An Analysis of Pilotage Task Maneuver Metrics

Chris L. Blanken
Aeroflightdynamics Directorate
US Army Aviation and Missile Command
Ames Research Center
Moffett Field, California, USA

Carl J. Ockier
Deutsche Forschungsanstalt für
Luft- und Raumfahrt e.V. (DLR)
Institut für Flugmechanik
Braunschweig, FRG

Abstract

A helicopter handling qualities investigation was conducted to characterize the pilot's basic flying task and its impact on handling qualities. This study involved complementary use of a NASA ground-based and a DLR in-flight simulator. Over 150 evaluations were collected while performing three roll-axis slalom-type maneuvers at three different speeds over a range of control-response bandwidths. Putting the results into the traditional flying qualities metrics like bandwidth and attitude quickness parameters shows that: some increase is recommended in the Level 1 attitude quickness boundary for Air Combat, the Level 1 bandwidth boundary for Air Combat is fairly well supported, and decreases are recommended in the Level 2 attitude quickness and bandwidth boundaries. Using these results to correlate with frequency-domain task-characterization metrics had mixed results: the metrics varied for different tasks but their relationship to handling qualities was unpredictable. Using a time-domain task-characterization metric had similar results but was somewhat more predicable.

Notation

L_p	Roll axis damping derivative
$L_{\delta y}$	Roll axis control sensitivity
p	Roll rate
$p_{pk}/\Delta\phi_{pk}$	Roll attitude quickness
δ_y	Lateral stick input
ϕ	Bank angle
η_v	Number of flight path changes required in a given task
θ	Pitch angle
τ_p	Phase delay
$\omega_{BW\phi}$	Vehicle response bandwidth
ω_{BWt}	Task bandwidth
$\omega_{c\text{-}o}$	Cut-off frequency, the frequency at which 70% of the control input energy is reached.
ω_t	Natural frequency of the task
ω_{t1}	Natural frequency of the task based on a single-cycle slalom.
ω_ϕ	Natural frequency of the roll-flap regressive mode

Introduction

Aircraft handling qualities are defined as "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role" (Ref. 1). The key words here are *ease*, which covers the workload associated with performing the task, and *precision*, which covers the task performance. Both influence the pilot's perception of handling qualities and are highly dependent upon the task. It is well recognized that the development of handling qualities criteria and requirements are task dependent. Figure 1 illustrates a typical scheme for the development of handling qualities data from which criteria and requirements can be defined. This involves using complex ground-based and in-flight simulators to investigate a wide range of inceptor and stability and control parameters for a specific task; collecting supporting qualitative pilot opinion data using the Cooper-Harper rating scale (Ref.1); and correlating these quantitative and qualitative data to formulate criteria. This iterative and expensive process is valid for the task investigated. If the task changes, the process must be repeated. The key to breaking this iterative process is a thorough characterization of the task and its impact on handling qualities. Then one might be able to expand the data base analytically instead of having to investigate handling qualities while performing every specific task; this would reduce the design-development costs for upgrades to current aircraft and for new aircraft through unifying results and requirements for a variety of tasks and missions.

The importance of tasks is recognized in the US Army's handling qualities requirements for military

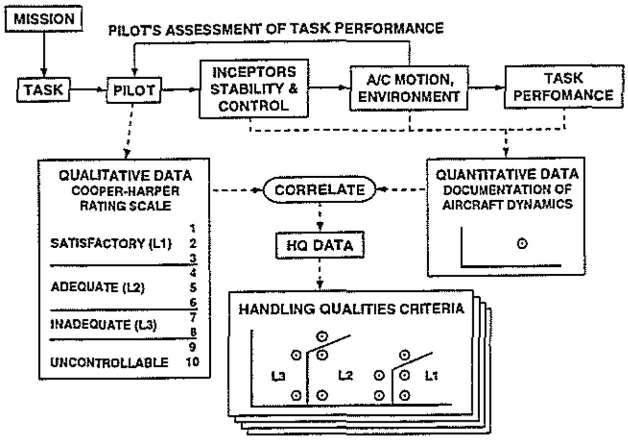


Fig. 1. Schematic for handling qualities evaluation and criteria development.

