Analysis, Design, & Optimization of the Helicopter Active Control Technology (HACT) Flight Control System

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ABSTRACT

This paper outlines the analysis, design, and optimization of the Helicopter Active Control Technology (HACT) Flight Control System (HFCS). The HACT program's use of a high fidelity aircraft model and advanced design tools and methods is reviewed. The Control Designer's Unified Interface (CONDUIT®) environment is utilized as the keystone of the HACT Program's advanced design methodology task. The HACT CONDUIT model of the HFCS, the linear aircraft model, and the analytical metrics and handling qualities specifications are explained. The airframe model is a high fidelity linear representation of the AH-64D generated using Boeing's Blade Element FLYRT (BEFLYRT) modeling and simulation tool. The linearization process and verification of the model are discussed. The HACT analytical handling qualities metrics are used in CONDUIT to evaluate the HFCS and to optimize the control law parameters. The current results of the analysis and optimization are presented.

NOTATION

ASE	Aeroservoelastic
CONDUIT®	Control Designer's Unified Interface
FCS	Flight Control System
HACT	Helicopter Active Control Technology
HFCS	HACT Flight Control System
K_I	Integrated attitude feedback gain
K_p	Roll rate feedback gain
K_q	Pitch rate feedback gain
K_r	Yaw rate feedback gain
K_θ	Pitch attitude feedback gain
K_φ	Roll attitude feedback gain
K_ψ	Yaw attitude feedback gain
RCAH	Rate-Command, Attitude-Hold
β	Flapping angle (rad)
β_0	Collective flapping angle / coning (rad)
β_{1c}	Longitudinal cyclic flap angle (rad)
β_{1s}	Lateral cyclic flap angle (rad)
ζ	Modal damping (unitless)
φ	Main rotor azimuth angle (rad)
Ω	Main rotor speed (rad/s)
ω	Modal frequency (rad/s)
ω_d	Desired bandwidth (rad/s)

Presented at the American Helicopter Society 58th Annual Forum, Montréal, Canada, June 11-13, 2002.

INTRODUCTION

The Helicopter Active Control Technology (HACT) program is a research and development project that was developed and is being run by the U.S. Army Aviation and Missile Command (AMCOM). The U.S. Army Aviation Applied Technology Directorate (AATD) manages HACT from Fort Eustis, Virginia with support by the U.S. Army Aeroflightdynamics Directorate (AFDD) in Moffett Field, California. Phase 1 of the HACT program is reported on in the Phase 1 final reports of Sikorsky Aircraft, Bell Helicopter Textron, and McDonnell Douglas Helicopter Systems [1,2,3]. McDonnell Douglas Helicopter Systems (MDHS), an indirect subsidiary of The Boeing Company, is the main contractor for Phase 2 of the HACT. An overview of the HACT program was presented by the HACT contractor and customer in a joint paper for the American Helicopter Society International (AHS) 57th Forum in [4].

The HACT program has several goals and objectives designed to demonstrate various aspects of next generation flight control systems and their design [4]. This paper is primarily associated with the program objective to "determine the contribution that high fidelity modeling, simulation techniques, and design methods make to reduce flight test time." Specifically, the contributions of these design tools and methods are examined from the perspective of the linear model.

At the heart of any analysis is the issue of the fidelity of the modeling of the aircraft dynamics and all of the related control system components. The ability to accurately predict flight test performance and achieve optimized design parameters (gains, filters, etc) that do not require extensive and costly flight test tuning is critically dependent on a simulation model that accurately represents the frequency-response characteristics as well as key nonlinearities. In the case of this HACT program example, the central element of the analysis model is a high-order linearized state-space representation of the AH-64D Apache Longbow airframe. This state-space model is obtained via numerical perturbation of a high-fidelity, nonlinear model of the AH-64D in the modeling and simulation tool Blade Element FLYRT (BEFLYRT). The extraction of the HACT linearized airframe model from BEFLYRT and an analysis of its fidelity are discussed in this paper.

The HACT analysis is performed in the Control Designer's Unified Interface (CONDUIT®) Software Environment. CONDUIT is a sophisticated software application that is utilized by a flight control system (FCS) designer to analyze an aircraft's FCS and perform multi-objective function optimization. It was developed by AFDD in conjunction with NASA, the University of Maryland, Raytheon Systems Company, and California Polytechnic State University, San Luis Obispo, and is described in detail in [5,6,7]. The HACT Flight Control System (HFCS) is modeled for CONDUIT analysis in The MathWorks' SIMULINK® and MATLAB® software applications, which are the standard CONDUIT modeling interfaces. It should be noted that the SIMULINK representation of the HFCS includes important nonlinear FCS elements (such as actuator rate and position limiting) in addition to the linear BEFLYRT-derived model of the AH-64D airframe.

The HACT program analytical metrics are handling qualities and stability metrics primarily based on the ADS-33 standard [8]. The HFCS model is evaluated with respect to these metrics via specification libraries built into CONDUIT. CONDUIT also uses this set of user-selected specifications as constraints and objects for the optimization of control system parameters such as feedback gains.

Another HACT objective is to "demonstrate rotor state sensing as part of a flight envelope limit measurement system." To this end, the demonstrator aircraft is being equipped with rotor state sensors. One of the ways that the HFCS uses the feedback is through an inner-loop flapping regulator to improve aircraft control and handling qualities. The HACT analytical model includes this feedback.

METHODOLOGY

MATLAB, SIMULINK, and CONDUIT have been used throughout HACT Phase 1 and Phase 2 to evaluate updates to the linear aircraft model, evaluate aeroservoelastic stability, design flapping controller filtering, evaluate effects of control law update changes, and evaluate and optimize stability and handling qualities characteristics. This section discusses how the HACT program has used its advanced spec-compliance and optimization tools to evaluate and optimize the HFCS.

One of the most critical inputs to the HACT analytical evaluation and optimization process is the linear aircraft model. Therefore the first step of the HACT analysis was the creation of the plant – a linear AH-64D bare airframe model. The linear AH-64D model is created by numerical linearization of the full nonlinear BEFLYRT simulator model. The HACT program has generated linear models of the aircraft in hover, 40 knot, 80 knot, 120 knot, and 160 knot forward-flight conditions. A section of this paper describes the linear modeling process and the validation of its output.

