MANUDYNE
SYSTEMS INCORPORATED 349 First Street, Los Altos, CA 94022 • (415) 949-1747

AIAA-85-1786

TASK PERFORMANCE MODELING FOR HANDLING QUALITIES SPECIFICATION

Robert K. Heffley and Simon M. Bourne

Presented at:
AIAA Atmospheric Flight Mechanics Conference
Snowmass, Colorado
19-21 August 1985

TASK PERFORMANCE MODELING FOR HANDLING QUALITIES CRITERIA SPECIFICATION

Robert K. Heffley* and Simon M. Bourne**
Manudyne Systems, Inc.
Los Altos, California

Abstract

A structure for roll axis handling qualities criteria specification is presented for helicopters based upon closed-loop task performance modeling. The criteria form is based upon task margin, i.e., the excess task performance capability over the task performance demand. Helicopter roll-axis dynamic models and discrete maneuver analysis techniques are defined. The maximum (bandwidth) performance capability of the closed-loop system is defined using a square-wave control input. A clear audit trail is established between key vehicle design parameters and task performance capability. Task elements, representative of lateral control usage in operational missions, are defined from analysis of flight data. Both near-earth and up-and-away maneuvering phases are considered. The results of a moving-base simulation study are reported. This program allowed refinement of task performance characteristics in a controlled environment. Control power and short-term response variations were made; pilot commentary, opinion rating and time history data were collected. A contol power criteria specification is presented in terms of task margin based upon the simulator data. The criteria structure is independent of the specific task. The task margin approach unifies the concepts of short-term response and control power into a common framework for criteria specification.

Notation

Symbols

A_1	Lateral swashplate angle
K_1	Pilot gain
K	Stick to swashplate gearing
L_{b1}	Flapping stiffness
p_{max}	Maximum peak roll rate
p_{pk}	Peak roll rate
s	Laplace operator
T_1	Average outer loop task interval
T_2	Average inner loop task interval
t	Time
y	Lateral displacement
y_c	Lateral displacement command
γ	Lock number
τ_b	Tip-path-plane lag
$\Delta\phi_c$	Net bank angle change command
ζ	Damping ratio
η	Task margin factor
ϕ	Bank angle
ϕ	Roll rate
Ω	Rotor angular velocity
ω_{bw}	Bandwidth
ω_c	Crossover frequency
ω_n	Natural frequency

Subscripts

man	Maneuver
veh	Vehicle

I. Introduction

The intent of the military specification MIL-H-8501A, General Requirements for Helicopter Flying and Ground Handling Qualities (Reference 1), is to define vehicle characterisics necessary for adequate handling qualities while permitting the designer latitude for innovative solutions. MIL-H-8501A specifies criteria primarily in terms of open-loop response to step inputs. For lateral response to control the criteria are:

- A lower limit on roll damping
- A lower limit on roll attitude change in 0.5 or 1 second following step control input
- An upper limit on control sensitivity, i.e., roll rate per unit stick deflection.

This criteria form has been criticized (References 2 and 3) as being independent of the specific mission and rotor configuration, being only a function of gross weight. Indeed, the pending update of 8501A (Reference 4) requires specification of control system type as function of specific mission elements. Mission task elements are catagorized under: Hover, Take-off, Landing, Near-Earth Maneuvering, Autorotation, VMC Flight, IMC Flight and Up-and-Away Maneuvering flight phases.

There have been several recent efforts to address the mission dependent handling qualities issues. Attack helicopter requirements have been investigated by Aiken (Reference 5). The Nap-of-the-Earth agility and maneuverability requirements have been examined in References 6, 7 and 8, while more recently the D-318 evaluations have considered the air-to-air combat maneuvering requirements (Reference 9).

Until now mission task elements have only been defined by labels, e.g., "slalom", "turn", "scissors maneuver". There has been little attempt to define quantatively the task objectives or to model desired closed-loop task execution characteristics. The current open-loop criteria specifications for handling qualities, even if mission oriented, do not address closed loop task performance. The relationship between short-term response and control power parameters and the closed loop task execution is not defined in the current framework.

Two decades ago Edenborough and Wernicke (Reference 10) attempted to set handling qualities requirements based on closed-loop task execution demands. They utilized flight data from NOE flight tasks such as "evasive action" and "jump-fire-run" to define maximum attitude rate requirements in task execution. The resulting handling qualities criteria were therefore tailored to desired closed-loop task performance demands.

---

*President, Member AIAA.

**Staff Engineer, Member AIAA.

A program presently sponsored by the U.S. Army Aeroflightdynamics Directorate (Reference 11) is applying the concept of task-tailored handling qualities using closed-loop pilot and task models. The primary objective is to examine roll control effectiveness requirements in an operational mission context. Specific program objectives are:

- To model quantatively closed-loop task performance for tasks involving lateral control usage.
- To establish clearly the relationship among key vehicle design parameters, short term response and control power, and closed-loop task execution.
- To provide a handling qualities criteria specification structure based upon closed loop task performance capability and demand.
- To provide a criteria structure that is independent of the specific task and which unifies the concepts of short-term response and control power into a common framework.
- To provide criteria that are suited to demonstration of compliance.

