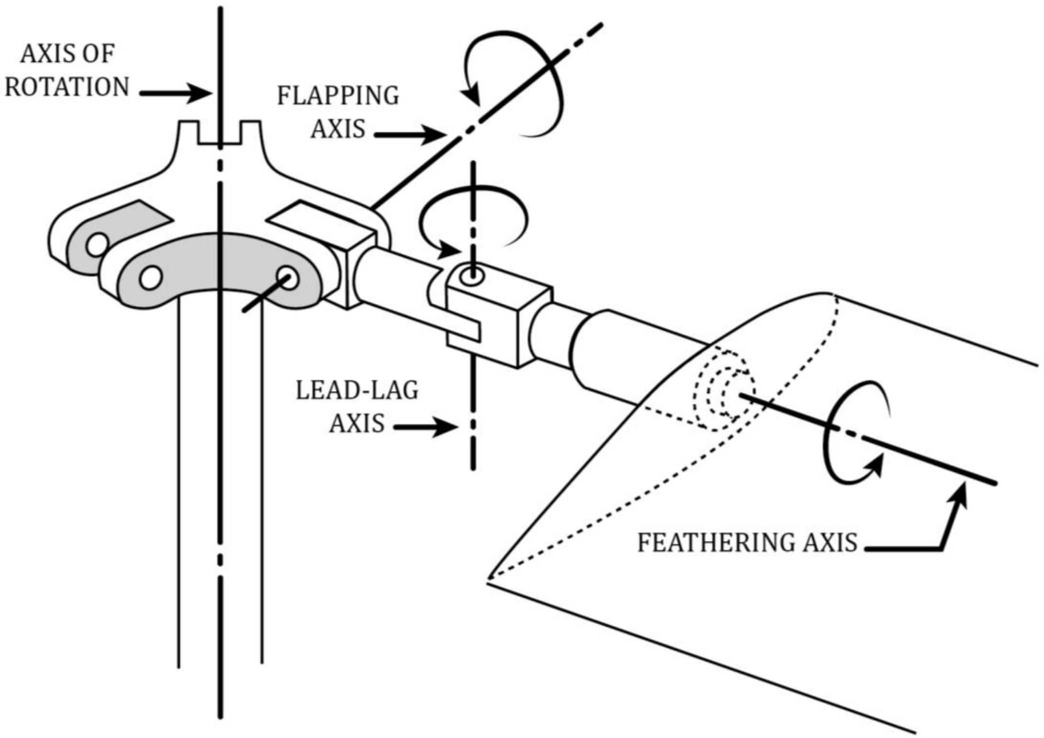
- Lightly damped rotor modes for RC helicopters
- Effectiveness of feedback loops with low (<10 hz) low-pass filter cutoff frequencies
- Significant lags (~100 msec) in aircraft response
  - Rotor response time constant around 50-70 msec
  - Potentially longer lags with softer rotor systems or larger aircraft
  - Addition lag up to 50 msec or more for actuator lag
- Unrealistic target response for larger/slower aircraft

Rotor Dynamics

- Lightly damped rotor modes limit rate controller P and D gain tuning
  - Feedback loops drive rotor unstable
- Flap regressive
  - Rotor mode most likely to excite
  - Hard to compute natural frequency
    - Depends on vehicle inertia and rotor head stiffness
  - Typically frequency approximately 3 to 5 hz
- Lead-lag regressive
  - Higher frequency than flap regressive
  - Easier to compute natural frequency due to pinned blades
  - Frequency around 50% rotor speed