The HFCS design work is similar to many other flight control system (FCS) design efforts in that it did not start from the proverbial "blank sheet of paper." Rather, the HFCS was built by intelligently including lessons learned from previous design and flight experience with the AH-64 airframe and the VITAL and RAH-66 Comanche control systems [4, 9]. The VITAL control system is the full authority, digital, triply redundant Vehicle Management System (VMS) from the VMS Integrated Technology for Affordable Life Cycle Costs (VITAL) program. The VITAL control laws are based on the previous Apache digital FCS experience of the Rotorcraft Pilot's Associate (RPA) program [9,10]. The HACT Program was able to set its initial feedback gains to be equivalent to the VITAL inner-loop gains, which produced stable responses in the RPA flight test. During the early design process, the nominal HFCS gains were modified from strict VITAL equivalence to levels more suitable to the architectural control law differences in the HFCS. The gain changes were motivated by piloted simulation experience, and CONDUIT was used to show that gain changes did not degrade stability and handling qualities of the HFCS, i.e., no spec that predicted Level 1 compliance was driven to Level 2.

The HACT linear AH-64D model underwent a major enhancement during the later stages of the HFCS Detailed Design Phase, only a few weeks before a scheduled piloted flight simulator evaluation. CONDUIT was used to rapidly evaluate the stability and handling qualities of the HFCS with the new hover, 40 knot, 80 knot, 120 knot, and 160 knot airspeed airframe models. The rapid CONDUIT evaluation indicated that there was one immediately required reduction, and that gain optimization was required to ensure full stability and handling qualities specification compliance.

The starting point for the optimization was the HFCS and the validated hover AH-64D model. This paper will refer to the HFCS feedback gains at the time of the BEFLYRT model enhancement as the nominal HFCS gains. The optimization process involves several parts that often occur at least partially in parallel. Their basic outline is:

1. Show the extent to which the existing CONDUIT model (i.e., the Simulink FCS model and the linear airframe model) can achieve optimized results. In this step, the CONDUIT optimizer is tested, and the constraints that influenced the solution are examined. If necessary, the constraints are adjusted, and the optimizer test is repeated. This step helps to ensure that CONDUIT reaches an optimal, properly constrained solution.

2. Verify that the analytical FCS model represents the full FCS model with adequate fidelity. This step is the comparison of the two models through time- and frequency-domain responses. Instances of insufficient fidelity are addressed by adding unmodeled filters, delays, and feedbacks.

3. Compare CONDUIT's optimal solution to real-time, pilot-in-the-loop simulation. In this step, the pilot flies the simulator at both the nominal and optimal gain settings. He compares gains and explains in detail any deficiencies in the optimized gains. A relative deficiency in the optimized gains indicates either that (a) the optimization problem lacked an important constraint, or (b) the gain optimization addressed a constraint that the manned simulator did not adequately model.

4. If necessary, modify the set of constraints in order to address any discrepancies between the simulation and analytical models. In this step, existing CONDUIT specs are modified and new specs are added. The optimizer is again run and produces a new optimal set of gains. Step 3 is repeated.

At the writing of this paper, the HACT optimization work is ongoing.

AIRCRAFT MODEL

Modern control design has evolved powerful tools to evaluate the characteristics of systems containing complex physics and equally complex control laws. These systems are modeled using well-known techniques and methods, but there is some amount of invention and development required to address unique situations and our growing understanding of the physics involved. This is especially true for helicopters, which continue to provide challenges to improve handling qualities, and the math models that describe them. When the HACT program was started, the decision was made to use the current Apache math model and upgrade the code as required for HACT. These upgrades included additional model details and the ability to extract high order linear models.

The simulation code (BEFLYRT) used for HACT, has been developed in parallel with the Apache helicopter. BEFLYRT or FLYRT has been a part of every Apache improvement/growth program since the early years of Apache development. Most recently the model has been incorporated in the Longbow Crew Trainer (LCT) and used in evaluation of the WAH-64 Longbow Apache. The LCT is a high fidelity training simulator recently fielded by the Army that provides a mobile simulator to crews that are away from normal simulator facilities. The WAH-64 Longbow is the UK version of the Longbow Apache.

The pre-HACT version of FLYRT had been intended primarily for manned simulation and the code was structured accordingly. This meant that many of the model terms such as tail rotor drivetrain dynamics, fuselage elasticity, and rotor inflow either did not exist or were modeled at the lowest order required. The main rotor inflow models available included the traditional Pitt-Peters three state model, but with no off-axis correction [12,13]. Thus, the pitch-roll cross-coupling fidelity of the model was poor. These simplifications, while appropriate for manned evaluation where the pilot is not going to notice their effect on handling qualities, did not permit the full evaluation of high bandwidth control laws. As part of the 'carefree' philosophy for HACT, the control system is required to monitor many of the details that have not normally been required.

Upgrading the BEFLYRT code included adding the following degrees of freedom:

1. Elastic fuselage (including mast)
2. Tail rotor drivetrain dynamics
3. Tail rotor inflow lag
4. Main rotor wake curvature lags

To upgrade the fuselage model, a normal mode representation was extracted from the full NASTRAN model of the Apache fuselage. This model contained node points for all the main components including rotor hubs, gearboxes, wings, and tail. In addition, the locations for the normal aircraft rate/acceleration sensors and palletized flight test instruments were included. Each node was represented by three rotations and three translations. The modes used for the HACT model were limited to those that have frequencies of 10Hz or less. An exaggerated view of the resulting fuselage deflections with the modes used is shown in Figure 1.

The time constant for the tail rotor inflow had traditionally been ignored. This has been acceptable for the manned simulations but for HACT the model required an explicit time constant to permit extracting derivatives. A time constant of 0.04 seconds was used for the tail rotor inflow.

Upgrading the main rotor inflow model involved adding the (Kr) correction for angular wake distortion [12] and tuning the value of the correction for speed to match the frequency response flight test data over the speed envelope. When the wake distortion was added as an instantaneous correction, the model showed a tendency for instability. This was solved, as suggest by Curtiss, by including a 0.44 sec lag on the wake correction – which accounts for the finite time needed for the distortion to build up [13]. Including the lag in the angular distortion correction eliminated the instability and provided the off-axis correction required.

