DEVELOPMENT AND PILOTED SIMULATION TESTING OF ADVANCED
RESPONSE TYPES FOR SHIP-BASED ROTORCRAFT

A Thesis in
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by
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Abstract

Piloted simulation tests were conducted to develop and evaluate advanced control laws and optimal response types for ship-based rotorcraft. Simulations used the GENHEL-PSU non-linear flight model of the H-60 integrated with the Penn State rotorcraft flight simulator. The simulation includes ship motion, a visual model of a FFG-7 frigate, and the Control Equivalent Turbulence Input (CETI) model for airwake turbulence. The controller uses a Non-Linear Dynamic Inversion (NLDI) scheme to accurately track a variety of response types. An Attitude Command / Attitude Hold (ACAH) control mode was used as the baseline control law. Different variants of Acceleration Command / Velocity Hold (ACVH) and Translational Rate Command / Position Hold (TRC/PH) response types were designed to make use of ship deck motion measurements. Filtered deck states are fed into the control laws to command velocity and position relative to the landing spot. Piloted simulation tests were performed for a variety of control configurations with and without ship motion and airwake turbulence effects using a maritime MTE. Pilot comments and handling qualities ratings indicated that the best performance was achieved using an ACVH response type for the pitch axis on approach, which then automatically transitions to TRC/PH over the ship deck. Level 1 Handling Qualities were achieved in all test cases when using the optimized ship-relative ACVH/TRC Automatic Transition control mode. Simulation results indicated that it is best to filter out most of the dynamic ship deck motion (primarily ship roll) and to maximize the lateral axis TRC bandwidth.
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List of Symbols

\[ F \] feedback linearization vector (rad/sec\(^2\), ft/sec\(^2\))
\[ G^{-1} \] control mixing matrix (\(\%\) rad/sec\(^2\), \(\%\) ft/sec\(^2\))
\[ I_x, I_y, I_z \] 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\(^2\))
\[ K \] scaling gain
\[ L, M, N \] body aero roll, pitch, yaw moments (ft-lb)
\[ X, Y, Z \] body aero forward, right, downward forces (lb)
\[ X_u, Z_w, L_p \] etc. stability derivatives, e.g. \(X_u = \frac{\partial X}{\partial u}\) (lb ft/sec etc.)
\[ M_{\delta_{lon}}, Z_{\delta_{col}} \] etc. control derivatives, e.g. \(M_{\delta_{lon}} = \frac{\partial M}{\partial \delta_{lon}}\) (ft-lb etc.)
\[ V \] velocity (ft/sec)
\[ e \] error vector
\[ g \] acceleration due to gravity (ft/sec\(^2\))
\[ m \] vehicle mass (lb\(_m\))
\[ p, q, r \] body roll, pitch, yaw angular rates (deg/sec)
\[ s \] Laplace operator
\[ t \] time (sec)
\[ u, v, w \] body forward, right, downward velocities (ft/sec)
\[ u \] control vector
\[ x \] state vector
\[ y \] output vector
\[ \delta \] pilot input (\%)
ζ  damping ratio
ν  pseudo commands vector (rad/sec², ft/sec²)
τ  time constant (sec)
φ  roll attitude (deg)
θ  pitch attitude (deg)
ψ  heading (deg)
ωₙ natural frequency (rad/sec)

Subscripts

cmd  command
col  collective
lat  lateral
lon  longitudinal
ped  pedals
rel  ship-relative
x   forward
y   right
z   downward

Acronyms

ACAH attitude command attitude hold
ACVH acceleration command velocity hold
CLAW control law
HQR Cooper-Harper handling qualities rating
MTE mission task element
NLDI non-linear dynamic inversion
PID proportional-integral-derivative (control)
RCHH rate command heading hold
SAS stability augmentation system
TRC/PH translational rate command position hold
VSC vertical speed command
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Chapter 1

Introduction

1.1 Motivation and Background

Rotorcraft operations from navy ships are some of the most demanding of all rotorcraft piloting tasks. Pilots are faced with a moving ship deck in high sea-states, turbulent airwakes behind the ships superstructure, adverse weather conditions, degraded visibility, and a confined and cluttered landing environment in the vicinity of deck personnel. These conditions can sometimes present pilots with excessive workload and push the aircraft to its operational limits. In Figure 1.1 a SH-60B Seahawk can be seen operating in such an environment as it hovers over a lively deck.

![SH-60B Seahawk Hovering Over Deck of Arleigh Burke-Class Destroyer (from Ref. [1])](image)

Figure 1.1. SH-60B Seahawk Hovering Over Deck of Arleigh Burke-Class Destroyer (from Ref. [1])

Improvements in control law design can increase the safety levels of shipboard operations; however quantitative handling qualities requirements have not yet been fully defined in ADS-33 [2]. The fundamental purpose of ADS-33, which is to “assure that no limitations on flight safety
or on the capability to perform intended missions will result from deficiencies in flying qualities” needs to be applied to the helicopter/ship interface. Piloted simulation testing is a relatively cost-effective method of evaluating handling qualities of rotorcraft in a shipboard environment and has been successful in the preliminary definition of these requirements as seen in References [3, 4]. These baseline boundaries for required maritime aircraft response characteristics need further verification.

Pilot visual cues for shipboard recoveries have been investigated in References [4, 5] and have been recognized as providing significant improvements in helicopter/ship operational capabilities. Cues such as a roll-stabilized horizon reference bar and a hover position indicator have been seen to provide pilots with better ship motion prediction and increased landing confidence. These have potential to alleviate handling qualities requirements by reducing pilot workload over the ship deck.

Additional progress is being made towards the development of maritime handling qualities requirements as shown in Ref. [6], and new Mission Task Elements (MTE) have been designed for qualitative handling qualities assessment such as the NRC SuperSlide as seen in Ref. [7]. This MTE focuses on assessing maneuvering characteristics that match the motion of a ship by having the pilot track a moving target and hoverboard. The NRC Superslide MTE can be seen in Figure 1.2.

![Figure 1.2. NRC SuperSlide with Motorized Target and Hover Board to Simulate Effects of Ship Flight Deck Motion (from Ref. [7])](image)

Pilots, however, will often use a strategy of holding a stable hover over the deck and waiting for a quiescent period (rather than following deck motion). It is not clear whether a more maneuverable configuration is preferable to a more stabilized configuration with highly augmented
control laws. Further research into quantitative and qualitative handling qualities requirements is needed for the design of advanced flight controls for these operations.

A highly augmented control response type, such as translational rate command and position hold (TRC/PH), where stick displacements correspond to longitudinal and lateral velocities and stick detent commands a trimmed hover, is known to enhance handling qualities in low speed flight, especially in degraded visual environments (DVE) as discussed in References [8, 9]. A less augmented control response type, such as attitude command attitude hold (ACAH), where stick displacements correspond to aircraft pitch and roll attitudes has been shown to provide adequate flying qualities for vertical ship landings in calm seas. However, for rough seas and increased deck motion, a TRC response type has been preferred and shown to provide desirable flying qualities as seen in References [10, 11, 12, 13]. In addition to a TRC response type for vertical landings, an acceleration command velocity hold (ACVH) response type has been shown as desired on approach to the ship, especially in the longitudinal axis of the aircraft as seen in Ref. [14]. ACVH is a highly augmented response type where stick displacements correspond to longitudinal and lateral accelerations and stick detent holds the current velocity. Simulation testing has been done with a Ship-Relative TRC mode in the Pilot Assisted Landing System (PALS) from Ref. [15], where stick detent matched the velocities of the ship and held a position relative to the ship and stick deflection commanded a deviation from the ships velocities. These modes showed positive results for reducing the pilot workload and increasing inherent stability of the aircraft in ship-based operations.

Quantitative gust rejection requirements in shipboard operations are still being developed as discussed in References [16, 17, 18]. In the context of TRC and other advanced response types, airwake disturbance rejection can be improved with higher control law feedback gains, however these increased gains lead to the degradation of stability margins. Further investigation into these design tradeoffs is needed for the development of successful advanced response types.

Nonlinear Dynamic Inversion (NLDI) control laws have been shown to simplify flight control design by eliminating the need to schedule compensator gains across the flight envelope as introduced in References [19, 20]. The control laws accomplish this by reducing the dynamics of the selected controlled variables of the aircraft to simple integrators, allowing for a closed loop system to be designed capable of forcing the controlled variables to follow commanded responses. Variations of the NLDI control methodology have been investigated for both fixed wing [21, 22, 23]
and rotary wing [24, 25] control systems in recent years. The NLDI control scheme is suitable for this study because it provides the ability to modify the aircrafts commanded response types without changing other components of the controller.

1.2 Research Objectives and Thesis Organization

The objectives of the current research are to gain an understanding of the handling qualities requirements for ship-based rotorcraft (with specific emphasis on response types) and to develop control design methodologies utilizing NLDI control laws to meet these requirements. This thesis presents the development of a piloted simulation environment for the investigation of advanced response types for shipboard operations. This thesis also presents a simulation study of advanced control laws that feature augmented response types that regulate acceleration, velocity, and position relative to the landing deck. Preliminary and formal handling qualities evaluations for several different response types are conducted to assess potential workload reductions when using augmented response types as well as the relative effects of ship motion and airwake turbulence. A preliminary investigation of the optimal time and frequency domain characteristics of the response types is also conducted.

The derived flight control laws used in this study can be seen in Chapter 2 and a discussion of the different response types investigated can be seen in Chapter 3. Chapter 4 details the simulation environment as well as the piloted simulation test conditions. Chapter 5 presents the test results including the handling qualities evaluations as well as sample ship approach simulation data. Chapter 6 concludes the thesis with closing remarks and recommendations for future work.
Flight Control Laws

2.1 GENHEL-PSU Flight Model

The flight simulation facility used in this study uses a modified version of GENHEL, a full non-linear flight dynamics model of the Sikorsky UH-60, which is well-established and validated with flight test data as seen in Ref. [26]. GENHEL models the six degrees of freedom of the rigid body fuselage (3 velocities, 3 angular rates, and 3 Euler angles) as well as rotor flapping and lagging degrees of freedom in multi-blade coordinates and a rotor rotational degree of freedom. Dynamic states due to the main rotor inflow, engine dynamics, and actuators are also modeled. The landing gear geometry was modified to replicate that of an SH-60 Seahawk. The modified software was developed at Penn State for basic research in rotorcraft dynamics and control and is called GENHEL-PSU.

