NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper n° H10

# A Landing and Takeoff Control Law for Unique-Trim, Fly-by-wire Rotorcraft Flight Control Systems

by

Carl J. Bauer

Boeing Defense and Space Group, Helicopters Division
USA

September 14-16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

# A Landing and Takeoff Control Law for Unique-Trim, Fly-by-wire Rotorcraft Flight Control Systems

**Carl J. Bauer**
**Technical Specialist**
**Boeing Defense & Space Group, Helicopters Division**

**Abstract**

A control law for unique-trim, fly-by-wire rotorcraft flight control systems has been developed to specifically address the landing and takeoff maneuver. Through the use of weight-on-wheels discretes generated from each landing gear, the control law provides the pilot with many of the inherent advantages of displacement controls while reducing workload via command shaping and stability augmentation. Inherently robust to variations in gross weight, c.g. and ambient conditions, the control law accommodates a variety of maneuvers such as precision, slope and running landings and takeoffs. Piloted simulation and an experimental flight test vehicle were used to demonstrate the performance of the control law for a variety of landing and takeoff conditions. Through these experiments, it has been concluded that the control law supports all RAH-66 Comanche handling qualities requirements related to landing and takeoff maneuvers.

## Introduction

Rotorcraft flight control system technology has expanded dramatically over the last several decades and new technologies continue to be developed. Many interesting design challenges have unfolded whereby military and civil markets require a competitive edge through affordable alternatives and significant increases in capability over existing aircraft.

Military attack and scout/attack (SCAT) rotorcraft which incorporate teetering and low hinge offset rotors driven by mechanical flight control systems continue to be replaced by high performance rotors and multi-mode, digital fly-by-wire (FBW) flight control systems. The US Army Advanced Digital-Optical Control System (ADOCS) (Ref. 1) program provided a technology base for engineering development of a digital flight control system designed to meet the requirements of the scout/attack mission. This technology is now being utilized in the development of the US Army RAH-66 Comanche helicopter.

Digital FBW flight control systems offer significant advantages over traditional systems such as reduced weight, multi-mode capability, and improved survivability and maintainability. However, control law architecture and level of stability augmentation which are optimized for in-flight modes of operation may not be appropriate for maneuvering the aircraft to and from a ground state condition. Therefore, a complete and comprehensive design solution includes a flight control law specifically tailored for the landing and takeoff maneuver. This paper addresses design considerations, implementation, and performance of a landing and takeoff control law for unique-trim, FBW rotorcraft flight control systems.

## Background

### Mechanical v. Digital FBW Flight Control Systems

Fig. 1 illustrates the advances in rotorcraft flight control system technology over the last several decades. The early pioneers of fixed wing and VTOL aircraft began with mechanical flight control systems which include an array of mechanical linkages that translate pilot cockpit commands into control surface deflections. As system requirements became more demanding, such as increased payload and

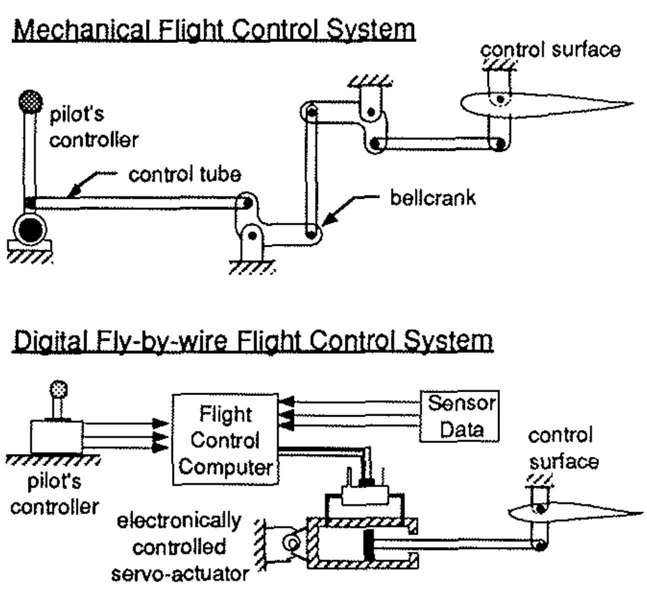


*Fig. 1 Mechanical v. digital FBW flight control systems.*

performance, the technology progressed to a similar approach employing hydraulically assisted systems. More recently, the advances in digital microelectronics have made digital FBW flight control systems much more practical. These systems replace mechanical linkages with electronically controlled servo-actuators driven by pilot and/or flight director commands processed by a flight control computer.

Digital FBW flight control systems offer significant advantages over mechanical flight control systems. Although production digital FBW systems carry relatively high fixed costs, variable costs are minimized because very little hardware is required to support additional modes in comparison to their mechanical flight control system counterparts. Since the control law is processed by a computer, the basic aircraft response may be easily augmented and multiple response types can be optimized for different flight regimes. Digital FBW flight control systems are also attractive due to improved maintainability. Finally, digital FBW systems are more survivable and utilize redundancy to enhance mission and safety reliability.