Rotor Dynamics

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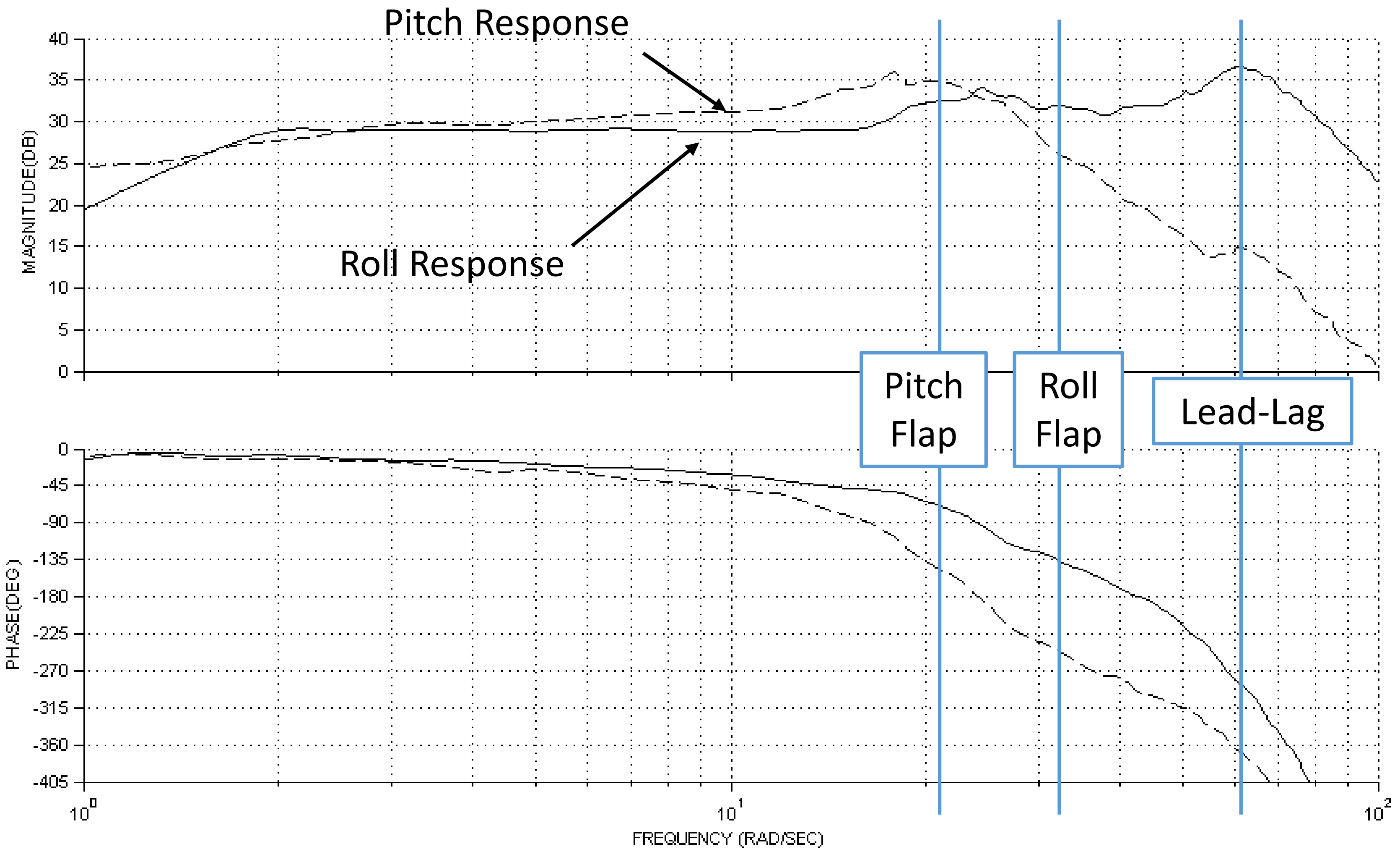
- Synergy 626 – 2 bladed
  - Time Delay
    - Pitch – 54 ms
    - Roll – 30 ms
  - Pitch flap regressive
    - Natural Freq - 3.5 hz
    - Damping ratio - 0.27
  - Roll flap regressive
    - Natural Freq - 5.2 hz
    - Damping ratio - 0.33
  - Lead-lag regressive
    - ~10 hz



Pitch and Roll Tuning Philosophy

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- Poor disturbance rejection due to low P and D gains
- Attitude feedback is necessary to provide stronger disturbance rejection
- Rate Controller
  - Rate Feedforward (VFF) used to match actual response to requested response
  - Rate P and D gains taken to oscillation and cut in half
  - Rate I gain set to match Rate VFF gain
- Attitude Controller
  - Increase ANG_P gain to at least 6 and as high as 10 if able with no unstable oscillations
- Harmonic Notch used to clean up response signals used for rate controller

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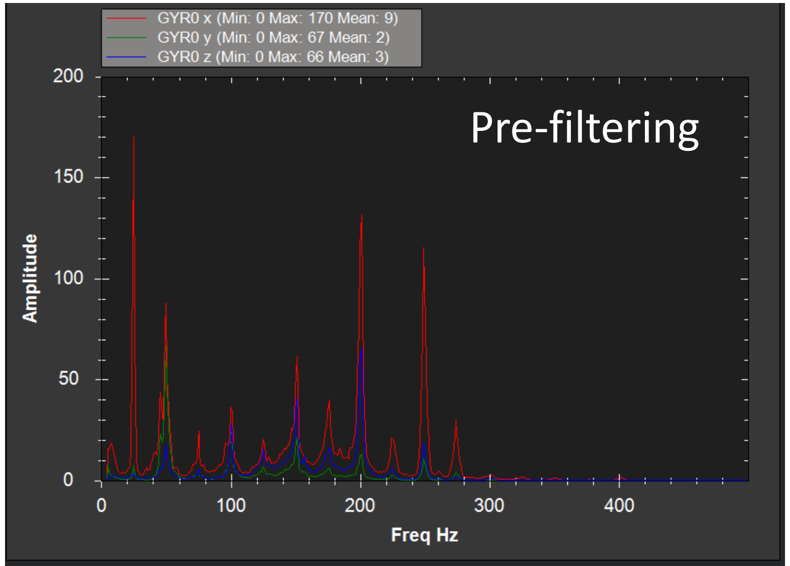
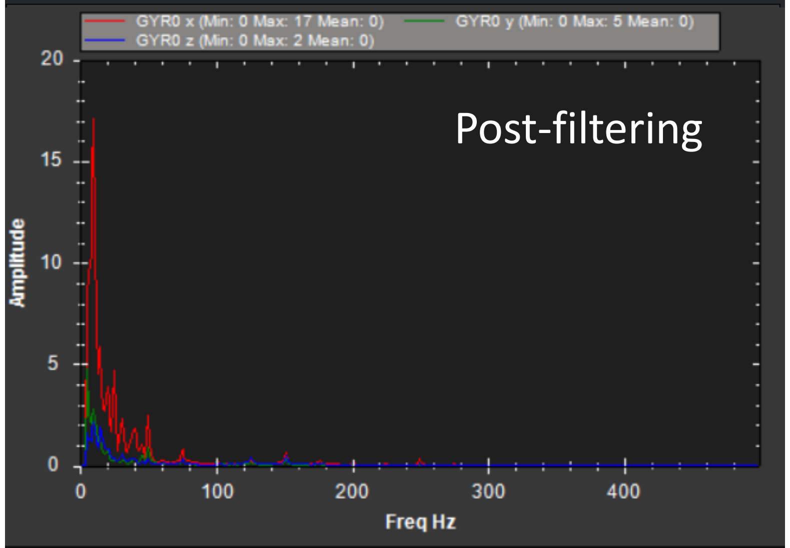
Harmonic Notch