2.2 Non-Linear Dynamic Inversion Control Laws

To evaluate advanced response types, a high performing non-linear model-based control law is implemented in the MATLAB/Simulink environment and integrated with the full non-linear GENHEL-PSU flight model. The Non-Linear Dynamic Inversion (NLDI) controller is designed around a simple 6 degree of freedom non-linear dynamic model of the helicopter. The controller uses full state feedback (all rigid body states) in order to track the ideal response dictated by the command filters (ideal response models). The non-linear flight model uses a stability and control
derivatives representation of aero loads, but exact representation of the non-linear dynamics and
kinematics. The stability derivatives are extracted from GENHEL-PSU using a perturbation
method at different airspeeds. The derivatives and trim states, controls, and forces are scheduled
with airspeed. The non-linear state-space model is of the form,

$$\dot{x} = f(x) + g(x)u \quad (2.1)$$

The chosen states are body forward velocity, $u$, body right velocity, $v$, body downward velocity, $w$,
body roll rate, $p$, body pitch rate, $q$, body yaw rate, $r$, as well as the aircraft Euler angles, $\phi, \theta, \psi$,
corresponding to aircraft roll attitude, pitch attitude, and heading, respectively. The controls
available are lateral cyclic, $\delta_{lat}$, longitudinal cyclic, $\delta_{lon}$, collective, $\delta_{col}$, and pedals, $\delta_{ped}$. The
state and control vectors, $x(t)$ and $u(t)$, are shown in Equations 2.2 and 2.3, respectively.

$$x(t) = \begin{bmatrix} u & v & w & p & q & r & \phi & \theta & \psi \end{bmatrix}^T \quad (2.2)$$

$$u(t) = \begin{bmatrix} \delta_{lat} & \delta_{lon} & \delta_{col} & \delta_{ped} \end{bmatrix}^T \quad (2.3)$$

The aircraft forces and moments are calculated by the expression shown in Equation 2.4 and
coupled with the full non-linear equations of motion.
\[
\begin{bmatrix}
X \\
Y \\
Z \\
L \\
M \\
N
\end{bmatrix} = 
\begin{bmatrix}
X_u & X_v & X_w & X_p & X_q & X_r \\
Y_u & Y_v & Y_w & Y_p & Y_q & Y_r \\
Z_u & Z_v & Z_w & Z_p & Z_q & Z_r \\
L_u & L_v & L_w & L_p & L_q & L_r \\
M_u & M_v & M_w & M_p & M_q & M_r \\
N_u & N_v & N_w & N_p & N_q & N_r
\end{bmatrix} \cdot 
\begin{bmatrix}
\Delta u \\
\Delta v \\
\Delta w \\
\Delta p \\
\Delta q \\
\Delta r
\end{bmatrix} + 
\begin{bmatrix}
X_0 \\
Y_0 \\
Z_0 \\
L_0 \\
M_0 \\
N_0
\end{bmatrix} 
\tag{2.4}
\]

Note that all of the derivatives and trimmed force and moment terms in Equation 2.4 are scheduled with airspeed. In addition, the states and controls are perturbations from trim, so trimmed state and control values are stored and scheduled with airspeed. Many of these values are 0 (e.g. trimmed angular rates and moments) since all derivatives are linearized around rectilinear trim conditions. The well-known rigid body equations of motion are shown in Equations 2.5 - 2.13. The function \( f(x) + g(x)u \) in Equation 2.1 represents the combinations of Equations 2.4 - 2.13.

\[
\dot{u} = \frac{X}{m} - g \sin \theta - qw + rv 
\tag{2.5}
\]

\[
\dot{v} = \frac{Y}{m} + g \cos \theta \sin \phi - ru + pw 
\tag{2.6}
\]

\[
\dot{w} = \frac{Z}{m} + g \cos \theta \cos \phi - pv + qu 
\tag{2.7}
\]

\[
\dot{p} = \frac{1}{I_x I_z - I_{xz}^2} \left[ I_x L + I_{xz} N + I_{xz}(I_x - I_y + I_z)pq - (I_x^2 - I_z I_y + I_{xz}^2)qr \right] 
\tag{2.8}
\]

\[
\dot{q} = \frac{1}{I_y} \left[ M - (I_x - I_z)rp - I_{xz}(p^2 - r^2) \right] 
\tag{2.9}
\]

\[
\dot{r} = \frac{1}{I_x I_z - I_{xz}^2} \left[ I_x N + I_{xz} L - I_{xz}(I_x - I_y + I_z)qr + (I_x^2 - I_x I_y + I_{xz}^2)pq \right] 
\tag{2.10}
\]

\[
\dot{\phi} = p + q \sin \phi \tan \theta + r \cos \phi \tan \theta 
\tag{2.11}
\]
\[ \dot{\theta} = q \cos \phi - r \sin \phi \] (2.12)
\[ \dot{\psi} = \frac{q \sin \phi}{\cos \theta} + \frac{r \cos \phi}{\cos \theta} \] (2.13)

A complete derivation of the NLDI CLAWs can be seen in References [22, 27]. A derivation specific to the application of this research is presented here.

The NLDI controller requires one “controlled variable” per input channel. These variables are tied directly to the pilot inceptors and ideal response model, also called a “command filter”. The controlled variables for the inner loop control law of this application of NLDI are defined by:

\[ y = \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ V_z \\ r \end{bmatrix} \] (2.14)

Thus, the four pilot control axes regulate roll attitude, pitch attitude, vertical speed, and yaw rate. The output function for the controlled variables is then defined by:

\[ y = h(x) = \begin{bmatrix} p + q \sin \phi \tan \theta + r \cos \phi \tan \theta \\ q \cos \phi - r \sin \phi \\ u \sin \theta - v \sin \phi \cos \theta - w \cos \phi \cos \theta \\ r \end{bmatrix} \] (2.15)

The time derivative of the controlled variables is then:

\[ \dot{y} = \frac{\partial h(x)}{\partial x} \dot{x} = \frac{\partial h(x)}{\partial x} f(x) + \frac{\partial h(x)}{\partial x} g(x) u = F(x) + G(x) u \] (2.16)

where the functions \( F(x) \) and \( G(x) \) can be derived from Equations 2.4 - 2.15 and are shown in Equations 2.17 and 2.18, respectively.
\[ \mathbf{F}(\mathbf{x}) = \frac{\partial}{\partial \mathbf{x}} \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ V_z \\ r \end{bmatrix}^T \mathbf{f}(\mathbf{x}) \]

\[ = \begin{bmatrix} \dot{\phi} + (\dot{q} \sin \phi + \dot{r} \cos \phi) \tan \theta + (q \cos \phi - r \sin \phi) \dot{\phi} \tan \theta \\
\quad + (q \sin \phi + r \cos \phi) \frac{\dot{\theta}}{\cos^2 \theta} \\
\dot{q} \cos \phi - \dot{\phi} q \sin \phi - \dot{r} \sin \phi - \dot{\phi} r \cos \phi \\
\dot{u} \sin \theta + \dot{\theta} u \cos \theta - \dot{v} (\dot{\phi} \cos \phi \cos \theta - \dot{\phi} \sin \phi \sin \theta) \\
- \dot{w} \cos \phi \cos \theta + \dot{w} (\dot{\phi} \sin \phi \cos \theta - \dot{\phi} \cos \phi \sin \theta) \\
\frac{1}{I_{xI_z - I_{xz}}^2} \left[ I_x N + I_{xz} L - I_{xz} (I_x - I_y + I_z) q r + (I_x^2 - I_x I_y + I_z^2) pq \right] \end{bmatrix} \]

\[ \mathbf{G}(\mathbf{x}) = \frac{\partial}{\partial \mathbf{x}} h(\mathbf{x}) - \frac{\partial}{\partial \mathbf{x}} \mathbf{f} \cdot \mathbf{CD} \]

\[ = \begin{bmatrix} 0 & 0 & 0 & \frac{I_x + I_{xz} \cos \phi \tan \theta}{I_{xI_z - I_{xz}}^2} & \frac{\sin \phi \tan \theta}{I_y} & \frac{I_x + I_{xz} \cos \phi \tan \theta}{I_{xI_z - I_{xz}}^2} \\
0 & 0 & 0 & \frac{-\sin \phi I_{xz}}{I_{xI_z - I_{xz}}^2} & \frac{\cos \phi}{I_y} & \frac{-\sin \phi I_{xz}}{I_{xI_z - I_{xz}}^2} \\
\frac{\sin \theta}{m} & -\frac{\sin \phi \cos \theta}{m} & -\frac{\cos \phi \cos \theta}{m} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{I_{xz}}{I_{xI_z - I_{xz}}^2} & 0 & \frac{I_z}{I_{xI_z - I_{xz}}^2} \end{bmatrix} \]

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

Where \( \mathbf{FM} \) is the aircraft forces and moments, and \( \mathbf{CD} \) is the control derivatives. Note that \( \mathbf{G}(\mathbf{x}) \) must be invertible for all values of \( \mathbf{x} \). In order for the system to track desired values, \( \mathbf{y}_c(t) \), the tracking error of the system is defined as \( \mathbf{e}(t) \) in Equation 2.19 with the time derivative shown in Equation 2.20:

\[ \mathbf{e}(t) = \mathbf{y}_c(t) - \mathbf{y}(t) \]  
\[ \dot{\mathbf{e}}(t) = \dot{\mathbf{y}}_c(t) - \dot{\mathbf{y}}(t) \]
Substituting Equation 2.20 into Equation 2.16 results in an alternate form of the time derivative of the controlled variables:

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

(2.21)

A vector of auxiliary inputs, or “pseudo commands” can be defined as seen in Equation 2.22.

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

(2.22)

Substituting \( \nu \) into Equation 2.21 and solving for the control inputs, \( \mathbf{u} \), results in a control law of the form:

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

(2.23)

Simple PID compensators can be used to satisfy the error dynamics, \( \dot{\mathbf{e}} = -\nu \), thus:

\[ \nu = K_{PID}(s) \cdot \mathbf{e} \]  

(2.24)

The final non-linear dynamic inversion control law is given as:

\[ \mathbf{u} = \mathbf{G}^{-1}(\mathbf{x}) \cdot [\dot{\mathbf{y}}_c + K_{PID} \cdot \mathbf{e} - \mathbf{F}(\mathbf{x})] \]  

(2.25)

To summarize this control law, the command filters in the inner loop of the controller yield the desired response of the controlled variables, \( \mathbf{y}_c \), and their first derivatives, \( \dot{\mathbf{y}}_c \). The control inputs that track these ideal responses are found by multiplying a control mixing matrix, \( \mathbf{G}^{-1}(\mathbf{x}) \), by the sum of the time derivatives of the ideal response, the feedback linearization term, \( \mathbf{F}(\mathbf{x}) \), and the pseudo commands (simple PID feedback compensation on the tracking errors). PID type compensators can be picked for stable, well-damped tracking error in order to satisfy the error dynamics seen in Equation 2.26.

\[ \dot{\mathbf{e}} = -K_{PID} \cdot \mathbf{e} \]  

(2.26)

Given no disturbances and no model error, the aircraft will follow the ideal response perfectly. In practice the feedback compensation will help account for both disturbances and modelling error.

Note that the controller is ultimately tested on the full GENHEL-PSU model which includes higher order dynamics and additional non-linearities not seen in the stability derivative model.
used in the inversion controller. A diagram of the NLDI controller structure can be seen in Figure 2.1.

