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THE U.S. ARMY APPROACH TO AIRWORTHINESS ANALYSIS AND DESIGN OF ROTORCRAFT FLIGHT CONTROLS AND HANDLING QUALITIES

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Key words: Airworthiness, handling qualities, ADS-33, rotorcraft, rapid prototyping, optimization, control, flight simulation

Abstract: The U.S. Army Aviation Engineering Directorate, the airworthiness authority for the Army, has adopted a set of modern, well-integrated tools and techniques for system identification; flight control system design; handling qualities analysis and optimization; immediate, pilot-in-the-loop simulation; and rapid progression to higher fidelity simulations and flight test. These tools and techniques constitute an approach that draws deep system knowledge into an early stage of combined control systems design and handling qualities evaluation. These capabilities are explained in the context of recent applications to the AH-64D and the UH-60M.

1 NOTATION

ADS = Aeronautical Design Standard
AED = US Army Aviation Engineering Directorate
APEX = Advanced Prototyping and Experimentation (A fixed-based, reconfigurable flight simulator)
CIFER = Comprehensive Identification from Frequency Responses
CONDUIT® = Control Designers Unified Interface
DVE = Degraded Visual Environment (ex. night flight)
FMC = Flight Management Computer (where the flight control laws reside)
MCLAWS = Modern Control Laws
RIPTIDE® = Real Time Interactive Prototype Technology Integration Environment (a general purpose control laws prototyping flight simulator)
RACRS = Risk and Cost Reduction System (A fixed-base AH-64D cockpit simulator)
RTW = Real Time Workshop
SAS = Stability Augmentation System

2 INTRODUCTION

The U.S. Army has adopted a technical process and engineering toolset for rotorcraft handling qualities to meet the increasing demands of its missions and environments. Harsh desert conditions of recent operations have highlighted the need for improved handling qualities. Flying in Degraded Visual Environments (DVE), such as brownout when blowing dust and sand encompasses the aircraft (Figure 1), leads to higher pilot workload and lack of outside visual cues (Figure 2). The U.S. Army's rotorcraft, including the AH-64 Apache, the UH-60 Blackhawk, and the CH-47 Chinook, were designed decades ago to such standards as MIL-F-8501[1], which made no specific requirements for DVE flight. Since then, the Aeronautical Design Standards have evolved. Modern flight control systems can and must provide handling qualities with more automated, high level modes to compensate in such environments.

Figure 1: Imminent brownout at landing

Figure 2: Pilot's outside view during brownout

There is an art and a science to the design of an aircraft's handling qualities. The general design steps for handling qualities of an aircraft include dynamical modeling of the plant (i.e. the aircraft), flight control law design, crew interface design, piloted simulation, integration into flight hardware, and flight test. The plant modeling and control law design are both forms of dynamical modeling and each may be partitioned into architectural (non-parametric) design and parametric design. The architecture, which defines the number of states in the system and the relationships among them, depends largely on matching the complexity of the model with that of the problem to be solved, including all those states which would impact the answer. But the parametric optimization evolved through science to become an automated technology. Crew interface design, with addresses the Useable Cue Environment (UCE), emphasizing visual, but including aural and tactile cues, still relies on the combined talents of crew station working groups, but are supported with aerodynamic models, flight simulation, and physical cockpit prototypes

2.1 Traditional and Simulation Based Acquisition

The U.S. Department of Defense has long relied on computer simulations for its weapons systems designs. But until about a decade ago, defense acquisition still followed a "traditional" approach in which detailed knowledge of the weapon system could only be gained after the physical prototypes had been manufactured and tested. Then, as today, flight control engineers often evolved flight control laws from previously successful programs. It was taken for granted that extensive tuning would be made during the flight test program. The discrepancies between design parameters chosen in simulation versus flight tests were recognized but were still not fully understood or transferred among engineers. This approach implies that knowledge is hard won and expensive. For handling qualities, the gain tuning remained very much an art that relied on the designer's experience. It is an environment where considerable design, error checking, and preparation is devoted to each handling qualities design iteration or flight test because each is expensive and mistakes are costly. In general, the design iterations are few because the test and evaluation cycles are long. The approach might require full-time participation of flight control systems design and test teams, and full employment of test assets, especially aircraft, for experimentation. In recent programs, flight control laws have grown increasingly sophisticated and combinations of design parameters have multiplied. The flight test matrix necessarily becomes large in order to amass the requisite knowledge to recognize errors and tune the control law gains.

Simulation Based Acquisition (SBA) is a major initiative within the U.S. Department of Defense that encourages robust and interactive use of modeling and simulation (M&S) throughout the product life cycle – for system design, test and evaluation, modification and upgrade. The use of high fidelity models helps the airworthiness engineer gain a deeper understanding of the aircraft systems and their associated requirements prior to completing design and flight testing of a prototype aircraft. The principles of SBA adopted by the Army have been most intensively applied to training, tactics experimentation, and battle visualization. Now, they are increasing the depth and effectiveness of aviation engineering simulations supporting flight control system design and the handling qualities they affect.