**Displacement v. Unique-Trim Controllers**

Focusing our attention on digital FBW flight control systems, it is important to identify the primary differences between two different types of cockpit controllers used in the implementation of these systems, namely, the displacement controller and the unique-trim controller. Widely used in today's existing aircraft, displacement controllers employ a mechanical trim system which allows the pilot to re-reference the zero force position virtually anywhere within the control range. As shown in Fig. 2a, the pilot's controller position, relative to the crew station neutral position, is a direct indication of the control surface position. For example, if the pilot desires to increase airspeed from 30 to 60 knots, forward cyclic control is applied followed by a small reduction in power as the helicopter develops additional translational lift. Upon achieving the intended airspeed, the

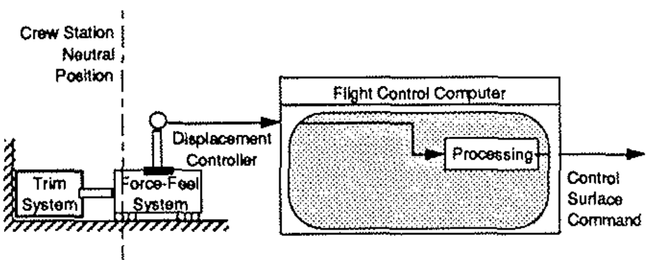


*Fig. 2a Displacement flight control system.*

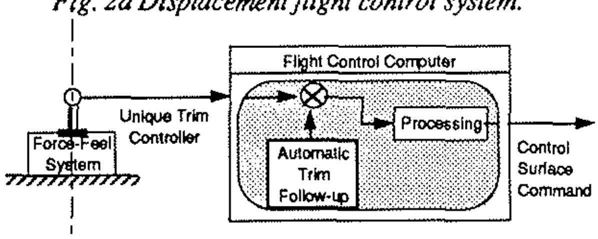


*Fig. 2b Unique-trim flight control system.*

pilot finds it necessary to hold longitudinal cyclic control displaced forward of the previous trim condition (30 kts). To relieve the accompanying forces, the magnetic brake or beep trim control functions are employed which invoke the trim system to reset the zero force position.

In contrast, the 3-axis unique-trim controller has a unique zero force position on each axis. As shown in Fig. 2b, the magnetic brake and beep trim functions are replaced by an automatic trim follow-up function resident within the control law. The trim follow-up acts as an integration of pilot inputs and the total control surface command is the summation of the pilot's stick position and the trim follow-up. For steady flight conditions, the controller is centered (zero output) and 100% of the total command is contributed by the trim follow-up. Therefore, the position of the pilot's controller is no longer a good indication of the total command.

Unique-trim controllers continue to receive attention in the rotorcraft industry because they offer significant advantages. Sidearm controllers, or compliant force controllers, consume much less cockpit volume and, hence, provide the pilot with improved visual field of critical avionics/displays. Moreover, unique-trim controllers are very adaptable to digital FBW flight control systems. Since FBW systems substitute many of the mechanical linkages used in traditional flight control systems, substantial weight savings can be realized.

This paper considers a control system configuration which includes a unique-trim, sidearm controller for control of the longitudinal, lateral and directional axes. The sidearm controller is mounted on the starboard side of the crew station. The crew station incorporates an armrest which isolates the pilot's forearm to assist coordination of controller inputs effected by fore/aft, side-to-side and twisting motion of the wrist. It was concluded in the ADOCS program that the use of a force type (unique-trim) collective controller was limited to tasks which do not require large or abrupt changes in collective setting. Since the Comanche requires aggressive maneuvering, the vertical axis incorporates a medium displacement (6 inches), true displacement collective controller.

**Limitation of Unique-Trim Controllers for Landing and Takeoff Maneuvers**

Displacement control systems provide a direct relationship between absolute stick position and the total control surface command. When the aircraft is in contact with the ground, it is less responsive to control inputs. For takeoff operations, the pilot initially holds the stick out of detent to compensate for a strong wind or to pick up the down slope gear during a slope takeoff. The pilot relies on experience to anticipate the magnitude of the initial input until the collective is raised and the aircraft is more responsive to cyclic and directional commands.

A fundamental limitation of unique-trim control systems in conjunction with landing and takeoff maneuvers is that the pilot cannot adequately judge the magnitude of the total control surface command based on controller position. For unique-trim systems, the trim follow-up acts to trim out steady pilot inputs such that the stick always ends up in the detent (zero force) position for steady trimmed flight. The direct relationship between stick position and total control surface command does not exist in unique-trim control systems which employ full-time automatic trim follow-up because a portion of the total command is contributed by the trim follow-up. This is not a problem for in-flight operations because the pilot adjusts the controls based on aircraft response. If the pilot holds the controller out of detent when the aircraft is constrained by the ground, however, the rotor will migrate to an undesirable position before the pilot can detect it based on aircraft response. Consequently, predictability is compromised resulting in poor handling qualities for landing and takeoff maneuvers. Therefore, a control law transition is introduced upon ground contact to provide the pilot with kinesthetic cues that resemble displacement control systems. Specifically, automatic trim follow-up is eliminated in ground state to restore the direct relationship between controller position and total control surface command.