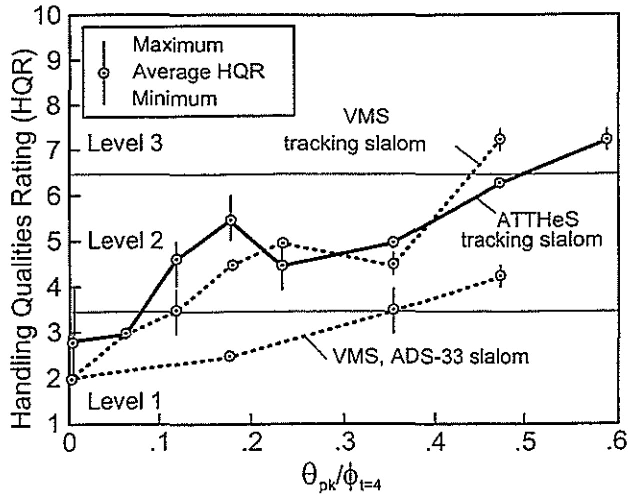
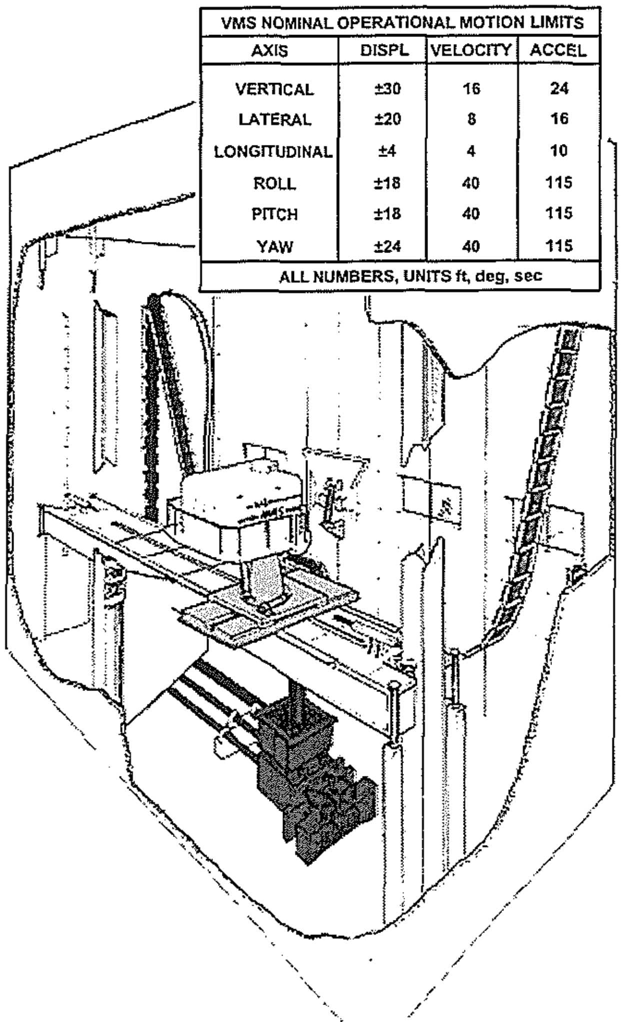


Fig. 2 Comparison of HQRs with the ADS-33D coupling parameter for two different slalom tasks.

rotorcraft, i.e., Aeronautical Design Standard–33 (ADS-33D)(Ref. 2), through the use of Mission Task Elements (MTEs) and flying qualities criteria that distinguish between different Performance Parameter Categories (PPCs). Generally, the MTEs are partitioned in terms of low-amplitude precision tasks and larger-amplitude aggressive tasks. There is also a distinction between performing the task on a clear day or in a degraded visual environment, such as at night or in poor weather. The quantitative requirements are grouped in terms of PPCs that are related to the precision and aggressiveness of the MTEs. The task dependent boundaries are largely based upon results of individual tests, and not a systematic task-characterized database that would allow a more thorough understanding of the relationship between the task demands and handling qualities.

An example of these task demands or influences on handling qualities is shown in Fig. 2. Presented are ground-based and in-flight simulation results from a pitch-roll cross coupling investigation (Ref. 3) conducted under the US/German Memorandum of Understanding (MOU) for Cooperative Research in Helicopter Aeromechanics. Two different roll-axis slalom tasks were evaluated with increasing amounts of off-axis coupling. One task was a tracking slalom task with precise tracking phases through a set of ground-marked gates (ground based and in-flight tracking tasks are labeled 'VMS tracking slalom' and 'ATTHeS tracking slalom', respectively). The other task was a slight modification of the ADS-33D slalom task which consists of flying around a series of evenly-spaced markers on alternating edges of the runway (labeled 'VMS, ADS-33 slalom'). The slight modification was a tighter tolerance on maintaining height and speed. The pilot handling qualities ratings (HQRs) are shown versus the ADS-33D cross coupling metric, i.e., the peak off-axis response divided by the on-axis response four seconds after the control input. One can clearly see that more coupling can be tolerated for the ADS-33 slalom task than for the tracking slalom task while still remaining within the Level 1 region. Although there are other influences on handling qualities, such as the effects of the quality and amount of cueing available to the pilot between the ground-based and in-flight simulator, the basic flying task plays the dominant role.