- In most cases, rotor speed is kept constant
- Vibrations in helicopters are harmonics of the rotor speed
    - 1st Frequency – rotor speed
    - 2nd Frequency – N blades x rotor speed
    - 3rd Frequency – 2 x N blades x rotor speed
- If rotor speed is governed, make notch bandwidth small, ~10 hz
- Result is cleaner (less noise) signals for control feedback loops (rate controller)
- Doesn't exclude need to track and balance rotor





Improving the Controller

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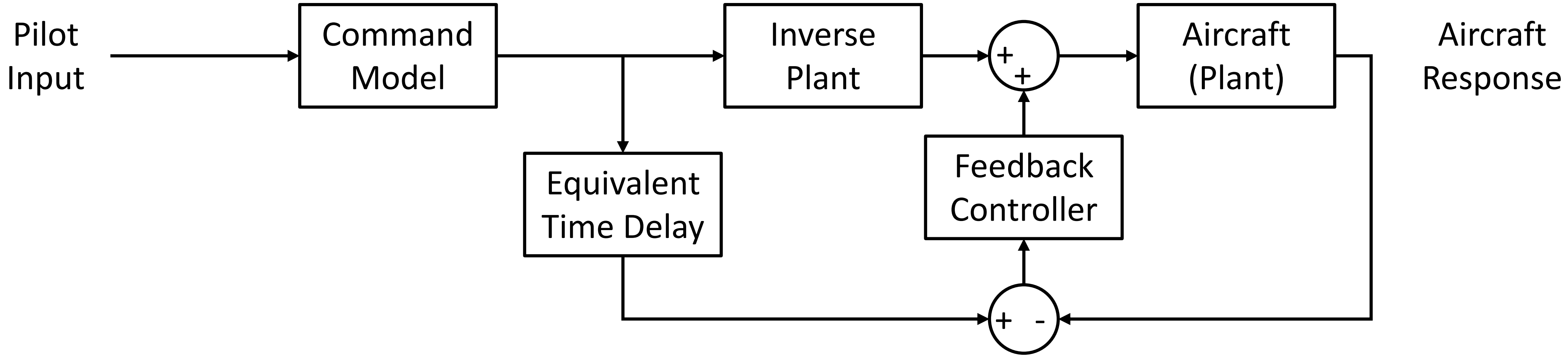
- Shaping functions (command model) that better represent vehicle dynamics
- Account for delays in system to account for better target value (command model) comparison with aircraft response
  - Delays due to actuator lag, filters, and aircraft response
  - Requires feedforward control
- Use a derivative term on feedforward to improve vehicle response
  - Can be used as feedforward for axes that are acceleration command
  - Act as a lead filter for axes that are rate command to help system overcome lags in response

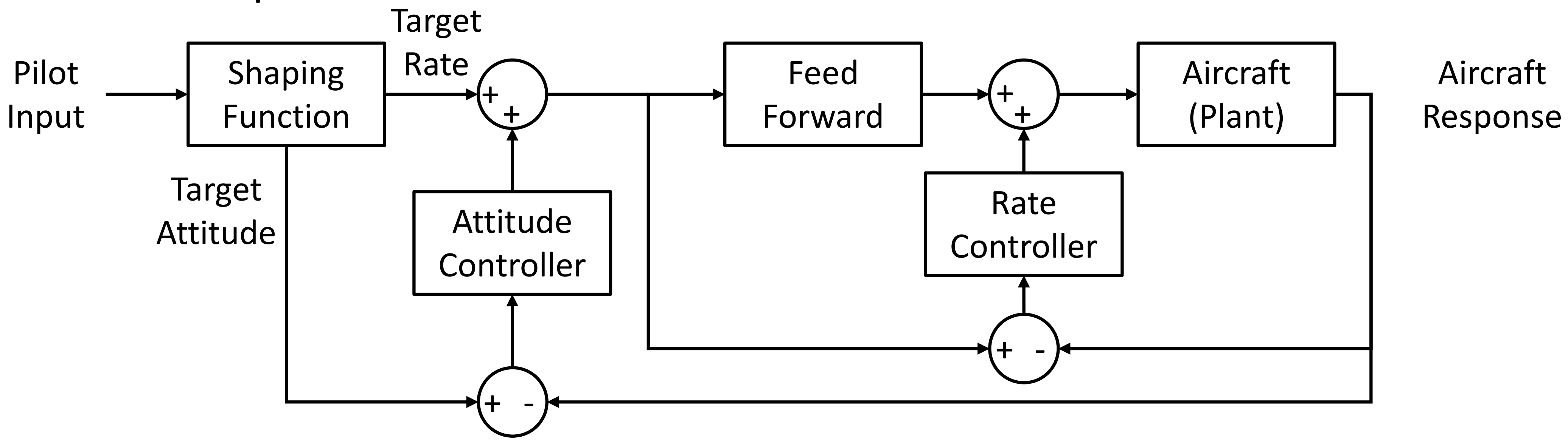
Control Law Architecture

- Explicit model following control law design
  - Command model defines desired target aircraft response
  - Inverse plant used to approximate controls required for target response
  - Feedback controller accounts for imperfect inverse plant and disturbances
  - Equivalent time delay accounts for aircraft delays to better match aircraft response