To provide the linear models required that the model be perturbed in the fixed axis, the perturbations translated into the rotating frame, and finally the various accelerations be extracted and transformed back into the fixed frame. This was done using multiblade coordinates. Initially the model was trimmed for a flight condition, then the blade displacements and velocities were saved at each azimuth location. A perturbation of the required state was then defined in the non-rotating frame and translated into the rotating frame using the following equations for flapping:

$$\beta = \beta_0 - \beta_{1c} * \cos(\varphi) - \beta_{1s} * \sin(\varphi)$$

$$\dot{\beta} = \dot{\beta}_0 - (\dot{\beta}_{1c} + \Omega * \beta_{1s}) * \cos(\varphi) - (\dot{\beta}_{1s} - \Omega * \beta_{1c}) * \sin(\varphi)$$

Similar equations are used for lag degrees of freedom. The translated perturbation was added to the saved blade positions and velocities, and then the entire model interrogated for the resulting change in accelerations in the remaining unperturbed states. These accelerations, when divided by the initial perturbation, became the required derivatives. The high order rotor degrees of freedom included position and velocity for coning and cyclic flapping. The lag degree of freedoms had the similar states for a total of twelve rotor degrees of freedom. The remaining linear model derivatives were evaluated with the rotor held at its trim conditions.

Validation of the math models used frequency response results from previous flight test programs. BEFLYRT was chirped using a frequency sweep generator developed at Ames Research Center in conjunction with a rotor wind tunnel test project [14]. The sweep generator includes provision for optimal levels of on-axis and off-axis excitation. The off-axis excitation was uncorrelated noise that significantly improved the ability of the following analysis to remove the effects of off-axis inputs required to stabilize the model. The flight test data and BEFLYRT model results were analyzed using the frequency response tool CIFER® [15]. CIFER was developed by the Army AFDD and NASA at Ames Research Center and has been used in numerous programs to evaluate aircraft dynamics in support of advanced control projects. The results from CIFER for BEFLYRT and flight test were then compared to the linear model frequency responses; the results from the lateral axis are shown in Figure 2.

HACT ANALYTICAL MODEL

The HACT analytical model, as setup in CONDUIT, is comprised of three principle components. The key element is a detailed SIMULINK block diagram model of the HFCS dynamic elements (e.g., airframe, actuators, filters, gains, etc), including important delays and nonlinearities. The second element is the selection of CONDUIT specifications, including desired handling-qualities, stability metrics, and ultimate performance goals. Finally the user defines an initialization file, which contains additional digital data such as input command signal definitions, sample rates, and state-space model matrices.

Control Laws And System Model:

The HFCS SIMULINK model is shown in Figure 3. Its principle parts are the HFCS control laws – including software mixing and rotor state control laws – the actuators, the airframe model, and applicable feedbacks and system delays.

The HACT control laws employ a model-following architecture with command model, plant canceller, feed-forward compensation, and feedback compensation components. At its basic level, the HFCS contains a rate-command, attitude-hold (RCAH) control law structure and feeds back sensed pitch, roll, and yaw rates. Higher levels of augmentation are built around the RCAH core; this paper will therefore focus on the CONDUIT analysis of the HFCS RCAH core.

The command model translates the pilot's stick input in a given axis into the desired aircraft rate response. The commanded aircraft response is calculated in the command model based on the desired bandwidth, which is an important controller design parameter.

The feed-forward path uses the plant canceller to convert the desired rate response signal into the command needed to produce that response. The plant canceller contains an inverted, low-order model of the aircraft's dynamics. Its parameters are derived from BEFLYRT's description of the aircraft's dynamics. The theory is that the well-known dynamics of the airframe can be cancelled so that the airplane's response closely matches that commanded by the pilot. Therefore, the feed-forward path is most closely associated with the airplane's command response.

The feedback path, on the other hand, is primarily designed for stability, disturbance rejection, and control system robustness. The feedback path takes the desired rate signal and first applies a "command model delay" to account for system delays and dynamics not modeled by plant canceller. An attitude command is calculated, and then the desired rate and attitude responses are compared to the attitude and rate feedback signals. The rate and attitude errors are passed through a network that contains rate, attitude, and integrated attitude gains, which are all designated as design parameters within the CONDUIT problem.

The feed-forward and feedback compensation signals are summed in each of the pitch, roll, yaw, and vertical axes and then passed to the mixing matrix. The mixing matrix is a four-by-four matrix that transforms the uncoupled control law commands into the combination of collective, cyclic, and tail rotor blade-angle commands needed to produce decoupled aircraft responses.

As seen in Figure 3, the HFCS's rotor state feedback control laws are architecturally situated between the mixing matrix and the actuators. The HFCS inner-loop flapping controller regulates longitudinal and lateral cyclic flapping via feedback control of those states.

The longitudinal flapping controller compares measured longitudinal cyclic flapping with a commanded longitudinal cyclic flapping signal. In the HFCS control laws, the commanded flapping signal is a function based on the longitudinal cyclic pitch command, pitch rate, and longitudinal velocity. The neural net specifically avoids the consideration of any off-axis (lateral) components that would in reality affect longitudinal flapping. In this way, the controller works to reduce off-axis coupling while maintaining the natural effects that enhance the rotor's on-axis stability. Likewise, the lateral flapping controller's neural net command model is driven by the desired lateral cyclic pitch signal and augmented with natural on-axis contributions to lateral flapping such as roll rate and lateral velocity.

Many of the higher-level, outer-loop control system advances of the HFCS are not detailed here, but are discussed in [9] and [11]. Many of these functions are integrally tied to the model-following character of the control laws. For example, the calculation of some tactile cues relies on the ability of a particular axis's command model to predict the actual response.

The HACT analytical model is not restricted to linear elements. It also includes critical nonlinearities such as actuator rate and saturation limits and internal control law limits. CONDUIT evaluates the linear response of the system with frequency-domain criteria, while the effect of the nonlinearities are captured in CONDUIT's time-domain simulations.

HACT CONDUIT® Environment:

The HACT CONDUIT environment uses ADS-33E handling qualities requirements and MIL-F-9490 stability requirements to evaluate the HFCS system performance. The model is assessed with respect to these requirements in an automated process facilitated by the CONDUIT software. CONDUIT includes specification, or "spec," libraries, from which an engineer can select evaluation and optimization criteria. The libraries include selectable criteria from ADS-33E (rotary wing), MIL-F-9490 (generic flight control), MIL-F-1797 (fixed-wing), MIF-F-83300 (V/STOL), as well as many traditional control system design metrics (e.g., rise time, settling time, overshoot, actuator RMS, eigenvalue locations, etc). Each CONDUIT spec contains pre-coded (MATLAB m-file) functions that calculate the relevant data from the SIMULINK/MATLAB model (such as bandwidth) and display the results in a standard graphical format (such as an ADS-33 bandwidth/phase-delay plot).