To achieve these goals the technical approach has involved three phases. First, theoretical roll-axis dynamic models were defined. The concepts of closed loop task performance modeling were identified and the relationship among key vehicle model parameters and closed-loop task execution developed. Analysis was then applied to several flight data bases to define roll control usage representative of operational missions. A simulation phase was conducted on the NASA Ames Vertical Motion Simulator (VMS) where task execution could be examined in a controlled environment and cases of degraded control power and short-term response evaluated. Finally, handling qualities criteria specifications were prescribed based upon the simulation data using a "task margin" concept applied to closed-loop performance.

II. Theoretical Development

Helicopter Roll Axis Dynamics

A model of helicopter roll axis dynamics appropriate for helicopter handling qualities analysis was needed for this application. A minimal complexity model was sought which contained only the essential parameters affecting closed-loop task performance.

The rotor dynamics alone were examined as a starting point. Chen (Reference 12) provides a comprehensive derivation of the tip-path-plane equations modeling the effects of hinge offset, hinge compliance, and pitch-flap coupling. The rotor modes are identified in order of reducing natural frequency as the advancing flapping, coning, and regressing flapping modes. It can however be shown that the complete transfer function b_1 due to A_1 closely resembles a first order lag to frequencies beyond $1/\tau_b$, i.e. about 10 rad/sec.

When the helicopter body is coupled to the rotor shaft, the resulting applied force and moment relations are formidably complex (Reference 13). The model is greatly simplified if the thrust is considered to act normal to the tip-path-plane and only the rolling moment applied to the body is considered. This approach ignores higher order effects of some aerodynamic feedbacks but adequately models the dominant effects of coupling between the regressing flapping mode and the body.

The resulting roll-axis dynamic model appropriate for handling qualities analysis takes the form:

$$p(s) = \frac{L_{b_1}/\tau_b}{s^2 + 1/\tau_b\, s + L_{b_1}} A_1(s)$$

The general response is thus second order, not first order as implied by quasi-static models (References 14 and 15). The effective tip-path-plane lag, τ_b, represents a kind of actuator lag. It adds directly to the roll damping for low flapping stiffness (e.g. teetering rotors) and results in an oscillatory roll mode for higher flapping stiffness. The general trend of the dominant roll mode eigenvalue location with rotor stiffness is shown in Figure 1.

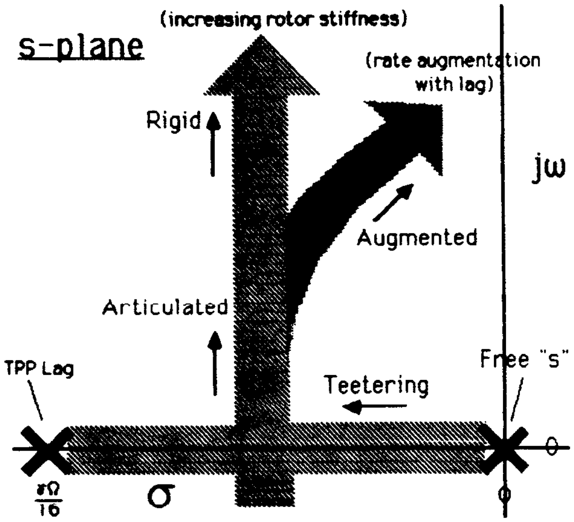


Figure 1. General Trend of Dominant Short Term Mode with Increasing Flapping Stiffness

Task Performance Modeling for Discrete Maneuvers

A general procedure is outlined for analyzing and quantatively describing closed-loop performance of discrete-maneuver flight tasks.

Discrete maneuvers represent an important class of piloting tasks. Most tasks, in fact, are composed of a series of several discrete commands of attitude and power. These commands may not be either periodic or numerous. Thus the classical spectral analysis techniques requiring long record lengths and normally applied to long-term continuous tracking tasks may be of only limited use in describing real piloting tasks.

The analysis of discrete-maneuver tasks is not necessarily more difficult than continuous tasks. Discrete tasks can be portrayed using conventional feedback control block diagrams and Laplace transforms as shown in Figure 2.

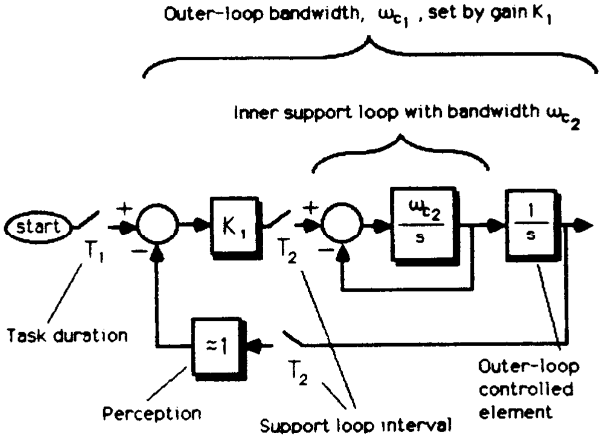


Figure 2. Block Diagram Structure for Discrete-Maneuver Task and Support Loop

This formulation is more thoroughly described in Reference 16 but several features are notable:

- A task generally involves both an inner and an outer-loop.
- The discrete nature can be represented by sampler elements.
- Activity in the inner loop is quicker and more frequent than the outer loop.
- The purpose of the inner loop is to support the outer loop controllability.
- The purpose of the outer loop is to control the basic maneuver.

