The Pennsylvania State University
The Graduate School
College of Engineering

INVESTIGATION OF BANDWIDTH AND DISTURBANCE REJECTION PROPERTIES OF A DYNAMIC INVERSION CONTROL LAW FOR SHIP-BASED ROTORCRAFT

A Thesis in
Aerospace Engineering
by
Albert Zheng

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The thesis of Albert Zheng was reviewed and approved* by the following:

Joseph F. Horn
Professor of Aerospace Engineering
Thesis Adviser

Edward C. Smith
Professor of Aerospace Engineering

George A. Lesieutre
Professor of Aerospace Engineering
Head of the Department of Aerospace Engineering

*Signatures are on file in the Graduate School.
Abstract

This thesis is an investigation to better understand the bandwidth and the disturbance rejection requirements of a non-linear dynamic inversion (NLDI) controller (and for rotorcraft control characteristics in general), when operating in a range of sea states and airwake conditions. The US Army’s rotorcraft handling qualities specification, ADS-33E-PRF, provides no specific design guidance on bandwidth or disturbance rejection properties for maritime operations. A family of controllers was developed to test varying levels of bandwidth and disturbance rejection properties of Attitude Command / Attitude Hold (ACAH) and TRC control modes. The controllers’ gain sets for bandwidth were baselined at the minimum Level 1 ADS-33 requirements for response to pilot inputs. Two gain sets for disturbance rejection were developed with the first set of gains baselined at the 45° / 6-dB stability margins recommended by standard flight control design specifications. The second gain set was baselined at the proposed disturbance rejection criteria developed by the Aerolightdynamics Directorate (AFDD).

Piloted simulation tests were conducted to evaluate the handling qualities of the family of controllers in the midst of high sea states and a turbulent airwake. A Computational Fluid Dynamics (CFD) airwake model was used for testing the disturbance rejection gain set baselined at the standard stability margins. The second gain set using the AFDD baseline was assessed with a Control Equivalent Turbulence Equivalent (CETI) model. Simulations used the GENHEL-PSU UH-60 model integrated with the Penn State rotorcraft flight simulator. A maritime mission task element (MTE) was flown to evaluate handling qualities ratings (HQR) using the various response types and gain parameters. Time-frequency metrics were used to supplement the pilot ratings in order to assess the impact of pilot workload and strategy on the handling qualities in the shipboard environment.
Results indicate that ACAH can improve HQRs over the conventional rate command mechanical control system of the UH-60A. HQRs with ACAH were still Level 2, and the required bandwidth in order to improve HQRs is significantly higher than that currently specified in ADS-33E-PRF. Results also demonstrated that HQRs can be improved by increasing the disturbance rejection bandwidth (DRB) in ACAH in mild sea states or without ship motion. Pilot ratings indicated ACAH can achieve Level 1 HQRs in sea state 3, but the required DRB is much greater than the proposed minimum criteria recommended by the AFDD. The HQRs also show that sea state 4 diminishes the benefit of DRB where the ratings become strictly Level 2.

Results indicated that a Level 1 HQR could be achieved with ship-relative TRC in sea state 5, but that handling qualities were sensitive to rise time, with the required rise time at the low end of the range recommended by ADS-33E-PRF. Initial results also show that HQRs can be improved by increasing the DRB in ship-relative TRC in sea state 4. Pilot ratings indicated ship-relative TRC can achieve Level 1 HQRs, but the required DRB is again significantly higher than AFDD’s minimum criteria.

The results also demonstrate that utilizing time-frequency metrics for pilot workload provide useful indicators on the impact of gain selection to the handling qualities in shipboard operation. The metrics tended to correlate with pilot comments and ratings for the family of controllers.
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List of Symbols

CD  control derivatives matrix
$e$  error
$e$  error vector
$f(x)$  state dependent vector function
$F(x)$  feedback linearization vector function
$FM$  forces and moments vector
$g$  acceleration due to gravity, $ft/sec^2$
$g(x)^{-1}$  control effectiveness matrix function
$G(x)^{-1}$  control mixing matrix
$h(x)$  output vector function
$I_x, I_y, I_z$  vehicle moments of inertia about the x, y, and z axes, $slug*ft^2$
$I_{xz}$  vehicle product of inertia about the x and z axes, $slug*ft^2$
$J_A$  Aggressiveness of pilot input, %
$K$  scaling gain
$l$  moment arm length from ship’s c.g., $ft$
$L, M, N$  body aero rolling, pitching, yawing moment, $ft-lb$
$m$  vehicle mass, $slug$
$M_{\delta_{ion}}, etc.$  control derivatives e.g. $M_{\delta_{ion}} = \frac{\partial M}{\partial \delta_{ion} }, \frac{ft-lb}{\%}, etc.$
$p, q, r$  body roll, pitch, yaw angular rates, $deg/sec$
$P$  Position, $ft$
$SD$  stability derivatives matrix
$t_r$ rise time, sec

$T$ transformation matrix

$u, v, w$ body forward, right, downward velocities, $ft/sec$

$u$ control vector

$V$ Velocity, $ft/sec$

$s$ Laplace operator

$x$ state vector

$X, Y, Z$ body aero forward, right, downward force, $lb$

$X_u, Z_w, etc.$ stability derivatives e.g. $X_u = \frac{\partial X}{\partial u}$, $lb/ft/sec$, etc.

$y$ output vector

$\delta$ input, %

$\zeta$ damping ratio

$\nu$ psuedo command, $rad/sec^2$, $ft/sec^2$

$\tau$ command filter time constant, sec

$\phi$ roll attitude, deg

$\theta$ pitch attitude, deg

$\psi$ heading angle, deg

$\omega_n$ natural frequency, $rad/sec$

Subscripts

0 initial condition

2 double

$ac$ aircraft

$B$ body-fixed frame

$c$ ideal command

$cmd$ command

$col$ collective

$d$ disturbance input

$dr$ disturbance rejection
f  final
fb  feedback
h  horizontal distance in ship plane
I  inertial-fixed frame
lat lateral cyclic
lon  longitudinal cyclic
max maximum
min minimum
ped pedals
v  vertical distance in ship plane
x  forward
y  right
z  downward

Acronyms

AACA attitude command attitude hold
ACVH acceleration command velocity hold
ADS aeronautical design standard
AFCS automatic flight control system
AFDD Aeroflightdynamics Directorate
BW  bandwidth
CETI control equivalent turbulence input
CFD computational fluid dynamics
CLAW control law
CV  controlled variable
DR  disturbance rejection
DRB disturbance rejection bandwidth
DRP disturbance rejection peak
DVE degraded visual environment
<table>
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<tr>
<td>GM</td>
<td>gain margin</td>
</tr>
<tr>
<td>HQR</td>
<td>Cooper-Harper handling qualities rating</td>
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<tr>
<td>MTE</td>
<td>mission task element</td>
</tr>
<tr>
<td>NLDI</td>
<td>non-linear dynamic inversion</td>
</tr>
<tr>
<td>PI</td>
<td>proportional-integral (control)</td>
</tr>
<tr>
<td>PIO</td>
<td>pilot induced oscillation</td>
</tr>
<tr>
<td>PONG</td>
<td>portable optical naval guidance</td>
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<td>PM</td>
<td>phase margin</td>
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<tr>
<td>PSD</td>
<td>power spectral density</td>
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<tr>
<td>RM</td>
<td>relaxed margins</td>
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<tr>
<td>RMS</td>
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<td>RCHH</td>
<td>rate command heading hold</td>
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<td>SAS</td>
<td>stability augmentation system</td>
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<td>standard stability margins</td>
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<td>SS</td>
<td>sea state</td>
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<tr>
<td>TRC</td>
<td>translational rate command</td>
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<tr>
<td>UCE</td>
<td>useable cue environment</td>
</tr>
<tr>
<td>VSC</td>
<td>vertical speed command</td>
</tr>
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<td>WOD</td>
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Chapter 1

Introduction

1.1 Research Motivation and Background

Pilots of ship-based rotorcraft frequently face challenging flight conditions. Poor visibility, a confined landing environment, a moving flight deck, unfavorable weather conditions, and turbulent airwakes due to the ship’s superstructure expose the rotorcraft to a number of safety and handling qualities challenges. In some cases, pilot workload limitations will define the operational envelope of ship-based rotorcraft. Unfavorable wind over deck conditions can result in unsteady disturbances (airwake turbulence) which can play a major factor in the pilot workload. Figure 1.1 demonstrates a UH-60 Black Hawk landing on a moving ship deck.

Figure 1.1: UH-60 Black Hawk Landing on the Ship Deck of a FFG-41 [1]
Higher levels of flight control augmentation have become an area of research due to the challenges that shipboard operations present. Prior research has shown that advanced automatic flight control systems (AFCS) provide benefit to safe operational capability and reducing pilot work load in degraded visual environments (DVE) [2]. An advanced AFCS will also provide disturbance rejection for the aircraft, i.e. reduce un-commanded state changes due to wind gusts.

The US Army’s rotorcraft handling qualities specification, ADS-33E-PRF [3], is well-established for land-based operation. However, quantitative handling qualities requirements for maritime operation are not explicitly addressed. A number of researchers have declared the need to expand ADS-33 to cover maritime missions [4]. There has been preliminary development of handling qualities guidelines towards the helicopter and ship dynamic interface environment for ADS-33 [5], but there is still a lack of understanding on the appropriate maritime-specific requirements.

In ship-based operations, the response characteristics for the rotorcraft become even more crucial due to the confined environment and lack of visual cueing. Pilots will often use a strategy of holding a stable hover over the deck and waiting for a quiescent period (rather than following deck motion), but as they descend they need maneuverability to prevent inadvertent contact or a hard landing. Therefore, a configuration will ideally have both stability in hover and maneuverability for the approach and landing. The established Level 1 ADS-33 requirements may not guarantee the handling qualities required for this configuration. Further research is required to expand the response requirements needed for the design of an AFCS in these operations.

The ability of an AFCS to adequately reject atmospheric disturbances is desirable in degraded weather and visibility conditions. It becomes of significant interest in shipboard operations, where the superstructure of the ship can generate increased levels of unsteady gusts (“airwake turbulence”). There is ongoing research towards developing a real-time dynamic interface simulation which accurately models the effect of the ship airwake’s flow field coupled with the rotor blade inflow [6]. Figure 1.2 demonstrates an example of the flow fields from a CFD model which compares the interaction between helicopter’s main rotor and the ship’s airwake versus a no-coupled airwake.

Currently, ADS-33 disturbance rejection requirements focus solely on steady-state response, but not transient behavior. Due to this lack of completeness, the US Army has included suggested values for the criteria of disturbance rejection bandwidth in the test guide of ADS-33 [7]. However, there are still no quantitative disturbance rejection requirements for the shipboard environment.
There have been several studies which have focused on the design of advanced control laws for rejecting airwake disturbances in the shipboard environment [8] [9] [10]. In the context of control design, higher feedback gains can improve disturbance rejection, but this leads to degradation of stability margins resulting in a design trade-off [11]. The compromise between stability margins and disturbance rejection requires further investigation in order to fully define the disturbance rejection requirement for shipboard operations.

1.2 Literature Review

Maritime handling qualities were studied extensively in flight tests on the Canadian National Research Council’s variable-stability helicopter, simulating a series of different aircraft response types using the Superslide surrogate MTE [12]. The Superslide is a Precision Hover MTE modified to simulate aircraft motion over a ship deck. The study investigated simulated sea states 3, 4, 5, and 6 on the Superslide, in both good and degraded visual environments. Response types included low and high bandwidth variants of basic rate command and ACAH, as well as a TRC system with a large rise time (low bandwidth). HQRs indicated there was no improvement with the advanced modes (ACAH and TRC) in the higher sea states (5 and 6). Figure 1.3 shows the NRC helicopter

Figure 1.2: CFD Model Comparison between Fully Coupled Helicopter with Airwake and No-Coupling Airwake [6]
performing the Superslide MTE.

Figure 1.3: Canadian NRC Helicopter tracking Superslide Hover Target [13]

The AFDD has recently conducted a number of flight tests geared towards validating the proposed disturbance rejection criteria attached in the ADS-33 test guide [7]. These flight tests were performed on a number of rotorcraft programs which include the CH-47F [14], AH-64 [15] and UH-60 [16]. The RASCAL JUH-60A variable stability helicopter used to validate the appropriate Level 1 boundaries for ACAH is seen in Figure 1.4.

Figure 1.4: RASCAL JUH-60A Variable Stability Helicopter [16]

Pilots rated the standard ADS-33 Precision Hover and Hovering Turn MTEs with and without CETI turbulence while varying the disturbance rejection properties relative to the proposed Level 1
boundary. In the presence of CETI, HQRs demonstrated Level 1 handling qualities when enhancing the disturbance rejection properties just beyond the boundary. The results validated the proposed DRB using ACAH for a UH-60 for standard hover-related tasks.

In previous efforts, a Non-Linear Dynamic Inversion (NLDI) Controller architecture was designed to track a variety of augmented responses types with the goal of improving handling qualities during shipboard landings [17]. The NLDI architecture was best suited for the study because of its advantage in allowing the disturbance rejection and command following components of the controller to be separately designed.

Piloted simulation testing in that study developed a control mode that demonstrated Level 1 handling qualities in the midst of both a moving ship deck and an airwake behind the ship's superstructure. The control mode used a combination of a Ship-Relative Acceleration Command and Velocity Hold (ACVH) on approach and Ship-Relative TRC upon ship proximity. Accurate telemetry of the ship's position and velocity is required for the success of the control laws.

In the previous investigation, the simulator tests used a relatively mild ship motion (sea state 4 for a FFG-7 frigate) using moderate turbulence from the CETI model [18]. Furthermore, the bandwidth and gust rejection characteristics were not investigated in full detail. The ideal response characteristics were tuned to achieve desired handling qualities, but not fully evaluated for various bandwidth levels as defined by ADS-33 [3]. The feedback gains were selected to give reasonable disturbance rejection properties and stability margins, but the study did not analyze the impact of feedback gain selection on task performance or workload.

Piloted simulation testing has shown to be a cost-effective method in the evaluation of handling qualities for ship-based rotorcraft [10] [17] [19]. In addition, the simulation environment facilitates more rapid development of maritime MTEs. Another surrogate MTE called Portable Optical Naval Guidance (PONG), which is essentially a more modular and portable version of the surrogate Superslide was flight tested for similarities between the original Superslide [20]. The validation and utility of new maritime MTEs such as PONG can be streamlined in the simulation environment. Figure 1.5 shows the PONG display used in the flight test study.
Research in quantitative analysis of pilot control activity has shown progress in better understanding the handling qualities challenges in the maritime environment. In particular, the usage of time-frequency analysis of pilot control activity have shown promise in providing insight on pilot-in-the-loop control strategy as well as workload [21]. There has been a preliminary investigation into how frequency and time representation of the control activity can be strong indicators of handling qualities of the shipboard environment [22]. Similar usage of these time-frequency metrics will be applied to this research to gain insight on the impact that the controller’s properties have on the pilot’s workload and control strategy.
1.3 Objectives and Thesis Organization

The specific objectives of this research are:

1. To understand the design tradeoffs in feedback gain selection and the bandwidth levels within the NLDI control architecture for shipboard operations.

2. To determine the optimal design point for the NLDI architecture and to provide future guidelines on control design efforts or handling qualities requirements for ship-based rotorcraft.

3. To evaluate the impact of gain selection on pilot workload and task performance for ship board operations

This thesis presents the results of the handling qualities evaluations for a family of controllers with various levels of bandwidth and disturbance rejection. The control variants are tested in simulation using an approach, hover and landing maritime MTE. Piloted simulations were conducted using the same simulation facilities used in Ref. 17 with the GENHEL-PSU model of a UH-60A helicopter operating from a frigate, but some updates on the ship motion and airwake models were developed for this study.

The full authority fly-by-wire flight control system used in this study with a derivation of nonlinear dynamic inversion control for this application can be seen in Chapter 2. A discussion of the bandwidth properties for the response types investigated can be seen in Chapter 3. Chapter 4 details the evaluation of the disturbance rejection versus stability margins trade-off for the feedback component of the controller. Chapter 5 presents the simulation environment and various test configurations. Chapter 6 presents the test results including the handling qualities evaluations, task performance, pilot workload assessments, and sample ship hover and landing simulation data. Chapter 7 concludes the thesis with a summary of remarks and recommendations for future work.
Chapter 2

Flight Control System

2.1 GENHEL-PSU Rotorcraft Model

The rotorcraft model utilized in this study is representative of the Sikorsky UH-60A Black Hawk. The full non-linear blade element flight dynamics model is called GENHEL, which is a well-established flight simulation code which has been validated with flight test data [23]. GENHEL models the six degrees of freedom of the rigid body fuselage as well as rotor flapping and lagging degrees of freedom and a variable RPM degree of freedom. A modified version of the GENHEL software has been developed at the Pennsylvania State University and is called GENHEL-PSU. This version is utilized for basic research on rotorcraft flight dynamics and control [24]. The tail landing gear location was moved forward to be more representative of the SH-60 landing gear configuration operating from frigates. Simulations were performed in sea level standard conditions and at the UH-60A design gross weight (16,825 lbs), so torque and power limitations were not a significant factor in these studies. Sensor error models were included for all measurements used in the NLDI control laws as described in Ref. 17. Actuators were modeled as a first-order system (6 Hz break frequency) in series with the second-order primary servo model included in the GENHEL-PSU code (natural frequency of 70 rad/sec).
2.2 Baseline Mechanical Control System

The UH-60A Black Hawk possesses a mechanical control system with a 10% authority stability augmentation system (SAS). The simulation definitions of the pitch, roll, and yaw SAS channels can be seen in Ref. 23. Figure 2.1 shows a simplified block diagram of the partial authority SAS where gyro sensors are used to measure the body angular rates \((p, q, r)\).

The mechanical controls will serve as the baseline control system to compare to the fly-by-wire control architecture. The bandwidth levels and response characteristics of the mechanical controls will be discussed later in Chapter 3.

2.3 Non-Linear Dynamic Inversion Controller

The control design method used in this study is Non-Linear Dynamic Inversion. The scheme uses a 6 degrees of freedom non-linear aircraft model for the inversion. The non-linear model uses a stability and control derivatives representation of the aerodynamic forces and moments which are then used by the exact equations representing the aircraft kinematics and dynamics. These derivatives are extracted a priori from GENHEL-PSU using a perturbation technique at various airspeeds. The controller uses full state feedback (all rigid body states) for the feedback linearization loop in order to track the ideal responses defined by the command filters. The controller utilizes an inner loop which uses ACAH for roll and pitch, Rate Command Heading Hold (RCHH) in yaw, and Vertical Speed Command (VSC) in the vertical axis. The outer loop provides translational control for control modes such as TRC and ACVH in roll and pitch. In addition, accurate ship measurement information is assumed to be readily available and is fed to the outer loop for Ship-
Relative control. The various control modes can be engaged and disengaged via switches. The controller was implemented in MATLAB/Simulink and interfaced with the GENHEL-PSU UH-60 flight dynamics model. Figure 2.2 shows a high level overview of the flight control system architecture.

![Flight Control Architecture Diagram](image)

**Figure 2.2: High Level Flight Control Architecture**

### 2.3.1 Inner Loop

NLDI is specifically used for the inner loop control which corresponds to the ACAH control mode. A complete derivation of the NLDI design method can be seen in Ref. 25. An abbreviated derivation of the non-linear dynamic inversion will be now be shown for this application.

The non-linear state-space model is shown below in Eqn. 2.1,

\[
\dot{x} = f(x) + g(x)u
\]

(2.1)

where \(f(x)\) is defined as the state dependent component of the \(\dot{x}\) and \(g(x)\) is defined as the control input dependent component.