All the spec data are categorized in an ADS-33-motivated format, with an implicit connection to the Level 1-2-3 Cooper-Harper scale. Level 1 indicates that the system is "satisfactory without improvement," Level 2 suggests "adequate performance attainable with a tolerable pilot workload," and Level 3 implies "deficiencies require improvement" [16]. ADS-33 requirements were originally defined to correlate to the Cooper-Harper scale; other requirements are nominally defined in CONDUIT so that Level 1 means that the system has successfully met the requirement. The Level 2–Level 3 (L2/L3) boundary is set relatively arbitrarily. In some cases, the L2/L3 boundary is effectively coincident with the L1/L2 boundary, thus removing the Level 2 region. In other cases, an artificial L2/L3 boundary is defined such that a nontrivial Level 2 region is created. The artificial Level 2 region is necessary in some specs because the width of the Level 2 region is used to normalize the weights of the specs for the optimization process [17]. The Level 1, 2, 3 boundaries are stored as splines that can be adjusted by the user as part of the optimization. Finally a "design margin" can be selected that ensures a specified level of overdesign into the Level 1 region (typically 5% of the width of the Level 2 region).

Figure 4 displays the graphical representation of these metrics. The colors (shades of gray) indicate the requirement level: blue (dark gray) is Level 1, magenta (light gray) is Level 2, and red (medium gray) is Level 3. The data points on the specs show how the system – in this case, the pre-optimization "nominal" system – measures relative to the selected spec requirements. The data in this figure will be discussed in the Results section of this paper. A key aspect of CONDUIT is that each spec also presents a series of supporting plots to help the users understand how a particular metric was obtained. So for example, the bandwidth/phase delay spec will also show all the relevant Bode plots and calculations.

Each spec can be classified in CONDUIT as a "hard," "soft," "objective," or "check only" constraint. These classifications define the way in which CONDUIT uses each spec in the optimization process. As a general description, the CONDUIT optimization procedure works to automatically vary user-specified control system parameters in order to obtain better performance against the user-specified metrics. The optimization occurs in three phases. In Phase 1, CONDUIT works to ensure all "hard" constraints are Level 1 – at the expense of performance in all other areas. These are typically eigenvalue stability and stability margin requirements. Once the hard constraints are all Level 1, the system proceeds to Phase 2, where CONDUIT works to drive all "soft" and "objective" constraints to Level 1 (without moving any of the hard constraints out of Level 1 compliance). All handling qualities requirements are generally specified as "soft" constraints. Finally, if the system is able to achieve full Level 1 spec compliance, CONDUIT enters Phase 3, where it works to optimize all "objective" specs. The objective specs are driven as far into the Level 1 region as possible – i.e., until one of the hard or soft specs reaches an L1/L2 boundary, or until a minimum objective is reached. Typical objectives include actuator RMS activity, crossover frequency, or short-term damping ratio. Finally, as the name indicates, a "check-only" spec is ignored by the optimizer; it is only included so that the data can be viewed by the engineer during the CONDUIT analysis and optimization process. The reader should refer to [17] for a more detailed discussion of CONDUIT and its optimization process.

The following list details the analytical metrics – specs – used for this HACT CONDUIT model.

Hard Constraints:

1. Pitch, Roll, and Yaw Low Frequency Gain and Phase Margins (MIL-F-9490).
2. Robust Stability (measures the Nichols Chart-based avoidance of the 0dB gain, -180° phase point, GARTEUR).
3. Eigenvalue from the Linearization of the Closed Loop System – are required to have positive real parts.

Soft Constraints:

1. Bandwidth vs. Phase Delay for Pitch, Roll, & Yaw Control Inputs (Target Acquisition and Tracking Requirements, ADS-33E).
2. Bandwidth vs. Phase Delay for Pitch, Roll, & Yaw Disturbance Inputs (Target Acquisition and Tracking Requirements, ADS-33E).
3. Mid-Term Time Domain Damping Ratio (ADS-33E).
4. Damping Ratio of the Short-Term Eigenvalues (ADS-33E).
5. Open Loop Crossover Frequencies for Pitch, Roll, and Yaw Axes (Generic requirement defined by Ames Research Center).
6. Actuator Rate and Authority Saturation in Pitch, Roll, and Yaw Axes (defined by Ames Research Center, used to prevent relative increases in actuator saturation).
7. Pitch-Roll Control Coupling (time-domain-based, ADS-33E).
8. Pitch-Roll Control Coupling (frequency-domain-based, ADS-33E).
9. Maximum Achievable Pitch, Roll, and Yaw Rates (Aggressive Maneuvering Requirements, ADS-33E).
10. Normalized Attitude Hold (disturbance rejection capability requirement for pitch, roll, and yaw axes, ADS-33E).

Objective Function:

1. Minimize actuator RMS activity for Pitch, Roll, and Yaw (defined by Ames Research Center, used to reduce actuator usage).
2. Maximize Damping Ratio of the Short-Term Eigenvalues (ADS-33E).

Check-Only Specs:

1. Attitude Quickness in Pitch, Roll, and Yaw (Target Acquisition and Tracking Requirements, ADS-33E). These were specified as check-only because, to a large extent, they are characteristics of the airframe maneuver capability and cannot be improved via the control law gains.

The HACT block diagram parameters selected for optimization using CONDUIT were:

1. Rate feedback gains for pitch (K_q), roll (K_p), and yaw (K_r).
2. Attitude feedback gains for pitch (K_θ), roll (K_φ), and yaw (K_ψ).
3. Integrated-Attitude feedback gains for pitch ($K_{I\theta}$), roll ($K_{I\varphi}$), and yaw ($K_{I\psi}$).
4. Desired bandwidth (ω_d) for pitch, roll, and yaw command models.

RESULTS

This section presents and discusses analytical data from the HACT Program's nominal HFCS evaluation, aeroservoelastic stability analysis, and initial optimization results.

Evaluation of nominal HFCS:

An advantage of the CONDUIT software is its ability to enable a rapid analytical evaluation of a new FCS configuration or updated aircraft model. This capability enabled the HACT Program to quickly assess its nominal HFCS design with an updated aircraft model in time to support the scheduled start of a five-week pilot-in-the-loop simulation. The analysis indicated that some adjustments were necessary, but that optimization could occur in parallel with the piloted simulation evaluation.