One factor which can complicate effective task performance measurement is the sometimes short, transitory nature of task execution. For example, a simple sideward translation of a helicopter might span only a dozen seconds and involve one quick bank to start, a second one to stop, and a third to maintain the final position. Each command might typically occur every three or four seconds, and the closed loop response to a command need be only about one half cycle of the dominant mode of the bank angle task. Finally, bank angle commands may not be very periodic. Some of these features are illustrated in the timing diagram of Figure 3. The term "timing diagram" is used because of the resemblence of the sequence of commands to a digital computer software timing sequence. The outer-loop lateral position commands correspond to the slow duty cycle while the inner-loop bank angle commands occur more frequently. However, a typical flight task may involve only a few cycles of commands, and it is therefore necessary to use response identification techniques which will work over a fairly short sample.

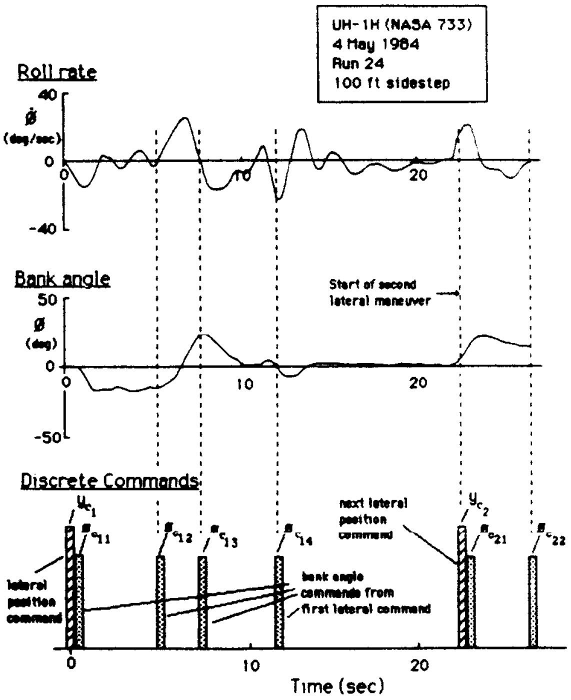


Figure 3. A Timing Diagram for a Typical Helicopter Sidestep Maneuver

One method of handling individual short term discrete maneuvers is illustrated in Figure 4. If the features of a roll maneuver are to be studied, the first step is simply to obtain time history information which indicates the magnitudes of roll rate and corresponding bank angle change. Alternatively, this can be expressed on a phase-plane portrait in which case two important features are clearly seen: (1) The net bank angle change and (2) the peak roll rate during the change. Finally these two features can be cross-plotted to yield a concise summary of a single-discrete maneuver task execution.

Roll rate versus net bank angle change can be interpreted in at least two ways. First the proportion of peak rate to the net change in displacement is proportional to the closed-loop natural frequency or approximate bandwidth (Reference 17). For a broad range of closed-loop damping ratios, the bandwidth is about twice the ratio of the peak rate to the net command. Figure 5 shows the relationship for an ideal second order system. A detailed explanation of this relationship is given in Reference 18 using general second-order system phase plane plots. A more exact determination of closed-loop frequency can be made using routine system identification techniques.

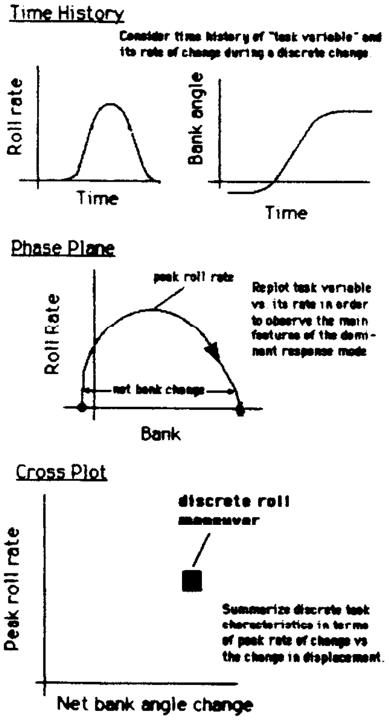


Figure 4. Analysis of Discrete Roll Maneuver Data

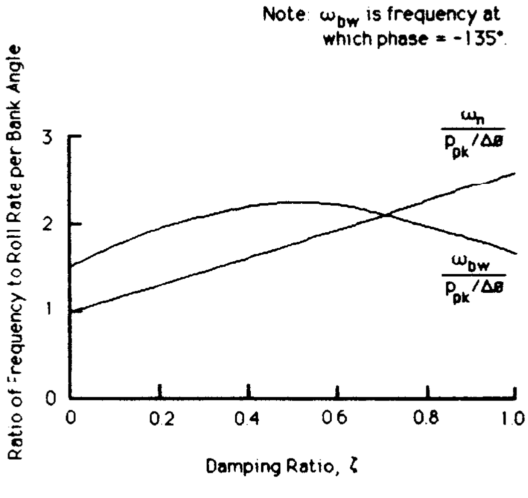


Figure 5. Natural Frequency as a Function of Peak Rate, Net Change, and Damping Ratio

The second important facet of the roll rate versus bank angle change is the "magnitude" of the maneuver in terms of either roll rate or bank angle. It is considered that the former is perhaps a more significant parameter to use in connection with handling qualities since it can be directly compared with the vehicle roll rate capability.