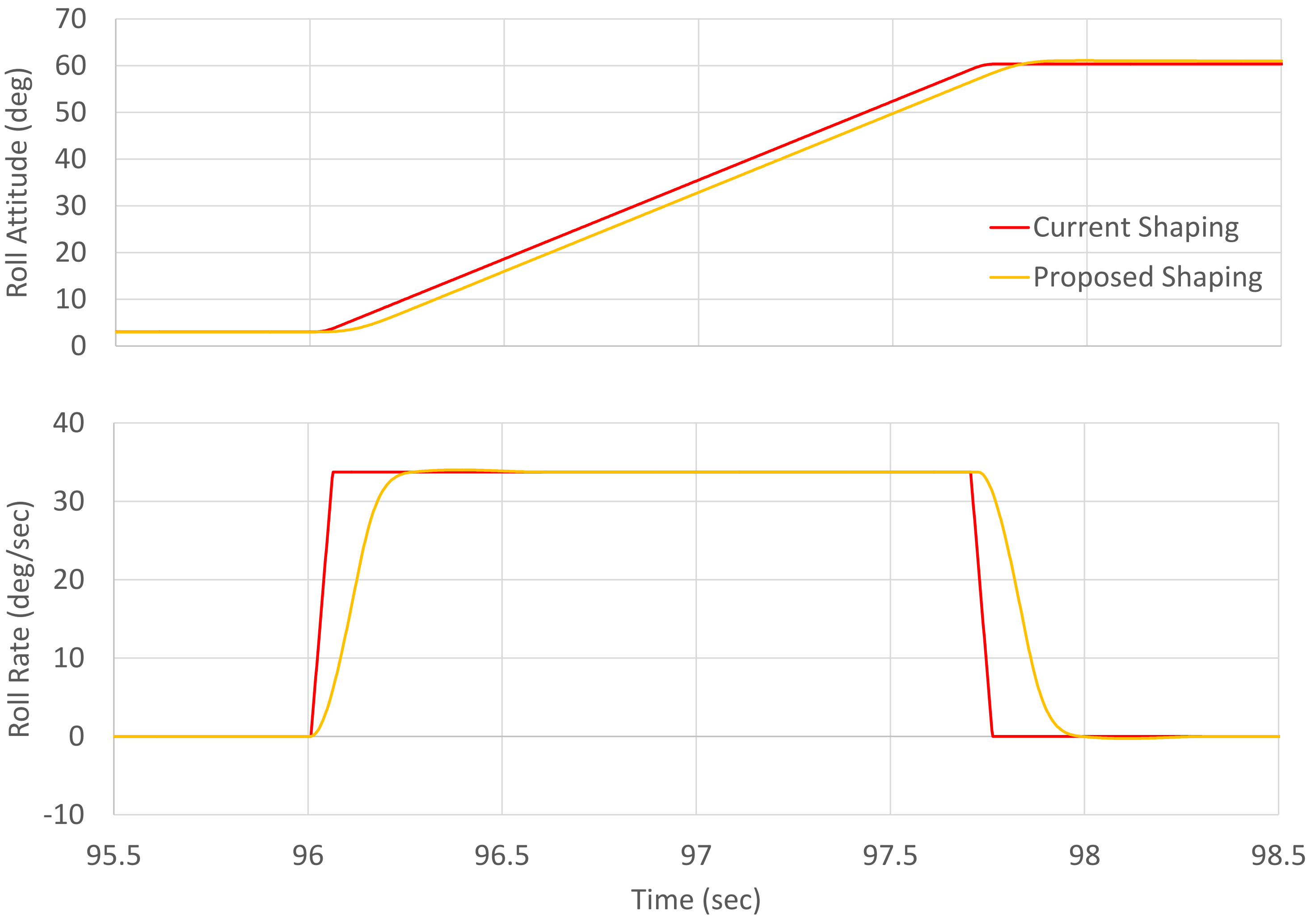
Control Law Architecture

- Copter control law design
  - User sets target (model) response through parameters that define shaping function
  - PID controllers drive actual aircraft response to target (model) response
  - Controller has no knowledge of vehicle to determine output for desired response