With the aforementioned as a basis and motivation, a study was initiated to gain a more thorough understanding of the relationship between pilotage tasks (as opposed to mission management tasks) and handling qualities. The objectives were to develop a methodology that characterizes or quantifies the task and then, define a relationship between this task characterization and the required rotorcraft response characteristics for Level 1 and Level 2 handling qualities. Recent and past experience with slalom-type maneuvers made it logical to continue to concentrate on the roll axis. The approach was to conduct piloted ground-based and in-flight simulations to evaluate several different task geometries over a range of control response bandwidths at three different airspeeds. The data were then compared against traditional flying qualities requirements like the bandwidth and attitude quickness requirements from ADS-33D. Then several task characterization metrics and their relationships with the handling qualities were evaluated. This paper will describe the piloted simulation facilities, the tasks evaluated, conduct of the tests, and some initial results. This work was



VMS NOMINAL OPERATIONAL MOTION LIMITS			
AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	±30	16	24
LATERAL	±20	8	16
LONGITUDINAL	±4	4	10
ROLL	±18	40	115
PITCH	±18	40	115
YAW	±24	40	115
ALL NUMBERS, UNITS ft, deg, sec			

Fig. 3. Vertical Motion Simulator (VMS) at NASA-Ames Research Center.

performed by the Aeroflightdynamics Directorate (AFDD), US Army Aviation and Missile Command and the German Institute of Flight Mechanics, German Aerospace Research Establishment (DLR) under the US/German MOU. This topic also forms an element of an on-going collaborative effort into helicopter handling qualities between the AFDD, the German Institute of Flight Mechanics, and the Flight Management and Control Department, UK Defense Evaluation and Research Agency (DERA).

Ground-Based and Airborne Simulator

This section will describe the ground-based and in-flight simulation facilities that were used for the piloted evaluations.

Ground-Based Flight Simulator

The ground-based simulation was conducted on the NASA-Ames six-degree-of-freedom Vertical Motion Simulator (VMS) (Fig. 3). The cockpit had a single pilot seat mounted in the center of the cab and three image presentation "windows" to provide outside imagery. The visual imagery was generated using an Evans and Sutherland CT-5A Computer Image Generator. The baseline stick-to-visual delay was 72 milliseconds plus the cycle time for the math model (12 milliseconds) for a total of about 84 milliseconds. A seat shaker provided vibration cueing to the pilot, with frequency and amplitude programmed as functions of airspeed, collective position, and lateral acceleration. Aural cueing was provided to the pilot by a WaveTech sound generator and cab-mounted speakers. Airspeed and rotor thrust were used to model aural fluctuations. Standard helicopter instruments and inceptors were installed in the cockpit.

Mathematical models of the following items were programmed in the simulation host computer: (1) trim capability, (2) dynamics of the helicopter, and (3) ground effects. The dynamics of the helicopter were represented by a stability-derivative model with known dynamics and no coupling (Ref. 4), and the character of its response was easily manipulated by changing the stability derivatives. In addition, the minimum power airspeed ("bottom of the bucket") was purposely set at around 29 knots, such that for the speed ranges being investigated, i.e., 40 through 80 knots, the rotorcraft response was always on the "same side" of the power curve.

Airborne Flight Simulator

Using a BO 105 helicopter as the testbed, the DLR – Institute of Flight Mechanics – developed the in-flight simulator ATTHeS (Advanced Technology Testing Helicopter System). ATTHeS (Fig. 4) had a full-authority non-redundant fly-by-wire (FBW) control system for the main rotor and a fly-by-light (FBL) tail rotor actuator. The aircraft was operated by a crew consisting of an evaluation pilot and a safety pilot. The safety pilot's position was equipped with the standard mechanical link to the rotor controls, whereas the evaluation pilot's controls were linked to the rotor via a control computer and the FBW/L system. The FBW/L actuator inputs, which were commanded by the evaluation pilot via the control computer, were mechanically fed back to the safety pilot's controls who could override the FBW/L actuator inputs at any time.