For a specific task execution time history the peak rate/net change analysis technique allows definition of the task "signature". An associated task demand limit can then be defined as shown in Figure 6. The boundary is defined quantatively in terms of the amplitude characteristics (maximum peak roll rate and maximum commanded attitude change) and the aggressiveness characteristics (identified closed-loop natural frequency and damping ratio for small attitude changes).

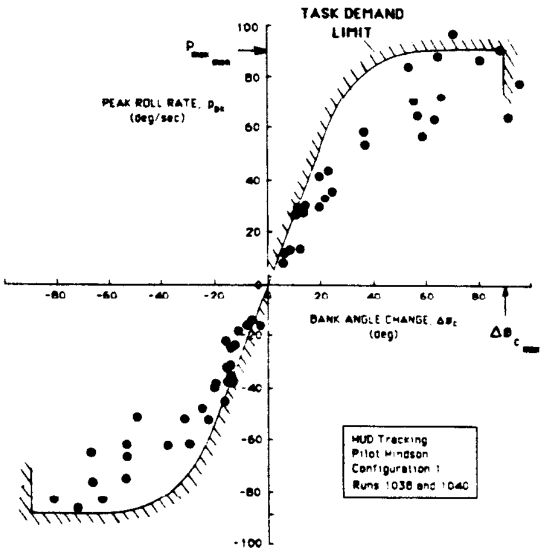


Figure 6. Task Signature and Task Demand Limit.

Maximum Closed Loop Task Performance Capability

Discrete maneuver analysis has allowed quantitative definition of task maneuver demands in terms of aggressiveness and amplitude characteristics. The maximum bandwidth capability of the closed loop pilot vehicle combination needs to be assessed, and the relationship between key vehicle design parameters and closed loop task performance defined.

It can be proven that the maximum bandwidth task performance corresponds to a switching strategy adopted by the pilot. However, for the purposes of defining maximum bandwidth capability a square wave input for a spectrum of amplitudes and dwell times is appropriate. Figure 7 defines the typical maximum bandwidth capability and relates key features of capability to the vehicle design parameters: swashplate authority (A_ϕ), flapping stiffness (L_{b_1}).

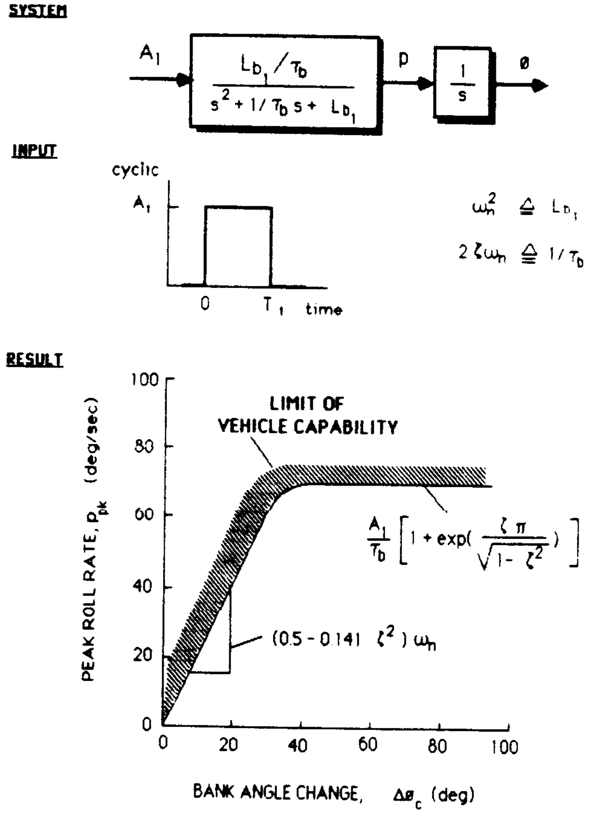


Figure 7. Definition of Maximum Bandwidth Capability Using Square-Wave Inputs.

Review of Flight Data

A wide selection of flight data bases have been analyzed in an effort to define lateral control usage requirements in operational flight phases. A number of in-flight evaluations have been conducted under the auspices of this program, however a diverse collection of data from other sources has been reviewed as detailed in Table 1.

Typical data for closed loop task execution is shown in Figure 8 for the scissors air combat maneuver which is considered by pilots to be a highly aggressive and large amplitude maneuver. In most cases peak roll rates are limited to 40 degs/sec. The helicopter may be capable of substantially greater roll rates yet the pilot does not exploit them. In these data one factor is the limitations imposed by safety considerations, but this trend can be seen even where there are not such restrictions. The phenomemon of roll rate limiting in large amplitude maneuvering has significant implications on swashplate authority and rotor stiffness requirements to achieve desired task performance.

Table 1. Maneuver Flight Data.