The rigid body states are body forward velocity, \(u\), body lateral right velocity, \(v\), body downward
velocity, \( w \), body roll rate, \( p \), body pitch rate, \( q \), body yaw rate, \( r \). In addition, we include the aircraft’s Euler angles, \( \phi, \theta, \psi \) which are roll attitude, pitch attitude, and heading. The control inputs are lateral cyclic, \( \delta_{\text{lat}} \), longitudinal cyclic, \( \delta_{\text{lon}} \), collective, \( \delta_{\text{col}} \), and pedals, \( \delta_{\text{ped}} \). The state and control vectors, \( x \), and \( u \) are shown below in Eqns. 2.2 and 2.3.

\[
x = \begin{bmatrix} u & v & w & p & q & r & \phi & \theta & \psi \end{bmatrix}^T \tag{2.2}
\]

\[
u = \begin{bmatrix} \delta_{\text{lat}} & \delta_{\text{lon}} & \delta_{\text{col}} & \delta_{\text{ped}} \end{bmatrix}^T \tag{2.3}
\]

The calculation of the aircraft forces and moments is shown as a linear expression in Eqn. 2.4.

\[
FM = \mathbf{SD} \cdot \Delta x + \mathbf{CD} \cdot \Delta u + FM_0 \tag{2.4}
\]

The terms for aircraft forces and moments, \( FM \), stability derivatives, \( \mathbf{SD} \), control derivatives, \( \mathbf{CD} \) and trimmed forces and moments, \( FM_0 \) are expanded in Eqns. 2.5-2.8.

\[
FM = \begin{bmatrix} X & Y & Z & L & M & N \end{bmatrix}^T \tag{2.5}
\]

\[
\mathbf{SD} = \begin{bmatrix}
X_u & X_v & X_w & X_p & X_q & X_r \\
Y_u & Y_v & Y_w & Y_p & Y_q & Y_r \\
Z_u & Z_v & Z_w & Z_p & Z_q & Z_r \\
L_u & L_v & L_w & L_p & L_q & L_r \\
M_u & M_v & M_w & M_p & M_q & M_r \\
N_u & N_v & N_w & N_p & N_q & N_r
\end{bmatrix} \tag{2.6}
\]

\[
\mathbf{CD} = \begin{bmatrix}
X_{\delta_{\text{lat}}} & X_{\delta_{\text{lon}}} & X_{\delta_{\text{col}}} & X_{\delta_{\text{ped}}} \\
Y_{\delta_{\text{lat}}} & Y_{\delta_{\text{lon}}} & Y_{\delta_{\text{col}}} & Y_{\delta_{\text{ped}}} \\
Z_{\delta_{\text{lat}}} & Z_{\delta_{\text{lon}}} & Z_{\delta_{\text{col}}} & Z_{\delta_{\text{ped}}} \\
L_{\delta_{\text{lat}}} & L_{\delta_{\text{lon}}} & L_{\delta_{\text{col}}} & L_{\delta_{\text{ped}}} \\
M_{\delta_{\text{lat}}} & M_{\delta_{\text{lon}}} & M_{\delta_{\text{col}}} & M_{\delta_{\text{ped}}} \\
N_{\delta_{\text{lat}}} & N_{\delta_{\text{lon}}} & N_{\delta_{\text{col}}} & N_{\delta_{\text{ped}}}
\end{bmatrix} \tag{2.7}
\]
The $SD$, $CD$, and $FM_0$ terms are scheduled with airspeed and linearly interpolated between flight conditions. In addition, the trimmed state and control inputs, $x_0$ and $u_0$, are also scheduled with airspeed. It is noted that these trimmed values are approximately 0 since the aircraft was linearized around nominal rectilinear trim conditions. The state and control input perturbations, $\Delta x$ and $\Delta u$, are expanded below in Eqns. 2.9-2.10.

$$\Delta x = \begin{bmatrix} \Delta u \\ \Delta v \\ \Delta w \\ \Delta p \\ \Delta q \\ \Delta r \end{bmatrix} = \begin{bmatrix} u - u_0 \\ v - v_0 \\ w - w_0 \\ p - p_0 \\ q - q_0 \\ r - r_0 \end{bmatrix}$$ \hspace{1cm} (2.9)$$

$$\Delta u = \begin{bmatrix} \Delta \delta_{lat} \\ \Delta \delta_{lon} \\ \Delta \delta_{col} \\ \Delta \delta_{ped} \end{bmatrix} = \begin{bmatrix} \delta_{lat} - \delta_{lat_0} \\ \delta_{lon} - \delta_{lon_0} \\ \delta_{col} - \delta_{col_0} \\ \delta_{ped} - \delta_{ped_0} \end{bmatrix}$$ \hspace{1cm} (2.10)$$

The nonlinear model from Eqn. 2.1 uses the well known rigid body equations of aircraft motion and found in standard texts such as Ref. 26. The equations are shown below in Eqns. 2.11-2.19. The combination of Eqn. 2.4 and Eqns. 2.11-2.19 represent the complete nonlinear model as defined in Eqn. 2.1.

$$\dot{u} = \frac{X}{m} - g \sin \theta - qw + rv$$ \hspace{1cm} (2.11)$$

$$\dot{v} = \frac{Y}{m} + g \cos \theta \sin \phi - ru + pw$$ \hspace{1cm} (2.12)$$

$$\dot{w} = \frac{Z}{m} + g \cos \theta \cos \phi - pv + qu$$ \hspace{1cm} (2.13)$$

$$\dot{p} = \frac{1}{I_x I_z - I_{xz}^2} \left[ I_z L + I_{xz} N + I_{xx}(I_x - I_y + I_z)pq - (I_z^2 - I_x I_y + I_{xz}^2)qr \right]$$ \hspace{1cm} (2.14)$$
\[
\dot{q} = \frac{1}{I_y} [M - (I_x - I_z)rp - I_{xz}(p^2 - r^2)] 
\]  
(2.15)

\[
\dot{r} = \frac{1}{I_xI_z - I_{xx}^2} \left[ I_x N + I_{xx} L - I_{xz}(I_x - I_y + I_z)qr + (I_x^2 - I_xI_y + I_z^2)pq \right] 
\]  
(2.16)

\[
\dot{\phi} = p + q \sin \phi \tan \theta + r \cos \phi \tan \theta 
\]  
(2.17)

\[
\dot{\theta} = q \cos \phi - r \sin \phi 
\]  
(2.18)

\[
\dot{\psi} = \frac{q \sin \phi}{\cos \theta} + \frac{r \cos \phi}{\cos \theta} 
\]  
(2.19)

For NLDI, one controlled variable (CV) per input channel is required. Each CV is tied directly to the pilot inceptors and passed through an ideal response model which is referred to as a command filter. The CVs for the inner loop are defined in Eqn. 2.20 below.

\[
y = \begin{bmatrix}
\dot{\phi} & \dot{\theta} & V_z & r
\end{bmatrix}^T 
\]  
(2.20)

The output vector, \( y \), is shown as a function of the aircraft states, \( x \), as seen in Eqn. 2.21.

\[
y = h(x) = 
\begin{bmatrix}
p + q \sin \phi \tan \theta + r \cos \phi \tan \theta 
q \cos \phi - r \sin \phi 
u \sin \theta - v \sin \phi \cos \theta - w \cos \phi \cos \theta 
r 
\end{bmatrix} 
\]  
(2.21)

The derivative with respect time of the output vector, \( y \), is shown as:

\[
\dot{y} = \frac{\partial h(x)}{\partial x} \dot{x} = \frac{\partial h(x)}{\partial x} f(x) + \frac{\partial h(x)}{\partial x} g(x)u = F(x) + G(x)u 
\]  
(2.22)

\( f(x) \) will retain both the \( \text{FM} \) dependent term and the nonlinear terms of \( \dot{x} \) which will be referred to as \( \dot{x}_{\text{nonlinear}} \). Since \( f(x) \) is only state dependent and excludes the control input dependencies, the \( \text{FM} \) term will only be affected by the \( \text{SD} \) and \( \text{FM}_0 \) terms in Eqn. 2.4. This is shown below in Eqn. 2.23.

\[
\text{FM} = \frac{\underbrace{\text{SD} \cdot \Delta x + \text{FM}_0}}{f(\text{FM})} + \frac{\underbrace{\text{CD} \cdot \Delta u}}{g(\text{FM})} 
\]  
(2.23)
An example of how parts of the $\dot{u}$ state equation are categorized is shown in Eqn. 2.24.

\[
\dot{x}(\text{FM}) = \frac{\dot{X}}{m} - \dot{q} \sin \theta - qw + rv \\
\dot{\dot{u}} = _{2}x_{\text{nonlinear}} (2.24)
\]

$F(x)$ can then be derived and is shown in Eqn. 2.25.

\[
F(x) = \frac{\partial h(x)}{\partial x} f(x) = \frac{\partial h(x)}{\partial x} \left[ \frac{\partial \dot{x}}{\partial \text{FM}} (SD \cdot \Delta x + FM_0) + \dot{x}_{\text{nonlinear}} \right] (2.25)
\]

The final expression of $F(x)$ is then shown in Eqn. 2.26. It is implied that $\dot{x}$ terms exclude the control input dependent expressions as just previously demonstrated.

\[
\frac{\partial h(x)}{\partial x} \left[ \dot{p} + (\dot{q} \sin \phi + \dot{r} \cos \phi) \tan \theta + (q \cos \phi - r \sin \phi) \frac{\dot{\phi}}{\cos^2 \theta} \right. \\
\left. + (q \sin \phi + r \cos \phi) \frac{\dot{\phi}}{\cos^2 \theta} \right] \\
\dot{q} \cos \phi - \phi q \sin \phi - \dot{r} \sin \phi - \dot{\phi} r \cos \phi \\
\dot{u} \sin \theta + \dot{\theta} u \cos \theta - \dot{v} \sin \phi \cos \theta - v(\dot{\phi} \cos \phi \cos \theta - \dot{\phi} \sin \phi \sin \theta) \\
- \dot{\dot{w}} \cos \phi \cos \theta + w(\dot{\phi} \sin \phi \cos \theta - \dot{\phi} \cos \phi \sin \theta) \\
\frac{1}{I_x I_z - I_{xz}} \left[ I_x N + I_{xz} L - I_{xz} (I_x - I_y + I_z) q r + (I_z^2 - I_x I_y + I_z^2) p q \right] (2.26)
\]

Similarly, we can derive $G(x)$ in a similar fashion where the $\text{FM}$ term in $\dot{x}$ will only be affected by the $\text{CD}$ term. The final expression is shown in Eqn. 2.27.

\[
G(x) = \frac{\partial h(x)}{\partial x} g(x) = \frac{\partial h(x)}{\partial x} \frac{\partial \dot{x}}{\partial \text{FM}} \text{CD} (2.27)
\]

Note that $G(x)$ must be invertible for all values of $x$. The term $\frac{\partial h(x)}{\partial x} \frac{\partial \dot{x}}{\partial \text{FM}}$ is shown as:

\[
\begin{bmatrix}
0 & 0 & 0 & I_x + I_{xz} \cos \phi \tan \theta & \sin \phi \tan \theta & I_x + I_{xz} \cos \phi \tan \theta \\
0 & 0 & 0 & -\sin \phi I_{xz} & \cos \phi & -\sin \phi I_{xz} \\
\frac{\sin \theta}{m} & -\sin \phi \cos \theta & \frac{\cos \phi \cos \theta}{m} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{I_x}{I_x I_z - I_{xz}} & 0 & \frac{I_x}{I_x I_z - I_{xz}} \\
\end{bmatrix} (2.28)
\]

We can define the tracking error of the system, $e$, as shown in Eqn. 2.29 with the time derivative.
shown in Eqn. 2.30.

\[ e = y_c - y \]  
\[ \dot{e} = \dot{y}_c - \dot{y} \]  
\[ (2.29) \]

By substituting the tracking time derivative of the tracking error of the system, \( e \), into Eqn. 2.22, we find an alternate form of the time derivative of the controlled variables which can be seen in Eqn. 2.31.

\[ F(x) + G(x)u = \dot{y}_c - \dot{e} \]  
\[ (2.31) \]

A vector of auxiliary inputs, or “pseudo commands” can be defined as seen in Eqn. 2.32.

\[ \nu = -\dot{e} \]  
\[ (2.32) \]

By substituting \( \nu \) into Eqn. 2.31 and solving for \( u \), a control law results in the form of:

\[ u = G^{-1}(x) \cdot [\dot{y}_c + \nu - F(x)] \]  
\[ (2.33) \]

**Inner Loop Feedback Compensation**

Simple proportional-integral (PI) type compensators can be used to satisfy the error dynamics, \( \dot{e} = -\nu \), thus:

\[ \nu = -K_{PI}(s) \cdot e \]  
\[ (2.34) \]

A detailed derivation of PI type compensation for this application is discussed in Ref. 27. We provide a brief derivation of the error dynamics in Eqn. 2.34 for this study. The error dynamics for the inner loop roll and pitch attitudes can be expanded with proportional, \( K_P \), integral, \( K_I \), and double integral, \( K_{I_2} \), compensation as seen in Eqn. 2.35.

\[ \dot{e} = -K_P \cdot e - K_I \cdot \int e - K_{I_2} \cdot \int \int e \]  
\[ (2.35) \]

If we consider the roll and pitch attitude dynamics, a disturbance can be modeled as a per-
turbation on the attitude measurement (as is used in disturbance rejection bandwidth analysis, Ref. 11). We can reconstruct the error dynamics as a third order transfer function from attitude response due to attitude disturbances as shown below:

\[
\frac{\phi}{\phi_d}(s) = \frac{s^3}{s^3 + K_P s^2 + K_I s + K_{I_2}} = \frac{s^3}{(s^2 + 2\zeta \omega_n s + \omega_n^2)(s + p)} \tag{2.36}
\]

\[
\frac{\theta}{\theta_d}(s) = \frac{s^3}{s^3 + K_P s^2 + K_I s + K_{I_2}} = \frac{s^3}{(s^2 + 2\zeta \omega_n s + \omega_n^2)(s + p)} \tag{2.37}
\]

The ideal error dynamics thus have three poles which are defined by damping ratio, \(\zeta\), natural frequency, \(\omega_n\), and a real pole, \(p\). The feedback gains are then related to the parameters as seen in Eqn. 2.38.

\[
K_P = 2\zeta \omega_n \\
K_I = \omega_n^2 + 2\zeta \omega_n p \\
K_{I_2} = \omega_n^2 p \tag{2.38}
\]

The error dynamics for yaw rate and vertical speed can be expanded with proportional, \(K_P\) and integral, \(K_I\) compensation as seen in Eqn. 2.39.

\[
\dot{e} = -K_P \cdot e - K_I \cdot \int e \tag{2.39}
\]

The error dynamics for yaw rate and vertical speed can be similarly transformed into a second-order transfer function from response due to disturbance:

\[
\frac{r}{r_d}(s) = \frac{s^2}{s^2 + K_P s + K_I} = \frac{s^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} \tag{2.40}
\]
The feedback gains are then related to the parameters as seen in Eqn. 2.42.

\[ K_P = 2\zeta \omega_n \]
\[ K_I = \omega_n^2 \]  

Simple PI type compensators are designed to govern the error dynamics in Eqns. 2.36-2.37 and Eqns. 2.40-2.41 for a stable, well-damped tracking error. Given no disturbances and no model error, the aircraft will follow ideal response perfectly, as the error decays to zero. In practice, the feedback compensation reacts to both disturbances and modelling error. Increasing gains will tend to increase the controller reaction to disturbances. In fact, by increasing the natural frequency parameter, \( \omega_n \), in the Eqns. 2.38 and 2.42, we can theoretically improve disturbance rejection without limit while ensuring stable and well-damped error dynamics. In practice, this is not the case, primarily because the inversion model is reduced order. It does not include rotor flap/lag, inflow, or actuator dynamics. If we increase gain too much, these dynamics will interact with closed-loop compensation resulting in reduced stability margins and eventually instability. In addition, increasing the \( \zeta \) parameter can also be tuned to improve the stability margins. Theoretically, increasing the damping of the error dynamics beyond the critically damped value of 1.0 should not improve stability of the system. Since the inversion is reduced order, there may be additional benefit in overdamping the error dynamics because the true error dynamics with the full order model with rotor mode coupling may actually have less damping than the reduced order model. In any case, the NLDI allows us to use two design parameters for each axis, \( \omega_n \) and \( \zeta \), to tune disturbance rejection and observe the design trade-offs.

**Inner Loop Command Filters**

As mentioned in Chapter 1, the NLDI control architecture was selected because of the separation between the response type via a command filter and the feedback compensation. The development
and investigation of the command filter architecture is derived in detail in Ref. 17. A brief overview is provided of the command filters used for this study.

The inner loop controller is designed to provide roll and pitch attitude command response to the pilot’s lateral and longitudinal stick inputs. Note that the controlled variables defined in the control law formulation, Eqn. 2.20, indicate that the roll and pitch attitude rates are commanded by pilot inputs (implying rate command as opposed to attitude command). However, an appropriate interface with the command filter actually yields attitude command response. The command filter is selected such that the output variable follows a second-order linear response due to the input. An example of the attitude command filter for ACAH in the lateral axis is mathematically represented in Eqn. 2.43. Maximum stick displacement commands a 45° roll attitude. The natural frequency, $\omega_n$, and damping ratio, $\zeta$, of the command filter can be adjusted for desired bandwidth properties.

$$\frac{\phi_{\text{ideal}}}{\delta_{\text{pilot \_lat}}} = 9 \text{ deg inch} \cdot \frac{\omega_n^2}{s^2 + 2\zeta\omega_ns + \omega_n^2}$$

The second order linear transfer function converts stick inputs to commanded attitude, attitude rate, and attitude acceleration. The commanded attitude is the integration of the controlled variable command, while the attitude rate and acceleration represent the commanded controlled variable and its first derivative, respectively. Proportional plus derivative compensation is applied to the attitude error, which is exactly equivalent to proportional plus integral compensation on the attitude rate error (as used to formulate the auxiliary commands seen in Eqn. 2.35). A block diagram of the pseudo command architecture for the roll attitude is shown in Figure 2.3.

The controller provides a vertical speed command to the collective input, and yaw rate command to the pedal inputs. Collective or pedal inputs from zero reference are proportional to a rate command. The rate response command filters utilize a first-order filter with a time constant, $\tau$. The linear response for vertical speed in the vertical axis is mathematically represented in Eqn. 2.44 with a maximum input commanding a vertical speed of 40 ft/sec.

$$\frac{V_{\text{z \_ideal}}}{\delta_{\text{pilot \_col}}} = 8 \text{ ft/sec} \cdot \frac{1}{(\tau s + 1)}$$

In the heave and yaw axes, the first-order command filters directly yield the commanded control variables (vertical speed and yaw rate) as well as their first derivatives, and PI compensation of the
controlled variables are then used to generate the auxiliary commands seen in Eqn. 2.38. A block diagram of the pseudo command architecture for vertical speed is shown in Figure 2.4.

Thus, the four pilot control axes regulate roll attitude, pitch attitude, vertical speed, and yaw rate.

As a summary of the NLDI controller, the command filters in the inner loop of the controller yield the desired response of the controlled variables, $y_c$, and their first derivatives, $\dot{y}_c$. The control inputs that track these ideal responses are found by multiplying a control mixing matrix, $G^{-1}(x)$, by the sum of the time derivatives of the ideal response, $\dot{y}_c$, the feedback linearization term, $F(x)$, and the pseudo commands, $\nu$. A block diagram of this summary can be seen below in Figure 2.5.
2.3.2 Outer Loop

When the outer loop control law is used, the controller is designed to control lateral and longitudinal velocities with the pilot’s lateral and longitudinal sticks. This controller is designed using a linear dynamic inversion formulation rather than NLDI where roll and pitch attitude commands are treated as controls. In this case, a simplified linear model of the lateral and longitudinal dynamics is used:

\[
\begin{bmatrix}
\dot{u} \\
\dot{v}
\end{bmatrix} = \begin{bmatrix} X_u & X_v \\ Y_u & Y_v \end{bmatrix} \cdot \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} 0 & -g \\ g & 0 \end{bmatrix} \cdot \begin{bmatrix} \phi_{cmd} \\ \theta_{cmd} \end{bmatrix}
\]

(2.45)

Dynamic inversion yields the following control law:

\[
\begin{bmatrix} \phi_{cmd} \\ \theta_{cmd} \end{bmatrix} = \left( \begin{bmatrix} 0 & -g \\ g & 0 \end{bmatrix} \right)^{-1} \cdot \left( \begin{bmatrix} \dot{V}_x \\ \dot{V}_y \end{bmatrix} - \begin{bmatrix} X_u & X_v \\ Y_u & Y_v \end{bmatrix} \cdot \begin{bmatrix} V_x \\ V_y \end{bmatrix} \right) + K_{PI}(s) \cdot \epsilon
\]

(2.46)

Where the variables \(V_x\) and \(V_y\) represent the forward and right velocities in the horizontal plane of the inertial frame but rotated to align with the aircraft heading. It should be noted that the stability derivatives in Eqn. 2.46 are negligible at low speeds and thus omitted in the controller.
Outer Loop Feedback Compensation

For the outer loop feedback compensation, $K_{PI}(s)$ operates on velocity tracking and position tracking errors. If the outer loop is not engaged in position hold, then we consider only the velocity tracking errors. As previously done in Eqn. 2.39, the error dynamics for lateral and longitudinal velocity can be transformed into a second-order transfer function from response due to disturbance:

$$\frac{V_y}{V_{yd}}(s) = \frac{s^2}{s^2 + K_P s + K_I} = \frac{s^2}{s^2 + 2\zeta \omega_n s + \omega_n^2}$$

(2.47)

The compensation is typically proportional plus integral, but it effectively switches to proportional plus integral plus double integral compensation in position hold. For position hold, we can similarly transfer the error dynamics as was previously shown in Eqn. 2.35. If we consider the position tracking dynamics, we can reconstruct the lateral and longitudinal position error dynamics as a third order transfer function from position response due to position disturbances as shown below:

$$\frac{P_y}{P_{yd}}(s) = \frac{s^3}{s^3 + K_P s^2 + K_I s + K_{I_2}} = \frac{s^3}{(s^2 + 2\zeta \omega_n s + \omega_n^2)(s + \tau)}$$

(2.48)

Outer Loop Command Filters

The main outer loop response type in the controller used for this study is Translational Rate Command Position Hold (TRC/PH). Stick deflections in the TRC/PH mode command lateral and longitudinal aircraft velocities and stick detent holds the aircraft’s current position. The linear response for TRC/PH in the lateral axis is mathematically represented in Eqn. 2.49. The outer loop utilizes a second-order command filter combined with a first-order filter with a maximum stick deflection commanding a velocity of 35 ft/sec. The second-order command filter’s natural frequency, $\omega_n$, is selected to be at least five times greater than the time constant, $\tau$, used with a first-order filter.

$$\frac{V_y}{\delta_{pilot}} = \frac{\omega_n^2}{7 \text{ ft/sec} \cdot \text{in} \cdot (\tau s + 1)(s^2 + 2\zeta \omega_n s + \omega_n^2)}$$

(2.49)

The second order linear transfer function converts stick inputs to commanded velocity and
acceleration. For position hold, the command filter generates a commanded position by integrating commanded velocity while the velocity and acceleration commands represent the commanded CV and its first derivative, respectively.