2.2 Role of the Aviation Engineering Directorate

The program managers of the U.S. Army Program Executive Office for Aviation are responsible for funding development and qualification, ensuring airworthiness, and obtaining an airworthiness release prior to fielding their aircraft systems. Each major airframe, such as the Blackhawk, Apache, Chinook, and Armed Reconnaissance helicopters, has its own program management office (PMO). The Army Aviation Engineering Directorate (AED) is the primary airworthiness authority supporting all of these programs. Its divisions provide systems engineering support and airworthiness coordination for the programs, plus functional expertise in structures, propulsion, mission equipment, and aeromechanics.

AED has adopted a set of tools and an approach that facilitates and improves the handling qualities design and assessment process. In the last three decades, aeronautical design standards have evolved and control systems design tools and simulation methods have improved. Today, the U.S. Army's rotorcraft handling qualities specifications are defined primarily by Aeronautical Design Standard ADS-33E[2], which establishes quantifiable standards for rotorcraft handling qualities. The Army approach to airworthiness qualification of flight controls and handling qualities relies heavily on a well integrated set of modeling and simulation-based design and analysis tools. The foundation of the approach (Figure 3) is the modeling of the aircraft flight dynamics. The Aeromechanics Division creates and maintains flight dynamics models of Army rotorcraft and their flight control systems for the purposes of airworthiness assessment. Non-linear, physics-based models are created with Advanced Rotorcraft Technology's FLIGHTLAB® using *a priori* knowledge of the aircraft design. Linear models are often determined *a posteriori* through system identification of flight test data with Comprehensive Identification from Frequency Responses (CIFER®)[3], which also facilitates verification and validation of the FLIGHTLAB (and other) physics-based, nonlinear models. The product of the aircraft modeling effort is a linear plant model for Matlab and Simulink® to which is added a model of the aircraft's flight control system. Using the Control Designers Unified Interface (CONDUIT®)[4] in the Matlab / Simulink® environment, engineers optimize control law parameters and evaluate the performance of the flight control laws. The handling qualities metrics used to evaluate and optimize the control laws are defined by ADS-33E and other handling qualities specifications. The handling qualities evaluation continues with pilot-in-the-loop simulation in the Real-time Interactive Prototype Technology Integration Environment (RIPTIDE®)[5]. When higher fidelity models are required, FlightLab® is frequently used to create physics-based, flight dynamics models independent of those generated by the manufacturer. Alternatively, pre-existing models and simulations may be used, as was recently the case for modernization of the AH-64D flight control system in a prototype training simulator[6]. All of these tools are described in more detail below, in the context of the Army's approach to airworthiness qualification of flight control systems and aircraft handling qualities.

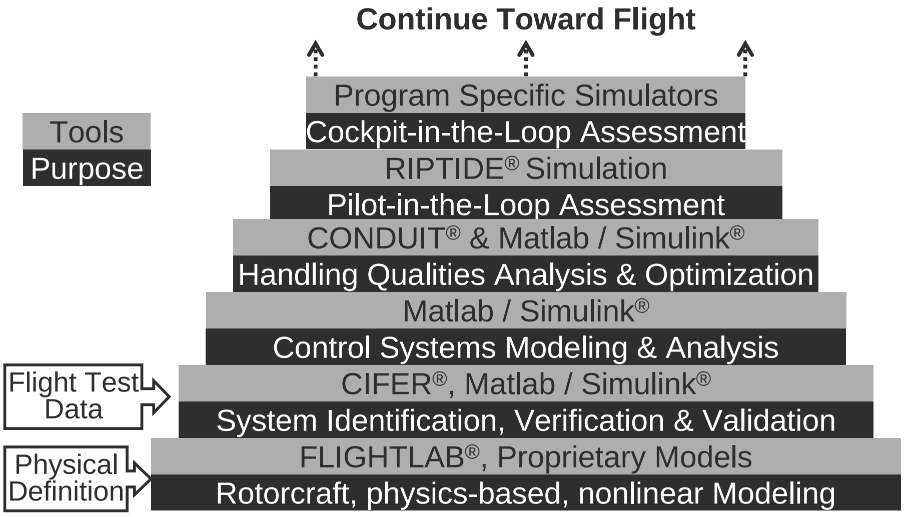

Figure 3: Technical Approach to Handling Qualities Airworthiness

3 FLIGHT DYNAMICS MODELING AND ANALYSIS

The approach to aircraft flight dynamics modeling differs depending upon the available information and the intended purpose of the model. For pre-existing aircraft, with a completed flight test program that includes frequency response testing, the flight test data becomes the basis for system identification of the aircraft system a posteriori. This was the approach taken for the ongoing modifications and upgrades for the AH-64 Apache[7] and the UH-60 Blackhawk models. For a new program, when a prototype aircraft does not yet exist, but the knowledge of the aircraft's physical design is available, a physics-based, global, non-linear model is created *a priori*. In either case, the resulting model is verified and validated. At times, both physics-based and system-identified models are available. In these cases, the physics-based, non-linear model can be reconciled with the system-identified linearized model and validated with the flight test data.