### Landing and Takeoff Control Law Design

As an extension of the in-flight control law, the landing and takeoff control law is designed to provide a smooth and predictable transition to and from a ground state condition. As shown in Fig. 3, weight-on-wheels (WOW) discretes are generated from switches mounted on each landing gear (left main, right main and tail gear). In addition, a discrete is included to indicate when the tail wheel caster is locked. These discretes are used to control the transition of the primary functions within the control law such as feed-forward shaping, rate stabilization, attitude stabilization, and automatic trim follow-up.

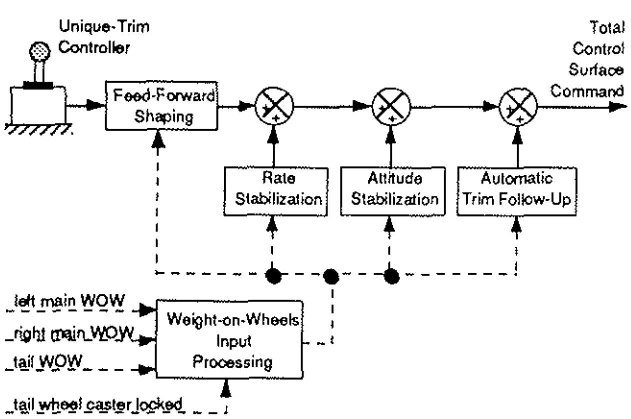


*Fig. 3 Unique-trim control law architecture.*

### Weight-on-Wheels Discrete Input Processing

There are four important ground state conditions that are a function of various weight-on-wheels combinations that describe to what extent the aircraft is constrained by the ground. These conditions include:

- initial contact of any landing gear
- aircraft axis constrained by the ground (pitch, roll or yaw)
- initial contact of all three landing gear
- heavy on all three landing gear

Weight-on-wheels discretes corresponding to each of the three landing gear are processed according to Fig. 4 and signal the transition of other functions within the landing and takeoff control law. Initial contact of any landing gear, denoted as ANYWOW, is computed via an OR of these individual weight-on-wheels discrete inputs.

Specific combinations of weight-on-wheels discrete inputs are used to determine if a particular axis of the aircraft is constrained by the ground. The pitch axis is constrained (PCNSTR) when the tail gear and either main gear are in contact with the ground. The roll axis is constrained (RCNSTR) when both main gear are in contact with the ground. Finally, the yaw axis is constrained (YCNSTR) when the tail gear is in contact with the ground and the tail wheel caster is locked.

The condition whereby all three landing gear are in contact

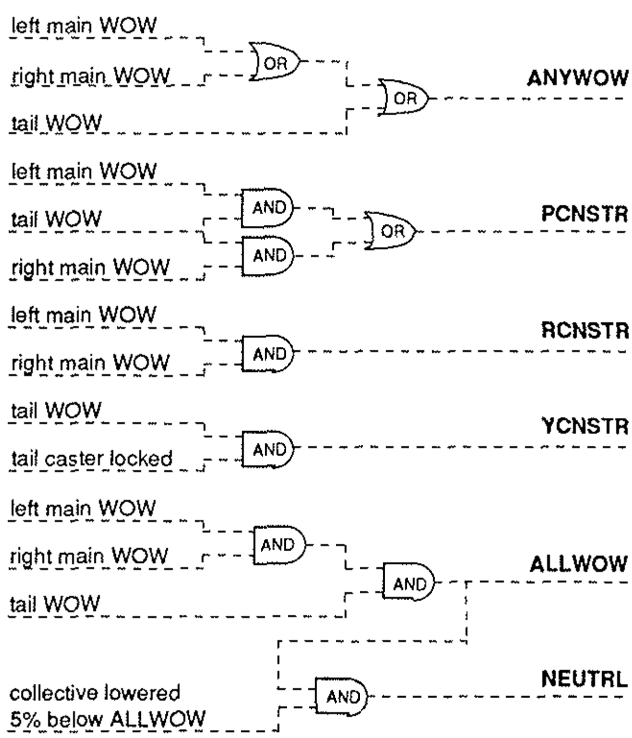


*Fig. 4 Weight-on-wheels discrete input processing.*

with the ground, denoted as ALLWOW, is used to identify the condition when the aircraft is light on all three landing gear during a smooth and controlled landing. Note that all rotational axes are constrained when the ALLWOW condition is satisfied and the tail wheel caster is locked.

The landing and takeoff control law includes a feature known as neutral rotor positioning which references a common, or "neutral", rotor position to the detent position of the sidearm controller. The neutral positioning process begins when the aircraft is sufficiently heavy on the gear. Therefore, the aircraft is considered to be heavy on the gear when the collective is lowered 5% below the condition where the ALLWOW condition was satisfied and is denoted as NEUTRL. Note that this methodology is robust to variations in gross weight, c.g. position, air density, etc.