A Ship-Relative response type architecture was developed in the previous investigation [17]. The full details of the position hold logic and Ship-Relative features may be found in Ref. 17. We provide a brief description of the Ship-Relative usage for the outer loop for the context of this study.

A significant assumption is made that the ship’s center of deck position and velocities are made available via a data link with the aircraft. The ship’s deck position is passed through a second order filter that allow the ship’s acceleration, velocity and position to be summed with the output of the outer loop command filter. These measurements are rotated to the aircraft’s heading in order for the aircraft to continue to command any deviations with respect to it’s local aircraft coordinate system.

Figure 2.6 demonstrates the outer loop architecture where pseudocommands are sent to the inner loop.
Chapter 3

Bandwidth Properties

This study investigates the baseline mechanical control system, inner and outer loop command filters and their effect on bandwidth. Bandwidth is the measure of speed of response and correlates with common time domain measures such as rise time. The bandwidth properties of the NLDI controller are varied by adjusting the parameters of the command filters as described in Chapter 2. We investigate the bare aircraft, rate response type of the mechanical controls, inner loop response type of ACAH and the outer loop response type of Ship-Relative TRC.

3.1 ADS-33E-PRF Definition of Bandwidth

The bandwidth properties of the aircraft are defined from ADS-33 [3]. The bandwidth is selected as the lesser of the two values between the gain and phase bandwidth definitions for the input/output response from command to output variable. As seen in Figure 3.1, the gain bandwidth is defined as the frequency crossing which is 6 dB greater than the $-180^\circ$ phase frequency crossing. The phase bandwidth is defined as the frequency of the phase crossing at $-135^\circ$. In practice for our application, the bandwidth definition will default to the phase bandwidth.

For the roll, pitch and yaw axes, frequency-domain analysis is used to analyze the bandwidth of the system. The nonlinear GENHEL-PSU model was linearized at 20 knots of airspeed, a trim condition representative of the flight condition during the landing task. The resulting 24-state linear aircraft model includes the main rotor flap, lag, and inflow dynamics (i.e., higher-order dynamics). This linear aircraft model is coupled with the stability augmentation system channels which can
been seen in Ref. 23 or a SIMULINK model of the controller, which includes actuators, sensors and control laws seen in Appendix A.

The following examples demonstrate the bandwidth properties for the roll, pitch and yaw axes of the mechanical control system compared to the bare airframe.

### 3.1.1 Mechanical Control System with SAS Bandwidth Examples

Figures 3.2(a)-3.2(c) demonstrate the bandwidth of the roll, pitch and yaw axis with the mechanical control system with SAS and the bare aircraft. The results show the benefit of the SAS by increasing the bandwidth and providing damping on each axis.
Figure 3.2: Mechanical Controls w/SAS and Bare Aircraft Bandwidth at V = 20 kts
3.1.2 Attitude Command / Attitude Hold Bandwidth Examples

Figures 3.3(a)-3.3(c) demonstrate how the frequency response of the closed-loop roll, pitch and yaw bandwidth is measured in the context of the NLDI controller for ACAH.

![Graphs showing frequency response for roll, pitch, and yaw](image)

Figure 3.3: ACAH Bandwidth at V = 20 kts
The ACAH results demonstrate how the bandwidth can be adjusted accordingly via each respective command filter. The natural frequency, $\omega_n$, of the roll and pitch command filters were increased for the desired bandwidth properties with the damping ratio, $\zeta$, left at 0.8. The time constant, $\tau$, in the yaw rate command filter was also increased for a similar effect.

3.2 ADS-33E-PRF Definition of Rise Time

The response requirement applied to both the vertical axis and translational velocities is defined by an equivalent rise time which corresponds to a qualitative first order appearance as described in Ref. 3. The rise time is defined as the time to reach 63.2% of the steady state (ss) command due to a step input.

3.2.1 Vertical Axis

For the vertical speed command filter, the requirement applied to the response type is defined by the rise time which correlates with time constant, $\tau$, in the first-order filter. ADS-33 [3] recommends a maximum rise time of 5 seconds as the minimum requirement for the first-order appearance. Figure 3.4 demonstrates the rise time of the vertical axis while increasing $\tau_{V_z}$ in the command filter. Note that the rise time in the vertical axis achieved is quite faster than $\tau_{V_z}$ in the command filter i.e. response reaches 0.632 ss at 0.6 seconds for $\tau_{V_z} = 1$.

![Figure 3.4: Vertical Speed Rise Time](image-url)
3.2.2 Translational Rate Command

For the outer loop TRC command filters, ADS-33 [3] recommends a maximum rise time of 5 seconds and a minimum of 2.5 seconds. Rise times less than 2.5 seconds are achievable in the NLDI architecture as implemented in this study. Practical actuator limitations may not allow for such a responsive TRC controller, but the goal of the present study is to determine ideal response characteristics. Figure 3.5 demonstrates the rise time of the lateral axis while increasing $\tau_{V_y}$ in the command filter.

![Lateral Velocity Rise Time](image)

Figure 3.5: Lateral Velocity Rise Time

3.3 Gain Selection using ADS-33E-PRF

The controllers were baselined starting from the minimum requirements for Level 1 as recommended in ADS-33 [3]. The pitch axis was selected to match the roll axis in order to synchronize the cyclic axes. The selection of the ACAH bandwidth relative to ADS-33’s recommended boundaries are shown for roll, pitch and yaw in Figures 3.6-3.8. The bandwidths of the bare aircraft and mechanical control system are shown as additional points of reference.
Figure 3.6: Roll Bandwidth Selection Relative to ADS-33 Levels

Figure 3.7: Pitch Bandwidth Selection Relative to ADS-33 Levels
Table 3.1: Bandwidth Properties of ACAH

<table>
<thead>
<tr>
<th>Level</th>
<th>$\omega_{BW}$ (rad/s)</th>
<th>$\omega_{\phi}$ (rad/s)</th>
<th>$\zeta_{\phi}$</th>
<th>$\omega_{n\phi}$ (rad/s)</th>
<th>$\zeta_{\theta}$</th>
<th>$\tau_r$ (s)</th>
<th>$t_{V_z}$ (s)</th>
<th>$\tau_{V_z}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>2.0</td>
<td>1.2</td>
<td>0.8</td>
<td>0.75</td>
<td>0.8</td>
<td>0.66</td>
<td>4.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Medium</td>
<td>3.0</td>
<td>2.1</td>
<td>0.8</td>
<td>1.2</td>
<td>0.8</td>
<td>0.44</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>High</td>
<td>4.0</td>
<td>3.2</td>
<td>0.8</td>
<td>2.3</td>
<td>0.8</td>
<td>0.3</td>
<td>0.6</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 3.2 shows the rise time properties and associated command filter parameters of both longitudinal and lateral velocity commands. The low bandwidth parameters represent the maximum rise time guidelines in ADS-33 [3], the medium bandwidth is the minimum rise time, and the
high bandwidth represents a case with even lower rise time. The case labeled medium / high uses medium bandwidth for longitudinal and high bandwidth for lateral (the case was added during the tests as the high bandwidth was found to be more useful in the lateral axis while it sometimes contributed to pilot induced oscillation (PIO) in the longitudinal axis).

<table>
<thead>
<tr>
<th>Level</th>
<th>( t_{TV_y} )</th>
<th>( \tau_{V_y} )</th>
<th>( \omega_{n\theta} )</th>
<th>( t_{TV_x} )</th>
<th>( \tau_{V_x} )</th>
<th>( \omega_{n\theta} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>4.6</td>
<td>5.0</td>
<td>2.25</td>
<td>5.1</td>
<td>5.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Medium</td>
<td>2.7</td>
<td>2.5</td>
<td>2.5</td>
<td>2.4</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Medium/High</td>
<td>1.6</td>
<td>1.5</td>
<td>3.5</td>
<td>2.4</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>High</td>
<td>1.6</td>
<td>1.5</td>
<td>3.5</td>
<td>1.4</td>
<td>1.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 3.2: Bandwidth Properties of TRC
Chapter 4

Disturbance Rejection Properties

The effect of varying gain and disturbance rejection was evaluated for the NLDI controller and the GENHEL-PSU model of the UH-60. High feedback gain tends to improve disturbance rejection and command tracking, but degrades gain and phase margins, resulting in a design tradeoff as described in Ref. 11. Frequency-domain analysis is used to analyze the tradeoff between closed-loop stability and disturbance response of the controller. Again, the nonlinear GENHEL-PSU model was linearized at 20 knots of airspeed, a trim condition representative of the night condition during the landing task. Linear analysis is conducted using the same resulting 24-state linear aircraft model coupled with a SIMULINK model of the controller.

4.1 Broken Loop Stability Margin Analysis

We use the well-known Nyquist stability criterion which is derived in standard control design textbooks such as Ref. 28 to incorporate the design-tools of stability margins which measure how far away the closed loop system is approaching instability. The gain margin is the magnitude in gain that is allowable before the feedback loop reaches instability. The phase margin is the phase difference between the phase when the magnitude of the open loop response, $|G_{OL}(j\omega)|$, is equal to 1 and $-180^\circ$. In Figure 4.1, we can see how the stability margins demonstrate how close the open-loop frequency response comes to encircling the -1 point in the Nyquist plot.

We can easily extract the stability margins directly from the Bode plot which we utilize in this analysis. Loop breaks were implemented at the actuator input for each of the four control axes, and
open-loop linear models were generated using the SIMULINK linearization tools. The open-loop frequency responses are tested against standard stability margin requirements to ensure system robustness against the uncertainties of the real world environment which may include destabilizing unmodeled dynamics. Flight control design specifications recommend 6-dB of gain margin and 45° of phase margin as described in Ref. 29. However, there are examples of digital rotorcraft flight control systems known to violate 45° phase margin specifications in certain axes, as discussed in Ref. 30. Figure 4.2 demonstrates the loop break at the lateral cyclic input in the context of the NLDI controller while closing the other feedback linearization loops.
Figure 4.2: Broken Loop Analysis Demonstration with Lateral Cyclic Input

Figure 4.3 demonstrates an example of extracting the minimum stability margins from the open loop frequency response for a loop break at the lateral cyclic input.

Figure 4.3: Stability Margins from Open Loop Frequency Response with Broken Loop at Lateral Cyclic Input
4.2 Disturbance Rejection Analysis

4.2.1 ADS-33E-PRF Disturbance Rejection Criteria

ADS-33 [3] currently addresses the disturbance response of the aircraft with two criteria. For Attitude Hold Response-Types, the first criteria requires that the attitude response following a pulse input to the control actuator return to within 10% of the peak value or one degree (whichever is greater) within 20 seconds for an UCE (Usable Cue Environment) equal to 1 or within 10 seconds for an UCE greater than 1. The second criteria evaluates the bandwidth frequency due to the disturbance inputs directly sent into the actuator. As described in Ref. 31, both of these existing ADS-33 criteria are insufficient in properly evaluating the design to achieve satisfactory gust rejection. Ref. 31 highlights the limitation of the first criteria because of the neglect on short-term response recovery from the disturbance input. Ref. 31 describes how the second criteria only focuses on the verification that forward-loop shaping is not used to satisfy the bandwidth response requirement which fails to account for the possible disturbance rejection benefit in feedback.

4.2.2 AFDD Disturbance Rejection Criteria

Due to the lack of proper disturbance rejection coverage in ADS-33’s criteria, the AFDD has recently included a frequency-domain disturbance rejection criteria in the ADS-33 Test Guide [7]. The two requirements which were developed are based on the frequency response of adding a disturbance input to the measured output variable. This frequency response is based on the classical sensitivity function described in standard control design textbooks such as Ref. 28. The sensitivity function in the context of a roll attitude response can be described in Eqn. 4.1.

\[ S_\phi(s) = \frac{\phi}{\phi_d} = \frac{1}{1 + G_{fb}H_\phi} \]  \hspace{1cm} (4.1)

where \( G_{fb} \) represents the plant dynamics with the feedback linearization loop closed and \( H_\phi \) represents the feedback compensation that can be specified by the roll attitude error dynamics.

Figure 4.4 demonstrates how the sensitivity function is measured by adding a roll attitude disturbance input while closing the feedback linearization loops of the NLDI controller concurrently.
The two metrics which are used from the sensitivity function are Disturbance Rejection Bandwidth (DRB) and Disturbance Rejection Peak (DRP). DRB measures the speed at which the response recovers from the disturbance. It is defined as the frequency where the sensitivity function crossed the -3 dB point. In other words, this is the frequency where the response due to the disturbance is still attenuated by half the power. DRP measures the transient overshoot from the disturbance and is defined at the maximum magnitude of the sensitivity function. Figure 4.5 provides an example of how these metrics are extracted from the Bode plot.

Figure 4.5: Disturbance Rejection Bandwidth and Disturbance Rejection Peak Metrics
As discussed previously, the feedback gains are selected to specify the poles of the error dynamics in Eqn. 2.36 and 2.40. In previous piloted simulation testing [17], the inner loop gains were selected so the poles of the attitude error dynamics are critically damped and have the same natural frequency as the ACAH command filter. Similarly, outer loop gains were selected so velocity error dynamics matched the frequency of the TRC command filters. The precedence for the logical selection of the feedback gains is discussed in Ref. 27. This study will use the natural frequency and damping parameters of the error dynamics to vary the feedback gains which are related as seen in Eqn. 2.38 and 2.42.

DRB tends to increase as the natural frequency gain is increased. However, this also tends to result in the DRP being higher which can result in poor damping. An example of the disturbance rejection metrics is shown as natural frequency is increased seen in Figure 4.6.

![Figure 4.6: Natural Frequency Gain Effect on Disturbance Rejection Bandwidth](image)

The disturbance rejection effect can also be seen in the time domain where increasing disturbance rejection bandwidth results in a faster return to the trim state. In addition, increasing gain can result in oscillatory behavior due to the higher disturbance rejection peak. These behaviors are
demonstrated below in Figure 4.7. The necessary expansion of the ADS-33 disturbance rejection requirement of returning to within 10% of the peak value within 10 seconds is highlighted here because of how easily the requirement is met.

![Figure 4.7: Disturbance Rejection Bandwidth Effect on Roll Attitude in Time Domain](image)

As expected as well, as gain is increased, the DRB increases while stability margins generally decrease, resulting in the design tradeoff discussed in Ref. 11. This is demonstrated in Figure 4.8.

![Figure 4.8: Disturbance Rejection Bandwidth Effect on Stability Margins for Lateral Cyclic Input](image)
4.3 Gain Selection using Stability Margins

Similar to Ref. 11, an approach of using either the standard margins (SM) or a “relaxed” set of margins (RM), i.e. 4-dB of gain and 30° of phase, allows for the design of a family of controllers. Figures 4.9-4.10 show the lateral and longitudinal stability margins as a function of disturbance rejection bandwidth against the standard margins, SM, and relaxed margins, RM.

![Diagram showing lateral and longitudinal stability margins](image)

Figure 4.9: Lateral Stability Margins versus Disturbance Rejection Bandwidth

For the lateral axis, there is some initial improvement in stability margins with increased feedback gain, until they start to degrade at higher gains.
For the longitudinal axis, there is poor gain margin at low feedback gains which are then improved with increasing the gain. It is noted the negative gain margin occurs at a low $\omega_{gm}$ (0.1-0.2 rad/s) which corresponds to an unstable phugoid mode. Similarly as the lateral axis, the margins start to degrade at higher gains.

Figure 4.11 shows the yaw axis stability margins as a function of disturbance rejection bandwidth against the standard margins, SM, and relaxed margins, RM.
Note that the vertical axis is omitted because of nonlinearities in the variable RPM engine dynamics which are not represented by the linear model. These unmodelled dynamics prevented the usage of classical linear stability analysis. Tables 4.1-4.2 outline the family of controllers optimizing the disturbance rejection bandwidth while meeting a RM and SM specification. It is noted that only the natural frequency parameter, $\omega_{n,dr}$, was adjusted in each axis while the $\zeta$ value was left as the critically damped value of 1.0.

Table 4.1: Disturbance Rejection Properties for Standard Stability Margins

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>ACAH</th>
<th>TRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRB</td>
<td>GM</td>
</tr>
<tr>
<td>Lateral ($\phi$)</td>
<td>1.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Longitudinal ($\theta$)</td>
<td>0.35</td>
<td>15.1</td>
</tr>
<tr>
<td>Pedals (r)</td>
<td>3.7</td>
<td>3.2</td>
</tr>
<tr>
<td>Lateral (v)</td>
<td>0.7</td>
<td>8.3</td>
</tr>
<tr>
<td>Longitudinal (u)</td>
<td>0.4</td>
<td>13.8</td>
</tr>
</tbody>
</table>

*Inner loop frequency is set to be 7.15 times faster than outer loop natural frequency*
Table 4.2: Disturbance Rejection Properties for Relaxed Margins

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>ACAH</th>
<th>TRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral (ϕ)</td>
<td>DRB (rad/s)</td>
<td>GM (dB)</td>
</tr>
<tr>
<td>Longitudinal (θ)</td>
<td>1.8</td>
<td>5.7</td>
</tr>
<tr>
<td>Pedals (r)</td>
<td>1.0</td>
<td>10.9</td>
</tr>
<tr>
<td>Lateral (v)</td>
<td>5.0</td>
<td>7.8</td>
</tr>
<tr>
<td>Longitudinal (u)</td>
<td>0.8</td>
<td>5.6</td>
</tr>
<tr>
<td></td>
<td>0.48</td>
<td>10.8</td>
</tr>
</tbody>
</table>

*aInner loop frequency is set to be 7.15 times faster than outer loop natural frequency*
4.4 Gain Selection using AFDD Disturbance Rejection Criteria

Proposed boundaries for disturbance rejection criteria were developed by the AFDD that were based on simulation and flight testing of the UH-60 as described in Ref. 31. The boundaries are seen below in Table 4.3.

<table>
<thead>
<tr>
<th></th>
<th>Pitch (θ)</th>
<th>Roll (ϕ)</th>
<th>Yaw (ψ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRB (rad/s) ≥</td>
<td>0.5</td>
<td>0.9</td>
<td>0.7</td>
</tr>
<tr>
<td>DRP (dB) ≤</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Surge (u)</td>
<td>0.34</td>
<td>0.54</td>
<td>1.0</td>
</tr>
<tr>
<td>DRB (rad/s) ≥</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Axial (x)</td>
<td>0.17</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td>DRB (rad/s) ≥</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Another approach to the disturbance rejection variation was to utilize the proposed boundaries as the baseline disturbance rejection level rather than use the disturbance rejection at the standard stability margins as the baseline as shown in the previous section. This method developed a family of controllers with increasing disturbance rejection by varying the natural frequency and damping parameter while still adhering to the standard margins. The trade off between stability margins, DRB and DRP can be seen in the following Figures 4.12-4.18.

The low DRB design is selected using the minimum DRB boundary as seen in Table 4.3. The varying damping ratios are shown as an additional design parameter which can be tuned to recover stability margins. The medium and high disturbance rejection design points are shown as incremental increases in DRB. The high disturbance rejection design was tended to be bounded by the DRP parameter in order to prevent oscillatory responses as discussed previously. For the TRC/PH gain selection, the velocity disturbance rejection responses were used to select the gain design. The position responses are a result of using same velocity gains with the position hold compensation engaged with the addition of a pole fixed at 0.07. Therefore, the position DRB was not aligned to the proposed values in Table 4.3.
The roll axis gain selection can be seen in Figures 4.12(a)-4.12(d).

Figure 4.12: Roll Disturbance Rejection Gain Design with AFDD Boundaries at V = 20 kts
The pitch axis gain selection can be seen in Figures 4.13(a)-4.13(d).

Figure 4.13: Pitch Disturbance Rejection Gain Design with AFDD Boundaries at $V = 20$ kts
The yaw axis gain selection can be seen in Figures 4.14(a)-4.14(d).

Figure 4.14: Yaw Disturbance Rejection Gain Design with AFDD Boundaries at V = 20 kts
The lateral velocity gain selection can be seen in Figures 4.15(a)-4.15(d).

Figure 4.15: Lateral Velocity Disturbance Rejection Gain Design with AFDD Boundaries at $V = 20$ kts
The lateral position gain selection can be seen in Figures 4.16(a)-4.16(d).

Figure 4.16: Lateral Position Disturbance Rejection at $V = 20$ kts
The longitudinal velocity gain selection can be seen in Figures 4.17(a)-4.17(d).

Figure 4.17: Longitudinal Velocity Disturbance Rejection Gain Design with AFDD Boundaries at \( V = 20 \text{ kts} \)
The longitudinal position gain selection can be seen in Figures 4.18(a)-4.18(d).

![Graphs showing Gain Margin, Phase Margin, DRB, and DRP](image)

Figure 4.18: Longitudinal Position Disturbance Rejection at V = 20 kts
It is noted that relaxing margins was required in the longitudinal axis for both ACAH and TRC in order to get increasing levels of disturbance rejection from the proposed boundary in Table 4.3.

