Traditional Helicopter Update

Bill Geyer
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 has 4 degrees of freedom
• Rotational
  • Rotates about shaft
Rotor Dynamics – Degrees of Freedom

• Rotor has 4 degrees of freedom
  • Rotational
    • Rotates about shaft
  • Flapping
    • Blade vertical motion
    • Provides for helicopter control
• Rotor has 4 degrees of freedom

• Rotational
  • Rotates about shaft

• Flapping
  • Blade vertical motion
  • Provides for helicopter control

• Lead-Lag
  • Blade horizontal motion
  • Nuisance DOF with low damping
Rotor has 4 degrees of freedom

- Rotational
  - Rotates about shaft

- Flapping
  - Blade vertical motion
  - Provides for helicopter control

- Lead-Lag
  - Blade horizontal motion
  - Nuisance DOF

- Feathering
  - Blade pitch controlled by swashplate
• 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
• 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 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.

Tip path plane tilts creating pitching moment.
• 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

- 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
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

Linearized Servo Output
- Modifies servo arm throw to remove nonlinear movement due to arm arc
- Critical for 4 servo swashplate
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

- Linearized Servo Output
  - Modifies servo arm throw to remove nonlinear movement due to arm arc
  - Critical for 4 servo swashplate
Virtual Flybar

- 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

• 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
• 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
• 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
In most cases, rotor speed is kept constant.

Vibrations in helicopters are harmonics of the rotor speed:
- 1\textsuperscript{st} Frequency – rotor speed
- 2\textsuperscript{nd} Frequency – N blades x rotor speed
- 3\textsuperscript{rd} Frequency – 2 x N blades x rotor speed

If rotor speed is governed, make notch bandwidth small, \(\sim 10\) 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

- 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
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
• 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
• 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
• 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
• 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
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

- 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
- Delay in attitude target is 30 ms
To be more universally usable in the code, looking at time delay only in attitude target.
• 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
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