The nominal HFCS hover case's evaluation against the analytical metrics is shown in Figure 4. The evaluation shows that the HFCS is in compliance with the majority of the analytical metrics. Specifically, the figure shows that the pitch, roll, and yaw disturbance bandwidths all greatly exceed the minimum ADS-33 requirements for Level 1. The pitch and roll control input bandwidths both meet their requirements, as do the maximum achievable pitch, roll, and yaw rates. The HFCS meets the frequency-based and time-based coupling requirements, the time-domain, peak-overshoot-based damping ratio requirement, and the disturbance response requirement.

The metrics that show the HFCS to be Level 2 are noted in Figure 4 with arrows. The yellow left-pointing arrows indicate areas where the HFCS can be improved by feedback gain optimization.

The yaw gain margin and the pitch phase margin are not compliant with MIL-F-9490, but they are both near the Level 1 boundary. Additionally, the GARTEUR robust stability spec indicates that gain optimization might produce a solution more robustly stable to a combined gain-phase variation.

The nominal system has closed-loop underdamped pitch/roll eigenvalues. These low/mid-frequency modes ([ζ=0.22, ω=0.5 rps]; [ζ =0.37, ω =2.9 rps]) are visible in the pitch and roll disturbance responses.

A natural part of the optimization process is to identify which metrics can be improved upon with gain tuning and which are more heavily influenced by other factors (e.g. aircraft design, system delay, etc.). The green right-pointing arrows indicate areas of HFCS/AH-64D performance that control law gains optimization cannot influence.

The yaw bandwidth is 2.58 rad/sec, which is Level 2 by ADS-33. Preliminary – and subsequent – optimization tests indicated that the yaw bandwidth would not be able to reach Level 1 due to the command model delay in the directional axis. It was therefore decided that the optimization would not attempt to improve the HFCS's yaw bandwidth. Instead, the Level 1 / Level 2 boundary was moved so that CONDUIT treated the nominal yaw bandwidth as acceptable and so that no decreases in bandwidth were permitted.

The pitch, roll, and yaw attitude quickness predict Level 2 handling qualities for aggressive tracking tasks. Again, optimization tests showed that gain optimization was not capable of driving the HFCS/AH-64D models to Level 1 compliance. Additionally, the nominal HFCS attitude quickness levels are consistent with reported attitude quickness flight test data for the AH-64A [18]. The attitude quickness specs were set to "check only" status for the optimization, i.e., the optimizer completely ignored their status. It should also be noted that there is good reason to think that the HFCS's use of an active sidestick will maximize the airframe's usable agility [9].

Aeroservoelastic Stability:

Using the HACT HFCS/AH-64D model and CONDUIT's built-in "Analysis Tools," the nominal HFCS configuration's ASE stability margins were evaluated. Figure 5, Figure 6, and Figure 7 show the HFCS frequency response. The blue horizontal bars represent frequencies above that of the lowest structural mode, i.e. the ASE stability range. MIL-F-9490 requires gain margins greater than 8 dB and phase margins greater than 60 degrees in the ASE frequency range. Figure 5, Figure 6, and Figure 7 show that the HFCS's open loop Bode plot gain is less than 8 dB throughout the ASE frequency range for the pitch, roll, and yaw axes. Therefore, the HFCS is predicted to have adequate ASE stability and be robust to any amount of variation in phase loss throughout the structural mode frequency range.

Hover Case Optimization:

The twelve control system gains were automatically tuned by CONDUIT to achieve Level 1 behavior for all the specs (CONDUIT's Phases 1 and 2). Then in Phase 3, CONDUIT optimized the final gains to achieve best performance as measured by the summed objective (actuator RMS, and short-term eigenvalue damping ratio). The automated progression of gains is shown in Figure 8, Figure 9, and Figure 10, and the change in optimized gains relative to the nominal values is presented in Table 1. The associate handling qualities results are summarized in Figure 11. Key changes to the control system performance compared to the nominal results are:

1. Solid Level 1 stability margins and robustness margins.

2. Reduced over-design in roll and yaw bandwidths.

3. Significant increase in short-term response eigenvalue damping ratios.

4. Reduced feedback loop crossover frequencies.

These optimized gains are expected to yield improved handling-qualities, stability, robustness, and disturbance rejections, with reduced actuator saturation. At the time of the writing of this paper, the optimized control laws gains were being readied for evaluation in the piloted simulation.

Table 1 CONDUIT® Optimization Results

Gain	Change in Optimized Gains Relative to Nominal values [%]
$\omega_{d\,(roll)}$	-3
$\omega_{d\,(pitch)}$	6
$\omega_{d\,(yaw)}$	-8
$K_{\varphi I}$	-78
$K_{\psi I}$	128
$K_{\theta I}$	-13
K_p	-42
K_φ	-21
K_ψ	-39
K_q	5
K_r	-56
K_θ	-28

CONCLUSIONS

1. The HACT linear aircraft model is a high fidelity representation of the AH-64D Apache Longbow nonlinear simulation and closely matches flight test data.

2. The CONDUIT environment efficiently provides the HACT program with valuable handling qualities predictions.

3. The HFCS analytical model predicts adequate and robust aeroservoelastic stability in the roll, pitch, and yaw axes.

4. The optimized gain set achieved by CONDUIT demonstrates a significant improvement in HFCS handling qualities, stability robustness, and disturbance rejection, with a associated reduction in overdesign compared to the nominal HFCS gains.

ACKNOWLEDGMENTS

The authors are grateful for the advice and assistance of David Miller, Pieter Einthoven, James Keller, Bruce Kothmann, and Sean Swei.