Table 4.4: Properties for Low Disturbance Rejection using AFDD Boundaries

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>DRB (rad/s)</th>
<th>DRP (dB)</th>
<th>GM (dB)</th>
<th>( \omega_{gm} ) (rad/s)</th>
<th>PM (deg)</th>
<th>( \omega_{pm} ) (rad/s)</th>
<th>( \omega_{n,dr} ) (rad/s)</th>
<th>( \zeta_{dr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral (( \phi ))</td>
<td>0.92</td>
<td>3.7</td>
<td>13.4</td>
<td>8.4</td>
<td>72.0</td>
<td>2.1</td>
<td>2.25</td>
<td>1.4</td>
</tr>
<tr>
<td>Longitudinal (( \theta ))</td>
<td>0.5</td>
<td>3.9</td>
<td>15.0</td>
<td>9.4</td>
<td>43.5</td>
<td>3.0</td>
<td>1.6</td>
<td>1.0</td>
</tr>
<tr>
<td>Pedals (r)</td>
<td>0.72</td>
<td>0.5</td>
<td>28.0</td>
<td>17.0</td>
<td>94.0</td>
<td>0.04</td>
<td>0.65</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**TRC/PH**

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>DRB (rad/s)</th>
<th>DRP (dB)</th>
<th>GM (dB)</th>
<th>( \omega_{gm} ) (rad/s)</th>
<th>PM (deg)</th>
<th>( \omega_{pm} ) (rad/s)</th>
<th>( \omega_{n,dr} ) a (rad/s)</th>
<th>( \zeta_{dr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sway (v)</td>
<td>0.58</td>
<td>3.3</td>
<td>13.8</td>
<td>7.3</td>
<td>45.0</td>
<td>2.1</td>
<td>0.28</td>
<td>1.4</td>
</tr>
<tr>
<td>Surge (u)</td>
<td>0.43</td>
<td>1.9</td>
<td>12.5</td>
<td>10.6</td>
<td>42.0</td>
<td>3.9</td>
<td>0.21</td>
<td>1.4</td>
</tr>
<tr>
<td>Lateral (y)</td>
<td>0.1</td>
<td>1.34</td>
<td>16.9</td>
<td>8.6</td>
<td>45.9</td>
<td>2.0</td>
<td>0.28</td>
<td>1.4</td>
</tr>
<tr>
<td>Axial (x)</td>
<td>0.08</td>
<td>1.64</td>
<td>15.2</td>
<td>12.8</td>
<td>46.5</td>
<td>3.9</td>
<td>0.21</td>
<td>1.4</td>
</tr>
</tbody>
</table>

aInner loop frequency is set to be 7.15 times faster than outer loop natural frequency

Table 4.5: Properties for Medium Disturbance Rejection using AFDD Boundaries

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>DRB (rad/s)</th>
<th>DRP (dB)</th>
<th>GM (dB)</th>
<th>( \omega_{gm} ) (rad/s)</th>
<th>PM (deg)</th>
<th>( \omega_{pm} ) (rad/s)</th>
<th>( \omega_{n,dr} ) (rad/s)</th>
<th>( \zeta_{dr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral (( \phi ))</td>
<td>1.13</td>
<td>4.4</td>
<td>9.6</td>
<td>9.5</td>
<td>62.0</td>
<td>4.2</td>
<td>3.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Longitudinal (( \theta ))</td>
<td>0.77</td>
<td>4.3</td>
<td>13.2</td>
<td>9.4</td>
<td>38.6</td>
<td>3.4</td>
<td>1.85</td>
<td>1.0</td>
</tr>
<tr>
<td>Pedals (r)</td>
<td>1.5</td>
<td>1.3</td>
<td>22.0</td>
<td>17.3</td>
<td>82.0</td>
<td>2.0</td>
<td>1.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**TRC/PH**

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>DRB (rad/s)</th>
<th>DRP (dB)</th>
<th>GM (dB)</th>
<th>( \omega_{gm} ) (rad/s)</th>
<th>PM (deg)</th>
<th>( \omega_{pm} ) (rad/s)</th>
<th>( \omega_{n,dr} ) a (rad/s)</th>
<th>( \zeta_{dr} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sway (v)</td>
<td>0.74</td>
<td>3.7</td>
<td>11.0</td>
<td>9.5</td>
<td>50.0</td>
<td>2.9</td>
<td>0.39</td>
<td>1.4</td>
</tr>
<tr>
<td>Surge (u)</td>
<td>0.48</td>
<td>2.1</td>
<td>11.1</td>
<td>10.5</td>
<td>36.7</td>
<td>4.4</td>
<td>0.24</td>
<td>1.4</td>
</tr>
<tr>
<td>Lateral (y)</td>
<td>0.13</td>
<td>1.34</td>
<td>13.4</td>
<td>11.1</td>
<td>53.7</td>
<td>2.8</td>
<td>0.39</td>
<td>1.4</td>
</tr>
<tr>
<td>Axial (x)</td>
<td>0.09</td>
<td>1.6</td>
<td>13.8</td>
<td>12.7</td>
<td>41.4</td>
<td>4.5</td>
<td>0.24</td>
<td>1.4</td>
</tr>
</tbody>
</table>

aInner loop frequency is set to be 7.15 times faster than outer loop natural frequency
Table 4.6: Properties for High Disturbance Rejection using AFDD Boundaries

### ACAH

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>DRB (rad/s)</th>
<th>DRP (dB)</th>
<th>GM (dB)</th>
<th>$\omega_{gm}$ (rad/s)</th>
<th>PM (deg)</th>
<th>$\omega_{pm}$ (rad/s)</th>
<th>$\omega_{n,dr}$ (rad/s)</th>
<th>$\zeta_{dr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral ($\phi$)</td>
<td>1.27</td>
<td>5.0</td>
<td>7.4</td>
<td>9.8</td>
<td>45.0</td>
<td>5.6</td>
<td>3.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Longitudinal ($\theta$)</td>
<td>1.0</td>
<td>5.05</td>
<td>11.1</td>
<td>9.3</td>
<td>31.0</td>
<td>4.0</td>
<td>2.25</td>
<td>1.0</td>
</tr>
<tr>
<td>Pedals (r)</td>
<td>2.1</td>
<td>2.0</td>
<td>18.7</td>
<td>17.2</td>
<td>68.0</td>
<td>3.0</td>
<td>1.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### TRC/PH

<table>
<thead>
<tr>
<th>Control Axis</th>
<th>DRB (rad/s)</th>
<th>DRP (dB)</th>
<th>GM (dB)</th>
<th>$\omega_{gm}$ (rad/s)</th>
<th>PM (deg)</th>
<th>$\omega_{pm}$ (rad/s)</th>
<th>$\omega_{n,dr}$ a (rad/s)</th>
<th>$\zeta_{dr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sway (v)</td>
<td>0.87</td>
<td>4.2</td>
<td>7.5</td>
<td>9.9</td>
<td>50.0</td>
<td>5.0</td>
<td>0.49</td>
<td>1.4</td>
</tr>
<tr>
<td>Surge (u)</td>
<td>0.55</td>
<td>2.4</td>
<td>9.5</td>
<td>10.4</td>
<td>30.0</td>
<td>5.1</td>
<td>0.28</td>
<td>1.4</td>
</tr>
<tr>
<td>Lateral (y)</td>
<td>0.16</td>
<td>1.44</td>
<td>10.0</td>
<td>11.5</td>
<td>57.7</td>
<td>4.8</td>
<td>0.49</td>
<td>1.4</td>
</tr>
<tr>
<td>Axial (x)</td>
<td>0.10</td>
<td>1.5</td>
<td>12.2</td>
<td>12.6</td>
<td>35.6</td>
<td>5.0</td>
<td>0.28</td>
<td>1.4</td>
</tr>
</tbody>
</table>

*Inner loop frequency is set to be 7.15 times faster than outer loop natural frequency*

In ACAH, the AFDD baseline design has significantly lower DRB values in the roll and yaw axes compared to the standard stability margins baseline design. For example, the standard stability margins design in Table 4.1 demonstrates that the roll axis has a baseline DRB value of 1.5 rad/s while the AFDD design in Table 4.4 is baselined at a DRB of 0.9 rad/s. It is noted that the lateral and pedal axes still achieve standard stability margins in their highest DRB case as seen in Table 4.6. For the pitch axis, the AFDD design was very comparable to the standard stability margins design. This result is due to the fact that increasing levels of DRB still required a relaxation of the phase margin requirement.
Chapter 5

Pilot In The Loop Simulation Testing

Pilot-in-the-loop simulation tests were conducted with pilots who have served in the armed forces with various ranges of flying experience operating in ships. Note that all simulations were performed with the full GENHEL-PSU flight model. This is a fully non-linear, blade element simulation model (not the simplified non-linear model used in the NLDI control laws), which included models of sensor noise and bias drift which is described in Ref. 17. Piloted simulations were used to evaluate the handling qualities for a family of controllers based on the bandwidth and DRB properties presented in the previous sections. One set of testing was focused on varying the bandwidth properties while maintaining the disturbance rejection aspects of the controller. The other round of testing which focused on disturbance rejection was evaluated vice versa. The family of controllers which were tested are described in this section along with respective external environment which includes the ship and airwake models.

5.1 Simulation Environment

5.1.1 Flight Simulator

The simulator utilizes the original cockpit of a Bell XV-15 tilt-rotor experimental aircraft with custom instrumentation software in the cab displays. A control loading system provides the force-feel characteristics of the rotorcraft to the pilots. The flight simulation scenery is generated through the X-Plane software and outputted onto a cylindrical screen using 3 projectors which are then warped together to provide a 170 degrees field of view. One of the pilots flying in the simulator
environment can be seen in Fig. 5.1.

Figure 5.1: Flight Simulator Environment

5.1.2 Ship Model

As was done in prior simulation testing [17], a 3-D ship model of a FFG-7 Perry-class frigate is used. Figure 5.2 shows the ship model in the simulation as well as a photograph of the actual ship. In addition, the horizon reference bar seen in Fig. 5.2 aids the pilot with orientation cueing while hovering over the ship deck.

Figure 5.2: FFG-7 Frigate Model and Actual Ship
For this study, the pitch, roll and heave motion of the ship was derived from the lateral and vertical displacements prescribed to the varying sea state levels used in the original NRC Superslide [32]. The lateral and vertical displacements were originally derived from a Canadian Patrol Frigate. The horizon reference bar in Fig. 5.2 was selected as the relative point from the ship’s c.g. to derive the ship motion. Figure 5.3 demonstrates how the aforementioned displacements are transformed back into the ship’s pitch and roll motion.

Figure 5.3: Transformation of Superslide Aircraft Motion back to Ship Motion

\( Z \) is the origin of the body-fixed frame referenced at the ship’s c.g. Frame I is the inertial coordinate frame fixed at the same origin, O. Frame B is the ship body-fixed frame. \( l_h \) and \( l_v \) are the moment arm distances from the ship’s c.g. to the horizon reference bar. \( Z_\theta \) and \( Y_\phi \) represent the aircraft displacement due to the ship motion from the horizon reference bar. The total vertical displacement, \( Z_{total} \), was divided amongst the pitch and heave motion to produce the equivalent total. This was arbitrarily selected as seen in Eqns. 5.2-5.3.

\[
Z_{total} = Z_{heave} + Z_\theta \quad (5.1)
\]

\[
Z_{heave} = 0.4 \times Z_{total} \quad (5.2)
\]

\[
Z_\theta = 0.6 \times Z_{total} \quad (5.3)
\]
Using the inverse of the direction cosine matrix as seen in Eqn. 5.4, we can transform the ship’s body frame back to the inertial frame.

\[
T_{I/B} = \begin{bmatrix}
\cos(\theta)\cos(\psi) & -\cos(\phi)\sin(\psi) + \sin(\phi)\sin(\theta)\cos(\psi) & \sin(\phi)\sin(\psi) + \cos(\phi)\sin(\theta)\cos(\psi) \\
\cos(\theta)\sin(\psi) & \cos(\phi)\cos(\psi) + \sin(\phi)\sin(\theta)\sin(\psi) & -\sin(\phi)\cos(\psi) + \cos(\phi)\sin(\theta)\sin(\psi) \\
-\sin(\theta) & \sin(\phi)\cos(\theta) & \cos(\phi)\cos(\theta)
\end{bmatrix}
\] (5.4)

If we assume small angle approximation and negligible yawing motion, the transformation matrix is reduced to Eqn. 5.5.

\[
T_{I/B} = \begin{bmatrix}
1 & 0 & \theta \\
0 & 1 & -\phi \\
-\theta & 0 & 1
\end{bmatrix}
\] (5.5)

The body frame vector can now be transformed into the inertial frame vector as seen in Eqn. 5.6.

\[
\begin{bmatrix}
X_I \\
Y_I \\
Z_I
\end{bmatrix} = \begin{bmatrix}
1 & 0 & \theta \\
0 & 1 & -\phi \\
-\theta & 0 & 1
\end{bmatrix}\begin{bmatrix}
X_B \\
Y_B \\
Z_B
\end{bmatrix}
\] (5.6)

The position of the horizon reference bar in the body frame is first transformed into the inertial frame using Eqn. 5.6. Since we assume the aircraft to be at the initial position of the horizon reference bar, we subtract the initial position from the inertial frame vector in order to obtain the relative displacements. This is demonstrated in Eqn 5.7.

\[
\begin{bmatrix}
X_\theta \\
Y_\phi \\
Z_\theta
\end{bmatrix} = \begin{bmatrix}
1 & 0 & \theta \\
0 & 1 & -\phi \\
-\theta & 0 & 1
\end{bmatrix}\begin{bmatrix}
l_h \\
l_v \\
l_w
\end{bmatrix} + \begin{bmatrix}
-l_h \\
0 \\
-l_w
\end{bmatrix}
\] (5.7)

Since $Z_\theta$ and $Y_\phi$ are given from the Superslide motion files and we neglect the $X_\theta$, we can now solve for $\theta$ and $\phi$ as seen in Eqns. 5.8-5.9.

\[
\phi = \frac{-Y_\phi}{l_v}
\] (5.8)
\[
\theta = \frac{-Z_a}{l_h}
\]

(5.9)

The yawing motion was mild and unchanged relative to sea state. It originated from time histories of ship motion measured from an actual FFG-7, taken from Ref. 33. The starting point of the ship motion data was randomized for each run to remove any predictability of the ship’s motion when the aircraft approached the ship. Time histories of the ship motion used can be seen in the following Figure 5.4.

The corresponding root mean squared and maximum amplitude values for each respective sea state are shown in Table 5.1.

<table>
<thead>
<tr>
<th>Sea State</th>
<th>Roll (deg)</th>
<th>Pitch (deg)</th>
<th>Heave (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>2.0</td>
<td>4.8</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>8.5</td>
<td>0.5</td>
</tr>
<tr>
<td>5</td>
<td>4.1</td>
<td>12.5</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Figure 5.4: Ship Motion Derived from NRC Superslide and Actual FFG-7
5.1.3 Airwake Models

The first round of disturbance rejection testing was conducted with a Computational Fluid Dynamics (CFD)-based airwake model that has been integrated with GENHEL-PSU. For the simulation, the dynamic interface between the aircraft and the environment is based on a CFD solution of the Simple Frigate Shape #2 (SFS2). The results of the model have been validated with test data as shown in Ref. 6.

Due to limited observable results with the relatively benign CFD model which is discussed further in the next section, another round of disturbance rejection testing was conducted using a more intense airwake called the Control Equivalent Turbulence (CETI) airwake model seen in Ref. 18. The model is used to simulate the same effects of the turbulent airwakes behind the ship’s superstructure. The model was originally developed by the AFDD through the collection of flight test data from a UH-60 hovering in an airwake behind a large cube-shaped hangar. An inverse method was used to solve for the control inputs required to replicate the aircraft response due to the disturbances. The time histories of the control inputs are summed together with the control inputs from the controller. The airwake control inputs are scalable for different turbulence levels. A “moderate” turbulence level was used in this study based on the parameter values listed in Ref. 18. During simulation testing, pilots commented that the CETI model seemed to accurately simulate disturbances when the aircraft reached the ship’s fantail. One pilot was quoted as saying “the helicopter needed to push through a wall at the fantail, but then required me to pick up the nose quickly to avoid accelerating forward into the hangar.”

5.2 Task Descriptions

5.2.1 Shipboard MTE

The mission task element (MTE) used for evaluation was based on the maritime MTE presented in Ref. 8 combined with a similar psuedo-tracking hover task used in the NRC superslide evaluation [12]. The pilot was tasked with a direct-stern approach to a FFG-7 ship, which held a constant velocity of 20 knots. A headwind of either 5 or 20 knots was used to get the desired WOD condition when using the CFD-based airwake model. It is important to note that no headwind was included when using the CETI model. The aircraft began the task in a trimmed forward flight with 15 knots
of closure rate, approximately 1000 feet behind the ship, and 100 feet AGL. The pilot was asked to perform a constant rate descent to the ship fantail and then flare the aircraft prior to the deck edge. The pilot then maneuvered the aircraft to a hover over the center of the deck.

The pilot was tasked with maintaining the aircraft’s position above the center of the deck for approximately 60 seconds at a high hover (10-15 ft) above the deck. The desired lateral and longitudinal range of aircraft position was within a 10 foot square at the center of the deck and an adequate range within a 20 foot square. “Hard limits” were not imposed for the hover task. Pilots were allowed to exit the desired and adequate tolerances up to 5 second transients due to large ship roll excursions. Figure 5.5 shows the respective tolerances used for the hover and landing tasks.

![Figure 5.5: Position Tolerances for Desired and Adequate Performance](image)

Once the hover period ended, the pilot landed upon suitable deck conditions with a desired landing location within a 5 foot square at the center of the deck and an adequate landing location within a 10 foot square. Figure 5.6 demonstrates the entire shipboard MTE in a step-by-step manner.

For both hover and landing tasks, the pilot received verbal position cueing from a co-pilot analogous to a “crew chief” and utilized visual cues from the ship’s superstructure. The precedence for utilizing verbal instructions to assist the pilot in a MTE has been previously established [34].
Upon landing, the pilot assessed the handling qualities of the controller with the Cooper-Harper Rating Scale [35]. Initially, the pilots were asked to assess both the hover and landing tasks with one rating with 1 being the most desirable and 10 being the least. However, it was decided that the pilots provide HQRs for each task separately. The decision-making flow chart used to survey the pilots is seen in Fig. 5.7.

5.3 Testing Configurations

The control modes used for the evaluation include basic mechanical controls with a ±10% authority Stability Augmentation System, ACAH and what will be referred to as the TRC control mode. The TRC mode is actually an “Automatic Transition” mode as developed in Ref. 17. The mode uses a Ship-Relative Acceleration Command / Velocity Hold (ACVH) in the longitudinal axis and ship-relative TRC in the lateral axis during the approach phase. It then converts to Ship-Relative TRC/PH in both longitudinal and lateral axes near the ship. A major assumption is made that the ship’s position and velocities are available to the control laws via accurate telemetry. Since most of the pilot workload is associated with the hover and landing phases, the control design variations are focused on the TRC/PH mode. In the TRC mode, the vertical and yaw axes are identical to those used in the ACAH modes.
A total of seven variations in the AFCS design parameters were evaluated in piloted simulations as summarized in Table 5.2. The test cases include variations in both response bandwidth and disturbance rejection bandwidth. It is noted that the initial bandwidth variations use the standard margins as their baseline disturbance rejection. The first round of disturbance rejection was tested varying the stability margins in the roll, pitch and yaw axes. The second round of testing varied the DRB levels based on the proposed AFDD criteria. The two design sets of DRB are still designated by the same case number since they use the same bandwidth.

All of the cases were tested in the ACAH and TRC modes. With the exception of Case 7, the bandwidth and/or DRB were adjusted to low, medium, or high levels across all axes. For the DRB variation in TRC, only the cyclic axes were adjusted to focus on the TRC mode's effect. Note that for the TRC and vertical speed response, the bandwidth cases refers to a shorter rise time, while low bandwidth results in longer rise time. Case 7 used a medium bandwidth level in the longitudinal axis, while all other axes are high bandwidth. This case arose as early results indicated that the high bandwidth system was susceptible to PIO in the pitch axis.

Seven different permutations of ship motion and airwake turbulence were used for simulation testing. For the initial DRB variation testing using stability margins as design points, the sea states
Table 5.2: Test Cases

<table>
<thead>
<tr>
<th>Control Mode</th>
<th>Case</th>
<th>BW Level</th>
<th>DRB Level¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mech. w/SAS²</td>
<td>1</td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>ACAH</td>
<td>2</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>ACAH</td>
<td>3</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>ACAH</td>
<td>4</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>ACAH</td>
<td>5</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>ACAH</td>
<td>6</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>ACAH</td>
<td>7</td>
<td>Medium/High</td>
<td>Medium</td>
</tr>
</tbody>
</table>

¹Note that there are two separate DRB designs; One using the standard margins as baseline and the other using AFDD’s DRB proposed criteria
²Mechanical Controls with SAS
³Automatic Transition with Ship-Relative TRC/PH near the ship

3-5 was used in combination with varying wind over deck (WOD) speeds with a CFD airwake. For the disturbance rejection design using the AFDD criteria, no ship motion (sea state 0) was included in order to isolate the disturbance rejection properties of the controller as a baseline case. Sea states 4 and 5 were used in conjunction with a lower WOD speed to evaluate the bandwidth properties. Table 5.3 documents the flight condition permutations used in conjunction with the controller test cases.

Table 5.3: Flight Condition Permutations

<table>
<thead>
<tr>
<th>Sea State</th>
<th>WOD (CFD) (kts)</th>
<th>CETI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>No</td>
</tr>
</tbody>
</table>

Test cases were randomized so the pilot had no prior information of sea state and the bandwidth and DRB properties of the control mode. This allowed for an objective handling qualities evaluation per test run. The pilot was informed when the TRC mode was used since it requires a different piloting strategy.
Chapter 6

Test Results

A total of six pilots participated in the study to evaluate the handling qualities for a family of controllers defined in Table 5.2. The demographic of pilots ranged from highly experienced graduates of the United States Naval Test Pilot School (USNTPS) with extensive test and operational shipboard experience to limited shipboard experience. Table 6.1 demonstrates each pilot’s flight hours, aircraft type, service type and experimental test background.