### Transition of Feed-Forward Shaping

For in-flight operations, the feed-forward shaping provides control quickening and can be described as a first order lead/lag filter as shown in Fig. 5. Upon initial gear contact, the lead shaping is altered to provide proportional control while the steady state gain is adjusted to an appropriate level for ground state operations. The parameters of the feed-forward shaping are a function of a single transition variable, $\alpha$, such that the following requirements are satisfied:

(i) lead/lag shaping is provided in fly state

(ii) proportional control is provided in ground state

(iii) the steady state gain varies linearly with $\alpha$

(iv) the high frequency gain varies linearly with $\alpha$

where $\alpha$=1.0 corresponds to fly state and $\alpha$=0.0 corresponds to ground state. The transition variable is ramped from 1.0 to 0.0 when the ANYWOW condition is satisfied. Fig. 6 represents the frequency response of the feed-forward shaping for various values of $\alpha$. As the transition occurs, the forward loop shaping is bounded by the ground and fly state frequency response profiles.

Feed-forward shaping changes to proportional control on all three axes regardless of which landing gear contacts the ground first. The rationale for simultaneous transition of the feed-forward shaping in all three axes upon initial gear contact is as follows. For a typical landing task, the average stick displacement will be a minimum at initial gear contact. Since the ground/fly transition of feed-forward shaping involves changing the gain of the command path, uncommanded inputs can be transferred to the rotor if gain scheduling occurs when the stick is displaced. However, if the stick displacement is relatively small, gain scheduling can be introduced with minimal effect.

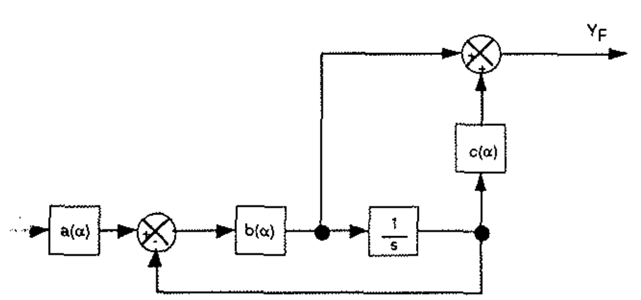


*Fig. 5 Feed-forward shaping block diagram.*

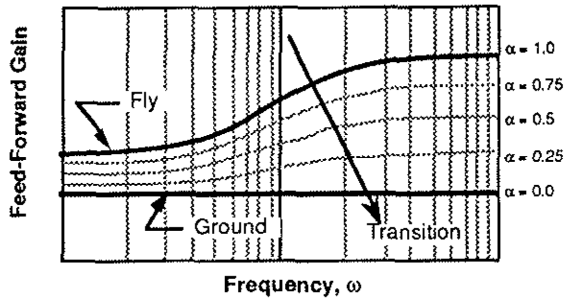


*Fig. 6 Transition of feed-forward shaping.*

### Transition of Rate Stabilization

Rate stabilization provides increased damping of aircraft rigid body modes in a frequency range of approximately 1 to 7 rad/sec. Rate feedback is retained in partial ground state when the aircraft rotational degrees of freedom are not significantly restricted by gear contact. Once a particular axis is constrained by the ground, the corresponding rate feedback channel is rapidly faded to zero. For example, in a cross slope landing, roll rate damping is provided in partial ground state so that the pilot has adequate control of the roll axis while establishing a stable two-point stance and slowly lowering the down slope gear. When both main gear have made contact with the ground, the roll axis is constrained and the roll rate stabilization is ramped to zero. Similar logic is applied to longitudinal and directional axis rate stabilization as well.

The transition of rate stabilization is particularly useful for shipboard landings. After the aircraft has settled on the deck, the pitching and rolling motion of the ship is sensed by the rate gyros but is not transferred to the rotor via rate feedback.

### Transition of Attitude Stabilization

For in-flight operations, attitude feedback is introduced to provide stabilization of low frequency (trim) rigid body modes. However, it is undesirable to allow the attitude loops within the control system to operate once the aircraft becomes constrained by the ground because the system would otherwise *attempt to* perform its primary function, namely, achieve the reference attitude. In a stable hover, the aircraft assumes the hover attitude (e.g. nose up and left wing low). If a landing is attempted to a stationary surface, an attitude error equal to the difference between the hover attitude and the landing surface attitude will develop rapidly. Consequently, if the attitude stabilization is not eliminated as a function of weight-on-wheels, a proportional-plus-integral command will be generated causing the rotor to migrate undesirably. Therefore, at initial gear contact the residual attitude error is rapidly faded to zero.