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FIGURES

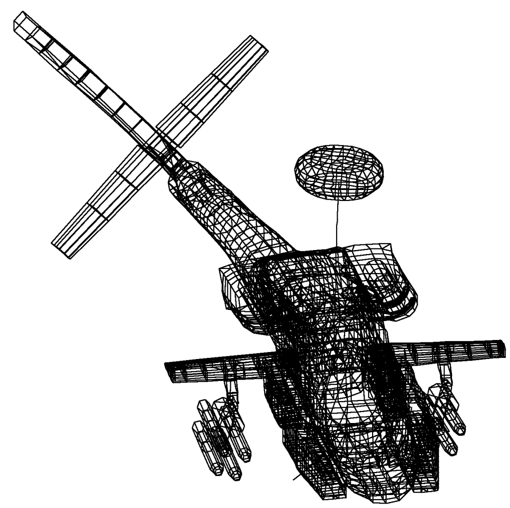

Figure 1 Exaggerated Motion of 4.5 Hz Lateral Bending/Tailboom Torsional Mode

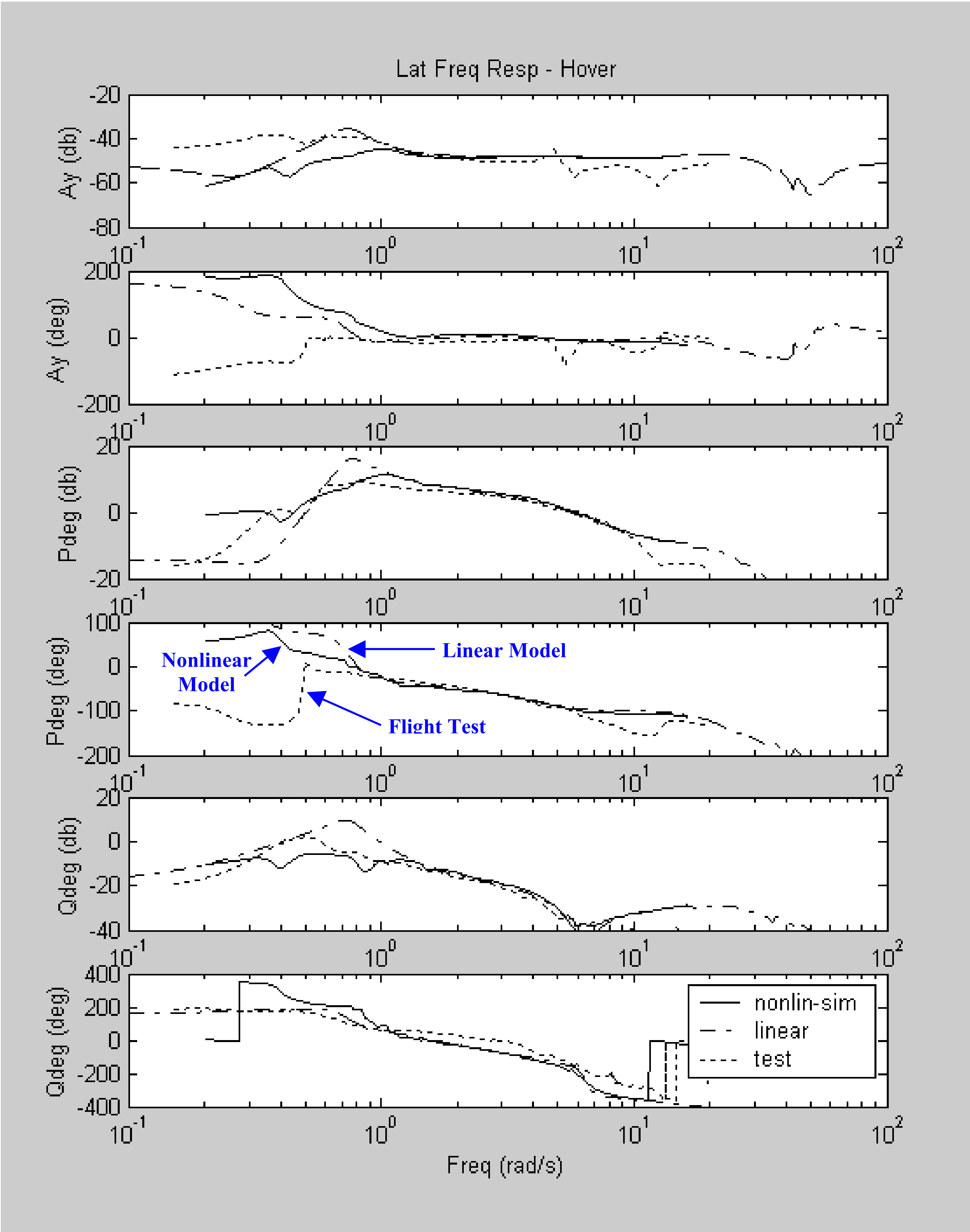

Figure 2 Model Verification and Validation Data: Lateral Acceleration, Roll Rate, and Pitch Rate Responses to Lateral Input