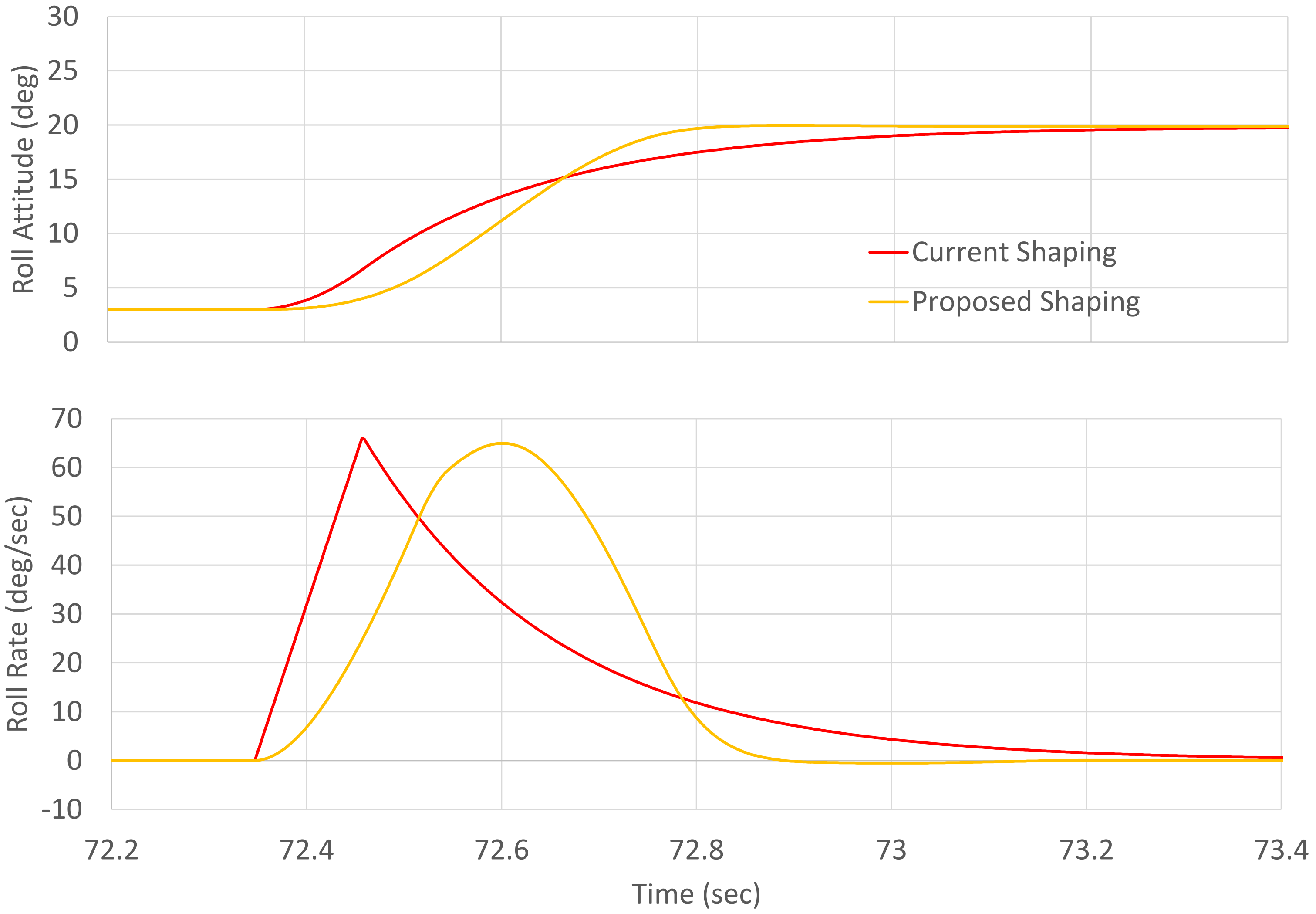
Command Model - Acro

- Current rate shaping
  - Acceleration limited
  - Unlimited Jerk
- Proposed rate shaping
  - 2nd order response in rate
    - Add INPUT_RATE_TC param
    - Damping ratio = 0.8
  - 1st order lag applied to jerk to provide more gradual build of initial acceleration



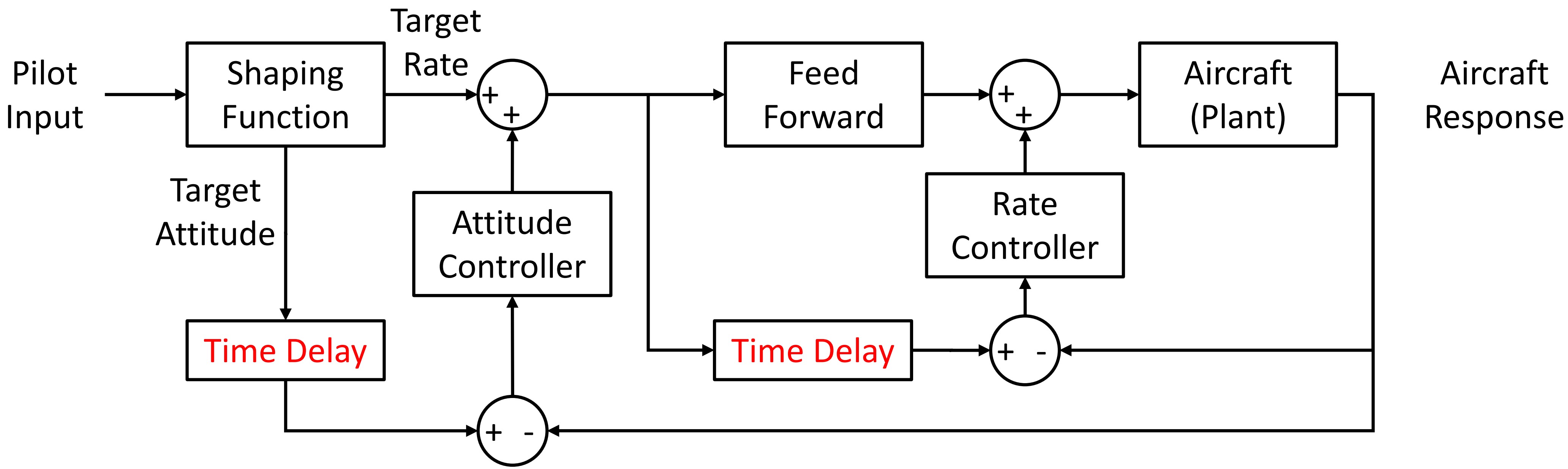
Command Model – Stabilize (Pitch & Roll)