### Transition of Automatic Trim Follow-up

As mentioned previously, the trim follow-up acts to trim out steady pilot inputs such that the stick always ends up in the detent position for steady trimmed flight. However, for ground state operations, the pilot requires a direct relationship between controller position and total control surface command. Based on these considerations, the trim follow-up control law must provide the following features:

- trim follow-up in fly state
- no trim follow-up in ground state
- common rotor position in ground state referenced to the detent position of the sidearm controller

For in-flight operations, the automatic trim follow-up rate reference is established as the difference between the total command and the trim follow-up output; the trim follow-up continues to integrate until this difference is zero (see Fig. 7). Upon the first gear touch (ANYWOW), the trim follow-up rate is switched to zero and changes in the total command are directly proportional to changes in the feed-forward command. Once the aircraft has all landing gear firmly planted on the ground, the trim follow-up command is driven to the ground state "neutral" position. In ground state, this causes a common rotor position to be referenced to the detent position of sidearm controller. As shown in Fig. 7, the trim follow-up command gradually changes to the ground state neutral position when the NEUTRL condition has been

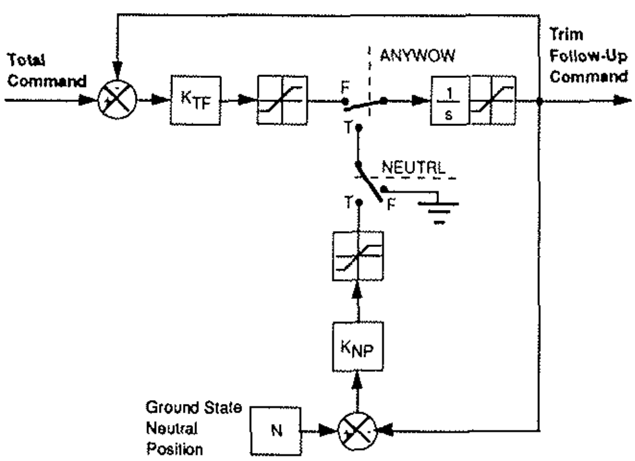


*Fig. 7 Trim follow-up control law.*

satisfied. In this way, the transition of automatic trim follow-up causes the position of the sidearm controller to become a good indication of absolute rotor position and the advantages of displacement control systems are essentially retained.

The ground state neutral position is chosen to minimize the amount of control the pilot applies during takeoff to achieve a smooth and transient-free separation. The longitudinal neutral position is set slightly aft to assist overcoming the forward tilt of the main rotor. The lateral neutral position is essentially zero. The directional neutral position is also very close to zero because most of the anti-torque balancing is provided by collective-to-yaw mixing.

Fig. 8 illustrates the transition of the trim follow-up command for a typical cross slope landing. For simplicity, this discussion is limited to the lateral axis which carries most of the interesting control activity for this maneuver. Time histories of the feed-forward, trim follow-up and total commands are presented whereby the stability augmentation commands (rate and attitude feedback) are assumed to be small. The pilot begins by establishing a stable hover over the intended landing position. A small reduction in collective is applied to establish a gradual rate of descent until the first gear contacts the slope. As the pilot maneuvers the aircraft in a two-point stance, trim follow-up ceases to integrate pilot commands and the changes in total command are proportional to the changes in the feed-forward command. Finally, the collective is lowered further until the down slope gear settles into the slope at which point the rotor is re-referenced to the ground state neutral position.

## Evaluation Methods

The performance of the candidate control law was assessed using two separate evaluation techniques, namely, piloted simulation and an actual flight test vehicle. Piloted simulation was initially used to identify and resolve many of the key issues regarding the functional requirements of the control law. The control law concept was then flight tested using an experimental flight test vehicle which facilitated a safe demonstration and additional refinements of the basic control law design.

## Results

### Piloted Simulation

Piloted simulation was used to evaluate the control law design for various landing and takeoff maneuvers such as the ADS-33C (Ref. 2) vertical landing task, vertical landing in a degraded visual environment (DVE), slope landing and takeoff, running landing in cross winds, in addition to all engines inoperative (AEI) emergency procedures. All of