Figure 2.1. Non-Linear Dynamic Inversion Controller Architecture

The inner loop command filters represent ideal response types, for roll, pitch, vertical speed, and yaw rate, which will be discussed in detail in the next chapter. For the inner loop, command filters were chosen such that pitch and roll attitude responses follow a second-order linear response. A simple modification allows the attitudes to be controlled directly (and not attitude rates as is used in the controlled variable vector). This is done by taking the integrated controlled variables from the command filters \((\phi_c, \theta_c)\) for use within the PID compensator. This effectively acts as PI compensation on \(V_z\) and \(r\) and proportional plus integral plus double-integral compensation on \(\dot{\phi}\) and \(\dot{\theta}\) as seen in Equation 2.27.

\[
\nu = \begin{bmatrix}
(\phi_c - \phi) & (\phi_c - \phi) & (\dot{\phi}_c - \dot{\phi}) \\
(\theta_c - \theta) & (\theta_c - \theta) & (\dot{\theta}_c - \dot{\theta}) \\
(V_{zc} - V_z) & (V_{zc} - V_z) & 0 \\
(r_c - r) & (r_c - r) & 0
\end{bmatrix}
\begin{bmatrix}
K_P \\
K_I/s \\
K_D
\end{bmatrix} \tag{2.27}
\]

First order command filters are used for yaw and vertical speed. The vertical axis controller achieves vertical speed command (VSC) with altitude hold, while the yaw axis achieves rate command / heading hold (RCHH). A turn coordination (TC) controller can be added to the yaw axis (although this study focuses on low speed operations without TC).
The outer loop CLAW (when engaged) is used to control lateral and longitudinal velocities and position. This controller is also designed using the dynamic inversion formulation 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:

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

(2.28)

Dynamic inversion yields the following control law:

\[
\begin{bmatrix}
\phi_{cmd} \\
\theta_{cmd}
\end{bmatrix} =
\begin{bmatrix}
0 & -g \\
g & 0
\end{bmatrix}^{-1} \cdot
\left(\begin{bmatrix}
V_{x,c} \\
V_{y,c}
\end{bmatrix} -
\begin{bmatrix}
X_u & X_v \\
Y_u & Y_v
\end{bmatrix}
\begin{bmatrix}
V_x \\
V_y
\end{bmatrix} + K_{PI}(s) \cdot e \right)
\]

(2.29)

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 Equation 2.29 are negligible at low speeds and thus omitted in the development of the controller. The compensation, \(K_{PI}(s)\), operates on velocity and position tracking errors. The compensation is typically proportional plus integral, but it effectively switches to proportional plus integral plus double integral compensation in position hold (there are gains operating on velocity error, position error, and integrated position error). Details of the position hold control mode as well as others will be discussed further in the next chapter. Detailed schematics of the controller can be seen in Appendix A.
Response Types

3.1 Example Transfer Functions

The controller is designed to track the ideal responses dictated by the command filters. The shape of these ideal responses (and thus the aircraft response) is determined by sets of transfer functions in the command filters. The time and frequency parameters of the transfer functions can be easily modified to adjust the aircraft response to pilot control inputs. The controller follows a first-order response in the collective and pedals axes for vertical speed command and yaw rate command, respectively. A first-order transfer function can be seen in Equation 3.1 and its response to a step input with varying time constants, $\tau$, can be seen in Figure 3.1.

$$
\frac{Y(s)}{U(s)} = \frac{K}{\tau s + 1} \tag{3.1}
$$

![Figure 3.1. Step Response of First-Order Transfer Function with Varying Time Constants](image-url)
A second-order response is used in the cyclic axes for certain control modes. A second-order transfer function is shown in Equation 3.2 and its response to a step input with varying natural frequencies, \( \omega_n \), can be seen in Figure 3.2. A damping ratio, \( \zeta = 0.8 \), is used here.

\[
\frac{Y(s)}{U(s)} = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n + \omega_n^2} \tag{3.2}
\]

Figure 3.2. Step Response of Second-Order Transfer Function with Varying Natural Frequencies

A second-order transfer function in series with a first order transfer function is also used in the cyclic axes for certain control modes. This transfer function can be seen in Equation 3.3 and its response to a step input can be seen in Figure 3.3 with varying time constants for a constant natural frequency and damping ratio. Values of \( \omega_n = 2 \text{ rad/s} \) and \( \zeta = 0.8 \) are used here.

\[
\frac{Y(s)}{U(s)} = \frac{K\omega_n^2}{(\tau s + 1)(s^2 + 2\zeta\omega_n + \omega_n^2)} \tag{3.3}
\]

Figure 3.3. Step Response of Second-Order Transfer Function in Series with First-Order Transfer Function with Varying Time Constants
3.2 Example Response Types

The inner and outer loop NLDI control architecture provides the ability to track a variety of ideal response types. The controller architecture allows the aircraft response types to be readily changeable via command filter modifications or engagement/disengagement of the outer loop. The response types investigated in this study are discussed below.

3.2.1 Attitude Command Attitude Hold

The baseline inner loop response type in the controller is Attitude Command / Attitude Hold. With this response type, cyclic stick deflections are proportional to aircraft pitch and roll attitudes. Yaw rate is commanded with the pedals and vertical speed is commanded in the collective axis. An example ideal response for ACAH in the lateral axis is shown in Equation 3.4. This example command filter uses a natural frequency, $\omega_n$, of 2.5 rad/sec and a damping ratio, $\zeta$, of 0.8. Maximum stick displacement commands a 45° roll attitude. The response to 1 inch lateral inputs can be seen in Figure 3.4.

$$\frac{\phi_{ideal}}{\delta_{lat}} = 9 \text{ deg} \cdot \frac{6.25}{s^2 + 4s + 6.25}$$

Results were produced using the full GENHEL-PSU flight model with the NLDI controller. The results show that the attitude and acceleration are approximately proportional to stick displacement. However, the controller does not use velocity compensation, so there is no tendency for the response to lock on to a commanded velocity. The parameters of the ideal responses can easily be adjusted for testing of various time and frequency domain characteristics or sensitivities, as it does not require modification of the feedback portions of the CLAW.
Figure 3.4. ACAH Response to 1” Lateral Inputs

The controller also includes several outer loop response types. These consist of an Acceleration Command Velocity Hold (ACVH) response type, a Translational Rate Command/Position Hold (TRC/PH) response type, and various combinations of these two control modes.

3.2.2 Acceleration Command Velocity Hold

Stick deflections in the ACVH mode command lateral and longitudinal aircraft accelerations and stick detent holds the current aircraft velocities. Yaw rate and vertical speed are commanded in the pedals and collective axis, respectively. An example ideal response for ACVH in the lateral axis is shown in Equation 3.5 with the same natural frequency and damping ratio as used in the attitude command filter. Maximum stick displacement commands 33.75 ft/sec$^2$ of lateral acceleration. The response to 1 inch lateral inputs can be seen in Figure 3.5.

\[ \dot{V}_{\text{lat,ideal}} = \frac{6.75 \text{ ft/sec}^2}{\text{inch}} \cdot \frac{6.25}{s^2 + 4s + 6.25} \]  \hspace{1cm} (3.5)

It can be seen that with outer loop velocity feedback, the controller is capable of maintaining a commanded velocity.
3.2.3 Translational Rate Command Position Hold

Stick deflections in the TRC/PH mode command lateral and longitudinal aircraft velocities and stick detent holds the aircraft’s current position. Yaw rate and vertical speed are commanded in the pedals and collective axis, respectively. An example ideal response for TRC/PH in the lateral axis is shown in Equation 3.6. This example uses linear command shaping with a maximum stick deflection commanding a velocity of 35 ft/sec. The same natural frequency and damping ratio were used with a first order filter with time constant, \( \tau = 3 \) seconds. The response to 1 inch lateral inputs can be seen in Figure 3.6.

\[
\frac{V_{y,\text{ideal}}}{\delta_{\text{lat}}} = 7 \text{ ft/sec} \cdot \frac{6.25}{\text{inch} \cdot (3s + 1)(s^2 + 4s + 6.25)}
\] (3.6)
Preliminary testing of the ship-relative TRC response type showed that a large magnitude longitudinal stick input was required to hold a velocity on approach to the ship. Non-linear command shaping was investigated in an attempt to decrease the stick input magnitude for lower pilot workloads. The resulting non-linear command shaping can be seen with respect to the range recommended by ADS-33 for TRC in Figure 3.7. Commanded velocities much higher than the recommended range were required to see significant decreases in stick input magnitudes on approach, resulting in undesirable performance in low relative speeds and hover over the deck. Hybrid response types were developed as a solution to this problem among others.
A CAH and ACVH provide for a responsive aircraft, but lack the ability to provide precision maneuverability at low-speeds. TRC allows for precision maneuvering, but lacks the responsiveness to evade a lively deck in the state of an emergency. Several hybrid advanced response types are being considered.

### 3.2.4 ACVH/TRC Amplitude-Dependent Hybrid

An ACVH/TRC Amplitude-Dependent Hybrid (ACVH/TRC Hybrid) response type uses TRC with low magnitude stick inputs and acceleration command with large magnitude stick inputs, providing the pilot with the benefits of both response types. The controller achieves this with a scaled hyperbolic tangent squashing function in the command filters feedback loop in order to limit velocity commands to a desired value. An example response to 0.25 inch and 0.75 inch lateral inputs can be seen in Figure 3.8. It can be seen that the controller responds with a velocity command to low magnitude inputs and commands an acceleration with large magnitude inputs. Here, commanded velocities are limited to 3 ft/sec.
3.2.5 ACVH/TRC Automatic Transition

An ACVH/TRC Automatic Transition (Auto Transition) response type commands aircraft accelerations until meeting certain aircraft position and velocity thresholds, at which point it smoothly transitions to a TRC response type. This is achieved by closing a feedback loop in the command filter via an Easy-On switch. The Auto Transition mode allows the pilot to approach the ship with an ACVH response type and automatically switch to a TRC response type as the aircraft reaches a hover over the deck.

Block diagrams of the outer loop command filters can be seen in Figure 3.9. Note that all the command filters produce commanded velocities and accelerations, which are used by the same inversion control scheme to track commands. By implementing command filters as a feedback loop, a smooth switch between TRC and ACVH response types is possible, as is done in the hybrid and Auto Transition modes.
Figure 3.9. Outer Loop Command Filters
3.3 Control Modes and Control Logic

The NLDI control laws feature two main selectable control modes:

1. The baseline control mode, which uses only the inner loop control laws and achieves an ACAH response type in roll and pitch, rate command / heading hold (RCHH) in yaw, and vertical speed command (VSC) in the vertical axis.

2. The advanced response type modes for ship operations. These modes engage the outer loop control laws in roll and pitch and include velocity and position feedback, including velocity and position information from the moving ship deck.

The advanced response types are the focus of this research, but the baseline ACAH mode is also evaluated for a basis of comparison. Within the advanced response type modes we evaluated several different variants using the response types discussed in the previous section. Note that the vertical axis and yaw axis controllers do not change (they continue to use the RCHH and VSC modes of the baseline control laws).

A major assumption made in this study is that the ship decks position and velocities are made available for use within the controller, whether obtained with sensors on the aircraft or received through a data link with the ship. This allows for the development of Ship-Relative advanced response types. All of the advanced response types feature various combinations of velocity and position feedback along with position and velocity information from the ship. The command filters presented in the previous section produce commanded velocities and accelerations in the lateral (y-axis) and longitudinal (x-axis) directions. These axes are defined in a local vehicle coordinate system where the x-axis is aligned with the aircraft heading, and both axes are parallel to the ground plane (i.e. they are rotated from the North-East-Down frame only through aircraft heading, $\psi$). The controllers ultimately seek to control velocities and position relative to the ship deck, with the ship deck motion suitably filtered to remove some of the higher frequency fluctuations due to rolling and pitching motion. The bandwidth to which the rolling and pitching motion is filtered is one of the parameters to be investigated in this study.

The controller passes the position of the deck center through a filter and sums the filtered deck velocities and accelerations with the corresponding variables from each command filter. This allows stick detent to command the aircraft to hold a position or velocity relative to the
ship and stick deflections to command relative velocities or accelerations. The ship filter uses a second order transfer function compensated by an integrator to eliminate steady-state error when the ship is moving at a steady velocity. The resulting filter transfer function is shown below in Equation 3.7 where \( x \) is the measured deck position and the output of the filter yields the filtered acceleration, velocity, and position.

\[
\begin{bmatrix}
\dot{V}_f \\
V_f \\
x_f
\end{bmatrix} = \begin{bmatrix}
\frac{(s + K)\omega_n^2}{s^3 + 2\zeta\omega_n s^2 + K\omega_n^2} \\
s^2 \\
1
\end{bmatrix} \cdot x
\] (3.7)

The deck position and velocities are then transformed into the local aircraft coordinate system (rotated by aircraft heading) and summed with the commands in the advanced ship-relative modes. The placement of the ship filter in the controller architecture can be seen in Figure 3.10. The deck position is used in the position hold feedback and logic as discussed below.