3.1 Modeling *A Priori*

AED uses information from the helicopter prime manufacturers in the format defined by ADS-10[8], and from other reliable sources, including flight tests conducted by the Aviation Technical Test Center and the Aeroflightdynamics Directorate, to build a flight dynamics model of each aircraft from first principles. The mass properties and aerodynamics of the major components of the aircraft, such as the fuselage, rotor system, fixed surfaces, and engines are modeled as elements of a multi-body system. But even when these components are defined in detail, the complexities of the process provide a great deal of freedom to the modeling and simulation engineer in the selection of the solution type, the resolution of the simulation, and still other aspects peculiar to rotorcraft.

In this endeavor, the primary engineering tool is FLIGHTLAB®, a product of Advanced Rotorcraft Technology (ART). FLIGHTLAB® is a physical-principle based, object-oriented modeling, prototyping, analysis and real-time simulation for nonlinear multibody dynamical systems. ART strives to incorporate the latest developments in rotorcraft aeromechanics analysis in the product and, under a Cooperative Research and Development Agreement, assists the Army in the development of a library of Army rotorcraft flight dynamics models. Moreover, while the prime rotorcraft manufacturers develop and maintain their own proprietary rotorcraft models, typically written in FORTRAN or C – examples include FLYRT[9] at Boeing Helicopters and GENHEL[10] at the Sikorsky Aircraft Corporation – for AED, FLIGHTLAB® serves as an objective tool whose models can be more freely exchanged and reused among the Army and industry stakeholders in support of SBA principles. Proprietary models may still be used when available and validated. For example, the recent effort to modernize the flight control system of the AH-64D Longbow relied on an AH-64D cockpit simulator with a FLYRT model.

3.2 Modeling *A Posteriori*

The use of frequency domain system identification methods to identify high order linear models for handling qualities analysis has become commonplace due to the CIFER® software package developed by the Army Aeroflightdynamics Directorate. CIFER® provides systematic procedures for identifying high fidelity linear models from frequency response flight test data. These models help bridge the gap between analytical, physics-based models and the actual aircraft by providing better accuracy in predicting vehicle response for specific flight conditions. Recent applications to the UH-60[11], AH-64[12], and CH-47 [13] have demonstrated the robustness of the techniques for a variety of Army rotorcraft.

Use of these analysis methods requires the collection of frequency response flight test data, in addition to the traditional time domain, perturbation response data that is used for model validation. When no physical prototype yet exists, physics-based modeling and flight simulation may provide preliminary data. Techniques for collecting this data have been specifically developed[14] to support handing qualities specification compliance and system identification, but have far reaching applications ranging from flight control law development to in-flight shake testing for structural mode identification.

Frequency domain data is processed using advanced spectral analysis techniques in CIFER® to produce non-parametric, frequency responses for selected input/output pairs which characterize the complex vehicle dynamics over a broad frequency range. These frequency responses can be directly used to validate analytical models. For system identification, the responses are fit with a state-space model structure to identify a parametric model in terms of the associated stability and control derivatives. The model structure is chosen to represent the dynamics of interest for the intended analysis. Handling qualities analyses, which are typically concerned with aircraft responses below about 2 Hz, are generally represented by a six-degree of freedom, rigid body model structure. Higher order models are required for high-bandwidth control systems or to identify explicit parameters associated with rotor or inflow dynamics in support of analytical model validation.

3.3 Verification, Validation, and Reconciliation

Flight dynamics models, regardless of origin or type, are validated using available flight test data. The *a priori* models, such as FLIGHTLAB®, are validated against flight test data acquired for steady-state (trim) flight conditions, maneuvering flight conditions and control frequency sweeps. Frequency responses from the model and flight test data frequency sweeps are generated and compared using the CIFER software package. For maneuvering flight conditions of relatively short duration, such as control doublets, time-domain validation is accomplished by replaying a flight test's control history for the model. For focused validation of specific predictive capabilities such as loads and accelerations during complex and extended flight test maneuvers, a virtual pilot (an advanced autopilot tool developed within AED) aggressively flies the model to replicate state or output trajectories.