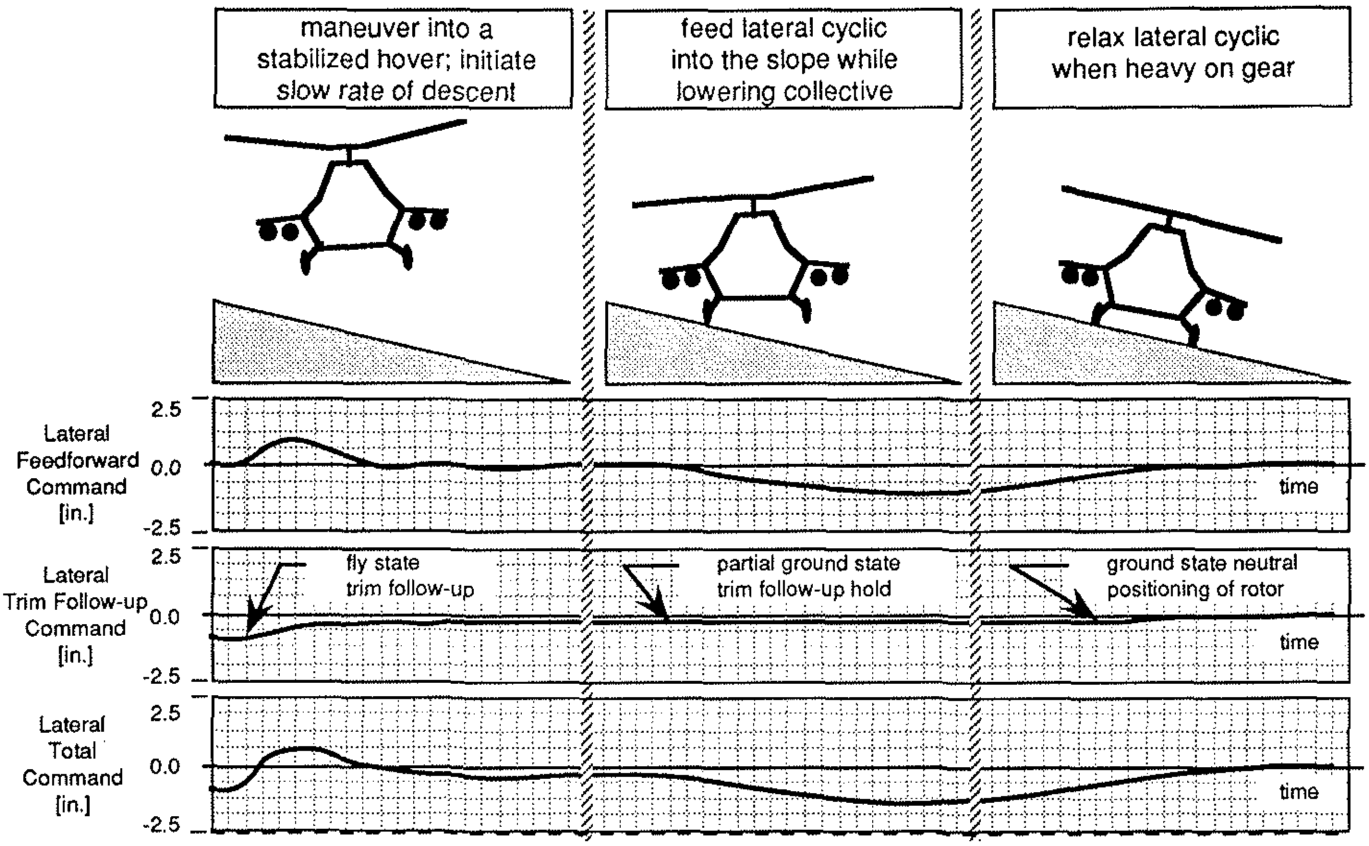


*Fig. 8 Transition of automatic trim follow-up.*

these maneuvers were tested with the Automatic Flight Control System (AFCS) engaged which provides rate and attitude stabilization. In addition, 8° cross slope landings and takeoffs were demonstrated for PFCS operation (AFCS disengaged).

The Cooper-Harper rating scale (Ref. 3) was used as the rating system for all handling qualities evaluations. Hover hold was utilized for both the vertical landing and the DVE vertical landing maneuvers. Hover hold reduced workload associated with maintaining horizontal position and permitted the pilot to apply rapid collective inputs required to meet the task performance criteria. In addition, these tasks demonstrated transient-free disengagement of outer loop stabilization once the aircraft contacted the ground.

For slope landing and takeoff maneuvers with the AFCS engaged (without hover hold), the pilots found it relatively easy to establish and maintain a stable hover over the desired landing position as the aircraft was slowly lowered into a two-gear stance. It was consistently noted by the pilots that rate stabilization offered a tremendous reduction in workload associated with coordinating collective and lateral cyclic for cross slope landings (or longitudinal cyclic for up slope landings) as to maintain proper fuselage attitude as the down slope gear was lowered into the slope. The ANYWOW trim follow-up hold feature facilitated a positive stick-into-the-slope cue as the down slope gear was slowly lowered. Once all three landing gear had made contact with the ground, the transition to the ground state neutral position was transparent to the pilot and considered complementary to the completion of the maneuver. For takeoff maneuvers, the ground state neutral position provided the pilot with a fixed reference point and increased predictability when leading the controller into the slope as the collective was raised. As shown in Fig. 9, Level 1 handling qualities were demonstrated for the rapid vertical landing tasks, in addition to 8° cross slope and up slope landing and takeoff maneuvers.