Source	Aircraft	Maneuver	Remarks
NASA (Manudyne roll control)	UH-1H	Low altitude U-turn	60 kt, 30-40' AGL
		210° turn at altitude	60 kt, 1000' AGL
		Sideward translation	Hover, 15-20' AGL
		In-line slalom	450' spacing, 60 & 80 kt
		Jinking maneuver	30 kt, 50' AGL
DFVLR	UH-1D & BO-105	"U. S. slalom"	60 kt, 100' AGL
		"German slalom" (jink)	
		High-g turn	
NATC/AVSCOM	OH-58, UH-60, S-76, & AH-1	Scissors maneuver	D-318 data base
NADC	X-22A	Lateral sidestep	No synthetic turbulence
NASA/Army (Corliss and Carico)	UH-1H (variable stability)	"U. S. slalom"	1000' spacing, 60kt, L_p and $L_{\delta A}$ variations

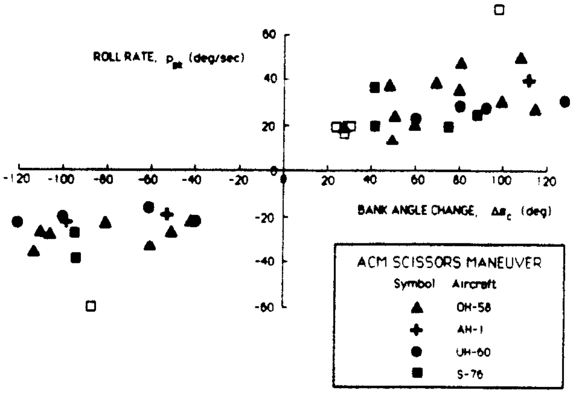


Figure 8. Scissors Maneuver Flight Data for a Variety of Helicopters.

III. Simulation Program

Objectives

Key maneuvers involving lateral control usage representative of operational helicopter missions were identified in Phase 1. A theoretical approach provided quantative modeling of closed loop task performance. Furthermore definition of closed-loop task performance capability has been defined in terms of key vehicle design parameters. With this background a six week simulation program was conducted on the NASA Ames Vertical Motion Simulator (Reference 19).

The simulation tasks chosen corresponded one-on-one with those tasks previously analyzed from flight data in both the near-earth and the up-and-away flight phases. The only additional task considered was a Head-Up-Display (HUD) roll tracking task similar to that detailed in Reference 20.

Simulation procedures consistent with those outlined in Reference 21 were used. Motion base and manipulator characteristic optimization was made prior to data collection. Pilot commentary and Cooper-Harper opinion ratings were collected, as well as time history data for control and response variables on magnetic tape. The discrete-maneuver analysis method was implemented on-line to recover aggressiveness and amplitude information.

The primary simulation objectives were:

- Define closed loop task performance characteristics under controlled conditions.
- Examine the effect of control power limitations on task execution
- Examine the effects of short term response parameters on task execution.

Definition of Task Performance Catalog

For each of the lateral maneuvers flown in the simulation the task signature and maneuver demand limits were assessed using the plot of peak roll rate versus attitude change. The amplitude characteristics could be assessed visually from the task signature. The aggressiveness characteristics for precision attitude control needed to be identified from the closed loop simulation data. Identification was made using the least squares technique within an equivalent second order system resulting in an effective closed loop natural frequency and damping ratio. Extensive identification was made in the HUD tracking and sidestep tasks, while relatively smaller samples of data were analyzed for the other maneuvers.

Table 2 presents the task performance catalog defined from the simulation data. A unique task signature and demand limit has thus been ascribed to each task.

Table 2. Lateral Task Performance Catalog.

Task	Aggressiveness (natural frequency)	Settling (damping ratio)	Amplitude (max roll rate) $p_{max_{man}}$	(max bank change) $\Delta\phi_{c_{max}}$
HUD Tracking	4.0 rad/sec	0.5	65 deg/sec	90 deg
ACM Tracking	2.5	0.5	40-50	110
ACM Free engagement	-	-	40	70
Sidestep	4.5	0.5	35	60
Jinking Maneuver	4.5	0.4	60	80
Slalom	2.0	0.6	30	50
Visual turn	1.5	0.45	40	40
IFR turn	-	-	10	25

Aggressiveness and settling identified for attitude changes < 10°.

Observations on Closed Loop Task Performance

Analysis of the peak roll rate/ attitude change task signature and the identified aggressiveness results led to the following observations:

- The closed loop bandwidth reduces with the amplitude of the maneuver. This is clearly shown in Figure 9 for the ACM tracking task. The task performance is clearly not constrained by the vehicle capability; the observed bandwidth reduction with amplitude is purely a human imposed phenomenon in multi-loop task execution. This feature is evident in all tasks examined.
- For precision attitude control (small $\Delta\phi$) consistent aggressiveness ($\zeta : \omega_n$) were observed for a diverse selection of tasks including HUD and ACM tracking, sidestep and jink maneuvers. Precision attitude control (short term response requirements) may therefore be independent of the specific task involved.
- The variability of task execution (i.e., identified natural frequency) is greatest for precision attitude control.

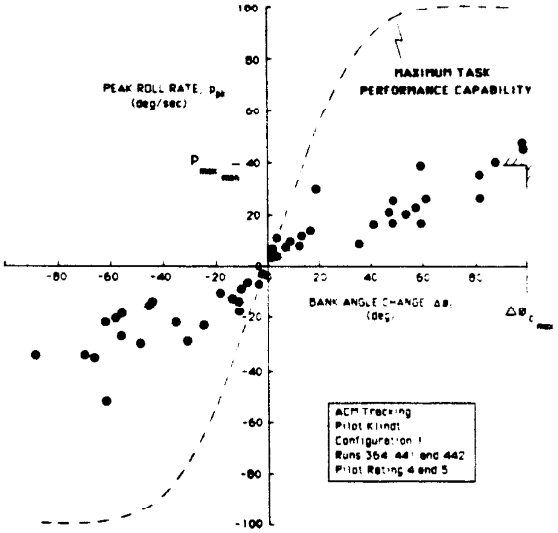


Figure 9. Task Signature for the Simulator Air Combat Maneuvering Task.