Since the physics-based models, whether from FLIGHTLAB® or another source, never conform perfectly to flight test results, they are refined through iterative improvement of the model architecture and parameters to reconcile the products of *a priori* and *a posteriori* modeling. However, in some instances, the physics-based models simply fail to adequately capture the phenomena observed in flight tests. In those instances, AED works closely with ART to improve the predictive capabilities of the FLIGHTLAB tool. For example, in an active Blackhawk helicopter modeling effort, AED found discrepancies with a model's trim solution despite an accurate physical definition of an aircraft. The simulation team traced the discrepancy to prediction of the flight loads on the empennage. To improve the modeling tool, the Army outfitted a test aircraft with supplemental sensors that provided detailed loading measurements for the empennage components. With the detailed flight test data, AED and ART improved FLIGHTLAB's downwash and dynamic pressure distribution tables. In another effort, AED worked with ART to develop modeling methods for external sling loads[15]. AFDD flight tested the modeled configurations and found good correlation with the predicted closed-loop attitude response, broken-loop stability margins, trim control positions and aircraft attitudes, and load dynamics.

4 CONTROL SYSTEMS MODELING AND DESIGN

The steady improvement in control systems modeling and design tools over the last decade has transformed the process of design and analysis of control systems. Mathwork's Simulink® has emerged as a standard tool of technical computing for many engineering disciplines. This powerful product has become AED's foundation for advanced design and analysis of control systems. As with plant modeling, the control systems design or analysis has architectural and parametric aspects.

4.1 Control Law Architecture

The overall architecture of the flight control system is driven by requirements related to criticality, reliability and failure tolerance, as well as by control modes, functionality and response types dictated by applicable design requirements and flying qualities specifications. The mechanical portion of the flight control systems were, and still are, subject to the requirements of the military design specifications (MIL-S-8698, MIL-H-5440, etc.). The approach for their qualification has changed little in recent years. But the approach taken for the electronic portion of the flight control system has evolved rapidly in recent years. The Army's integrated toolset now enables rigorous and independent analysis of an electronic or digital control system. The modern tools are more capable of analyzing and predicting performance and handling qualities concurrent with the manufacturer's design efforts and prior to flight testing.

Control system block diagrams were traditionally delivered to the government as part of stability and control reports, subsystem surveys, or in response to ADS-10 specifications. At AED's urging, most program managers now make the Simulink® model files of the flight control system a contract deliverable. The typical process, and one that is preferred currently, is for the prime contractor to directly supply AED with Simulink model files. AED then incorporates those files into Simulink® or FLIGHTLAB plant models. In cases where the model files are not available, AED creates the files from block diagram drawings.

In the specific case of the AH-64D Modern Control Laws (MCLAWS), AED designed the flight control laws in Simulink® and made them available to the manufacturer and other U.S. government agencies for analysis. The process started with the creation of linear models with CIFER and continued with a model-following architecture and a command model derived from ADS-33E. The subsequent steps of handling qualities optimization and live simulation for this prototyping effort are described below.

4.2 Handling Qualities Analysis and Optimization

Traditional handling qualities analysis involves evaluating model response including static trim characteristics, time history simulations, Bode plots of broken and closed loops, actuator saturation information, etc. to verify compliance with required specifications. But these analyses could only be applied individually and sequentially. Depending on the number of specifications to check, this process can be extremely time consuming. The Army now uses CONDUIT®, which provides a facility for flight control system analysis and design optimization in conjunction with specification compliance evaluation. CONDUIT® provides a means of evaluating multiple design specifications simultaneously using the combined model of the control laws and aircraft dynamics. CONDUIT® is built upon the capabilities of MATLAB®/SIMULINK® and is used extensively by U.S. industry, academia, and the government. As an example, the AH-64D with baseline control laws was evaluated against quantitative handling qualities and controller stability requirements provided in ADS-33 and MIL-F-9490D as described in reference 18. Although the AH-64D was not designed to meet ADS-33, it was worthwhile to compare it against the latest military handling qualities requirements to demonstrate the methodology AED uses to evaluate ongoing control law development efforts.

CONDUIT® also provides the capability to optimize controller gains, time constants, or dynamic block parameters by allowing the designer to tune the system, either manually or via a powerful, holistic, optimization engine, to best meet the selected set of requirements and ultimate performance objectives. These techniques have been successfully applied to various rotorcraft including the S-92[16], SH-2F[17] and UH-60A.