Slope landings and takeoffs were also performed in simulation to the structural capabilities of the aircraft. Therefore, 12° left and right cross slope, 12° up slope and 6° down slope landings and takeoffs were demonstrated. The down slope landing is very difficult for tail wheel aircraft because the tail wheel has no braking capability and large aft cyclic commands are required to maintain longitudinal position until the main gear contact the slope. Once again, the pilots commented on the benefit of rate stabilization when coordinating the down slope gear. As shown in Fig. 10, for these edge-of-the-envelope maneuvers, Level 2 handling quali-

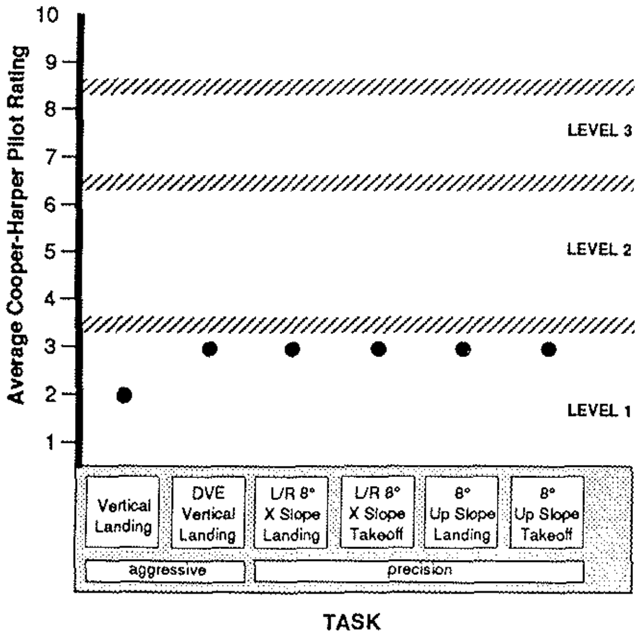


*Fig. 9 Handling qualities ratings from piloted simulation.*

ties were consistently obtained.

Finally, running landings were performed in 15 kt cross winds for a variety of touchdown airspeeds: 60, 35 and 10 kts. For the larger touchdown speeds, the aircraft was decelerated using aerodynamic braking until airspeed was well below translational lift. The nose of the aircraft was then lowered until the main gear contacted the ground at which point mechanical brakes were used to bring the aircraft to a complete stop. For these maneuvers, yaw excursions were noted at initial contact of the tail gear. Although desired performance was attained, task workload was considered to be slightly high resulting in Level 2 handling qualities as shown in Fig. 11. However, it was later shown that the simulator visual scene slightly distorted the pilot's perception of lateral drift during the approach. Lateral drift has a large effect on the magnitude of the yaw excursion as the aircraft tends to pivot about the tail gear after initial ground contact. Finally, 8° cross slope landings were attempted with the AFCS disengaged. Since pitch and roll rate stabilization are not provided in the PFCS configuration, workload associated with coordinating fuselage attitude as the down slope gear was lowered into the slope was higher than with the AFCS engaged. Otherwise, the task was considered to be very reasonable and Level 2 handling qualities were recorded.

### Flight Test Program

An experimental flight test vehicle was used to demonstrate the performance of the landing and takeoff control law, and employed a Comanche-representative PFCS control law architecture. The *SHADOW* aircraft is a modified S-76B helicopter and is configured to evaluate digital FBW rotorcraft flight control system design concepts. As shown in Fig. 12, the *SHADOW* aircraft includes an evaluation crew station mounted to the front of the standard S-76B and is fitted with a unique-trim, sidearm controller for control of the longitudinal, lateral and directional axes. A medium displacement, left hand collective controller is provided for control of the vertical axis. Strain gauges are mounted to each main gear strut and on either side of the nose gear yoke and are used for weight-on-wheels input processing. A safety pilot crew station is located directly behind the evaluation station and is fitted with conventional displacement controls. The safety pilot provides 100% authority over the evaluation station so that modifications to the candidate