The control system of ATTHeS was based on an explicit model following control system (MFCS) design (Ref. 5). It provided high quality simulation fidelity up to a frequency of about 10 rad/sec in the roll axis. For this study, a control computer cycle time of 40 msec was used. The equivalent time delay of the overall system – due to high order rotor

Fig. 4. DLR in-flight simulator ATTHeS.

effects, actuators dynamics, computational time and pilot input shaping – was about 110 msec in the roll axis and 160 msec in the pitch axis, related to the first-order rate command response.

On May 14, 1995, the ATTHeS in-flight simulator crashed during a routine ferry flight, killing the crew of two: Klaus Sanders (pilot) and Heinz-Jürgen Zimmer (mechanic). Both had actively taken part in the flight tests described in this report.

Description of the Tests

This section will describe the tasks evaluated and the details of the ground-based and in-flight simulation campaigns.

Definition of the Tasks

In addition to collecting data to help address the more subtle cueing effects between the ground-based and in-flight simulation results for the same task, handling qualities data were collected to cover variations in the overall task geometry. Three different slalom-type tasks were performed on both the VMS and the ATTHeS: a tracking slalom task, a gate slalom task, and a symmetrical slalom task. Additional tasks were performed on the VMS, but only the ADS-33D slalom will be briefly discussed in this paper (see Ref. 2 for a task description). Each of these tasks was separated into a primary and a secondary task. The primary task was defined as: "*Tracking through or rounding the gates marked on the ground. For tracking tasks, the center bar of the front window shall be used to minimize the error during acquisition and tracking phases. Position of the gates may be determined by the forward field of view, and not by the actual position of the helicopter.*" The secondary task was defined as: "*Maintaining the target height and speed.*"

Tracking slalom task

The tracking slalom task (Fig. 5) was identical to the US/German MoU slalom used for the 1991 bandwidth/phase delay (Ref. 6) and the 1992/93 pitch-roll coupling tests (Refs. 3 and 7). The tracking slalom is an asymmetrical slalom with precise tracking phases through a set of 3 m wide and 150 or 90 m long ground marked tracking gates.

Desired performance for the tracking slalom was defined as follows: "*Successfully tracking the 3 meter wide gates (± 1.5 meters from centerline), with height and speed within the tolerances (±10 ft and ±5 kt).*" Adequate performance for the tracking slalom was defined as follows: "*Tracking the gates while staying within 3 meters from the center line of the gate, and/or maintaining height ± 20 ft and speed ± 10 kt. Performing the slalom without a clear tracking phase is NOT adequate performance!*"

Gate slalom task

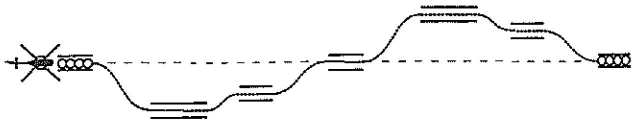
The gate slalom task (Fig. 6) is a modification of the tracking slalom. The 150 or 90 meter long tracking phases have been reduced to simple gates (or two posts). When passing the gate, the aircraft flight path must be parallel to the longitudinal axis of the course (*i.e. perpendicular to the gate*). Having only two posts to define a gate eliminates the tracking phase from the slalom and reduces the task to transition between and acquisition of the gates. On the VMS, the visual resolution of the imagery system made it difficult to see gates more than 150 m away.

Desired performance for the gate slalom was defined as follows: "*Passing through the 3 meter wide gates parallel to the longitudinal axis of the course, with height and speed within the tolerances (±10 ft and ±5 kt).*" Adequate performance for the gate slalom was defined as follows: "*Passing within 3 meters from the center of the gate parallel to the longitudinal axis of the course, and/or maintaining height ± 20 ft and speed ± 10 kt. Flying through the gates without trying to pass parallel through the axis of the course is NOT adequate performance!*"

Symmetrical slalom task

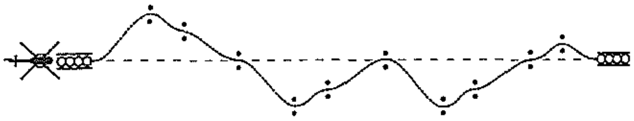
The symmetrical slalom (Fig. 7) is stylized after the ADS-33D slalom (Ref. 2), but has a tighter height and speed requirement. In addition, on the VMS the lateral offset of the gates was reduced to 10 m and the requirement to finish the slalom task on the centerline was dropped. The symmetrical slalom only has transition phases, no acquisition or tracking phases.