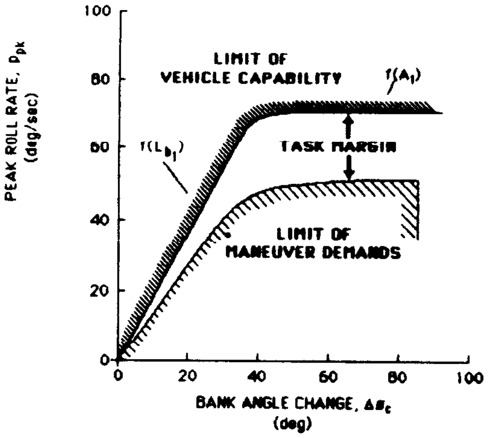
IV. Control Effectiveness Criteria

Definition of Task Margin

Task margin is defined as the excess task performance capability over maneuver performance demand. It is hypothesized to be a parameter appropriate for handling qualities criteria specification.

The specific means of viewing the vehicle capability versus demand in task performance is governed by the primary parameter of interest; whether it is control power or short-term response. Short-term response characteristics dominate in small-amplitude or precision attitude control tasks, while the control power effects are associated with large-amplitude maneuvering. In order to address both of the above characteristics adequately the task margin forms shown in Figure 10 are suggested.

a. Control Power Analysis



b. Short-Term Response Analysis.

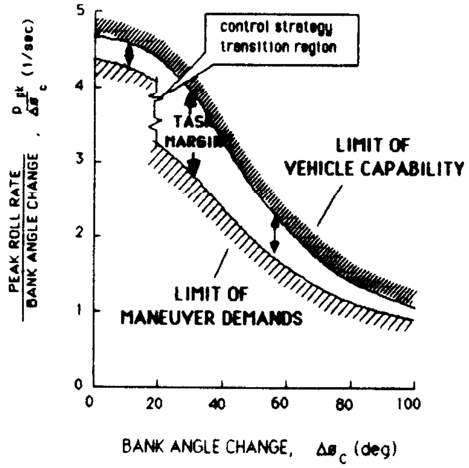


Figure 10. Definition of Task Margin for Handling Qualities Analysis.

This form of presentation provides a consistent framework within which to view the relationship of short term response and control power to closed loop task execution.

Roll-Axis Control Power

During the simulation, task performance was evaluated under degraded control power conditions for a diverse set of different tasks: HUD tracking, ACM tracking and sidestep tasks.

Figure 11 represents typical data for control power degradation in the HUD tracking task. This was effected by saturation of the pilot control input (no hard stops were imposed). Control saturation effects were measured for three maneuvers, HUD tracking, ACM tracking, and sidestep.

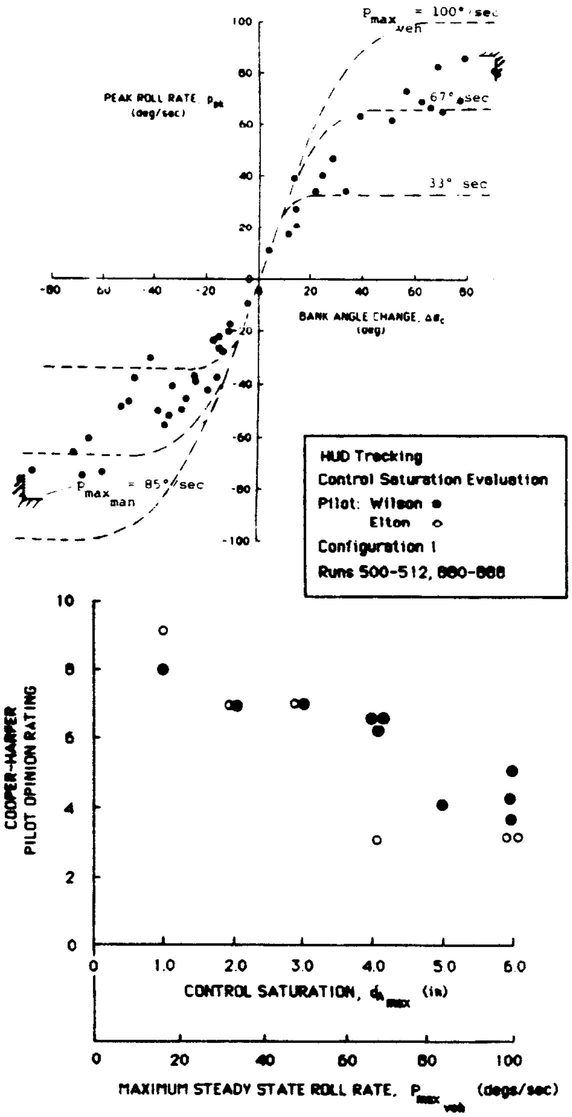
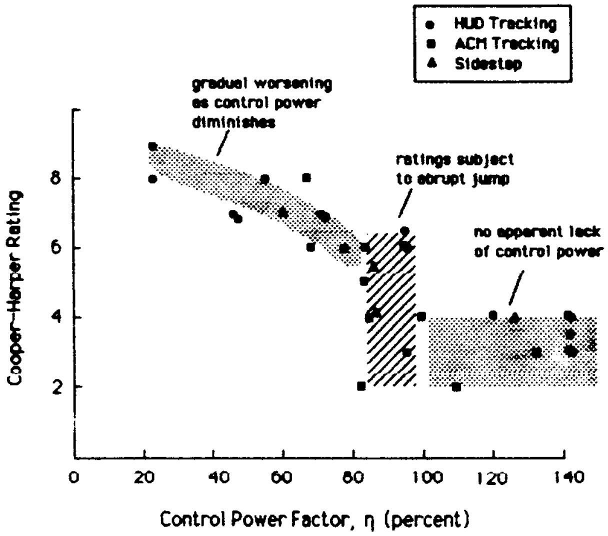