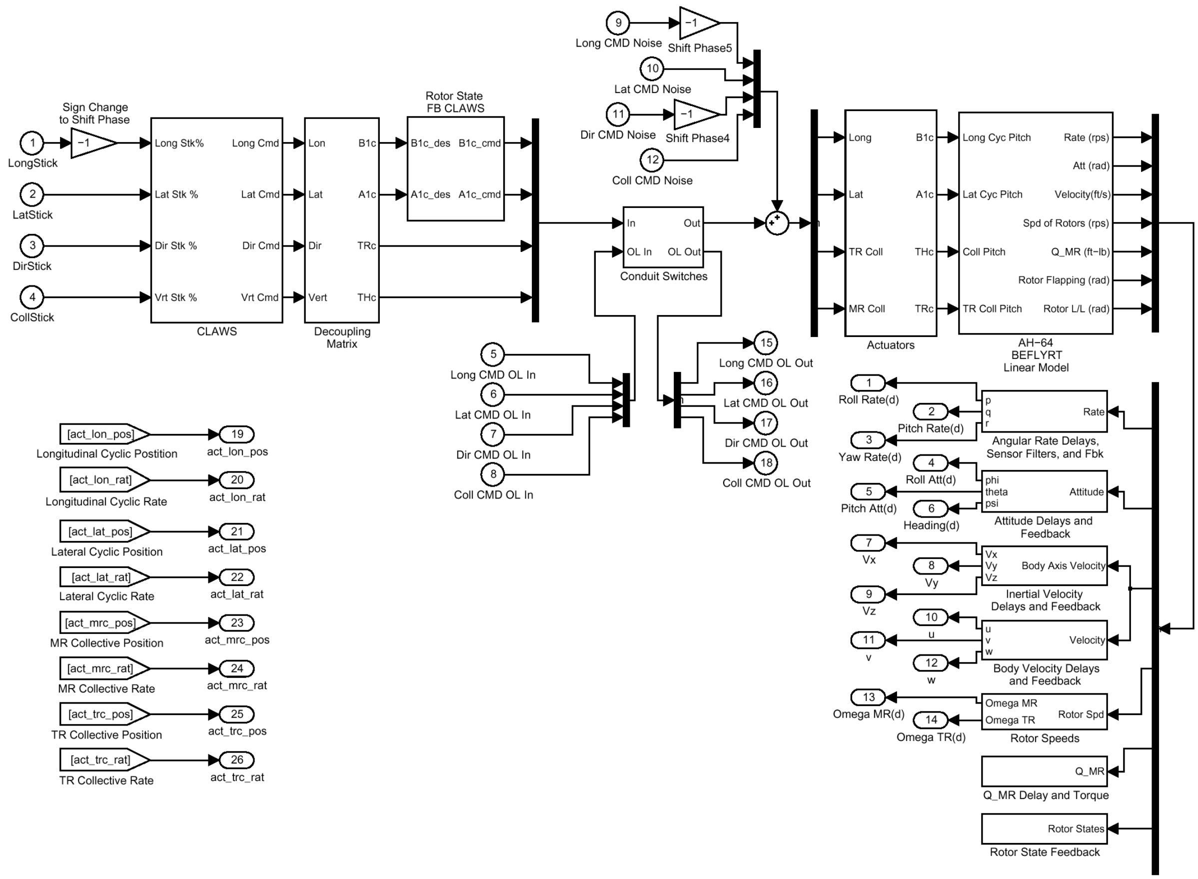

Figure 3 HFCS Analytical Model Block Diagram

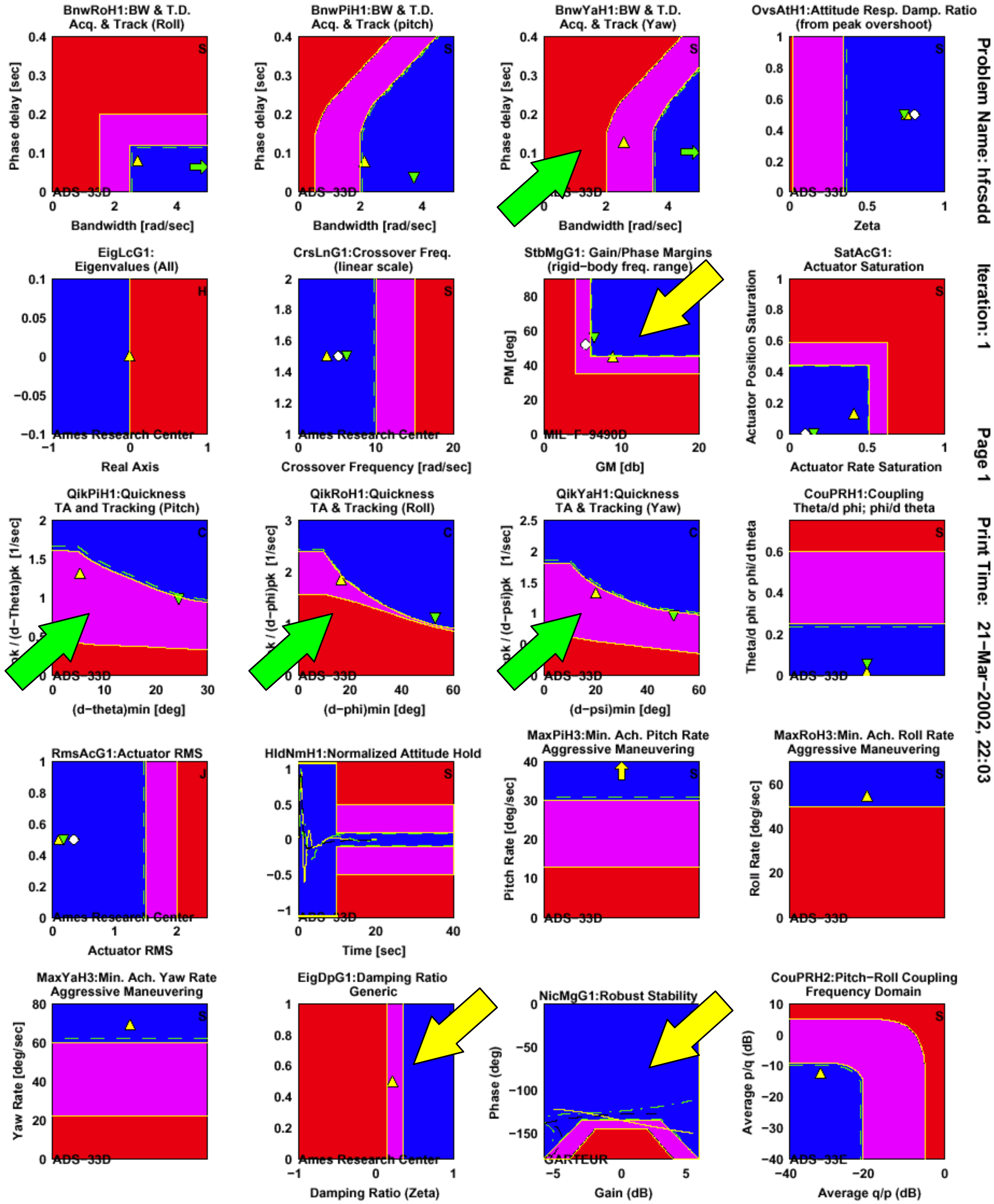

Figure 4 Nominal Gains, HFCS Hover Case

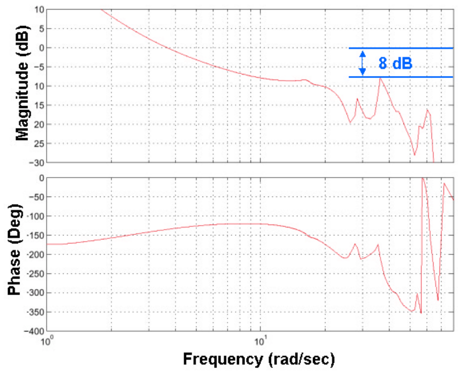

Figure 5 Longitudinal Hover Case ASE Stability

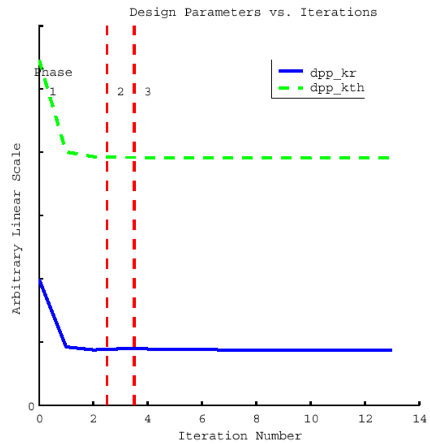

Figure 8 Automated Gain Progression

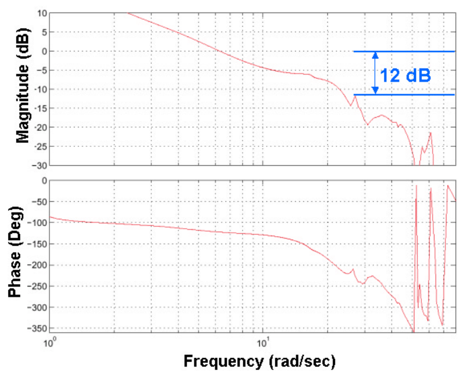