The most important aspect of setting up a design problem in CONDUIT® is the selection of the various specifications which embody the requirements of the system. These specifications can be selected from a large library of specifications built into CONDUIT®, encompassing both generic system stability and performance requirements, and aircraft response and handling qualities requirements. As an example, the AH-64D MCLAWS design problem (Figure 4) considered 46 separate design specifications including broken-loop stability margins, disturbance rejection response, bandwidth and phase delay, attitude response damping ratio, and pitch-roll coupling to name a few[18]. CONDUIT simulated the Simulink® based control laws in non-real time and evaluated the results of the simulations with the 46 specifications. It iteratively adjusted selected design parameters within the control laws to find the optimal combination to achieve Level 1 handling qualities. The “MCLAWS FMC” containing the control laws was the deliverable for the Flight Management Computer (FMC). The other subsystems modeled other aspects for the simulation environment. Because Simulink model was in the critical path of the control systems design and later flight simulations, the CONDUIT optimization was always timely and relevant during development.

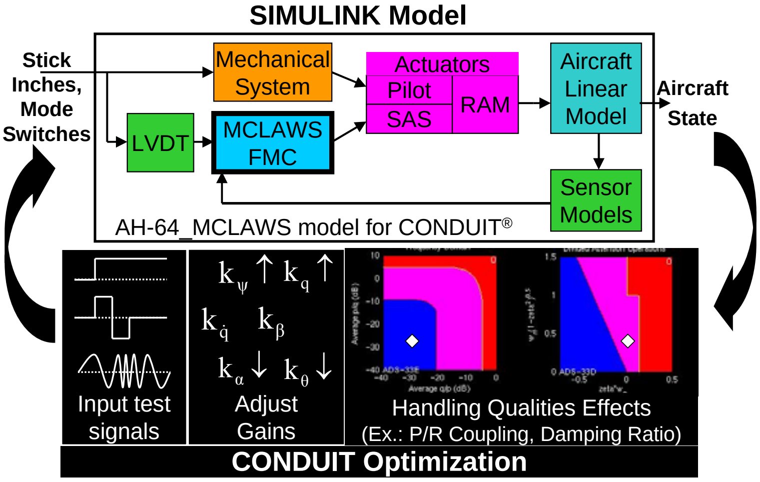

Figure 4: AH-64D MCLAWS design with CONDUIT

5 FLIGHT SIMULATION

The preceding steps of modeling and analysis take place in a non-real time simulation. When conducting these simulations, the models are typically fed a predefined time history of pilot control inputs, such as a step, a doublet, or a frequency sweep in one or more axes. The designers evaluate the resulting output and improve the architecture. They use optimization tools, especially CONDUIT, to automate the optimization of the parameters within that control law architecture. And this non-real-time, simulation-based design expedites the development of the control system and its airworthiness assessment. But later, piloted simulation is more efficient for holistic analyses. Specifically, real-time handling qualities prototyping is effective when analyzing or designing the mechanisms for transitioning among different control modes, enabling or disabling the modes, and identifying potentially undesirable effects of these modes on the ability of the pilot to perform a given mission task.

The piloted simulation is executed in increasingly immersive environments. Initially, for a low cost, “quick look” simulation, RIPTIDE or FLIGHTLAB may be employed in generic flight simulators using commercial off-the-shelf inceptors (joysticks). As control laws become more mature, and flight hardware integration is needed to explore the subtleties of the man-machine interface, the control laws and models are exported to higher fidelity simulation facilities. To facilitate rapid integration and evaluation of changes to the control laws, a common practice for most of these piloted simulations is to employ automatic coding of the models and control laws.

5.1 Automatic Code Generation and Export

The practical implementation of the control laws requires a translation from symbolic, block diagram programming to textual C-code. The procedure would be time consuming and prone to errors if it relied on a human programmer. A powerful add-on toolbox of the Mathwork's Simulink® environment is its Real Time Workshop, which converts the Simulink block diagram to C or C++ code that can execute independently. This autocoding capability is the key enabler to transition from batch simulation to piloted flight simulation. AED employs its engineering tools on a dual processor Xeon workstation with a Linux operating system. A Real Time Workshop template Makefile guides the code generation, and AED customizes that file to build code appropriate for its host machine or for other facilities, such as the hybrid Windows/Linux environment with Intel processors at the Advanced Prototyping and Experimentation (APEX) Lab or the IRIX environment with Silicon Graphics MIPS processors at the AH-64D Risk and Cost Reduction (RACRS) simulator.

5.2 Live Handling Qualities Prototyping

The Real-time Interactive Prototype Technology Integration Environment (RIPTIDE)[19] provides a fixed-base flight simulation capability. At AED, the RIPTIDE software resides with CIFER®, MATLAB/Simulink®, and CONDUIT® in the Scientific Linux operating system on computer workstations with dual Intel® Xeon® processors, 2 or more GB of onboard memory each, and dedicated nVIDIA® Quadro® graphics card driving twin displays. This control system is physically located on Redstone Arsenal, Alabama. A similar setup is used at the Army Aeroflightdynamics Directorate at Moffett Field, California, where both CONDUIT and RIPTIDE were developed.