- Current attitude shaping
  - Uses square root shaping function in attitude
- Proposed attitude shaping
  - Uses existing attitude shaping function to determine requested rate
  - Uses proposed rate shaping function to determine requested rate



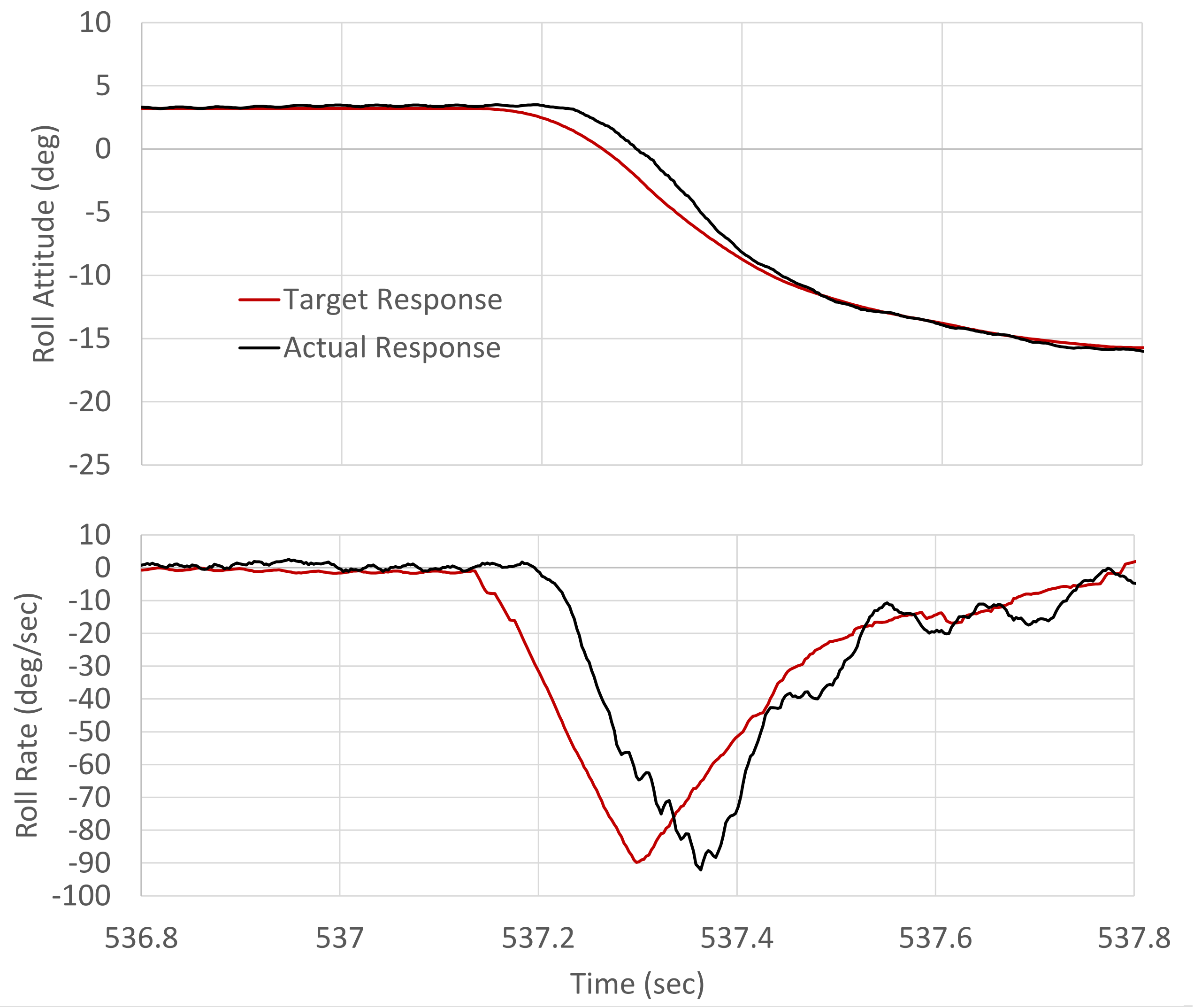
Time Delay

- Initially desired putting time delay in both rate and attitude feedback
- For this to work well, it requires the aircraft use feedforward
  - The feedforward path initiates the movement