Figure 6 Lateral Axis Hover Case ASE Stability

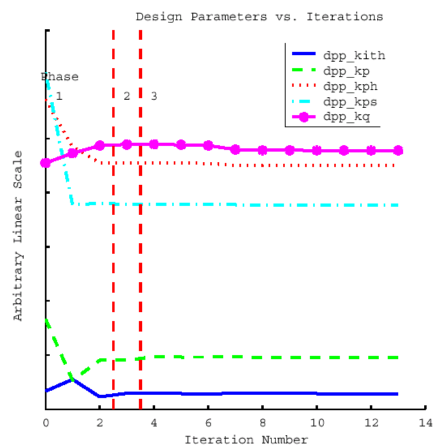

Figure 9 Automated Gain Progression

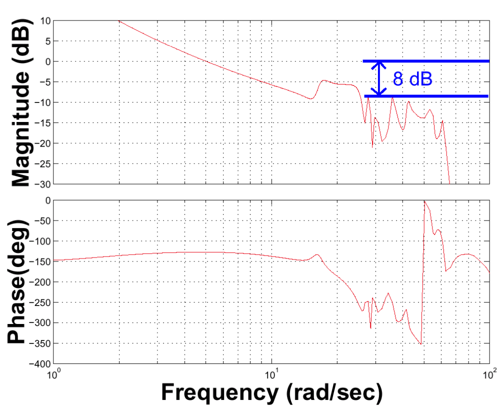

Figure 7 Directional Hover Case ASE Stability

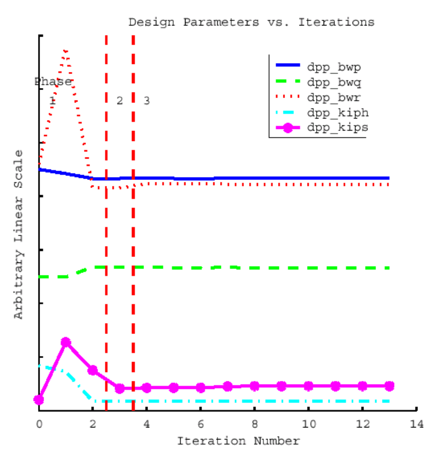

Figure 10 Automated Gain Progression

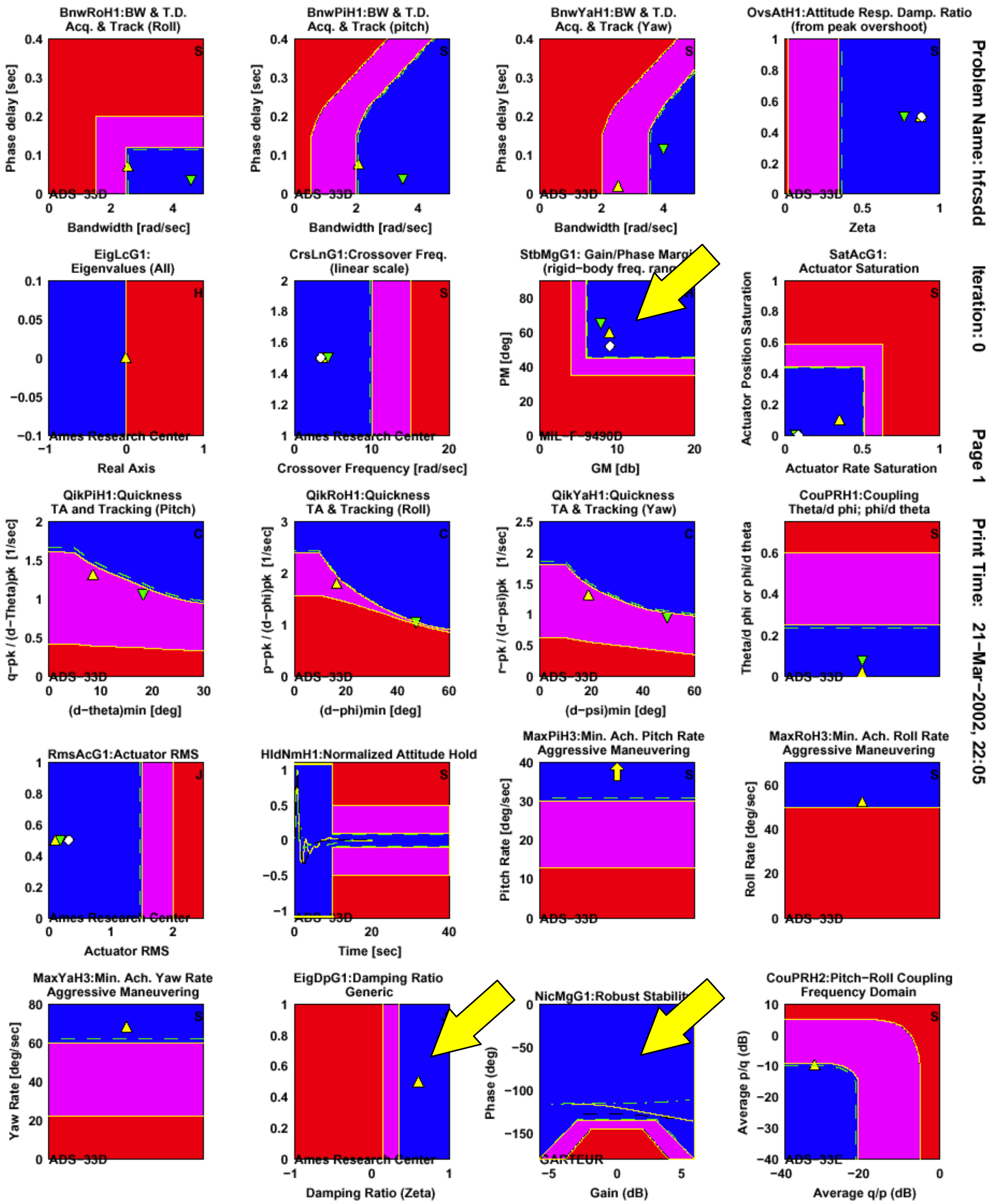

Figure 11 Optimized Gains, HFCS Hover Case