![Figure 3.10. Ship-Relative Response Type Architecture](image)

Table 3.1 describes the various types of feedback compensation used in the control laws. The baseline ACAH control law features rate and attitude feedback with integrated attitude compensation. Velocity and position feedback (including both aircraft and ship velocities to produce relative velocity and position control) are only used with the selection of the advanced modes. The velocity and position feedback compensations are exactly the same whether the controller is in ACVH, TRC, the ACVH/TRC Hybrid mode, or the Automatic Transition mode. Only the commands are changed with the different response types and feedback compensation is not affected. All of these feedback compensation paths exist in both the lateral and longitudinal
axes, and are essentially identical in both axes. This is possible due to the nature of the dynamic inversion control architecture. The inversion part of NLDI essentially transforms the vehicle dynamics into a set of decoupled integrators, so outside of the inversion, identical compensation is required in both axes.

The velocity feedback includes integrator compensation in normal operation. Once the aircraft is close to the landing deck, and the velocity and commanded velocity relative to the deck are below a certain threshold, position hold is engaged. At this time the integrated velocity compensation is turned off and replaced with position and integrated position compensation. One of the challenges of the control design was to ensure smooth transitions when switching control modes. This is important when the advanced modes are selected or de-selected and it is especially critical when the position hold mode is automatically engaged or disengaged. This was achieved through careful initialization of the integrators in each feedback loop. In ACAH mode the velocity integrators are initialized so that when advanced modes are engaged the commanded roll and pitch attitudes match the current attitude of the aircraft. The position error integrator is initialized to match the output of the velocity integrator to avoid transients when the velocity integrator is turned off upon engagement of PH. Likewise in PH mode the velocity integrators are initialized to avoid transients upon disengagement of the PH mode. Once the aircraft makes contact with the deck, all integrators are disabled and the system smoothly transitions to the baseline ACAH mode.

<table>
<thead>
<tr>
<th>Feedback Type</th>
<th>Control Mode</th>
<th>Weight on Wheels</th>
<th>ACAH (No advanced mode selected)</th>
<th>ACVH/TRC (Advanced mode selected, ( V_{rel} &lt; 40 ) kts)</th>
<th>Position Hold (Advanced mode selected, ( V_{cmd} ) and ( V_{rel} &lt; 10 ) ft/sec, near landing deck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate Feedback</td>
<td></td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>Attitude Feedback</td>
<td></td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>Attitude Feedback Integrator</td>
<td>(Hold Value)</td>
<td>OFF</td>
<td>ON</td>
<td>ON</td>
<td>ON</td>
</tr>
<tr>
<td>Velocity Feedback</td>
<td></td>
<td>OFF</td>
<td>OFF (Init. to match current attitude)</td>
<td>ON</td>
<td>OFF (Init. to match position hold feedback)</td>
</tr>
<tr>
<td>Velocity Feedback Integrator</td>
<td></td>
<td>OFF</td>
<td>OFF (Init. to match current attitude)</td>
<td>ON</td>
<td>OFF (Init. to match position hold feedback)</td>
</tr>
<tr>
<td>Position Feedback</td>
<td></td>
<td>OFF</td>
<td>OFF (Init. to match current attitude)</td>
<td>OFF</td>
<td>ON</td>
</tr>
<tr>
<td>Position Feedback Integrator</td>
<td></td>
<td>OFF</td>
<td>OFF (Init. to match current velocity integrator)</td>
<td>OFF</td>
<td>ON</td>
</tr>
</tbody>
</table>

When the position hold mode is engaged, the pilot velocity commands are integrated to produce the desired reference position relative to the ship. This provides the pilot with precision...
control of the hover position over the landing deck. One of the desired features of the advanced control modes was to have the system automatically latch on to a position directly over the landing spot. The position hold control logic for TRC is illustrated in Figure 3.11. Similar PH logic is also used in ACVH and the other advanced modes. Note that it is critical to properly initialize the commanded position integrator. The latch shaping function essentially commands zero relative position (i.e. a position directly over the landing spot) once the commanded position falls within a desired threshold.

![Figure 3.11. Position Hold Control Laws and Mode Logic](image)
Piloted Simulation Testing

Piloted simulation tests were conducted with experienced Navy H-60 pilots to evaluate the performance of the advanced response types. Two separate rounds of testing are presented in this study. Preliminary testing focused on optimizing the characteristics of the response types and sought to validate the fidelity of the simulation environment. The final testing focused on more formal handling qualities evaluations of the response types. Several differences in the testing environment existed between the preliminary and final tests and are detailed in the following sections.

4.1 Simulation Environment

The fixed-base simulator utilizes the cockpit of a Bell XV-15 tilt-rotor prototype outfitted with a four-channel, 300lb capable control loading system to provide programmable force-feel characteristics to the pilots. The displays are output through three projectors onto a cylindrical screen with a 15 foot diameter, height of 10 feet, and 170 degree field of view. The cab houses a set of monitors for customizable instrument displays. An external monitor is situated to extend the pilots field of view in the downward direction outside of the right window for ease of viewing the landing deck during approaches. The flight simulator is shown in Figure 4.1.

The flight simulator imagery is generated by the flight simulation software, X-Plane. X-Plane provides global scenery, customizable weather and visibility, the ability to implement custom scenery, and a large online community for technical support. A custom plugin was developed
Figure 4.1. Flight Simulator

for X-Plane to integrate with the external flight dynamics model (GENHEL-PSU). The plug-in receives aircraft position and attitude values through a shared memory block in order to generate out-the-window graphics. The plugin also sends the height above the terrain back for use in the ground contact model within GENHEL-PSU. The X-Plane plugin also allows the ability to externally drive the motion of the ship. In this research, a 3D ship model of a FFG-7 Perry-class frigate is used. The ship model used in the simulation as well as an actual photograph of the ship is shown in Figure 4.2. A stabilized horizon bar was also implemented to the simulation ship model, as suggested by the pilot, to aid with orientation while hovering over the ship deck. This feature can be seen highlighted in the lower part of Figure 4.2.

In the preliminary tests the time histories of the ship motion were modelled as sums of sine waves to replicate the motion of a TMV-114 Fast Ferry as discussed in Ref. [28]. The similar size and geometry of the TMV-114 deems its motion model reasonable for use with the naval ship used in the simulation. Pilot comments confirmed the realism of the ship motion, making it acceptable for use in this study. A higher fidelity ship motion model was used for the final piloted simulation tests. This model uses time-histories of ship motion measured from a FFG-7 Frigate, taken from Ref. [29]. Both ship motion models are representative of Sea State 4 conditions.

The Control Equivalent Turbulence Input (CETI) model is being used to simulate the turbulent airwakes behind the ships superstructure. The model was developed by the U.S. Army AeroFlightDynamics Directorate (AFDD) by collecting flight data from a UH-60 hovering within the airwake of a large cube-shaped hangar and extracting the control inputs required to repli-
cate the aircrafts response to the atmospheric disturbances. The time histories of the control inputs are summed with the controllers commanded control inputs and are scalable for different turbulence levels. CETI is discussed in full in Ref. [30].

A first order Gauss-Markov stochastic model is applied to the aircraft and ships position, attitudes, and velocities in order to simulate non-ideal sensor noise. The model adds zero-mean white Gaussian noise, $w_k$, and a walking bias to the sensor signal, $x$, of time step, $dt$, with time constant, $T_c$, as shown in Equation 4.1.

$$x_k = e^{-\frac{dt}{T_c}} x_{k-1} + w_k$$  \hspace{1cm} (4.1)

Further discussion of the sensor error model can be seen in Ref. [31].

The control laws are designed within MATLAB/Simulink and compiled into a dynamically linked library (DLL) using the auto-code features of Simulink. The GENHEL-PSU model interfaces with the DLL for programmable flight control laws. This method allows for rapid development and adjustment of complex control laws during piloted simulation tests.
4.2 Task Description

The mission task element (MTE) used for evaluation was based on the maritime MTE presented in Ref. [16]. The pilot was tasked with a direct-stern approach to a FFG-7 ship, which held a constant velocity of 20 knots. The aircraft began the task in a trimmed forward flight of 20 knots, approximately 1000 feet behind the ship, and 100 feet AGL. The pilot was asked to accelerate to 10-20 knots closure rate and perform a constant rate decent to the ship fantail. As the pilot neared the deck he was to execute a flare to a stable hover with a desired flare time of 8 seconds and an adequate flare time of 12 seconds. The pilot landed upon suitable deck conditions with a desired landing location within a 10 foot square at the center of the deck and an adequate landing location within a 20 foot square. Upon landing, the pilot assessed the handling qualities of the tested control mode with the Cooper-Harper Rating Scale [32]. A visual representation of the ship approach task can be seen in Figure 4.3.

The MTE is modified from Ref. [16] in that the pilot lands the helicopter (rather than just holding hover), and the position tolerances are based on final landing position. The pilot was originally asked to reach the hover spot in one smooth flare maneuver (as was done in Ref. [16]), but the pilot felt this was an unrealistically aggressive maneuver given the close proximity to the ship superstructure. Thus, the pilot was allowed to slowly approach the final hover spot after flaring. The net result was that it was probably somewhat easier to achieve desired performance compared to Ref. [16], resulting in better overall handling qualities ratings.

The desired and adequate landing location tolerances used in the preliminary simulation tests can be seen in Figure 4.4. It was decided after preliminary tests that the difficulty of the landing
tolerances should be increased to provide more of a challenge for the pilot. The new desired and adequate landing tolerances were selected as 5 and 10 foot squares, respectively, at the center of the deck. These tolerances were used in the final piloted simulation tests and can be seen in Figure 4.5.

Figure 4.4. Preliminary Testing Landing Location Tolerances
The pilots instrument display included an indicator showing the position of the center of the deck with respect to the aircraft as well as the desired and adequate landing location tolerances. The indicator simulated a downward view from the aircraft with the landing location represented by a black dot. The position indicator can be seen in Figure 4.6.

The preliminary piloted simulation tests utilized a single Navy H-60 pilot with experience in B, F, and H models. The final tests included an additional experienced Navy H-60 pilot.
Navy Test Pilot School graduate. In order to utilize both pilots in the task and to simulate a more realistic approach scenario, the copilot was asked to provide cues to the pilot such as aircraft closure rate and altitude. As the aircraft reached a stable hover over the deck, the copilot assumed the role of a “crew chief” and provided position cues to the pilot. In order to accomplish this an additional display was situated outside and below the copilots window with a downward facing view from the aircraft. The heads down position indicator was still included, but the pilots tended to keep their eyes out the window and rely on cues from the copilot/crew chief when over the deck. An example of the crew chief’s downward facing view from the aircraft can be seen in Figure 4.7. The landing tolerances were also displayed on the simulation ship model for position cueing purposes.

![Figure 4.7. Crew Chief View with Landing Tolerances on Deck](image)

### 4.3 Test Configurations

Initial piloted simulation tests suggested that ACAH or Ship-Relative ACVH were desired while approaching the ship due to their high-responsiveness, but each lacked low speed precision while hovering over the ship deck, resulting in high pilot workload. Ship-Relative TRC provided high precision and low pilot workload while hovering over the deck, but required large magnitude longitudinal cyclic inputs during the approach to maintain a closure rate. This resulted in large
forward force, requiring additional pilot workload to maintain lateral velocities. To some degree, this was addressed with non-linear command shaping, which allowed smaller forward stick forces on approach, but this solution proved to be still less than ideal.