<table>
<thead>
<tr>
<th>Pilot</th>
<th>Total Flight Hours</th>
<th>Service Type</th>
<th>Aircraft Type</th>
<th>USNTPS Graduate?</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5800</td>
<td>Navy</td>
<td>H-60</td>
<td>Yes</td>
</tr>
<tr>
<td>B</td>
<td>3800</td>
<td>Navy</td>
<td>H-60</td>
<td>No</td>
</tr>
<tr>
<td>C</td>
<td>6000</td>
<td>Marine Corps.</td>
<td>H-53</td>
<td>Yes</td>
</tr>
<tr>
<td>D</td>
<td>2500</td>
<td>Navy</td>
<td>H-53</td>
<td>Yes</td>
</tr>
<tr>
<td>E</td>
<td>3100</td>
<td>Marine Corps.</td>
<td>H-1</td>
<td>No</td>
</tr>
<tr>
<td>F</td>
<td>750</td>
<td>Navy</td>
<td>H-60</td>
<td>No</td>
</tr>
</tbody>
</table>

Due to availability constraints, some pilots were not able to evaluate every permutation in control law and ship environment. Table 6.2 details the breakdown of which controller variation was tested by each pilot for the respective MTE.
### 6.1 ACAH Bandwidth Variation

The ACAH bandwidth variation was tested with three of the available test pilots. The bandwidth variation was tested under the conditions of sea states 4 and 5 combined with the CFD-based airwake model using a WOD condition of 25 kts.

#### 6.1.1 Handling Qualities Ratings

The separate landing and hover HQRs were averaged per test case. The maximum, minimum and mean values of the assigned HQRs resulting from varying the bandwidth properties of the ACAH controller can be seen in Figure 6.1.

![Figure 6.1: Cooper-Harper Handling Qualities Ratings for ACAH Bandwidth Variation](image)
The ACAH controller often demonstrated better HQRs when compared to the baseline mechanical controls with SAS. The one exception was the low bandwidth controller (Case 1). Although Case 1 is considered Level 1 in ADS-33 [3], the HQRs did not improve over the mechanical system. For Case 1, one pilot was quoted as saying that “it was difficult to keep the helicopter over the landing spot even when the ship was quiet”. Another pilot also commented for Case 1 that “the inability to talk while flying indicates to me that I’m heavily focused on flying”.

The results in Figure 6.1 demonstrate that increasing the bandwidth of the ACAH controller improves the HQR as seen in Cases 1-3 for both sea states. The HQRs are shown to be slightly worse when moving from the medium bandwidth (Case 2) to high bandwidth (Case 3) in sea state 4. A couple of the pilots mentioned that the movements felt smaller and controllable in Case 2 as compared to Case 3 for sea state 4. One pilot was quoted as saying “the flight controls felt very loose” for Case 3 which referred to the highly responsive nature of the controller. When the pilots were forced to turn up the gains and frequency of inputs for sea state 5, pilots consistently rated Case 3 better than Case 2. However, none of the ACAH controllers were able to achieve a Level 1 rating. These HQR results reflect similar findings with the high bandwidth ACAH used in the Superslide evaluations for sea states of 4 or greater [12]. These results further support that for sea states of 4 or greater that ACAH alone is unable to provide Level 1 handling qualities.

6.1.2 Hover and Touchdown Performance

The hover and landing performance for the variations in the ACAH bandwidth for sea states 4 and 5 are shown in Figures 6.2-6.3. The sample data seen in Figure 6.2(a) was taken as the average distance from the center of the deck over the course of the hover task. All deviations relative to the center of the deck were converted to an absolute value so that all deviations were weighted equally.
(a) Average Hover Distance with respect to center of deck

Figure 6.2: Sea State 4 Hover and Landing Performance for ACAH Bandwidth Variation

(b) Landing Distance with respect to center of deck

Figure 6.3: Sea State 5 Hover and Landing Performance for ACAH Bandwidth Variation

In sea state 4, the mechanical controls and the low bandwidth (Case 1) are the only cases to
demonstrate inadequate hover performance. The average hover distance from the center of the deck improves as the bandwidth was increased from Case 1 to the medium bandwidth (Case 2). The high bandwidth (Case 3) does not demonstrate improved hover performance compared to Case 2. The landing performance did not show a consistent trend with respect to the bandwidth variation. Pilots were often able to achieve at least adequate performance for all test cases with 2 outliers of inadequate.

For sea state 5, the hover performance demonstrates improvement as the bandwidth is increased. Cases 2-3 demonstrated consistent desired performance with one instance of adequate. The high DRB and high bandwidth case (Case 6) enhanced the hover performance further. However, the sample size is fairly limited. The touchdown locations showed a trend of improved performance as the bandwidth was increased. The mechanical controls and Case 1 were the only test cases which had inadequate landing performance. Case 3 was able to achieve desired for all runs while Case 2 had a couple few samples within adequate.

6.1.3 Pilot Workload Metrics

In order to better quantify the changes in pilot workload due to the controller gains, a set of time domain metrics originating from Ref. 36 were utilized for this analysis. The pilot control inceptor time histories were processed through these metrics to gain insight on workload. The pilots commented that workload was a significant factor in the assigned HQRs. The metrics serve as identifiers on whether the actual workload correlates to the pilots’ assessment on the perceived level of compensation required to complete the MTE. Pilot workload is defined by the following three measures:

1. Aggressiveness, which is a measure of control deflection magnitude from the trim control input position over the course of the maneuver. The maneuver will be the portion of the approach spent over the deck which encompasses the majority of the workload as discussed previously. Equation 6.1 defines aggressiveness as the time-averaged summation of the difference between the actual pilot control inputs and the trim input position normalized by the total deflection
range of each control inceptor.

\[ J_A = \frac{100\%}{t_f - t_0} \sum_{t=t_0}^{t_f} \left( \frac{|\delta(t) - \delta_{trim}(t)|}{\delta_{max} - \delta_{min}} \right) \Delta t \]  

(6.1)

2. A peak, a measure of an adjustment change in the pilot’s input. A peak in Ref. 36 is arbitrarily defined as a change in magnitude greater than 0.5% of the total deflection range and in the direction opposite of the previous time step’s input. Figure 6.4 demonstrates an example of the peak detection algorithm applied to the longitudinal input data during the maneuver over the deck.

![Figure 6.4: Peaks for Longitudinal Inputs during Landing Portion of Ship Approach](image)

3. Duty cycle, the measure of the frequency of the adjustment change over the course of the maneuver. The average duty cycle is calculated by the number peaks over the length of time of the maneuver as seen in Eqn. 6.2.

\[ \text{Duty cycle} = \frac{\#\text{peaks}}{t_f - t_0} \]  

(6.2)

Figure 6.5 shows the workload metrics for the ACAH bandwidth variation for both sea states 4 and 5.
Figure 6.5: Workload Metrics of Control Inceptors of ACAH Bandwidth with Airwake Model and Sea States 4-5
For sea state 4, the results demonstrate that the pilot workload metrics correlate well with the mean values of HQRs. It is shown that the low bandwidth (Case 1) was worse in the cyclic axes for the aggressive metric and caused a significantly higher number of peaks than the mechanical controls. There’s a clear monotonic decreasing trend in the number of peaks from the low to high bandwidth. In addition, the cyclic axes’ aggressiveness is lowered as bandwidth is increased. Although the longitudinal axis’s aggressiveness is still greater than the mechanical controls, the aggressiveness benefit in the other axes supports the overall HQR improvement. The duty cycle results do not demonstrate any clear trends with exception to the benefit in the pedals.

In sea state 5, the pilot workload metrics also correlate well with the HQRs. Case 1 is shown to be very similar to the mechanical controls in terms of peaks and aggressiveness. As expected, the aggressiveness was again reduced considerably in the pedals and collective when using ACAH. For the peaks, there’s a clear monotonic decreasing trend when varying the bandwidth from low to high. The aggressiveness also shows this trend with the exception being the longitudinal axis. The duty cycle demonstrates the same trend in benefit although it is noteworthy that the benefit becomes diminished when moving from the medium to high bandwidth case. The final test case of increasing the disturbance rejection to the relaxed margins with high bandwidth shows minimal improvement in all three metrics.

### 6.1.4 Pilot Control Activity Frequency Ranges

The multiple frequencies in pilot control input activity present another identifier in how different piloting strategies are applied to the shipboard task. A previous study analyzed the frequency ranges of the control activity in order to categorize the various ranges into an associated pilot control strategy [37]. The proposed ranges of frequency are shown below in Table 6.3.
Table 6.3: Proposed Frequency Ranges for Pilot Control Tasks [37]

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Pilot Control Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25-0.8 rad/s</td>
<td>Typical open-loop control associated with trimming and flight path modulation</td>
</tr>
<tr>
<td>0.8-2.0 rad/s</td>
<td>Typical closed-loop control associated with transport aircraft maneuvering</td>
</tr>
<tr>
<td>2.0-4.0 rad/s</td>
<td>Higher-gain closed-loop control associated with increased task urgency or handling</td>
</tr>
<tr>
<td></td>
<td>issues with the aircraft, such as PIO</td>
</tr>
<tr>
<td>4.0-10.0 rad/s</td>
<td>Very high-gain closed-loop control, almost certainly associated with control</td>
</tr>
<tr>
<td></td>
<td>difficulties</td>
</tr>
</tbody>
</table>

The power spectral density (PSD) describes how the power of an input is distributed over all frequencies for a given time history. The PSD is the average of the Fourier transform magnitude squared over a time interval as in seen in Eqn. 6.3.

\[
PSD(f) = \lim_{T \to \infty} E \left\{ \frac{1}{2T} \left| \int_{-T}^{T} x(t) \exp^{-j2\pi ft} dt \right|^2 \right\} \quad (6.3)
\]

This analysis uses the MATLAB function \textit{pwelch} which uses Welch’s periodogram method [38] to solve for the power spectral density estimate. An example of a single PSD plot for a given history for each control axis is shown in Figure 6.6.

![Figure 6.6: Power Spectral Density for Single Time Series of Hover to Landing over the Ship Deck](image-url)
The total areas of the PSDs for each frequency range in Table 6.3 were calculated in order to provide a single value for each respective range. The mean of these single values were evaluated each control inceptor for the entire hover and landing task which yielded a useful measure of control activity across all datasets. Figures 6.7-6.8 demonstrate the average power of the frequency ranges for sea states 4 and 5 for the ACAH bandwidth variation.

**ACAH with Sea State 4 and WOD 25 kts**

![Graphs showing average power for different control inceptors with different bandwidths.](attachment:image.png)

Figure 6.7: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors for ACAH Bandwidth with Sea State 4.
A CAH with Sea State 5 and WOD 25 kts

For sea state 4, the PSD results indicate the emphasis in piloting control strategy for the family of controllers tested. In the lateral axis, the mechanical system displays the greatest average power in the “open-loop control” range. Additionally, the low bandwidth (Case 1) utilizes the highest power in the “closed-loop control” range. The “closed loop control” range also shows a decreasing trend in average power as the bandwidth is increased. For the longitudinal axis, the highest contributor of the average power when using ACAH is in the “open-loop control” range.
For the pedals, the mechanical system demonstrates a significantly greater average power for the “open loop” range compared to ACAH. The collective axis had the least relative differences in average power between the controller variations in all frequency ranges.

For sea state 5, the PSD results show similar trends as sea state 4. The additional case of high bandwidth and increased DRB does not show a significant difference in average power. For both lateral and longitudinal, the “closed loop control” range again demonstrates a decreasing trend in average power as the bandwidth is increased. However, the mechanical system demonstrates greater power in the “closed loop control” and “higher-gain closed-loop control” ranges. This is not unexpected given the increased task urgency and maneuvering induced by the higher sea state condition. For the pedals, the mechanical control system again demonstrates a significantly greater average power for the “open loop” range compared to ACAH.

6.1.5 Example Time Histories of Shipboard MTE

Figures 6.9-6.13 demonstrate the aircraft’s position relative to the center of the deck and the pilot control inputs during the hover and landing tasks. The time histories demonstrate the mechanical system and the ACAH bandwidth variations for sea states 4 and 5.

Figure 6.9: Time Histories for Mechanical Controls with SAS in Sea State 4
Figure 6.10: Time Histories for ACAH Low Bandwidth in Sea State 4

Figure 6.11: Time Histories for ACAH High Bandwidth in Sea State 4
Figure 6.12: Time Histories for ACAH Low Bandwidth in Sea State 5

Figure 6.13: Time Histories for ACAH High Bandwidth in Sea State 5
6.2 TRC Bandwidth Variation

The TRC bandwidth variation was tested with four of the available test pilots. The bandwidth variation was tested under the conditions of sea states 4 and 5 combined with the CFD-based airwake model using a WOD condition of 25 kts.

6.2.1 Handling Qualities Ratings

The maximum, minimum, and mean HQRs resulting from varying the bandwidth in TRC can be seen in Figure 6.14.

![Figure 6.14: Cooper-Harper Handling Qualities Ratings for TRC Bandwidth Variation](image)

The low bandwidth TRC (Case 1) did not show any improvement as compared to basic mechanical controls and was shown to be even worse in sea state 4 than the higher bandwidth ACAH controllers (Case 2 and Case 3). TRC Case 1 results were similar to the TRC results seen in the Superslide evaluations [12]. In addition, the TRC controller used in the Superslide had a similar low bandwidth as Case 1 so the inability for Case 1 to achieve Level 1 handling qualities is largely
expected. Pilots found Case 1 difficult to achieve desired performance and the responsiveness of the controller to be lacking. One pilot was quoted as saying, “it takes a while to achieve the stable hover and I felt almost out of phase with the system.”

When the pilots flew TRC with a higher bandwidth (Cases 2, 3 and 7), the HQRs moved immediately to the Level 1 range in the presence of both sea state 4 and 5. TRC with the highest bandwidth (Case 3) caused oversensitivity particular in the pitch axis and left pilots prone to PIO. One pilot commented that “the nose was bobbling quite a bit and I found myself fighting the natural tendency to compensate.” Case 7 used a medium bandwidth for the pitch axis while maintaining the high bandwidth in all other axes. However, Case 7’s HQRs were actually worse than Case 3. More data samples would need to be collected to verify this discrepancy.

The medium bandwidth controller (Case 2) demonstrated the best HQRs for both sea states. The HQRs provide strong evidence that a rise time smaller than 2.5 seconds is a diminishing return if not detrimental to the handling qualities. For Case 2, both pilots commented that there were minimal inputs required to meet desired performance. After a stabilized hover over the landing spot was established, often the landing task was reduced to waiting for a quiescent ship period in order to lower the collective. After completing the task in sea state 5 with Case 2, one pilot was quoted as saying, “it was highly desirable and I only had to make a few input adjustments.”

TRC demonstrated slightly better HQRs in sea state 5 as compared to sea state 4. Many of the sea state 5 test cases were tested subsequently of sea state 4 so a training factor may have been involved with pilots becoming more accustomed to TRC.

More data samples will be required to further support the TRC conclusions. However, the results point to a medium bandwidth TRC control mode as the optimal control scheme to achieve Level 1 handling qualities for sea states of at least 4.

### 6.2.2 Hover and Touchdown Performance

The hover and landing performance for the variations in the TRC bandwidth for sea states 4 and 5 are shown in Figures 6.15-6.16.
(a) Average Hover Distance with respect to center of deck

(b) Landing Distance with respect to center of deck

Figure 6.15: Sea State 4 Hover and Landing Performance for TRC Bandwidth Variation

(a) Average Hover Distance with respect to center of deck

(b) Landing Distance with respect to center of deck

Figure 6.16: Sea State 5 Hover and Landing Performance for TRC Bandwidth Variation
In sea state 4, the mechanical controls was the only controller to demonstrate inadequate hover performance. The average hover performance for TRC with low bandwidth (Case 1) was consistently within the adequate tolerances. The average hover distance is observed to be consistently within the desired range as bandwidth is increased from Case 1 to the medium bandwidth (Case 2). The high bandwidth (Case 3) and medium/high bandwidth (Case 7) demonstrate similar hover performance compared to Case 2. Both the landing and hover performance had similar trends with respect to bandwidth. The mechanical controls and Case 1 had inadequate landings while also often unable to meet desired tolerances. Cases 2 and 3 demonstrated consistency in attaining desired landings.

The hover trends are further accentuated when moving to sea state 5 in the hover performance. The progression of increasing bandwidth (lower rise time) improves the hover performance. The mechanical controls and Case 1 are only able to achieve adequate while Cases 2, 3 and 7 can attain desired. For the landing performance, Cases 2, 3 and 7 demonstrated the most frequent desired touchdown locations.

6.2.3 Pilot Workload Metrics

The workload metrics for sea states 4-5 with WOD conditions of 25 kts can be seen in Figure 6.17. For the sea state 4 condition, the results demonstrate that the pilot workload metrics correlate well with the mean values of HQRs. It is seen that the low bandwidth (Case 1) was worse in the cyclic axes for the aggressive metric than the mechanical controls. In addition, there’s a clear monotonic decreasing trend in aggressiveness from Case 1 to high bandwidth (Case 3). The conventional thought would indicate the higher bandwidth would have better handling qualities, but pilots did not rate Case 3 better than the medium bandwidth (Case 2) as seen in Figure 6.14. This decrease in aggressiveness could corroborate with the pilots’ comments on overly sensitive control inceptors. The peaks and duty cycle metrics support the conclusion that Case 2 is the optimal design choice. The number of peaks slightly increases in the Case 3 compared the Case 2.

In sea state 5, the workload metrics also exhibited very strong correlation with the mean values of HQRs. Similar as sea state 4, there’s a decreasing trend in aggressiveness from Case 1 to Case 3 with the mechanical controls displaying greater aggressiveness than Case 1. Additionally, the peaks and duty cycle metrics decrease in a similar manner which did not occur in sea state 4.
Figure 6.17: Workload Metrics of Control Inceptors of TRC Bandwidth with Airwake Model and Sea States 4-5
There is supporting evidence that Case 3 provides benefit in pilot workload for greater sea states despite the pilots did not necessarily rate the handling qualities better in Figure 6.14.

6.2.4 Pilot Control Activity Frequency Ranges

Figures 6.18-6.19 demonstrate the average power of the frequency ranges for sea states 4-5 with WOD condition of 25 kts.

**TRC with Sea State 4 and WOD 25 kts**

![Graphs of average power for different frequency ranges and control inceptors.](image)

Figure 6.18: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors for TRC Bandwidth with Sea State 4
For sea state 4, the mechanical control system displays the greatest average power in the “open-loop control” range for the lateral axis. The low bandwidth (Case 1) utilizes the highest power in the “closed-loop control” range. The “closed loop control” range demonstrates a decreasing trend in average power as the TRC bandwidth is increased. For the longitudinal axis, Case 1 exhibits a significantly greater average power in the “open-loop control” and “closed-loop control” ranges.
The average input power continues to be reduced when using a higher bandwidth.

In sea state 5, the average PSD results show similar trends as sea state 4. For the lateral and longitudinal axes, the mechanical control system exhibits a noticeable amount of power in the very high frequency ranges corresponding to higher gain closed loop control and control difficulties. For both axes, the “closed loop control” range also demonstrates a decreasing trend in average power as the bandwidth is increased.

6.2.5 Example Time Histories of Shipboard MTE

Figures 6.20-6.25 demonstrate the aircraft’s position relative to the center of the deck and the pilot control inputs during the hover and landing tasks. The time histories demonstrate the TRC bandwidth variations for sea states 4 and 5.

(a) Aircraft Position Relative to Center of Deck
(b) Pilot Inputs

Figure 6.20: Time Histories for TRC Low Bandwidth in Sea State 4
Figure 6.21: Time Histories for TRC Medium Bandwidth in Sea State 4

Figure 6.22: Time Histories for TRC High Bandwidth in Sea State 4
Figure 6.23: Time Histories for TRC Low Bandwidth in Sea State 5

Figure 6.24: Time Histories for TRC Medium Bandwidth in Sea State 5
6.3 ACAH Disturbance Rejection Variation using Stability Margins

The ACAH disturbance rejection variation using the stability margins was tested with four of the available test pilots. The DRB variation was tested under the conditions of sea states 3-5 with the CFD-based airwake model using WOD conditions of 25 and 40 kts.

6.3.1 Handling Qualities Ratings

The maximum, minimum and mean HQRs resulting from varying the disturbance rejection properties of the ACAH controller can be seen in Figure 6.26.
For the shipboard task MTE, the expected gust rejection performance showed a negligible effect even when using the highest DRB level. The HQRs in sea state 3 for a low WOD condition demonstrate a slight trend, but the improvement is minimal. However, the pilots were unable to identify any noticeable improvement in the increased 40 kts WOD condition. Pilots tended not to comment on either degradation in stability or benefit in gust rejection. Most pilot comments during the DRB variation still focused heavily on the bandwidth response characteristics. The HQRs indicate that the CFD solution used to model the airwake did not result in significant disturbances which would cause the pilot to be aware of the disturbance rejection benefit. Thus, the model was considered too benign.