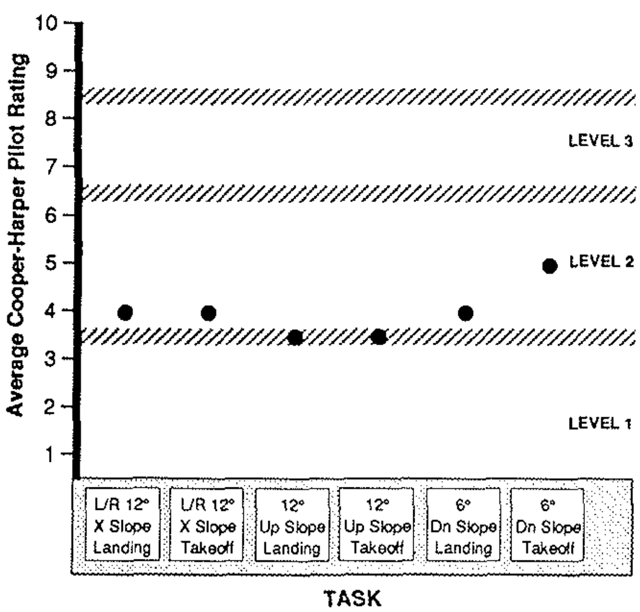


*Fig. 10 Handling qualities ratings from piloted simulation.*

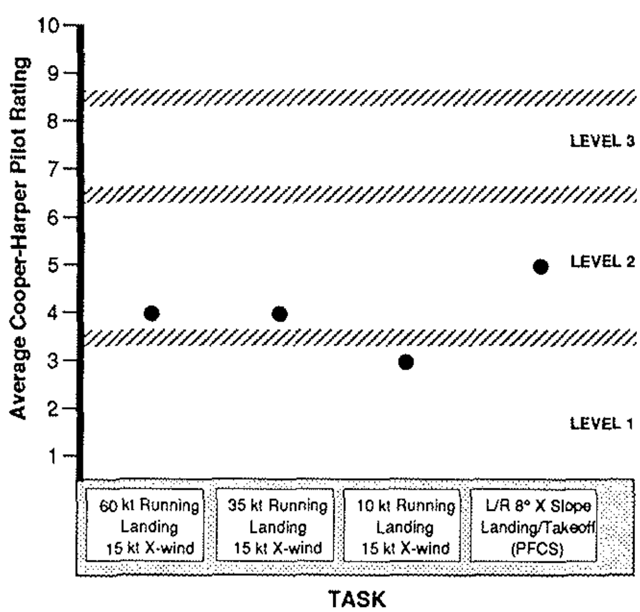


*Fig. 11 Handling qualities ratings from piloted simulation.*

*Fig. 12 SHADOW flight test vehicle.*

control law may be performed rapidly without compromise to flight safety.

The primary objective of the flight test program was to verify the basic control law concept using an actual flight test vehicle while aggressively collecting additional data and insight related to the control law design. Moreover, a thorough understanding of the various functions of the candidate control law and their effect on handling qualities was gained through in-flight demonstration of maneuvers such as vertical, slope and running landings and takeoffs.

A flight control law was included in the *SHADOW* flight control system software which represented the RAH-66 Comanche control laws for PFCS operation. The parameters used in the control law were selected to match the response of the Comanche aircraft for PFCS operation within practical limits. For all maneuvers, transition of the feed-forward shaping from a first order lead/lag filter optimized for in-flight operations to proportional control for on-ground operations was demonstrated to be favorable whereby the pilot had direct control of the rotor tip path plane. Furthermore, the *SHADOW* flight test program provided additional data that corroborated the piloted simulation results with respect to the transition of automatic trim follow-up. It was conclusively shown that the elimination of trim follow-up and use of neutral rotor positioning in ground state provided increased predictability for landing and takeoff maneuvers.

As mentioned previously, the ground state neutral position function re-references the trim follow-up command to fixed value once the aircraft is sufficiently heavy (5% collective command below the ALLWOW condition) on all three landing gear. Observations of the safety pilot control positions for a typical landing maneuver were recorded and used to set the time constant of the ground state neutral position loop to approximately 1 second. In addition, the ground state neutral position loop was rate limited to increase the effective time constant when the difference between the trim follow-up command established at ground contact and the ground state neutral position was relatively large.

Throughout the course of the flight test program, over 200 landings and takeoffs were performed to vertical and cross slope ground planes of up to 8°. Although no Cooper-Harper ratings were recorded, handling qualities were considered to be acceptable for landing and takeoff maneuvers consistent with PFCS operation, and compared favorably with the results from piloted simulation.

## Conclusions

A landing and takeoff control law has been developed for unique-trim, fly-by-wire rotorcraft flight control systems. Through the use of piloted simulation and an actual flight test vehicle, the following conclusions were drawn:

1) The candidate control law supports all handling qualities requirements of the RAH-66 Comanche with respect to landing and takeoff maneuvers.

2) The design solution directly addresses the fundamental limitation of unique-trim control systems for landing and takeoff operations.

3) The control law provides the pilot with kinesthetic cues necessary to maneuver the aircraft to and from a ground state condition.

4) The landing and takeoff control law concept has been verified using the *SHADOW* aircraft while handling qualities were considered to be acceptable for landing and takeoff maneuvers consistent with PFCS operation.

5) Based on piloted simulation:

    a) Level 1 handling qualities were demonstrated for rapid vertical landings and precision slope landing and takeoff maneuvers.

    b) Solid Level 2 handling qualities were demonstrated for slope landing and takeoff maneuvers within the structural capabilities of the aircraft.

    c) Level 2 handling qualities were demonstrated for 8° cross slope landings in PFCS operation (AFCS disengaged) and AEI emergency landings .

## Acknowledgement

The author gratefully acknowledges the *SHADOW* flight test team for their effort during the flight test program. Special thanks to R. Faull, R. Gradle, R. Murrell, S. Silder,

J. Skonieczny and L. Stiles for their contributions to the control law development.

## References

1. Glusman, S. I., Conover, H. W. and Black, T. M., "Advanced Digital Optical Control System (ADOCS), Volume III - Handling Qualities," USAAVSCOM TR 90-D-11C, November 1990.

2. Aeronautical Design Standard, "Handling Qualities Requirements for Military Rotorcraft," AVSCOM, ADS-33C, August 1989.

3. Harper, R. P. and Cooper, G. E., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN-D-5153, April 1969.