The ACVH/TRC Hybrid response type also offered a solution to this issue, however, the expected output of cyclic commands became difficult for the pilot to predict as the response type changed with varying magnitude cyclic inputs. The pilot preferred to know exactly what the response type was during operations.

The Auto Transition mode was developed to solve these issues. The lateral control was designed to use Ship-Relative TRC during the entire approach in order to provide better controllability of lateral position with respect to the ship, while the longitudinal axis was designed to use Ship-Relative ACVH response during approach, then smoothly transition to Ship-Relative TRC/PH once the aircraft gets near the landing spot. This mode was shown to provide the responsiveness and controllability of ACVH during the ship approach and the precision of TRC over the deck. The transition was programmed to occur over a period of 5 seconds as the aircraft was within 200 feet of the deck center and its closure rate to the ship was within ±10 knots.

The selection of advanced response types for preliminary testing was narrowed to ACAH, Ship-Relative ACVH, and the ACVH/TRC Automatic Transition mode. Final testing also used the same three control modes, but included an additional mode that used the UH-60A mechanical controls with a 10% authority stability augmentation system (SAS) in roll, pitch, and yaw. This mode achieves an angular rate response type and serves as a sufficient baseline for pilot control activity. This is the last major difference between the preliminary and final simulation tests. These differences are summarized below in Table 4.1.
Table 4.1. Differences Between Preliminary and Final Piloted Simulation Testing Environments

<table>
<thead>
<tr>
<th></th>
<th>Preliminary Tests</th>
<th>Final Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilots</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Ship Motion Model</td>
<td>TMV-114</td>
<td>FFG-7</td>
</tr>
<tr>
<td>Landing Tolerances</td>
<td>10, 20 ft</td>
<td>5, 10 ft</td>
</tr>
<tr>
<td>Control Modes</td>
<td>ACAH</td>
<td>Mech. w/ SAS</td>
</tr>
<tr>
<td></td>
<td>ACVH</td>
<td>ACAH</td>
</tr>
<tr>
<td></td>
<td>Auto</td>
<td>ACVH</td>
</tr>
</tbody>
</table>

The ship approach MTE was performed for several different test cases involving different combinations of airwake turbulence and ship motion (Sea-State 4 equivalent) as shown in Table 4.2. This allows for the identification of which factors contribute more difficulty to the pilot during the task. In cases 2 and 4, the CETI airwake model was programmed to engage while the aircraft was within 250 ft behind the superstructure of the ship.

Table 4.2. Ship Approach Test Cases

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Ship Motion</th>
<th>Ship Airwake</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The pilot assigned a Cooper-Harper Handling Quality Rating (HQR) for the control mode after each approach task, where an HQR of 1 is desirable and an HQR of 10 is undesirable as introduced in Ref. [32]. The pilot’s decision-making tree for assigning an HQR can be seen in Figure 4.8.
Figure 4.8. Cooper-Harper Handling Qualities Rating Scale
Results

5.1 Preliminary Testing Results

Preliminary piloted simulation tests were conducted with a single experienced Navy H-60 pilot for the refinement of response type characteristics and a preliminary evaluation of the aircraft handling qualities in each control mode.

5.1.1 Handling Qualities Ratings

In the preliminary tests, two approach tasks were evaluated in each test case and all four cases were completed in increasing order before continuing to the next control mode for a total of 24 ship approaches. Testing was performed with the ACAH response type, followed by Ship-Relative ACVH and then the ACVH/TRC Automatic Transition mode. The two HQRs were averaged for each test case and can be seen in Figure 5.1. Ratings for the same case never differed by more than 1. As expected, Case 4, with both ship motion and airwake turbulence proved to be the most challenging (worst HQRs). It can be seen that a 1.5 HQR improvement over the baseline ACAH response type was achieved by the Automatic Transition control mode in the most difficult test configuration, Case 4. Improvement was also achieved with the less demanding cases, with HQR 1 for the Auto ACVH/TRC mode in the cases without airwake turbulence. This very favorable rating may be partly influenced by the task being not particularly demanding, and the experience of the evaluation pilot (who also had considerable practice during the development phase). In any case, the results show reasonable expected trends in handling qualities.
Testing continued with variations in the time and frequency parameters of both the Ship Filter and the TRC command filters for Test Case 4. Evaluations and pilot comments indicated there were some minor deficiencies in keeping the aircraft over the landing spot with a rolling ship and airwake turbulence. It was hypothesized that this could be improved by one of two methods:

1. Increasing the bandwidth of the ship filter so the ship-relative position hold feature better tracks position over the landing spot without pilot input

2. Increasing the TRC bandwidth so that the aircraft is more responsive to pilot inputs for better position tracking when hovering over the landing spot

The ship filter used in the HQR results shown in Figure 5.1 was relatively low bandwidth, with a natural frequency of 0.1 rad/sec, filtering out most of the rolling motion of the ship. The TRC command filter used a first order transfer function in series with a second order filter that matches the attitude command filter ($\tau = 3.0$ sec, $\omega_n = 2.5$ rad/sec, $\zeta = 0.8$). Figure 5.2 shows the HQR results of the parameter tuning.

Results showed that increasing the ships bandwidth (i.e. allowing the ship to command higher aircraft velocities and accelerations over the moving deck) resulted in worse HQRs. The
ship filter was increased as high as 1 rad/sec. It appeared that the pilot ended up fighting the automatic velocity commands from the ship position feedback. Keeping the low ship bandwidth and increasing the pilots bandwidth (in the lateral axis only) allowed the pilot to better maintain a position over the lively deck, resulting in better HQRs (ultimately HQR of 1). The optimized time and frequency parameters are shown in Table 5.1. Detailed notes on arriving at the final values can be seen in Appendix B. Note that most of the dynamic ship motion is in the lateral direction, so maximizing lateral command filter bandwidth was ideal. Increasing longitudinal axis bandwidth actually resulted in an abrupt pitch response that was in some cases objectionable to the pilot.

Table 5.1. Optimized Time and Frequency Parameters for Auto ACVH/TRC in Test Case 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ship Filter</th>
<th>Lat. Cmd Filter</th>
<th>Long. Cmd Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_n$ (rad/s)</td>
<td>0.1</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>$\tau$ (sec)</td>
<td>-</td>
<td>1.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>
5.1.2 Example Ship Approaches with Ship Motion and Airwake Turbulence

Detailed piloted simulation results are shown for example approaches in Test Case 4 (ship motion and ship airwake turbulence) for both an ACAH approach and an ACVH/TRC Automatic Transition approach using the optimized time and frequency parameters. Figures 5.3 to 5.7 show results for the ACAH approach, while Figures 5.8 to 5.13 show results with the Auto ACVH/TRC approach.

5.1.2.1 Attitude Command Attitude Hold

The commanded and actual pitch attitude, roll attitude, and downward velocity throughout the ACAH approach can be seen in Figure 5.3. These represent three of the controlled states of the inner loop ACAH control law. The yaw rate command in the pedals axis was omitted here due to the lack of significant activity. Command tracking in all axes is reasonable. The pilot control inputs are shown in Figure 5.4. Note the pilot workload in the lateral axis is significant throughout the task.

The aircrafts altitude profile and position relative to the center of the deck throughout the approach can be seen in Figure 5.5. A close up of the aircrafts altitude and position with respect to the moving ship deck during the flare and landing portion of the task can be seen in Figure 5.6, and a more detailed close up of the aircrafts position relative to the center of the deck during the hover/landing portion of the task can be seen in Figure 5.7. The effect of the lateral rocking of the ship can be seen in the lateral aircraft position variation over the deck. Although the pilot could generally achieve desired or adequate position tolerances for landing, there was some annoying deficiencies in finding the landing spot. The flare to stable hover also sometimes took longer than desired.
Figure 5.3. Control Variables for ACAH Ship Approach
Figure 5.4. Pilot Inputs for ACAH Ship Approach
**Figure 5.5.** Aircraft Altitude and Position Relative to Deck Center for ACAH Ship Approach

**Figure 5.6.** Aircraft Altitude and Position Relative to Deck Center during Flare Portion of ACAH Ship Approach
5.1.2.2 ACVH/TRC Automatic Transition

The commanded and actual forward, right, and downward velocities throughout the ACVH/TRC Automatic Transition approach can be seen in Figure 5.8 with the 5 second transition period highlighted. These are the primary controlled states with the ACVH/TRC controller and show reasonable tracking. The pilots inputs throughout the approach can be seen in Figure 5.9 and show significantly lower control activity compared to the ACAH case. The aircrafts roll, pitch, and heading can be seen in Figure 5.10. Plots of the aircraft altitude and position at various phases of the maneuver are shown in Figures 5.11 to Figure 5.13, similar to the results from the ACAH controller. The maneuvers were performed more quickly with the ACVH/TRC
controller, and the pilot spent less time finding the landing spot.

Overall, the ACVH/TRC Automatic Transition control mode with optimized time and frequency parameters was shown to provide the pilot with less workload than the compared ACAH response type throughout the approach. It can be seen that the Auto Transition mode allowed for better control of aircraft position when hovering over the lively ship deck. The Ship-Relative ACVH response type in the longitudinal cyclic axis allowed for precise control of closure rate during the approach and the Ship-Relative TRC response type in lateral axis provided controllability of lateral position with respect to the ship on approach. In all response types, vertical speed command in the collective axis was shown to provide controllability of descent rate, allowing for successful maintenance of glide slope on approach.

The transition from ACVH to TRC was shown to take place towards the end of the flare as the aircraft reached a stable hover over the ship deck. Pilot comments indicated that the transition occurred at “the right time, speed, and distance from the ship”.
Figure 5.8. Control Variables for ACVH/TRC Ship Approach
Figure 5.9. Pilot Inputs for ACVH/TRC Ship Approach
Figure 5.10. Aircraft Attitudes for ACVH/TRC Ship Approach
Figure 5.11. Aircraft Altitude and Position Relative to Deck Center throughout ACVH/TRC Ship Approach

Figure 5.12. Aircraft Altitude and Position Relative to Deck Center during Flare Portion of ACVH/TRC Ship Approach
5.1.2.3 ACVH/TRC Automatic Transition (Non-Real-Time)

A non-real-time ship approach was performed in Test Case 4 with the ACVH/TRC Automatic Transition control mode using the optimized time and frequency parameters. Results similar to those previously presented can be seen in Figures 5.14 - 5.19. The control inputs necessary to complete the task were reduced to a series of simple step inputs prescribed with time and can be seen in Figure 5.15. Iterations were performed on the control inputs to converge on velocity profiles that were similar to those from the piloted approaches. The primary inputs seen are in the longitudinal axis for the acceleration and flare portions of the approach. After the aircraft
reaches a 15 knot closure rate, a constant collective input can be seen, resulting in a constant rate of descent to the ship fantail. This can be seen in the altitude profile in Figure 5.17. After the aircraft flares it can be seen to reach a stable hover over the deck, but outside of the adequate landing location threshold. A small cyclic input in TRC mode brings the aircraft into a hover over the desired landing location as seen in Figure 5.18 and more closely in Figure 5.19. The final landing portion of the approach task was omitted here due to the dependence on pilot judgement for landing timing within this project, however the controller was shown to execute the remainder of the task well with only simple commands prescribed with time.
Figure 5.14. Control Variables for Non-Real-Time ACVH/TRC Ship Approach
Figure 5.15. Pilot Inputs for Non-Real-Time ACVH/TRC Ship Approach
Figure 5.16. Aircraft Attitudes for Non-Real-Time ACVH/TRC Ship Approach
Figure 5.17. Aircraft Altitude and Position Relative to Deck Center throughout Non-Real-Time ACVH/TRC Ship Approach

Figure 5.18. Aircraft Altitude and Position Relative to Deck Center during Flare Portion of Non-Real-Time ACVH/TRC Ship Approach
Figure 5.19. Aircraft Position Relative to Deck Center during Hover Portion of Non-Real-Time ACVH/TRC Ship Approach

5.2 Final Testing Results

Additional piloted simulation tests were conducted, which involved more formal handling qualities evaluations. An experienced Navy H-60 pilot / Navy Test Pilot School graduate was included in the tests in addition to the pilot from previous tests. Several differences existed between the preliminary and final test environments such as a higher fidelity ship motion model, more difficult landing position tolerances, and the addition of a downward facing display for a “crew chief” position cueing. The simulation tests also included an additional control mode as a baseline
reference for pilot workload. This mode used the standard mechanical controls of the UH-60A with stability augmentation system (SAS) in pitch, roll, and yaw for an angular rate response type. The final four control modes tested include the mechanical controls with SAS, ACAH, ACVH, and the ACVH/TRC Automatic Transition mode.