Figure 11. Data for Control Power Degradation in the HUD tracking Task.

The deterioration in pilot rating due to task-dependent deficiency in control power followed a consistent trend in each case. For a control power capability about 15 deg/sec under the maximum task demand, the pilot rating was subject to an abrupt worsening. Additional saturation then produced a more gradual degradation. These data are plotted in Figure 12 using the control pwer task margin factor, η. Thus a control power criterion based upon the parameter η is <u>maneuver independent</u>. Note that there is no graceful degradation from Level 1 to Level 2. Rather, the jump essentially is from Level 1 to Level 3.



$$\eta \triangleq \frac{p_{max_{veh}}}{p_{max_{man}} - 15°/sec}$$

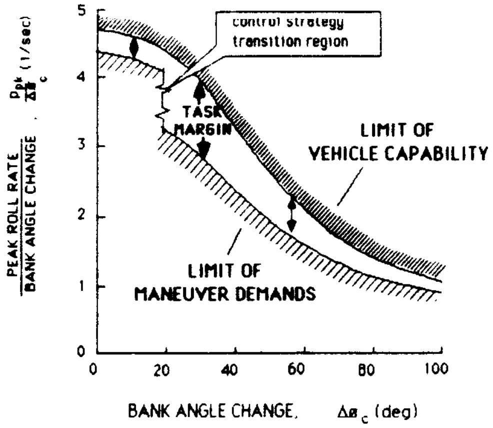
Figure 12. Plot of Control Power Data in Terms of Maneuver Margin Factor, η.

Short-Term Response

Vehicle short term response variations were made during the VMS simulation period. Figure 13 defines the vehicle capability limits for three vehicles representing a teetering rotor with a Bell-bar, an articulated rotor and a "rigid" rotor. The data points shown represent maximum bandwidth data collected for the three vehicles in the HUD tracking task. It is observed that the pilot exploits the increased bandwidth capability of the system in effecting the task. Furthermore, there appears to be two regions of distinctly different task execution. For small amplitudes (precision attitude control) the pilot may be using a pursuit strategy, using close to the maximum bandwidth capability of the system. This region corresponds to a pulsive type control strategy. For larger attitude changes there is a significant reduction in the closed loop bandwidth sought.

Due to the task design and the relatively long simulation time delay (about 200 msec) adequate pilot opinion ratings and commentary are not available to provide a criteria specification for short term response. The above data however suggest that the task margin approach is appropriate to the specification of short term response characteristics as well as to control power. The definition of specific numbers for the criteria will be pursued in the future.

a. **Implied Form of Short-Term Response Task and Vehicle Factors.**



b. **HUD Tracking Task Performance and Vehicle Characteristics from Simulator.**

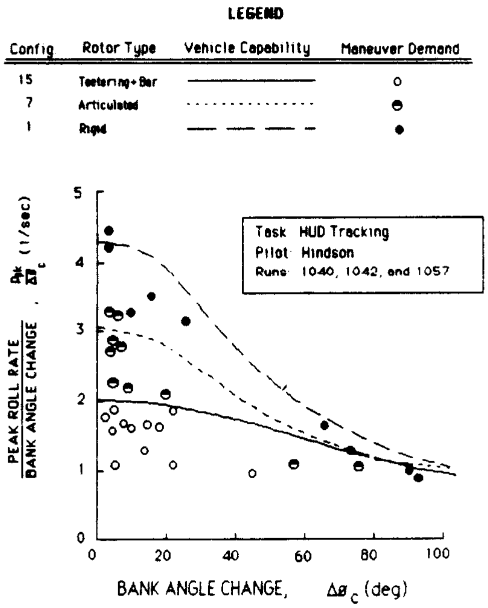


Figure 13. Short-Term Response Data for the HUD Tracking task.

V. Conclusions

Closed loop task performance can be defined in terms of the peak roll rate/attitude change signature. Quantitative values for maneuver amplitude and aggressiveness can be used to define maneuver demand limits. A quantitative catalog of task performance has been compiled for a diverse set of flight tasks from Nap-of-the-Earth to Air Combat Maneuvering.