### 6.3.2 Hover and Touchdown Performance

The hover and touchdown performance for sea state 3 for WOD conditions of 25 and 40 kts can be seen in Figures 6.27-6.28.
Figure 6.27: Sea State 3 with WOD 25 kts Hover and Landing Performance for ACAH Disturbance Rejection Variation

Figure 6.28: Sea State 3 with WOD 40 kts Hover and Landing Performance for ACAH Disturbance Rejection Variation
For sea state 3 with the lower WOD condition of 25 kts, the hover and landing performance displayed no monotonic trends as the DRB is increased and the stability margins were relaxed. In the hover task, the low DRB demonstrates similar performance as the high DRB case. The landing performance was also inconclusive as the precision of landing did not show any improvement that correlated with DRB. In sea state 3 with the higher WOD condition of 40 kts, the hover and landing performance failed to demonstrate any conclusive evidence that increasing the disturbance rejection provided any benefit. A similar result is also exhibited in sea states 4 and 5 as seen in Figures 6.29-6.30.

(a) Average Hover Distance with respect to center of deck
(b) Landing Distance with respect to center of deck

Figure 6.29: Sea State 4 with WOD 25 kts Hover and Landing Performance for ACAH Disturbance Rejection Variation
Figure 6.30: Sea State 5 with WOD 25 kts Hover and Landing Performance for ACAH Disturbance Rejection Variation

6.3.3 Pilot Workload Metrics

The workload metrics for sea states 3-5 with WOD conditions of 25 and 40 kts can be seen in Figures 6.31-6.32. The workload metrics provide additional evidence that increasing the disturbance rejection level with stability margins in the midst of the CFD-airwake model had little to no effect on pilot workload. The only identifiable trend was the workload improvement when switching to ACAH from the mechanical control system which was previously demonstrated in the bandwidth variation.
Figure 6.31: Workload Metrics of Control Inceptors of ACAH with Airwake Model and Sea State 3
Figure 6.32: Workload Metrics of Control Inceptors of ACAH with Airwake Model and Sea States 4-5
6.3.4 Pilot Control Activity Frequency Ranges

Figures 6.33-6.36 demonstrate the average power of the frequency ranges for sea states 3-5 with WOD conditions of 25 and 40 kts. The average power results provide further supporting data that the CFD-airwake model was relatively benign and had a limited effect on the handling qualities. The data support the assertion that there was no indication of disturbance rejection benefit when relaxing the stability margins to generate increasing levels of disturbance rejection.

**ACAH with Sea State 3 and WOD 25 kts**

![Graphs of Average Power](image)

Figure 6.33: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors for ACAH Disturbance Rejection using Stability Margins with Sea State 3 and WOD 25 kts
A ACAH with Sea State 3 and WOD 40 kts

Figure 6.34: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors for ACAH Disturbance Rejection using Stability Margins with Sea State 3 and WOD 40 kts
A CAH with Sea State 4 and WOD 25 kts

Figure 6.35: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors for ACAH Disturbance Rejection using Stability Margins with Sea State 4 and WOD 25 kts
6.3.5 Example Time Histories of Shipboard MTE

Figures 6.37-6.38 demonstrate the aircraft’s position relative to the center of the deck and the pilot control inputs during the hover and landing tasks. The ACAH disturbance rejection variations are demonstrated in the increased WOD condition of 40 kts.
Figure 6.37: Time Histories for ACAH Low Disturbance Rejection (Stability Margins) in Sea State 3 with WOD 40 kts

Figure 6.38: Time Histories for ACAH High Disturbance Rejection (Stability Margins) in Sea State 3 with WOD 40 kts
A couple of factors may have attributed to the inconclusive results using the standard stability margins as a baseline with the CFD-based model. As mentioned in the previous HQR discussion, the intensity of the CFD-based model was considered too benign based on pilot comments and the lack of HQR improvement when the disturbance rejection properties were enhanced. After reviewing the proposed disturbance rejection criteria from the AFDD, it was identified that the standard margins baseline was considerably greater than the recommended values in the roll and yaw axes. The lack of intensity in the turbulent airwake combined with an over designed baseline disturbance rejection likely lead to the inconclusive results. Therefore, actions were taken to reconfigure the disturbance rejection evaluation using the AFDD baseline and a more intense airwake model.

### 6.4 ACAH Disturbance Rejection Variation using AFDD Criteria

The ACAH disturbance rejection variation using the AFDD criteria was tested with three of the available test pilots. The DRB variation was tested under the conditions of no ship motion and sea states 3-4 with the CETI airwake model.

#### 6.4.1 Handling Qualities Ratings

The maximum, minimum and mean values of the assigned HQRs resulting from varying the disturbance rejection bandwidth properties of the ACAH controller using the AFDD criteria can be seen in Figure 6.39.
As expected, ACAH demonstrated better HQRs when compared to the baseline mechanical controls with SAS. The results in Figure 6.39 demonstrate that increasing the DRB of the ACAH controller improves the HQR as seen in all sea state conditions. For the low DRB case in all conditions, pilots were unable to achieve Level 1 handling qualities. In a condition without ship motion, one pilot was quoted as saying “the flight controls felt very sluggish during the hover especially the pedals.” The results demonstrate that without ship motion that the disturbance rejection is required to be at the high DRB case to achieve Level 1 HQRs. For the high DRB case in sea state 3, one pilot described the flight controls as “allowing me to trend back to my position with precision and felt controlled.” The results indicate that disturbance rejection does provide benefit when the pilot was exposed to the CETI turbulence model. However, the addition of the ship motion diminishes the return of the HQR benefit in higher sea states. This conclusion is supported due to the lack of improvement between the medium and high case in sea state 4. The results also further support the assertion that consistent Level 1 handling qualities are unable to achieved with ACAH in higher sea states.
6.4.2 Hover and Touchdown Performance

The hover and landing performance for the variations in the ACAH disturbance rejection for no ship motion and sea states 3-4 are shown in Figures 6.40-6.42.

Figure 6.40: No Ship Motion with CETI Hover and Landing Performance for ACAH Disturbance Rejection Variation (AFDD)

In the condition without ship motion, the mechanical controls and the low DRB case are consistently within the adequate range for the hover task. The average hover distance from the center of the deck demonstrates desired performance when shifting to the medium DRB case. The results indicated that the medium and high DRB cases have very similar improved hover performance. The landing performance did not show a consistent trend which correlated to the DRB variation. It is noted that the CETI airwake model was disengaged in the flight regime where the aircraft was directly behind the ship’s superstructure and unsteady disturbances were not expected to occur. Pilots were often able to achieve desired performance for all test cases with one or two outliers of an adequate landing.
Figure 6.41: Sea State 3 with CETI Hover and Landing Performance for ACAH Disturbance Rejection Variation (AFDD)

(a) Average Hover Distance with respect to center of deck

(b) Landing Distance with respect to center of deck

Figure 6.42: Sea State 4 with CETI Hover and Landing Performance for ACAH Disturbance Rejection Variation (AFDD)

(a) Average Hover Distance with respect to center of deck

(b) Landing Distance with respect to center of deck
For sea state 3, the hover performance demonstrates improvement as the DRB is increased. The mechanical system could not attain adequate performance while the low DRB had a large variance between inadequate and desired. The medium DRB was consistently within adequate while the high DRB was typically within desired with one case in adequate. The landing performance again did not show a consistent trend with respect to DRB variation. The mechanical system was unable to achieve adequate touchdown locations. The pilots were able to often land within desired tolerances for all ACAH cases.

For sea state 4, the hover performance showed very minimal improvement as the DRB is increased. The mechanical system’s hover performance degraded as the sea state increased. The high DRB case was the only controller variation with a data point within desired. All other ACAH controller test runs ended up within adequate. The landing performance still did not show any consistent trend similar to the first two flight conditions.

6.4.3 Pilot Workload Metrics

The workload metrics for the variations in the ACAH disturbance rejection for no ship motion and sea states 3-4 can be seen in Figures 6.43-6.44.

For no ship motion, the pilot workload metrics demonstrate a reduction in aggressiveness as the disturbance rejection is increased. The lateral and pedals in particular exhibit the strongest trend. The peaks and duty cycle fail to show a correlation with disturbance rejection.

For sea states 3 and 4, the pedals demonstrate the strongest correlation of reduction in aggressiveness while the lateral and longitudinal axes remain fairly consistent. In sea state 3, the peaks show a correlation of reduction with increased disturbance rejection in all axes. The duty cycle also exhibited a monotonic trend in the longitudinal and pedal axes. For sea state 4, the benefit in peaks and duty cycle had minimal returns in the longitudinal and lateral axes when moving from the medium to high DRB case. This result combined with the limited aggressiveness reduction correlated well with the limited HQR benefit seen in Figure 6.39.
Figure 6.43: Workload Metrics of Control Inceptors of ACAH with CETI and no Ship Motion
Figure 6.44: Workload Metrics of Control Inceptors of ACAH with CETI and Sea States 3-4
6.4.4 Pilot Control Activity Frequency Ranges

Figures 6.45-6.47 demonstrate the average power of the frequency ranges for no ship motion to sea states 3-4 with the CETI turbulence model.

Figure 6.45: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors of ACAH with CETI and no Ship Motion
Figure 6.46: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors of ACAH with CETI and Sea State 3
In the condition with no ship motion, the lateral axis demonstrates that the mechanical system exhibits the highest average power in the “open-loop control” and “closed-loop control” ranges. Additionally, all frequency ranges show a decreasing trend in average power as the DRB is increased. For the longitudinal axis, the highest average power range in ACAH is the “open-loop control” range with the mechanical system still exhibiting the greatest power. Similar to the lateral axis, the higher frequency ranges of “closed loop control” and “higher-gain closed-loop control” show a
decreasing trend in average power as the DRB is increased. For the pedals, the mechanical system demonstrates a significantly greater average power for the “open-loop control” range compared to ACAH. The low DRB had the highest power among ACAH which also correlates with the workload metrics. The collective axis as expected without any variations to its DRB had limited relative trends.

In sea state 3, the mechanical control system still dominates the average power in nearly all frequency ranges for the lateral axis. Unlike without ship motion, the decreasing trend was not clear in all frequency ranges with the “open-loop control” and “closed-loop control” range only showing a slight benefit in average power. The longitudinal axis demonstrated correlations in the higher frequency ranges of “closed-loop control” and “higher-gain closed-loop control” which exhibit reduced power with increased DRB. The pedal and collective results were similar to the no ship motion condition with the collective power being further accentuated.

For sea state 4, the disparity between the mechanical controls and ACAH is increased in terms of average power. The lateral axis only exhibited power reduction when varying the low to medium DRB. The longitudinal axis again demonstrated correlations in the higher frequency ranges of “closed-loop control” and “higher-gain closed-loop control”. However, ACAH showed greater average power in the “open loop control” range compared to the mechanical system. The pedals and collective again showed similar behavior as the prior conditions.

6.4.5 Example Time Histories of Shipboard MTE

Figures 6.49-6.50 demonstrate the aircraft’s position relative to the center of the deck and the pilot control inputs during the hover and landing tasks. The time histories demonstrate the mechanical system and the ACAH disturbance rejection variations for no ship motion and sea state 3 using the CETI turbulence model.
Figure 6.48: Time Histories for Mechanical Controls with SAS in No Ship Motion with CETI

Figure 6.49: Time Histories for ACAH Low Disturbance Rejection (AFDD) in No Ship Motion with CETI
Figure 6.50: Time Histories for ACAH High Disturbance Rejection (AFDD) in No Ship Motion with CETI

Figure 6.51: Time Histories for ACAH Low Disturbance Rejection (AFDD) in Sea State 3 with CETI
Figure 6.52: Time Histories for ACAH High Disturbance Rejection (AFDD) in Sea State 3 with CETI
6.5 TRC Disturbance Rejection Variation using AFDD Criteria

The TRC disturbance rejection variation using the AFDD criteria was tested with one of the available test pilots. The DRB variation was tested under the conditions of no ship motion and sea states 3-4 with the CETI airwake model.

6.5.1 Handling Qualities Ratings

The maximum, minimum and mean values of the assigned HQRs resulting from varying the disturbance rejection bandwidth properties of the Ship-Relative TRC controller using the AFDD criteria can be seen in Figure 6.53. It is noted that only the cyclic disturbance rejection properties were adjusted given TRC’s emphasis on the lateral and longitudinal axes. The yaw axis was held at the medium disturbance rejection case previous used in ACAH as seen in Table 4.5.

![Figure 6.53: Cooper-Harper Handling Qualities Ratings for TRC Disturbance Rejection Bandwidth Variation using AFDD Criteria](image)

The TRC controller clearly demonstrated better HQRs when compared to the baseline mechanical controls with SAS. The results in Figure 6.53 demonstrate that increasing the DRB of the
TRC controller improves the HQR as seen in all sea state conditions. In the condition without ship motion for the low DRB case, the pilot was quoted as saying “the flight controls had a lot of play where I forced to use large inputs up to 2-3 inches.” The results demonstrate that without ship motion that the low DRB case still provides Level 1 HQRs with a medium bandwidth. In sea state 3, the pilot felt the low DRB case was “too sluggish and felt unsafe at times with the large corrections near the ship.” The pilot further highlighted, that the aircraft feel delayed and lacked the maneuverability with respect to adjusting to the ship’s motion. For the high DRB case in sea state 3, one pilot described the flight controls as “very benign where the controls felt responsive.” For sea state 3, the results support that the high DRB case is required to achieve Level 1 handling qualities. As expected, the HQRs for all test cases continue to degrade in the sea state 4 condition. The pilot ratings indicate that the high DRB is still required to achieve Level 1 HQRs.

6.5.2 Hover and Touchdown Performance

The hover and landing performance for the variations in the TRC disturbance rejection for no ship motion and sea states 3-4 are shown in Figures 6.54-6.55.

Figure 6.54: No Ship Motion with CETI Hover and Landing Performance for TRC Disturbance Rejection Variation (AFDD)
In the condition without ship motion, the pilot was able to achieve nearly desired hover performance for each DRB case. The high DRB case was more consistent in achieving desired performance which supports the pilots’ comments that the “cyclic felt a lot tighter.” The landing performance demonstrated that the pilot was able to achieve desired performance for all test cases.

![Diagram](image)

(a) Average Hover Distance with respect to center of deck
(b) Landing Distance with respect to center of deck

Figure 6.55: Sea State 3 with CETI Hover and Landing Performance for TRC Disturbance Rejection Variation (AFDD)

For sea state 3, the hover performance demonstrates improvement as the disturbance rejection is increased to the medium DRB. The medium DRB was consistently within desired while the high DRB had two data points slightly outside desired. The pilot was able to consistently land within desired tolerances for all test cases. However, the pilot did comment that he felt he “could not fine tune the landing” using the low DRB in comparison to the high DRB. As seen in Figure 6.55(b), the pilots’ comment is supported by the touchdown location of the high disturbance rejection cases being more precise relative to the center of the deck.
For sea state 4, the hover performance again demonstrates improvement when varying the controller’s DRB from low to medium. The medium and high DRB were within desired for all test runs. The pilot was able to consistently land within desired tolerances for all test cases.

6.5.3 Pilot Workload Metrics

The workload metrics for the variations in the TRC disturbance rejection for no ship motion and sea states 3-4 can be seen in Figures 6.57-6.58.

For no ship motion, the pilot workload metrics demonstrate a reduction in aggressiveness, duty cycle and peaks as the disturbance rejection is increased for the lateral axis. The longitudinal axis showed a slight benefit in duty cycle and peaks when using the high disturbance rejection case.

In sea state 3, the lateral axis demonstrates a trend of reduction in aggressiveness as DRB is increased. The longitudinal axis shows a similar benefit in duty cycle and peaks which also correlates with DRB.

For sea state 4, there was only a trend with between the peaks and DRB for the lateral axis. There were limited correlations shown in the longitudinal axis.
TRC with No Ship Motion and CETI

(a) Aggressiveness

(b) Duty Cycle

(c) Peaks

Figure 6.57: Workload Metrics of Control Inceptors of TRC with CETI and no Ship Motion
Figure 6.58: Workload Metrics of Control Inceptors of TRC with CETI and Sea States 3-4
6.5.4 Pilot Control Activity Frequency Ranges

Figures 6.59-6.60 demonstrate the average power of the frequency ranges for no ship motion to sea states 3-4 with the CETI turbulence model.

TRC with No Ship Motion and CETI

![Graphs showing frequency ranges of average power for different control inceptors: Lateral, Longitudinal, Pedals, Collective.]

Figure 6.59: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors of TRC with CETI and no Ship Motion

In the condition with no ship motion, all frequency ranges showed a decreasing trend in average power as the DRB was increased for the lateral axis. The average power for the low disturbance
rejection is very similar to the mechanical system for the “closed loop” and “very high closed loop” control ranges. For the longitudinal axis, the highest contributor of average power in TRC is in the “open-loop control” range. Similar to the workload metrics, there was a limited benefit demonstrated in longitudinal axis as the DRB was increased. The collective and pedal inceptors as expected had limited relative trends.

**TRC with Sea State 3 and CETI**

![Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors of TRC with CETI and Sea State 3](image)

Figure 6.60: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors of TRC with CETI and Sea State 3
In sea state 3, the lateral axis is similar to the no ship motion condition in which all frequency ranges showed a decreasing trend in average power as DRB is increased. As expected, the overall average power for all frequency ranges was greater in this condition. The relative trends in the longitudinal axis was also quite similar to the no ship condition. A limited benefit was still demonstrated in longitudinal axis as the disturbance rejection was increased.

**TRC with Sea State 4 and CETI**

![Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors of TRC with CETI and Sea State 4](image)

Figure 6.61: Frequency Ranges of Average Power (Areas Under PSD) of Control Inceptors of TRC with CETI and Sea State 4
In sea state 4, the lowest average power in the lateral axis for all frequency ranges was the high DRB case. The trend was not monotonic as the previous two conditions, but the high disturbance still remains as the beneficial case. Again, a limited benefit was demonstrated in longitudinal axis as the DRB was increased.

6.5.5 Example Time Histories of Shipboard MTE

Figures 6.62-6.63 demonstrate the aircraft’s position relative to the center of the deck and the pilot control inputs during the hover and landing tasks. The time histories demonstrate the TRC disturbance rejection variations for no ship motion and sea states 3 using the CETI turbulence model.

Figure 6.62: Time Histories for TRC Low Disturbance Rejection (AFDD) in No Ship Motion with CETI
Figure 6.63: Time Histories for TRC High Disturbance Rejection (AFDD) in No Ship Motion with CETI

Figure 6.64: Time Histories for TRC Low Disturbance Rejection (AFDD) in Sea State 3 with CETI
Figure 6.65: Time Histories for TRC High Disturbance Rejection (AFDD) in Sea State 3 with CETI
Chapter 7

Conclusions

A family of controllers were designed to test various levels of bandwidth and disturbance rejection for a non-linear dynamic inversion controller in shipboard operations. A formal handling qualities assessment was conducted by a total of six pilots using the basic UH-60 mechanical controls and two augmented response types (ACAH and ship-relative TRC). In addition, task performance and workload metrics using pilot control activity were both analyzed to obtain further insight on the impact of the gain selection for shipboard handling qualities. The following conclusions from this study are listed below.

1. ACAH did show improvement over the rate response / mechanical control system, but only when the bandwidth values were significantly higher than the minimum Level 1 requirements from ADS-33 (e.g. Case 2 or Case 3). It is noted that ACAH mode also includes vertical axis compensation, whereas the mechanical system has none, which could be the driver in reduced workload. However, no increased level of bandwidth in ACAH could produce Level 1 handling qualities for a sea state equivalent of four or greater.

2. The results of this study support that a rise time of 5 seconds for a TRC controller is unable to provide any handling qualities improvement. The rise time for a TRC response type to achieve Level 1 handling qualities requires a much smaller value than the maximum ADS-33 recommendation of 5 seconds. The study has shown that a rise time of 2.5 seconds (low end of the range recommended by ADS-33) provides an optimal design point for consistent Level 1 HQRs using a limited sample size of pilots.
3. When using the initial CFD-based airwake model, there was a failure to identify any trends when enhancing the disturbance rejection properties in ACAH. The CFD-based airwake model was considered too benign and did not have a discernible impact on the handling qualities. The baseline disturbance rejection design corresponding to the standard stability margins was also considered too high in the roll and yaw axes. The combination of these two factors likely limited the expected benefit in disturbance rejection.

4. ACAH demonstrated Level 1 handling qualities in conditions of no ship motion and a sea state 3 condition with the more intense CETI turbulence model, but only when using greater disturbance rejection bandwidth than the minimum AFDD recommendation. The greater disturbance rejection bandwidth will also result in a high disturbance rejection peak nearing the AFDD proposed limit. The study also shows that there is a diminishing return of HQR benefit when the sea state is increased.

5. TRC demonstrated Level 1 handling qualities in the condition of no ship motion with the CETI turbulence model for the minimum disturbance rejection level recommended by AFDD. However, a significantly higher disturbance rejection bandwidth is needed to achieve Level 1 handling qualities for sea states 3 and 4.

6. The usage of time-frequency metrics show promising results in providing strong indicators of handling qualities in the shipboard environment. The impact on pilot workload and strategy due to the permutation of controller and external environment was often accurately represented. The metrics demonstrated strong correlations with the pilot comments and HQRs.

7.1 Future Work

There are several studies which can improve on this investigation and are listed below.

1. Future testing may include isolating effects in the individual axes, i.e. increasing DRB or BW one axis at a time.

2. Further testing may also investigate the consideration of torque margin limits in the collective axis. This is a major issue in ship landings, but was not a factor in this study as the aircraft was simulated at relatively low gross weights.
3. Pilot simulation testing with the Portable Optical Naval Guidance (PONG) task [20] is planned for the future. The PONG task is based on the original NRC superslide [32]. The concept is to provide a digital puck for the pilot to track on a moving board while meeting performance boundaries in a hover. The pilot’s objective is to maintain the puck within the boundaries from his or her viewpoint. The HQRs resulting from the PONG task will be evaluated for comparison with the HQRs from the shipboard MTE. The data will be used to assess the feasibility of the PONG task as a surrogate maritime MTE. The PONG MTE has been already implemented in the PSU rotorcraft flight simulator.