5.2.1 Handling Qualities Ratings

The maritime MTE was performed by one pilot for two runs in each test case for a given control mode. Their roles were then switched and the tasks were performed again for the same control mode. The control mode was then changed and the test pattern was repeated for a total of 64 ship approaches. Cooper-Harper HQRs were assigned after each ship approach and can be seen in Figure 5.20 with maximum, minimum, and mean values shown. Results show that Level 1 handling qualities were not achievable with the mechanical controls with SAS in any of the test cases. Level 1 handling qualities were achieved by ACAH and ACVH in test cases without airwake turbulence only. The ACVH/TRC Automatic Transition control mode was shown to achieve Level 1 handling qualities in every test case.

It can be seen that the airwake turbulence (red line) contributed towards worse HQRs than the ship motion (blue line) within this test environment. Pilot comments indicated that the ship motion model was slightly less aggressive than the previous model used in preliminary tests. The motion was considered to be less active in the roll axis, but more active in the pitch axis, which is typical of small frigates. Although the augmented response types achieved better HQRs than the mechanical controls, they were shown to be more sensitive to airwake turbulence and ship motion.
Preliminary testing showed good performance with ACVH, however the pilots had more difficulty tracking the landing location with tighter landing position tolerances. ACVH was seen to result in worse HQRs when compared to ACAH in some cases with ship motion or airwake turbulence engaged. The pilots described having difficulties with station keeping over the deck in ACVH. Their landing technique changed to timing the collective with the aircraft translations rather than holding a position over the landing spot. This is likely due to the velocity-hold features of the response type, which result in undesirable station keeping characteristics.

Two significant outliers exist in the data and can be seen in Test Case 4 of ACAH and ACVH/TRC Auto Transition. These were a result of missing the adequate or desired landing tolerances, respectively, and were expected with the increased difficulty of the task tolerances.

Overall, worse HQRs were seen on approaches with relatively longer times spent hovering over
the deck when compared to an approach with similar pilot controls activity. Although time spent hovering over the deck was not a metric in the MTE, it had an effect on the pilots’ opinion of their workload and thus their HQR assignments. For a better understanding of the relationship between pilot workload, control activity, and time spent over deck, this should be considered as a metric in a future version of the MTE.

Several example ship approaches with ship motion and airwake turbulence can be seen in Figures 5.21 - 5.32. These focus on the portion of the approach spent over the deck as it was concluded that the majority of the pilot workload extends from tracking a position on the deck. The approach to the ship deck was considered to have relatively little pilot workload and it was concluded that separating the two portions of the approach into different tasks should also be considered in future MTE refinement.

5.2.2 Example Ship Approaches with Ship Motion and Airwake Turbulence

Figures 5.21 to 5.23 show the aircraft position with respect to the moving landing location, aircraft attitudes, and pilot control inputs for a ship approach with ship motion and airwake turbulence using the Mechanical Controls. Similar results are shown in the following figures for ACAH, ACVH, and ACVH/TRC Auto Transition control modes. The colors are used to visualize time in the position plots and can be referenced with the appropriate time history plots of pilot controls and aircraft attitudes. Note that the colors are unique to each approach, as the range of time differs between each set.

The collective axis was identified as the largest contributor to pilot workload in the mechanical controls. This was due to the tracking of the heave motion of the deck. This workload was significantly less with the vertical speed command in the augmented control modes.

The lateral axis was the largest source of pilot workload in ACAH, which was associated with the deck roll motion. A smaller amount of longitudinal workload was mentioned by the pilots to be associated with a lack of longitudinal position cues to the pilot. Similar results were seen for ACVH. A proposed solution was to include Flight 3 frigate deck markings for future testing rather than Flight 1.

The pilots’ comments indicated minimal workload over the deck while in TRC of the ACVH
/TRC Auto Transition mode. Small pilot compensation was seen for position keeping. Further comments indicated that a possible improvement in order to achieve an HQR 1 would be a “snap-to-grid” function seen in Ref [15], where an automatic mode would engage that brings the aircraft over the landing location and holds a position. This allows the pilot to focus on timing the collective with a quiescent period in the deck motion. This is within the boundaries of the current controller and should be considered for further investigation.

5.2.2.1 Mechanical Controls with SAS

Figure 5.21. Aircraft Position Relative to Deck Center During Landing Portion of Mechanical Controls Ship Approach in Test Case 4 (HQR 6)
Figure 5.22. Pilot Inputs During Landing Portion of Mechanical Controls Ship Approach in Test Case 4 (HQR 6)
Figure 5.23. Aircraft Attitudes During Landing Portion of Mechanical Controls Ship Approach in Test Case 4 (HQR 6)
5.2.2.2 Attitude Command Attitude Hold

Figure 5.24. Aircraft Position Relative to Deck Center During Landing Portion of ACAH Ship Approach in Test Case 4 (HQR 4)
Figure 5.25. Pilot Inputs During Landing Portion of ACAH Ship Approach in Test Case 4 (HQR 4)
Figure 5.26. Aircraft Attitudes During Landing Portion of ACAH Ship Approach in Test Case 4 (HQR 4)
5.2.2.3 Acceleration Command Velocity Hold

Figure 5.27. Aircraft Position Relative to Deck Center During Landing Portion of ACVH Ship Approach in Test Case 4 (HQR 4)
Figure 5.28. Pilot Inputs During Landing Portion of ACVH Ship Approach in Test Case 4 (HQR 4)
Figure 5.29. Aircraft Attitudes During Landing Portion of ACVH Ship Approach in Test Case 4 (HQR 4)
5.2.2.4 ACVH/TRC Automatic Transition

Figure 5.30. Aircraft Position Relative to Deck Center During Landing Portion of ACVH/TRC Auto Transition Ship Approach in Test Case 4 (HQR 2)
Figure 5.31. Pilot Inputs During Landing Portion of ACVH/TRC Auto Transition Ship Approach in Test Case 4 (HQR 2)
Figure 5.32. Aircraft Attitudes During Landing Portion of ACVH/TRC Auto Transition Ship Approach in Test Case 4 (HQR 2)
Conclusions and Future Work

A simulation environment for evaluating advanced response types for shipboard operations was developed. A Non-Linear Dynamic Inversion controller was designed to be able to accurately track a variety of programmable response types, and three response types were tested in piloted simulations with experienced Navy H-60 pilots. The NLDI controller was shown to track the commanded ideal control responses well despite turbulent airwake disturbances and sensor noise. The CLAW architecture allows seamless partition of the response type (as dictated by command filters) and the feedback compensation on the aircraft making it well suited for this study.

Simulation results showed that the best response type evaluated was an ACVH/TRC Automatic Transition control mode. The mode consists of a Ship-Relative ACVH response type in the longitudinal axis during the first portion of the approach, which automatically switches to a Ship-Relative TRC response type as the aircraft meets ship proximity and closure rate thresholds. A Ship-Relative TRC response type is used in the lateral axis throughout the approach for maintenance of lateral position with respect to the ship. The mode was shown to provide the pilot with an aggressive and controlled approach combined with high precision maneuvering over the ship deck while minimizing pilot workload.

The ship-relative position feedback was found to be helpful to match the ship speed in TRC mode, and to latch on to a position reference over the landing spot when preparing to land. However, it was found that it was better to filter most of the high frequency rolling motion, rather than trying to force the aircraft to follow the lateral fluctuations. Variations in bandwidth parameters indicated that it is generally desirable to maximize pilot bandwidth so that they can
control position over the deck rather than using the deck motion feedback to automatically track rolling motion.

There are several areas that can be improved upon in future work:

- Additional piloted simulation tests including formal handling qualities ratings should be conducted with an expanded range of pilots to verify the results of this study.
- Higher fidelity ship motion and airwake turbulence models should be implemented for a more accurate representation of the shipboard operational environment.
- The ship approach mission task element structure and corresponding tolerances should be further refined based on pilot feedback. Separating the approach and landing portions of the MTE should be considered.
- The performance of a ship-relative heave command in the vertical axis CLAWs requires further investigation.
- Implementation of active stick cueing for deck proximity and vehicle operational limits should be considered.
- Further investigation is required in the variation of the inner loop feedback compensation for optimizing the balance between gust rejection characteristics and aircraft stability.
Appendix A

Controller Schematics

A.1 Inner Loop

Figure A.1. Inner Loop $G(x)$ Calculation
Figure A.3. Inner Loop Dynamic Inversion Control Laws
Figure A.4. Inner Loop PID Compensators with Gain Scheduling for High Airspeeds

Figure A.5. Inner Loop Turn Coordination Control Laws
**Figure A.6.** Inner Loop Command Filters

**Figure A.8.** Inner Loop Pitch Command Filter
Figure A.7. Inner Loop Roll Command Filter

Figure A.9. Inner Loop Yaw Command Filter

Figure A.10. Inner Loop Vertical Command Filter
A.2 Outer Loop

Figure A.11. Outer Loop Command Filters
Figure A.13. Example Ship Filter for Deck North Position
Figure A.14. ACVH Command Filters Summing with Commanded Ship Velocities and Accelerations for Ship-Relative Response

Figure A.15. Example ACVH Command Filter

Figure A.16. Example ACVH Command Filter Transfer Function
Figure A.17. TRC Command Filters Summing with Commanded Ship Velocities and Accelerations for Ship-Relative Response

Figure A.18. Example TRC Command Filter

Figure A.19. Example TRC Command Filter Transfer Function
Figure A.20. Amplitude-Dependent ACVH/TRC Hybrid Command Filters

Figure A.21. Example Amplitude-Dependent ACVH/TRC Hybrid Command Filter with Hyperbolic Tangent Function in Feedback Loop

Figure A.22. Example Amplitude-Dependent ACVH/TRC Hybrid Command Filter Transfer Function
A.3 Sensor Error Model

Figure A.23. Example Sensor Error Applied to Aircraft Angular Rates Feedback

Figure A.24. Example Sensor Noise Model with Gaussian White Noise and Random Walk Components