The fundamental dynamics governing helicopter roll response have been defined. A square wave input method has been used to define maximum task performance capability and clearly define the audit trail between key vehicle design parameters and closed loop task performance. This input is suited to the demonstration of vehicle capability in the flight test environment.

The definition of task margin (the excess of vehicle performance capability over the pilot's task demand) has proven viable for integrating the concepts of short-term response and control power into a common framework. The contribution of each to closed loop task execution has been clearly defined. The approach has provided a unified structure for the specification of short term response and control power handling qualities criteria. This structure is based upon closed loop performance and independent of the specific task involved in strict contrast to the current MIL-H-8501 criteria.

The simulation program allowed definition of specific numbers for a control power criteria based upon the task margin approach. Simulator limitations and task design did not provide an adequate definition of a short-term response criteria.

Additional work is required to refine and examine second order effects in the control power criteria specification. A future simulator or in-flight program also is required to define the short term response criteria. An in-flight program may be required if significant improvement cannot be made in simulator delay effects.

Acknowledgements

This work ws sponsored by the U. S. Army Aeroflightdynamics Directorate, U. S Army Aviation Research and Technology Activity (AVSCOM) under NASA Ames Research Center Contract NAS2-11665.

References

1 Anon., Military Specification: Helicopter Flying and Ground Handling Qualities, General Requirements for, MIL-H-8501A, 7 Sept. 1961.

2 Ashkenas, I. L., and R. P. Walton, Analytical Review of Military Helicopter Flying Qualities, Systems Technology, Inc., Technical Report No. 143-1, August 1967.

3 Key, D. L., A Critique of Handling Qualities Specifications for U. S. Military Helicopters, Paper Presented at the AIAA 7th Atmospheric Flight Mechanics Conference, Danvers, Mass., 11 August 1980, AIAA-80-1592.

4 Clement, W. F., R. H. Hoh, S. W. Ferguson, III, D. G. Mitchell, I. L. Ashkenas, and D. J. McRuer, Mission-Oriented Requirements for Updating MIL-H-8501, Volume 1 Proposed STI Structure, USAAVSCOM Technical Report 84-A-6.

5 Aiken, E. W., and R. K. Merrill, Results of Simulator Investigation of Control System and Display Variations for an Attack Helicopter Mission, AHS Preprint 80-28, May 1980.

6 Tomlinson, B. N., and G. D. Padfield, Piloted Simulation Studies of Helicopter Agility, Vertica, Vol. 4, Numbers 2-4, 1980, pp. 79-106.

7 Dooley, L. W., Handling Qualities Considerations for NOE Flight, Journal of the American Helicopter Society, October 1977, pp. 20-27.

8 Chen, R. T. N., P. D. Talbot, R. M. Gerdes and D. C. Dugan, A Piloted Simulator Study on Augmentation Systems to Improve Helicopter Flying Qualities in Terrain Flight, NASA TM-78571, March 1979.

9 Wolfrom, J. A., Data Presentation from Air-to-Air Combat Maneuvering between an OH-58 and an S-76, U. S. Army Research and Technology Laboratories (AVSCOM), Ft. Eustis, VA. USAAVSCOM TM-84-D-6.

10 Edenborough, H. K., and K. G. Wernicke, Control and Maneuver Requirements for Armed Helicopters, Paper Presented at the Twentieth Annual National Forum of the American Helicopter Society, Washington, D.C., May 1964.

11 Anon., Study to Develop Helicopter Roll Control Effectiveness Criteria, Manudyne Systems, Inc., Contract NAS2-11665, July 1983.

12 Chen, R. T. N., A Simplified Rotor System Mathematical Model for Piloted Flight Dynamics Simulation, NASA TM-78575, May 1979.

13 Talbot, P. D., B. E. Tinling, W. A. Decker and R. T. N. Chen, A Mathematical Model of a Single Main Rotor Helicopter for Piloted Simulation, NASA TM-84281, September 1982.

14 Heffley, R. K., W. F. Jewell, J. M. Lehman and R. A. Van Winkle, Compilation and Analysis of Helicopter Handling Qualities Data, Volume 1: Data Compilation, NASA CR-3144, August 1979.

15 Heffley, R. K., A Compilation and Analysis of Helicopter Handling Qualities Data, Volume 2: Data Analysis, NASA CR-3145, August 1979.

16 Heffley, R. K., Pilot Workload Modeling for Aircraft Flying Qualities Analysis, NADC Report No. NADC-82094-60, May 1984.

17 Heffley, R. K., Pilot Models for Discrete Maneuvers, AIAA 82-1519-CP, August 1982.

18 Heffley, R. K., T. M. Schulman and W. F. Clement, An Analysis of Airline Landing Flare Data Based on Flight and Training Simulator Measurements, NASA CR 1166404, August 1982.

19 Heffley, R. K., S. M. Bourne, H. C. Curtiss, Jr., W. S. Hindson, R. A. Hess, Study of Helicopter Roll Control Effectiveness Criteria: Preliminary Draft, Manudyne Systems, Inc., Los Altos, CA. Report 83-1, May 1985.

20 Monogan, S. J., R. E. Smith and R. E. Bailey, Lateral Flying Qualities of Highly Augmented Fighter Aircraft, Air Force Flight Dynamics Laboratory, WPAFB, AFWAL-TR-81-3171, June 1982.

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