RIPTIDE combines processes for control inceptors and graphics with the executable product of Real Time Workshop from the Simulink model and (optionally) a separate math model for the airframe. Because RIPTIDE resides in the same computer as CIFER, Simulink, and CONDUIT, it greatly facilitates rapid iterations between Simulink-based control system design and simulated flight tests. The process effectively prototypes the handling qualities for the control systems engineers and allows them to rapidly test modifications to control laws.

Figure 5: AED RIPTIDE desktop simulation

Figure 6: Full RIPTIDE simulation with Pirouette

Using a data exchange mode between SIMLINK and the RIPTIDE executable, the designers can adjust the flight control law gains in real-time, so that while flying, a pilot can provide immediate feedback regarding specific gain refinements. For rapid MCLAWS prototyping, RIPTIDE was used as a desktop simulation (Figure 5). For more immersive simulations, a second networked RIPTIDE workstation simulation helps drive three side-by-side projections to create a 135-degree pilot's field of view (Figure 6). The crew station for the RIPTIDE simulations is equipped with three PC compatible inceptors (joysticks) for cyclic, collective, and pedals.

RIPTIDE executes concurrent processes with shared memory arenas for information exchange (Figure 7). An inceptor process captures the pilot's commands. It saves the inceptor positions and buttons to a control arena. The aircraft process (inside the "RIPTIDE_wrapper") reads from the control arena and presents the inputs to the AH-64 MCLAWS process. The output of that process is saved in shared memory for the aircraft state. The graphics process then reads the state arena and generates a view for the pilot.

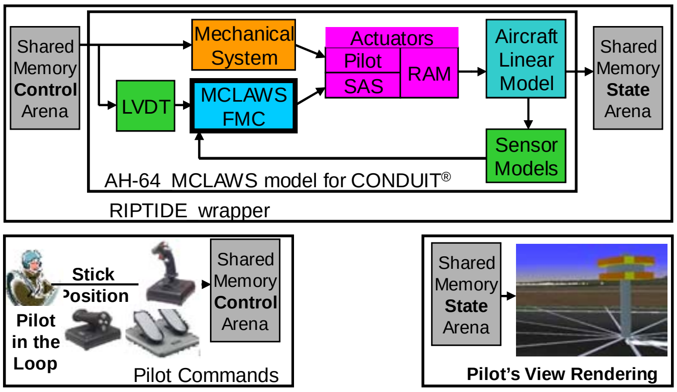

Figure 7: MCLAWS within a RIPITDE Simulation

Figure 7 depicts the RIPTIDE simulation approach as it was applied during the modernization of the AH-64D control laws. The core Modern Control Laws destined for the aircraft's Flight Management Computer (the "MCLAWS FMC") were developed for CONDUIT optimization in a Simulink environment that included subsystems for the actuators, sensors, and aircraft linear model. For the live RIPTIDE simulation, that overall AH-64D MCLAWS Simulink model was placed within a "RIPTIDE_wrapper" that translated to the output from, and input to, the shared memory arenas. The wrapper reconciled dimensions and data type mismatches between the CONDUIT and RIPTIDE environments. The wrapper also included switch logic and latches for translational rate command, force trim release, altitude hold, and hold disengage, all of which the pilot could select from a four-way button on the cyclic joystick.

The requirements of early live simulation with pilot interaction enforce practical requirements in batch simulations. With the first RIPTIDE simulations, the internal structure of the "MCLAWS FMC' was designed to include initial conditions, reset mechanisms, trim biases, and data type consistency. It evolved into an 'atomic subsystem', in which every control, pilot switch, aircraft bus parameter, or SAS command became an explicit input or output rather than a global variable reference. The "MCLAWS FMC" was postured from its earliest versions to become a self-contained, modular subroutine.

RIPTIDE provides a flyable simulation where real-time interaction gives AED's engineers and pilots a hands-on basis from which to judge aircraft handling and pilot workload. In piloted simulations following CONDUIT analyses, they witness the improvements wrought by the CONDUIT optimization and the ramifications of particular control system design decisions. In the transition from legacy control laws to MCLAWS in the AH-64D, the engineers employed CONDUIT® design optimization in non-real-time and strove for an improvement from Level 2 to Level 1 handling qualities in degraded visual environments. The RIPTIDE simulation demonstrated the noticeable improvement and aided the refinement of the control laws. RIPTIDE was particularly helpful in the analysis and development of flight mode switching logic. It facilitated the troubleshooting of control mode transition conditions. For example, the initial conditions of the Altitude Hold and Position Hold modes, along with their triggered activation by inceptor activity, were among the subtleties explored in live RIPTIDE simulation.