Figure A.25. Example Sensor Low Pass Filter
Piloted Simulation Test Notes

B.1 Preliminary Testing

B.1.1 Attitude Command Attitude Hold

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Bob</td>
<td>1</td>
<td>ACAH</td>
<td>Desired</td>
<td>Desired</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Bob</td>
<td>1</td>
<td>ACAH</td>
<td>Desired</td>
<td>Desired</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Bob</td>
<td>2</td>
<td>ACAH</td>
<td>Desired</td>
<td>Adequate</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Bob</td>
<td>2</td>
<td>ACAH</td>
<td>Desired</td>
<td>Desired</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Bob</td>
<td>3</td>
<td>ACAH</td>
<td>Adequate</td>
<td>Desired</td>
<td>5</td>
<td>increased time over deck</td>
</tr>
<tr>
<td>7</td>
<td>Bob</td>
<td>3</td>
<td>ACAH</td>
<td>Desired</td>
<td>Desired</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Bob</td>
<td>4</td>
<td>ACAH</td>
<td>Adequate</td>
<td>Desired</td>
<td>5</td>
<td>longer time to find spot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>not much more workload</td>
</tr>
<tr>
<td>9</td>
<td>Bob</td>
<td>4</td>
<td>ACAH</td>
<td>Desired</td>
<td>Desired</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
### B.1.2 Acceleration Command Velocity Hold

**Table B.2. Notes for Approaches with ACVH**

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Bob</td>
<td>1</td>
<td>ACVH</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>bad deck contact - go around</td>
</tr>
<tr>
<td>12</td>
<td>Bob</td>
<td>1</td>
<td>ACVH</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Bob</td>
<td>2</td>
<td>ACVH</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“turbulence not a big issue”</td>
</tr>
<tr>
<td>14</td>
<td>Bob</td>
<td>2</td>
<td>ACVH</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Bob</td>
<td>3</td>
<td>ACVH</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>“spot moved right before landing”</td>
</tr>
<tr>
<td>16</td>
<td>Bob</td>
<td>3</td>
<td>ACVH</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>bounced</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“same work, longer time”</td>
</tr>
<tr>
<td>17</td>
<td>Bob</td>
<td>4</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Bob</td>
<td>4</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>4</td>
<td>“more effort to track”</td>
</tr>
</tbody>
</table>

### B.1.3 ACVH/TRC Automatic Transition

**Table B.3. Notes for Approaches with ACVH/TRC Automatic Transition**

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
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<tbody>
<tr>
<td>19</td>
<td>Bob</td>
<td>1</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>1</td>
<td>“pretty easy”</td>
</tr>
<tr>
<td>20</td>
<td>Bob</td>
<td>1</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>1</td>
<td>“no problems”</td>
</tr>
<tr>
<td>21</td>
<td>Bob</td>
<td>2</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“little more work for turbulence”</td>
</tr>
<tr>
<td>22</td>
<td>Bob</td>
<td>2</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>1</td>
<td>less time over deck</td>
</tr>
<tr>
<td>23</td>
<td>Bob</td>
<td>3</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>1</td>
<td>“nothing to it”</td>
</tr>
<tr>
<td>24</td>
<td>Bob</td>
<td>3</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Bob</td>
<td>4</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>early deck contact</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>longer time over deck</td>
</tr>
<tr>
<td>27</td>
<td>Bob</td>
<td>4</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>
Table B.4. Notes for Time/Frequency Parameter Optimization for ACVH/TRC Auto Transition

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
</table>
| 28  | Bob   | 4    | Auto | 7 s / Desired | Desired | 4   | \( \omega_{\text{ship}} = 0.75 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \zeta_{\text{ship}} = 1.0 \)
|     |       |      |      |       |         |     | \( \omega_{\text{roll}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_y} = 3 \text{ sec} \)
|     |       |      |      |       |         |     | \( \omega_{\text{pitch}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_x} = 3 \text{ sec} \) |
| 29  | Bob   | 4    | ACVH | 7 s / Desired | Desired | 4   | \( \omega_{\text{ship}} = 0.75 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \zeta_{\text{ship}} = 1.0 \)
|     |       |      |      |       |         |     | \( \omega_{\text{roll}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_y} = 3 \text{ sec} \)
|     |       |      |      |       |         |     | \( \omega_{\text{pitch}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_x} = 3 \text{ sec} \) |
| 30  | Bob   | 4    | Auto | 7 s / Desired | Desired | 3   | change: \( \omega_{\text{ship}} = 0.7 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \zeta_{\text{ship}} = 0.7 \)
|     |       |      |      |       |         |     | change: \( \omega_{\text{roll}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_y} = 3 \text{ sec} \)
|     |       |      |      |       |         |     | \( \omega_{\text{pitch}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_x} = 3 \text{ sec} \) “heli moving a lot” |
| 31  | Bob   | 4    | Auto | / Desired | Desired | 4   | change: \( \omega_{\text{ship}} = 0.1 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \zeta_{\text{ship}} = 0.7 \)
|     |       |      |      |       |         |     | change: \( \omega_{\text{roll}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_y} = 3 \text{ sec} \)
|     |       |      |      |       |         |     | \( \omega_{\text{pitch}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_x} = 3 \text{ sec} \) “a whole lot easier” “tracked laterally well” |
| 32  | Bob   | 4    | Auto | 6 s / Desired | Desired | 1   | change: \( \omega_{\text{ship}} = 0.1 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \zeta_{\text{ship}} = 0.7 \)
|     |       |      |      |       |         |     | change: \( \omega_{\text{roll}} = 3.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | change: \( \tau_{V_y} = 1.5 \text{ sec} \)
|     |       |      |      |       |         |     | \( \omega_{\text{pitch}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_x} = 3 \text{ sec} \) “roll synced well” |
| 33  | Bob   | 4    | Auto | 6 s / Desired | Desired | 1   | \( \omega_{\text{ship}} = 0.1 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \zeta_{\text{ship}} = 0.7 \)
|     |       |      |      |       |         |     | \( \omega_{\text{roll}} = 3.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_y} = 1.5 \text{ sec} \)
|     |       |      |      |       |         |     | \( \omega_{\text{pitch}} = 2.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_x} = 3 \text{ sec} \) “roll synced well” |
| 34  | Bob   | 4    | Auto | 4 s / Desired | Desired | 2   | \( \omega_{\text{ship}} = 0.1 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \zeta_{\text{ship}} = 0.7 \)
|     |       |      |      |       |         |     | \( \omega_{\text{roll}} = 3.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | \( \tau_{V_y} = 1.5 \text{ sec} \)
|     |       |      |      |       |         |     | change: \( \omega_{\text{pitch}} = 3.5 \text{ rad/s} \)
|     |       |      |      |       |         |     | change: \( \tau_{V_x} = 1.5 \text{ sec} \) objectionable pitch in flare |
## B.2 Final Testing

### B.2.1 Mechanical Controls with SAS

#### Table B.5. Notes for Approaches with Mechanical Controls with SAS

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bob</td>
<td>1</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Bob</td>
<td>1</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Bob</td>
<td>2</td>
<td>Mech. Controls</td>
<td>/</td>
<td>Desired</td>
<td>5</td>
<td>long. axis was heavy work load, lat. axis was fine</td>
</tr>
<tr>
<td>4</td>
<td>Bob</td>
<td>2</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td>overshoot in long. axis</td>
</tr>
<tr>
<td>5</td>
<td>Bob</td>
<td>3</td>
<td>Mech. Controls</td>
<td>5 s</td>
<td>Desired</td>
<td>4</td>
<td>significant time over the deck</td>
</tr>
<tr>
<td>6</td>
<td>Bob</td>
<td>3</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>5</td>
<td>inverted performance and workload rating from previous run</td>
</tr>
<tr>
<td>7</td>
<td>Bob</td>
<td>4</td>
<td>Mech. Controls</td>
<td>7 s</td>
<td>Desired</td>
<td>6</td>
<td>Bounced and significant time over the deck</td>
</tr>
<tr>
<td>8</td>
<td>Bob</td>
<td>4</td>
<td>Mech. Controls</td>
<td>7 s</td>
<td>Desired</td>
<td>5</td>
<td>re-do due to not enough pilot workload put in</td>
</tr>
<tr>
<td>9</td>
<td>Steve</td>
<td>1</td>
<td>Mech. Controls</td>
<td>8 s</td>
<td>Inadequate</td>
<td>N/A</td>
<td>’accidently went into cockpit”</td>
</tr>
<tr>
<td>10</td>
<td>Steve</td>
<td>1</td>
<td>Mech. Controls</td>
<td>4 s</td>
<td>Desired</td>
<td>5</td>
<td>“again struggled with long. axis”</td>
</tr>
<tr>
<td>11</td>
<td>Steve</td>
<td>1</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td>re-do due to not enough pilot workload put in</td>
</tr>
<tr>
<td>12</td>
<td>Steve</td>
<td>2</td>
<td>Mech. Controls</td>
<td>4 s</td>
<td>Desired</td>
<td>5</td>
<td>“continuous long. axis activity with .25-.5 inch inputs”</td>
</tr>
<tr>
<td>13</td>
<td>Steve</td>
<td>2</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td>“not much workload for cyclic on approach”</td>
</tr>
<tr>
<td>14</td>
<td>Steve</td>
<td>3</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td>“much more collective activity”</td>
</tr>
<tr>
<td>15</td>
<td>Steve</td>
<td>3</td>
<td>Mech. Controls</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td>“didn’t chase deck as much and felt more comfortable”</td>
</tr>
<tr>
<td>16</td>
<td>Steve</td>
<td>4</td>
<td>Mech. Controls</td>
<td>8 s</td>
<td>Desired</td>
<td>4</td>
<td>“really high collective w/skip motion”</td>
</tr>
<tr>
<td>17</td>
<td>Steve</td>
<td>4</td>
<td>Mech. Controls</td>
<td>8 s</td>
<td>Desired</td>
<td>N/A</td>
<td>bad contact and a re-do was decided</td>
</tr>
<tr>
<td>18</td>
<td>Steve</td>
<td>4</td>
<td>Mech. Controls</td>
<td>7 s</td>
<td>Desired</td>
<td>4</td>
<td>“nice glidepath”</td>
</tr>
</tbody>
</table>