4. Given the added complexity of a ship-relative system, a similar handling qualities evaluation of a TRC system which is not dependent on ship sensing should be conducted to verify the benefits seen in this study. The evaluation would provide the validation of a TRC system which could be implemented without the requirement for a data link between the aircraft and the ship.
Bibliography


Appendix A

Linear Simulink Model

The controller used to conduct linear analysis was converted from the discrete-time NLDI controller implemented in the MATLAB/Simulink environment originally developed in Ref. 17. The 24 state space model operating at a trim flight condition of 20 knots was then integrated with the continuous-time NLDI controller. Since the ship’s motion did not affect the linear analysis as a feed forward command, the ship model was omitted from the linear model. The MATLAB \texttt{linearize} command was then used to define the respective I/O points in order to generate the frequency responses with the closed loop model.
Figure A.1: State Space Model of UH-60 Blackhawk

\[ x' = Ax + Bu \]
\[ y = Cx + Du \]
A.0.1 Inner Loop

Figure A.2: Inner Loop Feedback Compensation

Figure A.3: F(x) Calculation
Figure A.4: G(x) Calculation

Figure A.5: Roll Command Filter
Figure A.6: Pitch Command Filter

Figure A.7: Yaw Command Filter

Figure A.8: Vertical Speed Command Filter
Figure A.9: Inner Loop Nonlinear Dynamic Inversion with Feedback Compensation
A.0.2 Outer Loop

Figure A.10: TRC Lateral Outer 1st Order Command Filter

Figure A.11: TRC Lateral Inner 2nd Order Command Filter

Figure A.12: TRC Longitudinal Outer 1st Order Command Filter
Figure A.13: TRC Longitudinal Inner 2nd Order Command Filter

Figure A.14: Position Hold Feedback Compensation
Figure A.15: Outer Loop Dynamic Inversion with Feedback Compensation
Appendix B

Pilot Comments

B.1 Attitude Command Attitude Hold Bandwidth Variation Testing

Table B.1: Notes for Shipboard MTE with ACAH Bandwidth

<table>
<thead>
<tr>
<th>Pilot</th>
<th>BW</th>
<th>SS</th>
<th>WOD</th>
<th>Mode</th>
<th>Hover / Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>N/A</td>
<td>4</td>
<td>25 kts</td>
<td>Mech.</td>
<td>N/A / Desired</td>
<td>4</td>
<td>“lateral needed more to compensate for”</td>
</tr>
<tr>
<td>B</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>5</td>
<td>“controls were good”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>hit tail wheel</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>4</td>
<td>“pretty nice controllability in lat./long.” “No issues w/coll.”</td>
</tr>
<tr>
<td>B</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>5</td>
<td>“little activity lateral initially then the ship starts moving” “2” excursions due to much more active stick input” “collective a lot more active”</td>
</tr>
<tr>
<td>B</td>
<td>N/A</td>
<td>4</td>
<td>25 kts</td>
<td>Mech.</td>
<td>N/A / Desired</td>
<td>5</td>
<td>“nose with a little pitch that time” “that was work” “did not feel any attitude hold so I ended up having to catch the nose at 5 deg”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>3</td>
<td>“minor control inputs” “minor compensation due to ship not the controls themselves” Helicopter was steady with no big excursions</td>
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<tr>
<td>B</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>7</td>
<td>“that was tough” “Even when ship was ready, it was difficult to keep helicopter over spot” “collective was non-factor” “1.5 inch in lat/long inputs”</td>
</tr>
<tr>
<td>B</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>2</td>
<td>“that was easy” “minor inputs to compensate”</td>
</tr>
<tr>
<td>B</td>
<td>N/A</td>
<td>4</td>
<td>25 kts</td>
<td>Mech.</td>
<td>N/A / Desired</td>
<td>5</td>
<td>“similar to other pitchy case w/no attitude hold” “required constant forward force on stick which drove workload up” “collective more than active than before”</td>
</tr>
<tr>
<td>B</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>3</td>
<td>“control was not big deal” “Moderate lateral inputs needed to compensate for ship” “collective was steady” “slightly aft long. in order to keep from drifting”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>3</td>
<td>“Although flight controls felt loose, the actual controllability felt nice.” “It was sensitive as if it was almost SAS” “still able to land over the deck and steady out the helicopter very well”</td>
</tr>
<tr>
<td>B</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>7</td>
<td>“getting a little low on approach” “realized I was required collective a heck of a lot” “collective was non-factor” “lat-1.5 inches more frequency” “long 1 inch inputs”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>3</td>
<td>“60 second hover the landing spot prior to landing that time “that was a lot more challenging” “more lateral movement in controls” “During hover, didn’t stay within desired at all times, but definitely stayed within adequate”</td>
</tr>
<tr>
<td>B</td>
<td>Low</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Inadequate</td>
<td>7</td>
<td>“not attainable performance” “could barely keep helicopter within adequate range” “was so focused on flying and much more challenging”</td>
</tr>
<tr>
<td>B</td>
<td>Med</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>6</td>
<td>“following ship is a lot more challenging” “Definitely outside desired on occasion”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>4</td>
<td>“main workload due to lateral” “starting to use horz. Ref bar as rate indicator and to help” “moderate pilot comp. needed”</td>
</tr>
<tr>
<td>B</td>
<td>Low</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>7</td>
<td>“drifted quite a bit outside hover” “mainly lateral workload” “over concentration on lateral compensation which forced me not to spend enough time on long.” “vertical strategy was to avoid hitting deck rather than holding altitude”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>4</td>
<td>“considerably easier” “mostly desired for lat/long position”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>5</td>
<td>“some excursions into adequate” “was more forward than aft that time”</td>
</tr>
<tr>
<td>B</td>
<td>N/A</td>
<td>4</td>
<td>25 kts</td>
<td>Mech.</td>
<td>N/A / Desired</td>
<td>5</td>
<td>“I’m definitely having problems here” “not uncontrollable but major deficiencies” “multiple inputs beyond 2-3 inches” “active vertical”</td>
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<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>6</td>
<td>“lateral required a lot more inputs”</td>
</tr>
<tr>
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<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>6</td>
<td>“pretty constant collective”</td>
</tr>
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<td></td>
<td>“Fairly constant rate for lat./long.”</td>
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<td>“Fairly constant rate for lat./long”</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>“Couldn’t talk while flying which is an indicator to me that I’m heavily focused on flying”</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“During hover, the inputs were pretty excessive moving pedals more than I wanted”</td>
</tr>
<tr>
<td>D</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>6</td>
<td>“felt like larger displacement inputs than previous”</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“on the edge of adequate most of the time during hover”</td>
</tr>
<tr>
<td>D</td>
<td>N/A</td>
<td>4</td>
<td>25 kts</td>
<td>Mech.</td>
<td>N/A / Desired</td>
<td>6</td>
<td>“was maybe more luck than skill to get inside desired”</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>“felt like I was over controlling”</td>
</tr>
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<td>“fairly constant motion”</td>
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<td></td>
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<td></td>
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<td></td>
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<td></td>
<td>“pretty extensive workload”</td>
</tr>
<tr>
<td>D</td>
<td>Med</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>6</td>
<td>“felt like movements were smaller and controllable”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“got fatigued at the end due to hover plus landing”</td>
</tr>
<tr>
<td>D</td>
<td>N/A</td>
<td>5</td>
<td>25 kts</td>
<td>Mech.</td>
<td>N/A / Adequate</td>
<td>6</td>
<td>“Hard time trying to look at horizon ref. bar”</td>
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<td>“not moving controls fast but constantly over controlling”</td>
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<td>“never felt steady”</td>
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<td>D</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>5</td>
<td>“Was less workload comparable to others but still considerable”</td>
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<td>“moving controls less”</td>
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<tr>
<td>D</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>4</td>
<td>“starting to feel better about visual cues”</td>
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<td></td>
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<td>“didn’t feel like I was over controlling”</td>
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<tr>
<td>D</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>4</td>
<td>“felt like large inputs especially in cyclic” predominately lateral work</td>
</tr>
<tr>
<td>A</td>
<td>Med 4 25 kts</td>
<td>ACAH</td>
<td>Adequate / Adequate</td>
<td>5 / 5</td>
<td>“pretty large cyclic inputs which was more than I expected” “increased the gain to 1” inputs helps”</td>
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<tr>
<td>A</td>
<td>High 4 25 kts</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>5 / 5</td>
<td>“sensitivity is up” “challenge was wanting to turn up gain which is where I got into PIO” “felt like I wasn’t balanced in lat. and long.”</td>
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</tr>
<tr>
<td>A</td>
<td>N/A 4 25 kts</td>
<td>Mech.</td>
<td>Adequate / Desired</td>
<td>6 / 6</td>
<td>“Extensive comp. difficulty doesn’t change” “flight control inputs larger than previous”</td>
<td></td>
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<tr>
<td>A</td>
<td>Med 5 25 kts</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>5 / 6</td>
<td>“pretty large inputs” “turning up gain seemed detrimental” “precise task became more difficult and harmony seemed there”</td>
<td></td>
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</tr>
<tr>
<td>A</td>
<td>Low 5 25 kts</td>
<td>ACAH</td>
<td>Adequate / Inadequate</td>
<td>6 / 7</td>
<td>“there’s a lot of over control in long.” “feels like I’m borderline PIO” “control wasn’t the issue, but performance was”</td>
<td></td>
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</tr>
<tr>
<td>A</td>
<td>Med 4 25 kts</td>
<td>ACAH</td>
<td>Desired / Adequate</td>
<td>5 / 5</td>
<td>“lat was more sensitive” “harmony wasn’t bad and was able to turn gain up” “still a lot of control activity, felt like I was going to get desired performance”</td>
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<tr>
<td>A</td>
<td>N/A 5 25 kts</td>
<td>Mech.</td>
<td>Inadequate / Inadequate</td>
<td>7 / 7</td>
<td>“couldn’t stabilize in long.” “performance couldn’t be achieved”</td>
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</table>
### B.2 Attitude Command Attitude Hold Disturbance Rejection Variation using Stability Margins Testing

Table B.2: Notes for Shipboard MTE with ACAH Disturbance Rejection using Stability Margins

<table>
<thead>
<tr>
<th>Pilot</th>
<th>DRB</th>
<th>SS</th>
<th>WOD</th>
<th>Mode</th>
<th>Hover / Landing</th>
<th>HQR</th>
<th>Notes</th>
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</thead>
<tbody>
<tr>
<td>B</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>3</td>
<td>“most time was spent waiting for ship to quiet down” “minimal inputs required on stick 0.5-1 inch stick inputs”</td>
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<tr>
<td>B</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>5</td>
<td>“I felt like I was working a lot”</td>
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<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
<td>3</td>
<td>“minimal corrections both left and right”</td>
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<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Adequate</td>
<td>5</td>
<td>“ship rolled off to the left at landing”</td>
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<td>N/A / Desired</td>
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<td>“minimal inputs to steady over flight deck” “steady collective”</td>
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<td>ACAH</td>
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<td>“minimal inputs to steady” “less than 1 inch lat and long”</td>
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<td>25 kts</td>
<td>ACAH</td>
<td>N/A / Desired</td>
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<td>“lat/long compensation was a little more active” “felt like it took more workload to keep the helicopter steady”</td>
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<td>ACAH</td>
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<td>“lat. was very active due to ship” “again, I was very focused on flying”</td>
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<td>25 kts</td>
<td>ACAH</td>
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<td>“felt like pretty good control” “a couple excursions fwd/aft outside desired, but within adequate”</td>
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<td>B</td>
<td>Med</td>
<td>3</td>
<td>25 kts</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
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</table>

"initially felt pretty good"
"most of the workload in lat"
"Some excursions outside adequate range for lat"

"amplitude of inputs were a bit lower"
"input frequency felt the same as previous"

"cyclic almost const. rate"
"no pedal work"

"controls were fairly quiet"

"everything was smooth"
"collective and pedals pretty steady"
"frequency of cyclic felt moderate"

"I didn’t feel like I was being pushed around by the turbulence"
"collective was pumped when rolling to maintain relative altitude"

"pretty constant inputs in long/lat which never stopped"

"hover was pretty good"
"felt like small movements than previously"

"predominately lateral inputs"
"small directional inputs"
"frequency of lateral inputs pushed it towards moderate"

"lateral mostly 0.5 inch inputs sometimes 1 inch"
"ship rolled when I came down"

"maintained desired position until landing"
"small magnitude with constant frequency"

"mainly workload in roll"
"constant movement lateral to maintain position fwd and aft small excursions"
| B   | N/A  | 3 | 25 kts | Mech. | Desired / Desired | 5 / 5 | “more active in collective and pedals” “more loose in roll and active in pitch”
| B   | Low  | 3 | 25 kts | ACAH  | Desired / Adequate | 4 / 5 | “big lateral inputs” “easier to keep hover position”
| B   | High | 3 | 25 kts | ACAH  | Desired / Adequate | 4 / 5 | “minimal pilot compensation”
| B   | N/A  | 3 | 25 kts | Mech. | Adequate / Desired | 5 / 4 | “larger inputs to maintain position” “1.5-2 inches for lat and 1 inch for long.”
| B   | Med  | 3 | 25 kts | ACAH  | Desired / Desired | 3 / 3 | “minimal compensation while waiting for ship”
| B   | High | 3 | 25 kts | ACAH  | Desired / Desired | 3 / 3 | “was able to straighten out trip” “just needed to wait for ship on landing”
| B   | Low  | 3 | 25 kts | ACAH  | Desired / Desired | 5 / 4 | “pretty frequent inputs for hover” “moderate compensation needed for landing”
| E   | Med  | 3 | 25 kts | ACAH  | Adequate / Adequate | 5 / 6 | “fighting to keep it within the doors”
| E   | N/A  | 3 | 25 kts | Mech. | Adequate / Inadequate | 6 / | “squeezing the cyclic quite hard and working a lot” “workload not tolerable even though adequate performance”
| E   | Low  | 3 | 25 kts | ACAH  | Desired / Inadequate | 3 / 5 | “felt a lot better”
| E   | High | 3 | 25 kts | ACAH  | Desired / Adequate | 3 / 4 | “felt really manageable”
| E   | N/A  | 3 | 25 kts | Mech. | Adequate / Adequate | 6 / 6 | “a lot of workload of that one” “got lucky on the landing”
| E   | Med  | 3 | 25 kts | ACAH  | Desired / Adequate | 2 / 4 | “hover felt really good”
| E   | High | 3 | 25 kts | ACAH  | Desired / Adequate | 4 / 4 | “moderate compensation on hover” “cyclic not moving as much, workload not unreasonable”
| E   | Low  | 3 | 25 kts | ACAH  | Desired / Desired | 4 / 4 | “felt between moderate and desired”
| B   | Med  | 3 | 40 kts | ACAH  | Adequate / Desired | 4 / 5 | “adequate position wise during hover”
| B   | N/A  | 3 | 40 kts | Mech. | Adequate / Desired | 4 / 5 | “I’m moving quite a lot even though ship isn’t”


### B.3 Attitude Command Attitude Hold Disturbance Rejection Variation using AFDD Criteria Testing

<table>
<thead>
<tr>
<th>Pilot</th>
<th>DRB</th>
<th>SS</th>
<th>Airwake</th>
<th>Mode</th>
<th>Hover / Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Med</td>
<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“yaw axis had quite a bit of footwork” “vertical, roll and pitch felt alright”</td>
</tr>
</tbody>
</table>