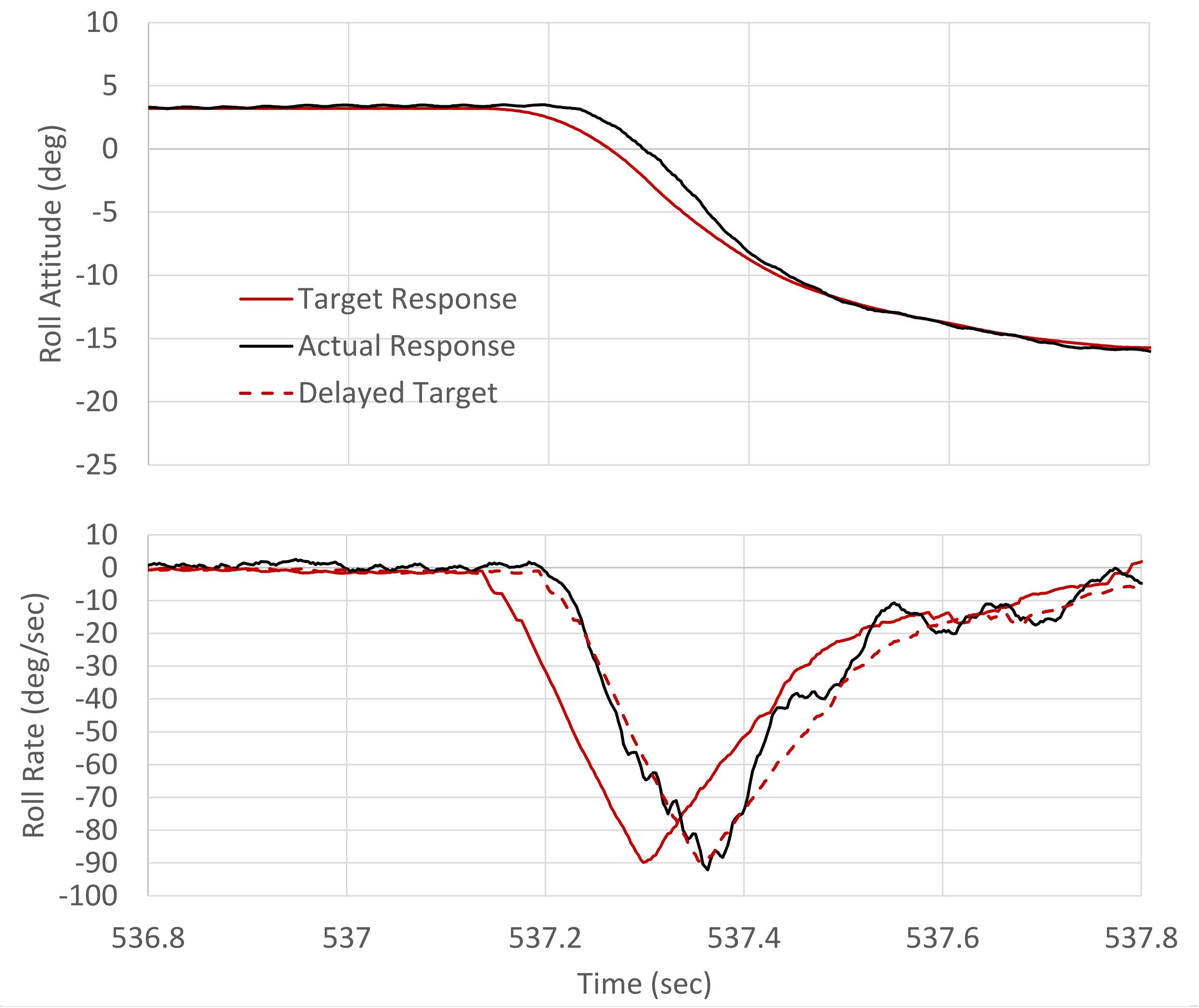
Time Delay

- Helicopters more likely to have higher delays
- Using time delay would help reduce overshoot in the PID controllers



Time Delay

- Helicopters more likely to have higher delays
  - Actuator lags
  - Linkage binding
- Using time delay would help reduce overshoot in the PID controllers
- Delay in rate target is 57 ms