### B.2.2 Attitude Command Attitude Hold

#### Table B.6. Notes for Approaches with ACAH

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Bob</td>
<td>1</td>
<td>ACAH</td>
<td>Desired</td>
<td>Desired</td>
<td>2</td>
<td>“minimal workload”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“fairly steady”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“more workload on long. for hover to landing”</td>
</tr>
<tr>
<td>20</td>
<td>Bob</td>
<td>1</td>
<td>ACAH</td>
<td>7 s</td>
<td>Desired</td>
<td>2</td>
<td>good alignment with small overshoot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“initially caught between minimal comp. required and negligible</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>deficiencies”</td>
</tr>
<tr>
<td>21</td>
<td>Bob</td>
<td>2</td>
<td>ACAH</td>
<td>8 s</td>
<td>Desired</td>
<td>3</td>
<td>similar dilemma between min. comp. required and negligible deficiencies</td>
</tr>
<tr>
<td>22</td>
<td>Bob</td>
<td>2</td>
<td>ACAH</td>
<td>6 s</td>
<td>Desired</td>
<td>3</td>
<td>“a little more work than previously”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“I caused myself additional workload when not staying in position</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>over the deck”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pilot technique: “I worked on getting the lateral alignment first then</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>straight out the fwd/aft rather than attempt to do it all at once”</td>
</tr>
<tr>
<td>23</td>
<td>Bob</td>
<td>3</td>
<td>ACAH</td>
<td>10 s</td>
<td>Adequate</td>
<td>2</td>
<td>Long flare, but ignore for HQR purposes</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“Flare felt smoother, but had to be longer”</td>
</tr>
<tr>
<td>24</td>
<td>Bob</td>
<td>3</td>
<td>ACAH</td>
<td>7 s</td>
<td>Desired</td>
<td>2</td>
<td>“real small inputs on the control”</td>
</tr>
<tr>
<td>25</td>
<td>Bob</td>
<td>4</td>
<td>ACAH</td>
<td>7 s</td>
<td>Desired</td>
<td>4</td>
<td>“minor but annoying”</td>
</tr>
<tr>
<td>26</td>
<td>Bob</td>
<td>4</td>
<td>ACAH</td>
<td>8 s</td>
<td>Desired</td>
<td>4</td>
<td>hit the tailwheel and forced to resettle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>longest time to complete the hover to landing with ACAH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“It is important when to recognize your control strategy is not working</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>and to pick a different strategy if the aircraft is wandering”</td>
</tr>
<tr>
<td>27</td>
<td>Steve</td>
<td>1</td>
<td>ACAH</td>
<td>6 s</td>
<td>Desired</td>
<td>2</td>
<td>“minor corrections”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“some minor long. compensation was needed”</td>
</tr>
<tr>
<td>28</td>
<td>Steve</td>
<td>1</td>
<td>ACAH</td>
<td>7 s</td>
<td>Desired</td>
<td>2</td>
<td>“controls are very quiet”</td>
</tr>
<tr>
<td>29</td>
<td>Steve</td>
<td>2</td>
<td>ACAH</td>
<td>6 s</td>
<td>Desired</td>
<td>4</td>
<td>“controls are still very quiet”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“a lot more lateral activity, a little more long.”</td>
</tr>
<tr>
<td>30</td>
<td>Steve</td>
<td>2</td>
<td>ACAH</td>
<td>7 s</td>
<td>Desired</td>
<td>4</td>
<td>“still much more lateral than long.”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>tailwheel touch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“found the lateral tendency annoying”</td>
</tr>
<tr>
<td>31</td>
<td>Steve</td>
<td>3</td>
<td>ACAH</td>
<td>5 s</td>
<td>Desired</td>
<td>4</td>
<td>“chasing lateral a bit on approach”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“lateral axis is more active with roll motion of the ship forcing me to</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>chase the deck a bit side to side”</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>“not perceiving difficult between case 2 and case 3”</td>
</tr>
<tr>
<td>33</td>
<td>Steve</td>
<td>3</td>
<td>ACAH</td>
<td>5 s</td>
<td>Desired</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Steve</td>
<td>4</td>
<td>ACAH</td>
<td>6 s</td>
<td>Inadequate</td>
<td>7</td>
<td>had contact with tail touching twice</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“small long. inputs”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“the tail wheel is pestering me”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“I failed in performance”</td>
</tr>
<tr>
<td>35</td>
<td>Steve</td>
<td>4</td>
<td>ACAH</td>
<td>7 s</td>
<td>Desired</td>
<td>5</td>
<td>tail touch</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“that was ugly”</td>
</tr>
<tr>
<td>36</td>
<td>Steve</td>
<td>4</td>
<td>ACAH</td>
<td>/</td>
<td>Desired</td>
<td>5</td>
<td>“ship was rolling pretty good”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Desired</td>
<td></td>
<td></td>
<td>“turning up the gain seemed to improve my performance”</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>“lateral workload was pretty high”</td>
</tr>
</tbody>
</table>
### B.2.3 Acceleration Command Velocity Hold

#### Table B.7. Notes for Approaches with ACVH

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
</table>
| 37  | Steve | 1    | ACVH | 8 s / | Desired | 2   | “controls are quiet”
|     |       |      |      | Desired|         |     | “impressive approach” |
| 38  | Steve | 1    | ACVH | 5 s / | Desired | 1   | “minor lateral corrections on approach”
|     |       |      |      | Desired|         |     | “excellent in those conditions” |
|     |       |      |      |        |         |     |                                |
|     |       |      |      |        |         | 4   | “I was fighting the system so much on the landing”
|     |       |      |      |        |         |     | lost hover again due to tail wheel |
|     |       |      |      |        |         |     | go around with second attempt of landing |
|     |       |      |      |        |         |     |                                |
| 39  | Steve | 2    | ACVH | 7 s / | Desired | 4   | “lateral drift on approach”
|     |       |      |      | Desired|         |     | “not sure if I like lateral velocity hold” |
|     |       |      |      |        |         |     | “I stopped trying to fight the system and put input in to slow down”
|     |       |      |      |        |         |     | “I timed the lateral velocity and collective by letting the aircraft drift and it worked”
|     |       |      |      |        |         |     | “I had a tough time getting zero velocity.”
|     |       |      |      |        |         |     |                                |
| 40  | Steve | 2    | ACVH | 4 s / | Desired | 4   | Tail wheel touch |
|     |       |      |      | Desired|         |     | “I’m setting up the drift now in order to get the helicopter to stay in the desired range and then timing the collective” |
|     |       |      |      |        |         | 4   | “workload wasn’t bad” |
| 41  | Steve | 3    | ACVH | /     | Desired | 4   | “bounced out of desired range box which was annoying”
|     |       |      |      | Desired|         |     | “response still feels too slow because when I get more active on gain then it feels like I get out of phase” |
| 42  | Steve | 3    | ACVH | 7 s / | Desired | 4   | “man that was a jump when I drifted to the right”
|     |       |      |      | Desired|         |     | lateral activity, bounced in and out of the box overshooting |
| 43  | Steve | 4    | ACVH | 6 s / | Desired | Adequate 4 | “turbulence was a major factor consistent overshoot again”
|     |       |      |      | Desired|         |     | “the controls don’t feel like they are directly placing the helicopter to a fixed position” |
| 44  | Steve | 4    | ACVH | 6 s / | Desired | Adequate 5 | “easily controllable” |
| 45  | Bob   | 1    | ACVH | 7 s / | Desired | 2   | “simple, easy landing”
|     |       |      |      | Desired|         |     | “Only if landing on the ship everytime could be like that everytime” |
| 46  | Bob   | 1    | ACVH | 6 s / | Desired | 1   | “turbulence was a major factor consistent overshoot again”
|     |       |      |      | Desired|         |     | “the controls don’t feel like they are directly placing the helicopter to a fixed position” |
| 47  | Bob   | 2    | ACVH | 6 s / | Desired | Adequate 5 | “annoyed” tail wheel touched twice and forced to go around twice to land “chasing the ship quite a bit” |
| 48  | Bob   | 2    | ACVH | 7 s / | Desired | 4   | tim of hover was considerable “mildly annoying again” |
| 49  | Bob   | 3    | ACVH | 7 s / | Desired | 3   | “easily controllable” |
| 50  | Bob   | 3    | ACVH | 8 s / | Desired | 2   | “seems like with this ship motion is less of a factor than airwake” |
| 51  | Bob   | 4    | ACVH | 6 s / | Desired | 4   | “annoyed” tail wheel touched twice and forced to go around twice to land “chasing the ship quite a bit” |
| 52  | Bob   | 4    | ACVH | 7 s / | Desired | 4   | “mildly annoying again” |
### B.2.4 ACVH/TRC Automatic Transition

#### Table B.8. Notes for Approaches with ACVH/TRC Automatic Transition

<table>
<thead>
<tr>
<th>Run</th>
<th>Pilot</th>
<th>Case</th>
<th>Mode</th>
<th>Flare</th>
<th>Landing</th>
<th>HQR</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>53</td>
<td>Bob</td>
<td>1</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>one minor overshoot</td>
</tr>
<tr>
<td>54</td>
<td>Bob</td>
<td>1</td>
<td>Auto</td>
<td>8 s / Desired</td>
<td>Desired</td>
<td>1</td>
<td>“very desirable with a slight overshoot”</td>
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<tr>
<td>55</td>
<td>Bob</td>
<td>2</td>
<td>Auto</td>
<td>8 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>“cyclic inputs are required to maintain position over the deck due to turbulence”</td>
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<tr>
<td>56</td>
<td>Bob</td>
<td>2</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>“better than last one”</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>“I utilized the heads down display that time to maintain desired position range which likely lead to the falling leaf observation”</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>“A couple minor overshoots, but nothing bad”</td>
</tr>
<tr>
<td>57</td>
<td>Bob</td>
<td>3</td>
<td>Auto</td>
<td>8 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>“A couple corrections near the ship”</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>“minor deficiencies with respect to finding position”</td>
</tr>
<tr>
<td>58</td>
<td>Bob</td>
<td>3</td>
<td>Auto</td>
<td>8 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>Tail touched</td>
</tr>
<tr>
<td>59</td>
<td>Bob</td>
<td>4</td>
<td>Auto</td>
<td>8 s / Desired</td>
<td>Adequate</td>
<td>5</td>
<td>outside of desired range otherwise would have been a 3</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>“ship moved out underneath me when I was just about to land”</td>
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<tr>
<td>60</td>
<td>Bob</td>
<td>4</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>“that one worked out pretty well”</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>“much easier compared to other control modes under case 4”</td>
</tr>
<tr>
<td>61</td>
<td>Bob</td>
<td>4</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“one small overshoot with little input on the controls”</td>
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<tr>
<td>62</td>
<td>Steve</td>
<td>1</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>1</td>
<td>“minor correction after slightly overshooting in long.”</td>
</tr>
<tr>
<td>63</td>
<td>Steve</td>
<td>1</td>
<td>Auto</td>
<td>8 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“minor correction after slightly overshooting in long.”</td>
</tr>
<tr>
<td>64</td>
<td>Steve</td>
<td>2</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>3</td>
<td>not extensive activity</td>
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<td></td>
<td></td>
<td></td>
<td>“nice system, but still needs my help”</td>
</tr>
<tr>
<td>65</td>
<td>Steve</td>
<td>2</td>
<td>Auto</td>
<td>8 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“nothing wrong with that one”</td>
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<td></td>
<td></td>
<td></td>
<td>“nothing objectionable”</td>
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<td>position keeping compensation</td>
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<tr>
<td>66</td>
<td>Steve</td>
<td>3</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“collective becomes more active due to deck motion”</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>“very little activity in cyclic”</td>
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<td></td>
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<td></td>
<td></td>
<td>“let lateral mostly take care of itself”</td>
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<td></td>
<td></td>
<td></td>
<td>“had to put in control for the deck height”</td>
</tr>
<tr>
<td>67</td>
<td>Steve</td>
<td>3</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“minor long overshoot”</td>
</tr>
<tr>
<td>68</td>
<td>Steve</td>
<td>4</td>
<td>Auto</td>
<td>7 s / Desired</td>
<td>Desired</td>
<td>4</td>
<td>“chased a little bit”</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
<td>“not significant workload for station keeping”</td>
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<td>“more patience would have helped”</td>
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<tr>
<td>69</td>
<td>Steve</td>
<td>4</td>
<td>Auto</td>
<td>6 s / Desired</td>
<td>Desired</td>
<td>2</td>
<td>“that was just patience that time”</td>
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<td>“workload wasn’t more than last time”</td>
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<td></td>
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<td></td>
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<td></td>
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<td>“still had the tendency to overshoot a bit”</td>
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<td></td>
<td></td>
<td>a snap-to-grid algorithm is the only way to reach to the higher rating where no workload is required and wait for the system to take over</td>
</tr>
</tbody>
</table>
References