Table B.3: Notes for Shipboard MTE with ACAH Disturbance Rejection using AFDD Criteria
<table>
<thead>
<tr>
<th>F</th>
<th>Low</th>
<th>0</th>
<th>CETI</th>
<th>ACAH</th>
<th>Desired / Desired</th>
<th>5 / 4</th>
<th>“drifting in and out out of desired during hover” “inputs felt delayed and more sluggish”</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>N/A</td>
<td>0</td>
<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Desired</td>
<td>6 / 5</td>
<td>“that was bad” “when I wanted to correct and come back to my original position, I was already there” “definitely vertical, lat/long. felt delayed”</td>
</tr>
<tr>
<td>F</td>
<td>High</td>
<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>2 / 2</td>
<td>“the controls were very tight” “collective felt worse than cyclic” “lat. felt very good and tight” “not much pedal movement”</td>
</tr>
<tr>
<td>F</td>
<td>Low</td>
<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“Felt like I was pushing the stick out a lot in order to get the response” “it look a lot of movement and playing with the controls”</td>
</tr>
<tr>
<td>F</td>
<td>Low</td>
<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“Felt like I was pushing the stick out a lot in order to get the response” “it look a lot of movement and playing with the controls”</td>
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<tr>
<td>F</td>
<td>Med</td>
<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 3</td>
<td>“it felt that at times that it was great, but then when I was pushed then I felt like I had to fight it to get to the original position” “the fwd and aft positions were drifting in and out cyclic felt sluggish”</td>
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<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Adequate</td>
<td>5 / 5</td>
<td>“needed to compensation for the floating around” “collective was definitely working harder that time” “landing required me to play with the cyclic and deal with the back and forth pendulum effect”</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>2 / 3</td>
<td>“felt fine with the workload” “1/4 inch inputs for lateral required” “collective had no workload”</td>
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<tr>
<td>F</td>
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<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“felt more sluggish and required more playing with the inputs in the cyclic” “more counter inputs required to correct for achieved the desired position” “it was a lot of determining the right rate input to keep the helicopter in the position area when forced to counter a response”</td>
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<tr>
<td>F</td>
<td>N/A</td>
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<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Inadequate</td>
<td>5 / 6</td>
<td>“pedals lagging that time” “a lot of control movements in all axes” “felt necessary to land because I couldn’t tell when turbulence was coming in”</td>
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<tr>
<td>F</td>
<td>Med</td>
<td>3</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>3 / 4</td>
<td>“got into some oscillations at touchdown, fwd/aft was good” “definitely was better in pedals and response cyclic mostly in workload”</td>
</tr>
<tr>
<td>F</td>
<td>Low</td>
<td>3</td>
<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Adequate</td>
<td>5 / 5</td>
<td>“pedals sluggish, didn’t feel tight” “little more cyclic work” “lateral better than long.”</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“pedals felt a lot better” “hover was a little more work fwd/aft” “benign in collective and all axes”</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
<td>“couldn’t retreat back into region quickly because of hangar proximity was more conservative because of this” “footwork and cyclic were high workload with constantly compensating against turbulence”</td>
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<td>F</td>
<td>N/A</td>
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<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Adequate</td>
<td>6 / 5</td>
<td>“didn’t have the precision that I wanted” “a lot of collective, more cyclic workload in long.”</td>
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<td>F</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“still getting pushed around a lot but able to adapt faster” “felt like I need to adjust collective though it was initially set at the power I wanted” “landing had more cyclic movement”</td>
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<td>F</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>3 / 4</td>
<td>“fairly controlled” “landing was playing with the lateral to find the null zone and desired landing spot”</td>
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<td>F</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
<td>“not quite precise in putting in where I wanted” “felt sluggish” “landing wasn’t difficult once I was over the spot”</td>
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<td>F</td>
<td>N/A</td>
<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Desired</td>
<td>6 / 6</td>
<td>“collective and pedal workload was high” “had to let go of collective to see if I was in PIO” “pretty violent all around motion” “it felt like a microburst when I was coming down”</td>
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<td>Desired / Desired</td>
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<td>“little pushes during hover, but I could trend back with precision” “felt controlled” “collective was easy, cyclic had some work”</td>
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<td>F</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>5 / 4</td>
<td>“pedals were sluggish / other controls felt alright” “workload felt fine if I didn't have to move the pedals”</td>
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<td>F</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Inadequate</td>
<td>5 / 5</td>
<td>“controls felt okay, trying to find stable hover near ship” “mostly lateral control” “ship caught the wheel that time”</td>
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<td>F</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Adequate</td>
<td>6 / 6</td>
<td>“pedals felt sluggish, a lot of pedal work” “more lateral workload but more long. Workload oscillations became very difficult when trying to correct pedals” “very difficult to place long. axis without cueing”</td>
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<td>“tons of collective work, a lot of adjustments which also induced pedal work” “very violent motion and got too close to the ship” “once turbulence kicked in, I had to reset and attempt the landing again. It was necessary to wait out the turbulence and ship motion”</td>
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<td>“major adjustments were lateral and fwd/aft mostly fine tuning” “landing had good stability, just a matter of timing”</td>
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<td>“mostly cyclic both fwd/aft and lateral” “could not get to exact point” “during landing, precision wasn’t there”</td>
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<td>“half of inch of pedal work, longer I stay there, the worse it gets” “couldn’t find the window of when to put the aircraft down”</td>
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<td>“a lot of control activity, a lot of play, definitely pedals, cyclic, not as much collective” “was able to time it within the ship motion that time”</td>
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<td>Level</td>
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<td>ACAH</td>
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<td>“a lot of control activity, a lot of play, definitely pedals, cyclic, not as much collective” “was able to time it within the ship motion that time”</td>
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<td>A</td>
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<td>CETI</td>
<td>Adequate / Adequate</td>
<td>5 / 6</td>
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<td>“turned up the gain on the controls” “continuous cyclic, occasionally large inputs” “when I tried turning frequency down, position suffered” “not getting what I wanted on the landing”</td>
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<td>CETI</td>
<td>Desired / Desired</td>
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<td>“controls were much quieter” “fairly continuous activity” “much lower workload” “fairly continuous activity, was playing with the pedals” “control response was predictable, primarily long”</td>
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<td>CETI</td>
<td>Adequate / Desired</td>
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<td>“hover, couple excursions with major inputs” “struggled more with the pedals, felt more active” “pedals were most obvious, long was 2nd active” “fairly continuous inputs in cyclic”</td>
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<td>CETI</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
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<td>“smaller magnitude in cyclic”</td>
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<td>Adequate / Desired</td>
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<td>“tolerable, I tried to turn down frequency in hover” “landing wasn’t bad, was all consumed with workload with no bandwidth available”</td>
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<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
<td>“over controlling in hover” “more cyclic” “making constant inputs” “collective and more pedals that time”</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>6 / 4</td>
<td>“hover, hard time with being forward of spot” “fwd/aft chasing with more input that time” “was over controlling” “not as hard as last time” “wasn’t working hard enough to get adequate perf. in hover” landing - “still making continuous inputs to correct”</td>
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<td>High</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Desired / Adequate</td>
<td>4 / 5</td>
<td>“hover- workload down, constant, long. With the pendulum effect” “adequate which was probably an anomaly landing” “probably could have caught drift”</td>
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<td>N/A</td>
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<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Desired</td>
<td>6 / 4</td>
<td>“both long/lat and collective with larger cyclic inputs in hover” “back to moving all 3 axes for inputs”</td>
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<td>Med</td>
<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“hover - “moving cylic fairly constant 0.25-0.5 inch inputs” “moving collective periodically 5-10 sec”</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“cyclic pretty constant” “increasing freq that time not size” “came through very fast and was close to hangar” “constantly moving cyclic when coming down”</td>
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<td>D</td>
<td>High</td>
<td>0</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 3</td>
<td>“continuous 2 per second input, fairly small cyclic” landing- “wasn’t chasing laterally, low workload towards the end” “still had the drive the long. But lowest workload in landing phase”</td>
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<td>CETI</td>
<td>Mech.</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
<td>“over controlling a bit, see if I can get pendulum to stop” landing “primarily long was annoying, workload went down once I was behind hangar”</td>
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<td>A</td>
<td>Med</td>
<td>3</td>
<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>6 / 4</td>
<td>“over controlling lateral axis” “chasing a lot which frustrated me” “wasn’t sure if I was going to get desired on the landing” “not a lot of work though”</td>
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<td>A</td>
<td>Low</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>6 / 4</td>
<td>“a bit of luck there on the landing” “couldn’t get the aircraft to do what I wanted” “didn’t really feel like a HQR of 4 on the landing” “it was more timing than anything”</td>
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<tr>
<td>A</td>
<td>High</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>6 / 4</td>
<td>“fairly big inputs laterally for ship with 0.5 inches about 1-2 per sec” “only one correct in long. For getting over the spot” “was able to push down straight with collective in hover”</td>
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<tr>
<td>A</td>
<td>N/A</td>
<td>3</td>
<td>CETI</td>
<td>Mech.</td>
<td>Inadequate / Inadequate</td>
<td>7 / 7</td>
<td>“couldn’t get where I wanted with a max. tolerable workload” “took more quite some time to do the landing” “good grief” “a lot of repositioning and multiple attempts to land”</td>
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<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>5 / 5</td>
<td>“swinging with the pendulum a bit” “workload wasn’t bad” “took 3 times to get inside landing spot and having to wave off the landing excursions”</td>
</tr>
<tr>
<td>A</td>
<td>Low</td>
<td>3</td>
<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>5 / 5</td>
<td>“hover felt better, but felt similar to the previous run” “transient perf, it wasn’t predictable” “big ship roll on landing” “another wing and prayer”</td>
</tr>
<tr>
<td>A</td>
<td>High</td>
<td>3</td>
<td>CETI</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“that one I felt like I had control” “could predictably put aircraft where I wanted” “still a constant workload” “moderate cyclic activity”</td>
</tr>
<tr>
<td>D</td>
<td>Med</td>
<td>4</td>
<td>CETI</td>
<td>ACAH</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
<td>“more collective inputs than I wanted” “considerable comp. constantly moving cyclic” “large inputs” “it wasn’t a blind landing, conscious control driving to get to the spot with a predictable response”</td>
</tr>
<tr>
<td>CETI</td>
<td>Mech.</td>
<td>ACAH</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
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<tr>
<td>D</td>
<td>High</td>
<td>4</td>
<td>Adequate / Desired</td>
<td>5 / 5</td>
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<td></td>
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<td></td>
<td>“tried both small freq inputs and lower freq inputs with larger gain, but neither helped” “considerable comp. for landing”</td>
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<tr>
<td>D</td>
<td>N/A</td>
<td>4</td>
<td>Inadequate / Adequate</td>
<td>7 / 6</td>
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<td></td>
<td></td>
<td></td>
<td>“couldn’t stabilize in hover even though it was controllable” “moving all 3 axes at time”</td>
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<tr>
<td>D</td>
<td>Med</td>
<td>4</td>
<td>Desired / Adequate</td>
<td>4 / 5</td>
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<td></td>
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<td></td>
<td>“couldn’t fine tune it in hover” “cyclic felt good” “it was okay as long I didn’t have to touch the controls too much” “long. not as responsive” “not inducing movements to maintain stability was key”</td>
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<tr>
<td>F</td>
<td>Low</td>
<td>4</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>“cyclic felt less response not as tight” “fairly benign on the landing”</td>
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<tr>
<td>F</td>
<td>N/A</td>
<td>4</td>
<td>Inadequate / Desired</td>
<td>7 / 6</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>“a lot of play in the collective and cyclic” “pedals weren’t bad” “couldn’t stabilize” “PIO” “tried to minimize movements” “didn’t feel safe on the landing”</td>
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<tr>
<td>F</td>
<td>High</td>
<td>4</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>“cyclic was sluggish” “minimizing the inputs on landing” “tough to distinguish between aircraft precision and ship”</td>
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</tr>
</tbody>
</table>
“little more play in the pedals” “more sluggish” “lateral was benign, I felt good once I got my fwd/aft corrected” “landing required a good amount of pedal work”

“pedals are bad” ”it felt controlled and I felt like I could get back into desired when the ship stopped”

“tightness of cyclic didn’t feel there” “had to thread the needle with the cyclic and try to minimize movement in controls”

B.4 Ship-Relative Translation Rate Command Bandwidth Variation Testing

Table B.4: Notes for Shipboard MTE with TRC Bandwidth

<table>
<thead>
<tr>
<th>Pilot</th>
<th>BW</th>
<th>SS</th>
<th>WOD</th>
<th>Mode</th>
<th>Hover / Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 4</td>
<td>“lateral workload felt higher” “works great when ship steadies out”</td>
</tr>
<tr>
<td>B</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 2</td>
<td>“fwd/aft easy to control, lateral was minor but annoying” “just needed to wait until ship stopped rolling”</td>
</tr>
<tr>
<td>B</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“definitely tighter laterally” “well within green for hover”</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Adequate / Inadequate</td>
<td>6 / 7</td>
<td>“working pretty hard” hit the tail wheel</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“pitch was very sensitive” “issue is staying out of the loop” “natural tendency to stay out is difficult”</td>
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<tr>
<td>C</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“not making big inputs”</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Adequate / Adequate</td>
<td>5 / 5</td>
<td>“retraining brain not to correct and let system take over”</td>
</tr>
<tr>
<td>C</td>
<td>Med / High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>3 / 5</td>
<td>“minimal compensation in hover” “thought I would get desired in landing, but only minor compensation”</td>
</tr>
<tr>
<td>C</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“minimal pilot comp.” “thought I was going to get desired on landing”</td>
</tr>
<tr>
<td>C</td>
<td>Med / High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>3 / 3</td>
<td>“timing the ship included in that one”</td>
</tr>
<tr>
<td>C</td>
<td>Med</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>tail wheel hit “fighting the system which made it challenging in pitch and roll”</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Adequate / Inadequate</td>
<td>6 / 7</td>
<td>“wasn't patient and mistimed” “lateral might not have been tight enough”</td>
</tr>
<tr>
<td>C</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“off control inceptors at times” “3 adjustments for landing” “both tasks were HQR easy”</td>
</tr>
<tr>
<td>A</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>3 / 5</td>
<td>“off control inceptors at times” “3 adjustments for landing” “both tasks were HQR easy”</td>
</tr>
<tr>
<td>A</td>
<td>Med / High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>2 / 2</td>
<td>“off control inceptors at times” “3 adjustments for landing” “both tasks were HQR easy”</td>
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</tr>
<tr>
<td>A</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 1</td>
<td>“highly desirable” “little bit of patience” “not making unwanted inputs”</td>
</tr>
<tr>
<td>A</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 1</td>
<td>“just mistimed a bit” “hands of cyclic mostly in hover” “not as responsive in roll axis” “all I’m doing is choosing when to lower the collective”</td>
</tr>
<tr>
<td>A</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 2</td>
<td>“almost out of phase that time” “it takes a long time to build the velocity” “takes a while to stabilize in hover”</td>
</tr>
<tr>
<td>A</td>
<td>Med / High</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 1</td>
<td>“a couple nose adjustments” “longitudinal response a bit slower”</td>
</tr>
<tr>
<td>A</td>
<td>Med</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 1</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 1</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Med</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 2</td>
<td>training factor involved in allowing system to hold stable hover</td>
</tr>
<tr>
<td>C</td>
<td>Med / High</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>1 / 2</td>
<td>“felt more active that time” “took longer to capture desired in hover”</td>
</tr>
<tr>
<td>C</td>
<td>Low</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Inadequate</td>
<td>5 / 7</td>
<td>“almost getting out of phase” “waiting game” “difficult to achieve desired perf.”</td>
</tr>
<tr>
<td>C</td>
<td>High</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>2 / 1</td>
<td>“sensitive pitch with a bobble that caused some PIO” “didn’t have to touch cyclic on landing phase”</td>
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<tr>
<td>C</td>
<td>Med / High</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
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<td></td>
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<td></td>
<td>“took control inputs to get aircraft to do what I wanted” “took a while to get stabilized”</td>
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<tr>
<td>E</td>
<td>Med</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>3 / 5</td>
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<td>“trouble finding the landing spot at the end”</td>
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<tr>
<td>E</td>
<td>Med / High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>3 / 5</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>“didn’t feel like considerable comp., but couldn’t get desired perf.”</td>
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<tr>
<td>E</td>
<td>Low</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Inadequate / Adequate</td>
<td>8 / 6</td>
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<td></td>
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<td>“a lot of work in hover” “wow, I almost hit the structure in hover” “kept overshooting”</td>
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<tr>
<td>E</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>4 / 4</td>
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<td></td>
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<td></td>
<td></td>
<td>“nose is extremely sensitive” “the pitch activity was distracting to me”</td>
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<tr>
<td>E</td>
<td>Medium</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>3 / 4</td>
<td></td>
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<td>“hardest thing was the fwd/aft in hover” “I was chasing more than I’d like with the cyclic”</td>
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<tr>
<td>E</td>
<td>Med / High</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Adequate / Desired</td>
<td>5 / 5</td>
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<td>“the hover was still a lot of work” “a little bit of luck on the landing, I could have easily ended up outside desired”</td>
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<tr>
<td>E</td>
<td>Low</td>
<td>5</td>
<td>25 kts</td>
<td>TRC</td>
<td>Inadequate / Adequate</td>
<td>9 / 6</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>“a lot of work in hover”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>High</td>
<td>4</td>
<td>25 kts</td>
<td>TRC</td>
<td>Desired / Adequate</td>
<td>4 / 5</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>“nose is sensitive again” “initial flare got me into PIO which affected me stabilizing in hover”</td>
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</tbody>
</table>
### B.5 Ship-Relative Translation Rate Command Disturbance Rejection Bandwidth Variation using AFDD Criteria Testing

Table B.5: Notes for Shipboard MTE with TRC Disturbance Rejection using AFDD Criteria

<table>
<thead>
<tr>
<th>Pilot</th>
<th>DRB</th>
<th>SS</th>
<th>Airwake</th>
<th>Mode</th>
<th>Hover / Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Low</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 2</td>
<td>“felt like a tailwind, pedals felt mushy” “got where I wanted fairly easily” “it wasn’t as tight, more play”</td>
</tr>
<tr>
<td>F</td>
<td>Med</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“was getting pushed out a bit more” “my nose had to pulled up a bit more on approach” “wanted it to respond quicker” “couldn’t get the precision the way I wanted”</td>
</tr>
<tr>
<td>F</td>
<td>High</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 2</td>
<td>“felt like a pendulum, was able to put in a correction when I wanted” “felt a bit loose” “landing felt much better”</td>
</tr>
<tr>
<td>F</td>
<td>Low</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 3</td>
<td>“a lot of play in the cyclic with big inputs as large at 2 inches” “play was 1 inch inputs with more workload” “landing was mostly fine tuning the precision”</td>
</tr>
<tr>
<td>F</td>
<td>High</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>2 / 2</td>
<td>“I can already tell the cyclic is better” “cyclic was a lot tighter” “0.25 inch inputs” “was able to fine tune landing and was benign”</td>
</tr>
<tr>
<td>F</td>
<td>Med</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“didn’t feel that bad” “little bit of play with 0.25-0.5 inch inputs” “I had to edge the aircraft over since I wasn’t able to get it where I wanted to be”</td>
</tr>
<tr>
<td>F</td>
<td>Med</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“didn’t feel that bad” “little bit of play with 0.25-0.5 inch inputs” “I had to edge the aircraft over since I wasn’t able to get it where I wanted to be”</td>
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<tr>
<td>F</td>
<td>High</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 2</td>
<td>“felt good on the hover and liked it with 1/16 inch play in the cyclic” “every now and then I would get pushed out which would require 1/4 inch input to correct” “it sort of shifted slightly on the way down although it initially felt great”</td>
</tr>
<tr>
<td>F</td>
<td>Med</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 2</td>
<td>“felt myself getting pushed out quite a bit which forced me to get back in smoothly” “it was sluggish even though I was able to where I wanted” “bigger inputs of 1-1.5 inch with play of 0.25 inches” “felt good on landing and was able to slow down and correct”</td>
</tr>
<tr>
<td>F</td>
<td>Low</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 3</td>
<td>“hover was sluggish which required some play” “some pendulum feeling where I felt like I had to to put in big inputs of 1-1.5 inches” “couldn’t fine tune the landing the way I wanted”</td>
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<tr>
<td>F</td>
<td>Low</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 2</td>
<td>“hover felt good” “a little lag back and forth” “landing was pretty benign, felt controlled although couldn’t fine tune”</td>
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<tr>
<td>Score</td>
<td>Freq</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>Notes</td>
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<tr>
<td>F Med</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>2 / 2</td>
<td>“didn’t feel like I was getting pushed out as much” “0.5-1 inch inputs with about 0.25 inch inputs of play” “had to adjust a couple times on the way down”</td>
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<tr>
<td>F High</td>
<td>N/A</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 3</td>
<td>“felt sluggish in hover” “felt like I had to take out the correction after I put it in” “big corrections about every 2 seconds as large at 2 inches” “felt fine on the way down for the landing”</td>
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<tr>
<td>F Med</td>
<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 4</td>
<td>“it felt good once I got stabilized in the spot” “wasn’t difficult to maintain position” “controls felt responsive with 1 inch inputs at most and 0.25 inch of play” “landing felt worse due to the loss of the horizon bar cue”</td>
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<tr>
<td>F Low</td>
<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“during the hover, the lag and ship syncing together pushed me out a lot” “it felt sluggish with 0.5 inch play with large 2-3 inch inputs” “landing didn’t feel that bad, was able to correct on the way down”</td>
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<tr>
<td>F High</td>
<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 3</td>
<td>“felt benign without ship motion, but had to fight to get it back in” “about 0.25 inch of play with most inputs about 0.5 inch every second” “little corrections on landing, waiting for the ship to quiet down”</td>
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<tr>
<td>F</td>
<td>Low</td>
<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>6 / 5</td>
<td>“very big corrections and sluggish during hover” “up to 3 inch inputs about every 2 sec” “felt unsafe at times and wouldn’t recommend controlling this way around the ship”</td>
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<td>F</td>
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<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“felt alright during hover, control inputs were large but not frequent” “easing up on controls made things better” “landing felt worse due to loss of horizon bar” “controlled slowly and would have lacked ability to rapidly move if necessary”</td>
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<tr>
<td>F</td>
<td>High</td>
<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>2 / 1</td>
<td>“controls felt responsive during hover with fairly minor inputs of 0.5 inch” “landing felt as well, able to adjust and put the aircraft where I wanted”</td>
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<tr>
<td>F</td>
<td>Med</td>
<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>4 / 4</td>
<td>“felt sluggish again, it didn’t feel that good” “fairly large inputs of 2-3 inches with about 0.5 inch of play” “couldn’t really fine tune on landing where I had to wait rather than pursue the landing”</td>
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<tr>
<td>F</td>
<td>Low</td>
<td>3</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>6 / 5</td>
<td>“was floating in and out of zone like an infinity sign” “didn’t feel like I was in control where I was more letting to see what would happen when I put in an input” “inputs weren’t that large, but bigger inputs didn’t help when I tried” “landing wasn’t so much cyclic where I was timing the collective”</td>
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<td>Tier</td>
<td>Freq</td>
<td>CETI</td>
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<td>Desired / Desired</td>
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<tr>
<td>F</td>
<td>High</td>
<td>3</td>
<td>CETI TRC</td>
<td>Desired / Desired</td>
<td>2 / 1 “felt pretty good in hover where I would get what I was expected when I put in corrections” “landing felt good where I just needed to wait out the ship”</td>
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<td>F</td>
<td>Med</td>
<td>3</td>
<td>CETI TRC</td>
<td>Desired / Desired</td>
<td>4 / 3 “the hover felt good” “when I gave counter inputs, it felt responsive” “pretty consistent 1 inch inputs in cyclic” “aircraft felt delayed more on the landing” “control movements didn’t feel as precise” “I couldn’t match the ship exactly”</td>
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<td>F</td>
<td>Low</td>
<td>3</td>
<td>CETI TRC</td>
<td>Desired / Desired</td>
<td>5 / 3 “during the hover, it felt lethargic when I tried to quickly put inputs in and taking it out” “landing didn’t feel that bad coming down and was able to adjust accordingly”</td>
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<td>F</td>
<td>High</td>
<td>3</td>
<td>CETI TRC</td>
<td>Desired / Desired</td>
<td>2 / 2 “aircraft was responsive to inputs” “only had small variation in position” “controlled coming down and just matter of waiting ship”</td>
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<td>F</td>
<td>Med</td>
<td>4</td>
<td>CETI TRC</td>
<td>Desired / Desired</td>
<td>4 / 3 “it wasn’t sluggish, but it felt a little slower to respond that I would have liked” “constant 1 inch inputs but not a lot” “control movement was taking out the input after putting it in” “landing didn’t feel bad and was able to adjust accordingly”</td>
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<tr>
<td>F</td>
<td>High</td>
<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>1 / 2</td>
<td>“very benign in hover where I only had to make inputs every 2-3 sec” “felt very responsive with 0.5 inch inputs” “landing was good and able to come down controlled”</td>
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<tr>
<td>F</td>
<td>Low</td>
<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Adequate / Desired</td>
<td>6 / 6</td>
<td>“did not have precision to return to desired in the small windows of time where I would get pushed out” “constant inputs where I was trying to compensate” “was fighting aircraft to stay in the middle” “landing was threading the needle to get desired, wouldn’t be able to repeat it consistently”</td>
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<tr>
<td>F</td>
<td>Med</td>
<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>5 / 5</td>
<td>“sluggish where I didn’t feel like I had precision” “it felt like I always behind the aircraft” “I kept having to readjust the center of oscillation” “constant 1 inch inputs” “felt always behind during the landing where I wasn’t able to adjust to the ship fast enough”</td>
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<tr>
<td>F</td>
<td>High</td>
<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 4</td>
<td>“it was responsive” “For the hover, I had to make intermittent adjustments with 0.5 inch inputs” “During landing, I was able to adjust fast and could attempt to keep up with ship motion”</td>
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<tr>
<td>F</td>
<td>Low</td>
<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Adequate / Desired</td>
<td>6 / 6</td>
<td>“it felt slow in hover where I was not able to affect the aircraft motion the way I wanted” “I tended not to focus on controlling the aircraft motion, but rather guiding the position relative to the ship” “it was the same in terms of waiting for the environment” “was trying not to induce movements because aircraft won’t respond as expected”</td>
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<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Adequate / Desired</td>
<td>5 / 4</td>
<td>“3-4 inch inputs that were quick and excessive” “a lot of plays in controls where it felt loose” “extreme stops to induce change”</td>
</tr>
<tr>
<td>F</td>
<td>Low</td>
<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Adequate / Desired</td>
<td>6 / 4</td>
<td>“slow and sluggish where I couldn’t keep up with the big ship movements” “unable to compensate for roll of ship and turbulence” “fairly benign in the landing while waiting for ship”</td>
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<tr>
<td>F</td>
<td>High</td>
<td>4</td>
<td>CETI</td>
<td>TRC</td>
<td>Desired / Desired</td>
<td>3 / 4</td>
<td>“intermittent, intense corrections and then suddenly no compensation” “had to put it compensation every 5-6 sec with inputs as large as 2 inch inputs” “more of waiting for ship motion, was able to match motion initially, but wasn’t able to after persistent ship motion”</td>
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</tbody>
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