Although only the CIFER-identified linear models of the aircraft were used for the AH-64D MCLAWS, it should be noted that RIPTIDE can also employ full non-linear simulation models. The linear models sufficed for piloted evaluation near the flight tested trim conditions with respect to the ADS-33E specifications. (These were the same trim conditions used in the CONDUIT® handling qualities optimization.) However, the linear models were only marginally useful or, in some cases, inadequate, for exploring the effects of large aircraft attitudes, large control inputs, transitions to forward flight, touchdown dynamics, and in-ground effect hover. Furthermore, the commercial joysticks with fixed force-displacement relationships could not simulate the nature of the aircraft's force-trim characteristics. In instances such as this, when a global, nonlinear model of the aircraft and a realistic cockpit are needed for further evaluation, the control laws are transferred to aircraft-specific simulations that include flight and flight-like cockpit hardware.

5.3 Cockpit-in-the-Loop Simulations

During the acquisition process, each program manager uses a gamut of simulators for various purposes. The engineering simulators, with the most accurate, physics-based, nonlinear models, are typically created by the prime rotorcraft manufacturers to support all aspects of design. As the aircraft moves toward detailed design and manufacturing, cockpit simulators with and without motion are created to support crew systems prototyping and aircrew training. During the flight control systems and handling qualities airworthiness assessment, some of these simulation systems are employed. They are augmented by reconfigurable simulators in Army facilities created and run by Army personnel and contractors.

The Army Aviation Risk and Cost Reduction System (RACRS) Apache Longbow Simulator is an example of a manufacturer's prototype cockpit training simulator. The RACRS simulator is now managed by the Camber Corporation and is located only a few miles from AED. It supports the Apache PMO as a multipurpose test facility for radio systems, display systems, flight test rehearsals, and a variety of other purposes. It also served as a cost-effective, low-risk, and reliable test bed for early MCLAWS development and evaluation. The RACRS flight model is Version 6.1 (1998) of the FLYRT[20] non-linear helicopter simulation model. RACRS cockpit uses AH-64D Apache Longbow flight hardware, including inceptors with control loading, to provide a realistic crew station for piloted evaluations (see Figure 8). Its high-fidelity visual model, with terrain from numerous regions worldwide, includes Cairns AAF and other Army Air Fields in Alabama where much of the ultimate flight testing will occur.

While the RACRS simulator offered a validated, global, nonlinear model and so served as an excellence test environment for the MCLAWS, it was not designed as an engineering simulator but as a training simulator. As such, its internal models for the legacy control laws, the actuator models, and the airframe dynamics were not separable, nor were SAS commands or actuator positions accessible. None of these models could be altered. Fortunately, as a training simulator, the RACRS did model the functions of the AH-64D cockpit which included a "FMC Release" switch that disables the SAS in its four axes. Through this mechanism, the SAS actuators within the FLIGHT_C flight model would be centered and the influence of the legacy FMC would be eliminated. Only the mechanical pilot command signal would remain.

Figure 8: Camber RACRS AH-64D Simulator

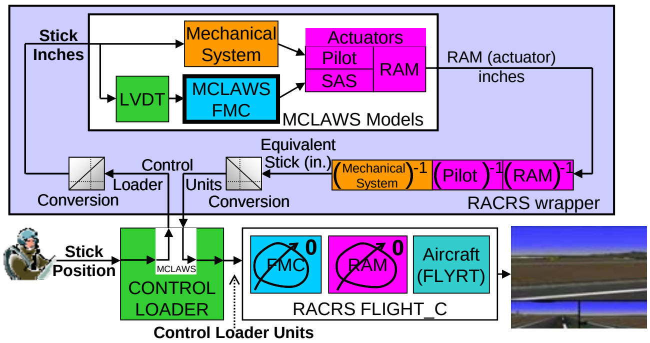

Figure 9: MCLAWS structured for RACRS

The RACRS Control Loader Process provided an interface to the control loader hardware, which made force trim changes possible in the cockpit. It was rewritten to include the MCLAW as a "RACRS wrapper" subroutine (Figure 9). The subroutine converted the MCLAWS ram actuator commands into an effective pilot command. In this way, the modern control laws supplanted the legacy control laws and the RACRS was used for handling qualities prototyping of the new laws.

Figure 10: Advanced Prototyping and Experimentation (APEX) Simulator

The Advanced Prototyping and Experimentation (APEX) simulator (Figure 10) is a reconfigurable fixed base cockpit simulator with flight-like displays and hardware. It is frequently used for crew station prototyping, such as, the display symbology for new handling qualities modes. Recently, the Modern Control Laws developed at the AED were adapted to control a FLIGHTLAB model of the UH-60M and provide its crew systems working group a basis to study the ramifications of higher order handling modes such as Translational Rate Command.