Time Delay

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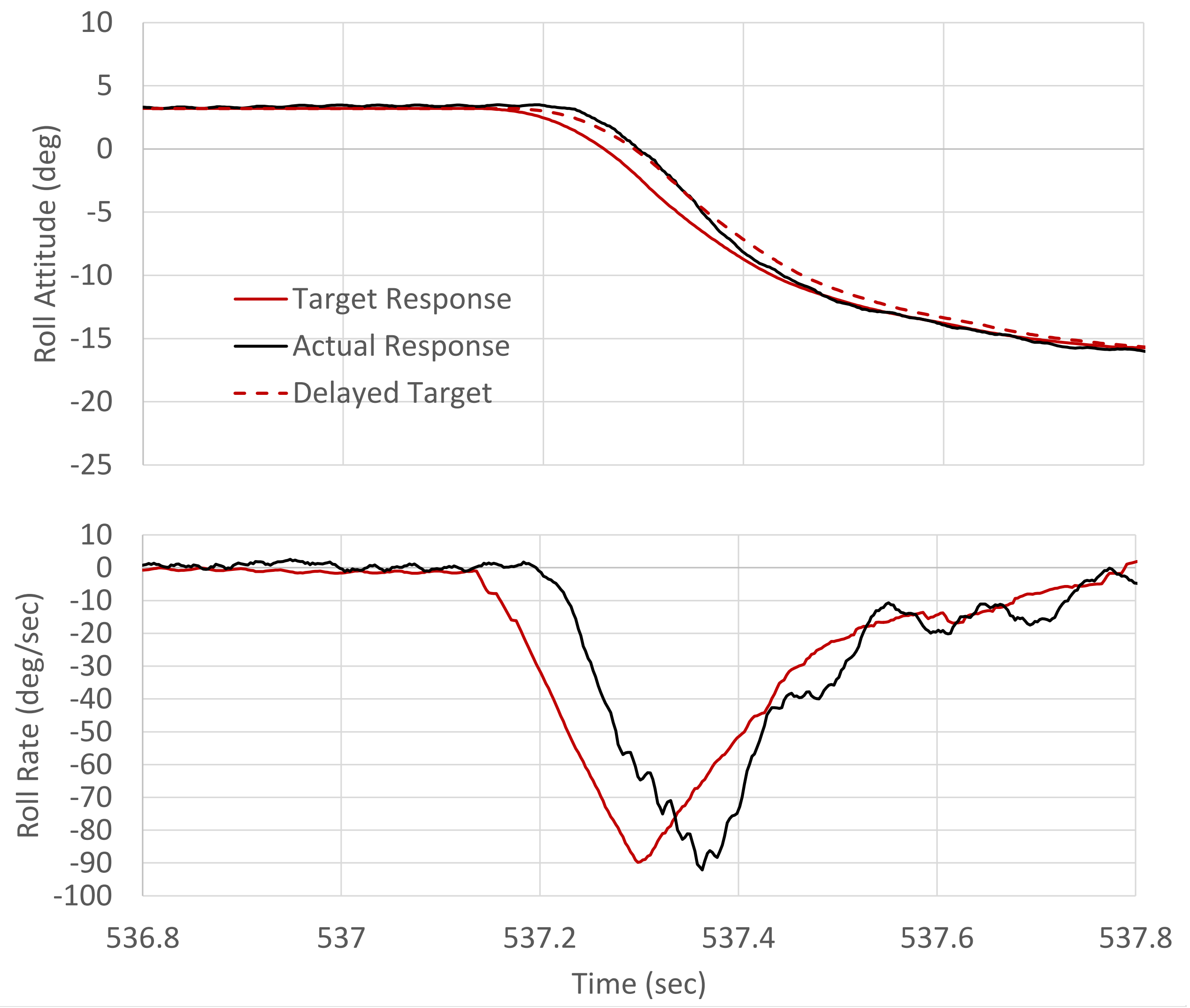
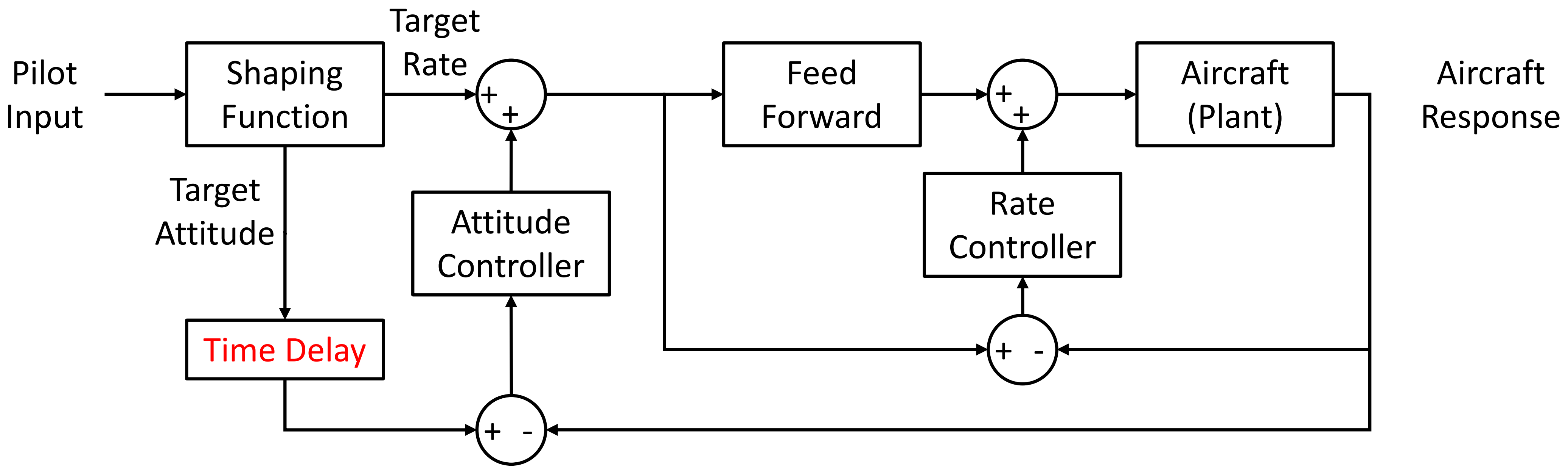
  - Actuator lags
  - Linkage binding
- Using time delay would help reduce overshoot in the PID controllers
- Delay in rate target is 57 ms
- Delay in attitude target is 30 ms



Time Delay

- To be more universally usable in the code, looking at time delay only in attitude target



Derivative Feedforward

- Currently only rate feedforward gain used in rate controller
  - Heli's use it in pitch and roll axes because axes primarily rate command
  - Multi's don't use it because axes are primarily acceleration command
- Derivative feedforward
  - Used for axes that are acceleration command
  - Provide immediate commanded response
  - Can be used in rate command systems to act like a lead filter

Future

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- Automated handling of engine throttle for autonomous operations
  - Mainly for Internal Combustion Engine helicopters
  - Provide for engine warm-up and cool-down in autonomous operations
- Better tuning instructions and possibly autotune
- Better I-term handling and limit handling
- Reliable fully autonomous flights from startup to shutdown
- Autonomous autorotation or at least assisted
- Clean up Tradheli specific files/improve code efficiency

Questions