6 AIRWORTHINESS PROCESS PARADIGM

Each of the engineering tools described above represents a technical advance or a *de facto* industry standard in its respective function: FLIGHTLAB® for physics-based rotorcraft aerodynamic modeling, CIFER® for system identification, Simulink® and it's toolboxes for control law design, CONDUIT® for handling qualities parameter optimization, Real Time Workshop for automatic code generation, and RIPTIDE for rapid prototyping with live simulation. With one exception, these well integrated tools have no technical obstacles between them, so the user can easily move forward or back in the engineering process to iteratively improve the product. The exception is the integration of FLIGHTLAB® aircraft models with Simulink based control systems, which still requires considerable time and effort. The Army's AED and AFDD are both working to reduce the difficulty of combining these powerful tools for holistic flight simulations.

The AED handling qualities team quickly grew comfortable with the process, and the nature of the control law design became one of making steady, incremental improvements. The first major phase of the AH-64D MCLAWS handling qualities prototyping lasted about six months and culminated with a milestone briefing. When viewed in relation to this program milestone (see Event D of Figure 11) the pattern of steady progress is evident. Simulink versions of the modern control laws existed more than a year before the milestone and were used initially to study the feasibility of AH-64D handling qualities improvements. When the modernization project began, a version tracking mechanism was put in place and the MCLAWS FMC revisions in Simulink progressed at a rate of about 1.3 revisions per week.

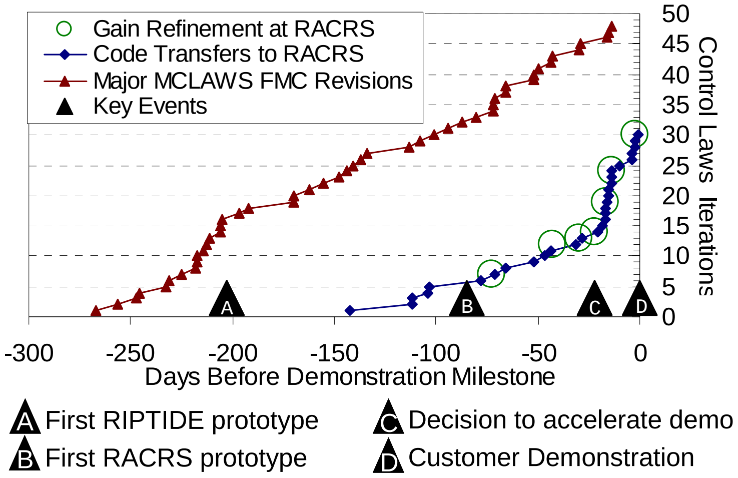

Figure 11: Prototyping Iterations and Key Events

The rate of revisions surged as the MCLAWS was restructured for its first piloted version and flown in RIPTIDE (Event A). The early code transfers to RACRS were purely integration tests used to explore the input/output interface for the MCLAWS subroutines and the general feasibility of the approach depicted in Figure 9. The modern control laws first flew in RACRS and controlled the global, non-linear FLYRT model 85 days (Event B) before the aforementioned milestone. Thence, structural revisions to the MCLAWS were transferred and tested in RACRS about once per week. During several of these simulated RACRS flight tests, the gains within the control laws were refined at RACRS by directly editing parameter variable assignments in the C files, rebuilding the MCLAWS subroutine, and repeating the simulation flight tests.

At a briefing rehearsal (Event C) three weeks prior to the decision meeting, after an assessment of the MCLAWS progress, the timeline was accelerated so that a flyable demonstration of the improved handling qualities could be included with the milestone briefing. The RACRS prototyping rate quintupled to 5.6 iterations per week. This unplanned acceleration in the project would have been impossible without the rapid prototyping process described above. The nature of an aircraft's handling qualities is not easily communicated with words and numbers, so the MCLAWS flight demonstration proved to be the key factor in a positive decision for the MCLAWS project.

7 SUMMARY AND CONCLUSIONS

The Aviation Engineering Directorate, as the U.S. Army's primary airworthiness qualification agency, has developed a process and adopted a well integrated engineering toolset to assess the flight control systems and handling qualities of Army rotorcraft. The combination of process and tools has provided the organization with unprecedented capability to rigorously, independently, and concurrently assess and design flight control laws and predict handling qualities during the manufacturer's development process and prior to flight testing. The approach encompasses physics-based rotorcraft modeling, system identification, control system modeling, handling qualities optimization, piloted flight simulation, and model interchange and reuse. The ease of moving among the well integrated tools has enhanced the speed of iterative development and deepened the understanding of the systems. The approach and tools have been applied to ongoing programs such as the AH-64D and UH-60M with demonstrated benefits. The selection of engineering tools has automated the "science" and facilitated the "art" of design and qualification of rotorcraft flight control systems and handling qualities.

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