Desired performance for the symmetrical slalom is defined as follows: "*Successfully rounding the poles,*



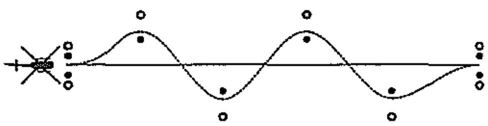
	VMS	ATTHeS
Number of gates	7	7
Overall course length (m)	1541	1546
Lateral offset of gates (m)	3 / 6½ / 10	3 / 6½ / 10
Target speed (kt)	40 / 60 / 80	40 / 60 / 80
Target altitude (ft)	30	100
Primary altitude cues	Cueing poles	Radio alt.

Fig. 5. The tracking slalom task.



	VMS	ATTHeS
Number of gates	7	12
Overall course length (m)	888	1546
Lateral offset of gates (m)	3 / 6½ / 10	3 / 6½ / 10
Target speed (kt)	40 / 60 / 80	40 / 60 / 80
Target altitude (ft)	30	100
Primary altitude cues	Cueing poles	Radio alt.

Fig. 6. The gate slalom task (ATTHeS in-flight simulation version).



	VMS	ATTHeS
Number of gates	7	6
Overall course length (m)	945	760
Lateral offset of gates (m)	± 10	± 15
Target speed (kt)	40 / 60 / 80	40 / 60 / 80
Target altitude (ft)	50	100
Primary altitude cues	Cueing poles	Radio alt.

Fig. 7. The symmetrical slalom task (ATTHeS version).

with height and speed within the tolerances (±10 ft and ±5 kt). At all times during the slalom, the helicopter must be within 25 meters from the centerline of the course." Adequate performance for the symmetrical slalom is defined as follows: "*Successfully rounding at least half the poles and passing close to or over the remaining poles, and/or maintaining height ± 20 ft and speed ± 10 kt.*"

Conduct of Test

For the study of pilotage task metrics in maneuvers, variations in three parameters were made: geometry of task, velocity through the task, and the vehicle control response bandwidth. These variations were explored through two simulator campaigns: a ground-based simulation on the VMS and an in-flight simulation on the DLR's ATTHeS helicopter. A third flight experiment was conducted on a US Army UH-60 Black Hawk helicopter, but will not be discussed here.

The ground-based simulation

The first test took place on the VMS during a two-week period in April 1994. This simulation was focused on collecting a preliminary data-base to aid in understanding of the issues and to aid in selecting courses and parameters for the in-flight simulation. During the ground-based simulation study, a total of seven slalom courses, each flown at three different velocities were evaluated. The helicopter response dynamics were varied through the stability derivatives and focused on variations to the roll-axis bandwidth through the roll damping derivative, L_p. As L_p was varied, the control sensitivity was also varied to keep an optimal response for the given bandwidth. The initial range on L_p was from -10 to -2 per second, which after considering visual transport delays provided a range of bandwidths from 4.40 to 1.54 rad/sec. During the test it was necessary to expand the range of L_p to include -1 and -0.5. The pitch-axis dynamics were varied in harmony with the roll axis, i.e., maintaining a two-to-one ratio between roll and pitch damping derivatives. As the roll bandwidth was decreased, if a corresponding low pitch bandwidth started to become a dominant influence in the ratings, then a change in this ratio between roll and pitch was investigated in an attempt to maintain a Level 1 pitch response.

Given the number of days allocated on the simulator for this study and based upon the number of task variables, helicopter response variables, and pilots, there was insufficient time to cover all the possible combinations. In total, 71 different configurations were evaluated, with three test pilots participating, two NASA pilots and one US Army pilot. Because of these time constraints, some prudent pairing of configurations was necessary. For each of these configurations, the pilot performed a number of training runs and at least two evaluation runs. After each configuration, he completed a questionnaire and assigned a handling qualities rating using the Cooper-Harper rating scale (Ref. 1).

The in-flight simulation
The second test took place on the DLR's variable stability helicopter at the German Forces Flight Test Center (WTD-61) in Manching in October 1994. The objective of this test was to collect a solid data base for the study of pilotage task maneuver metrics. The test plan was based on lessons learned and first impressions from the VMS tests. The two experimental variables in the test plan were the task definitions (3 courses and 3 velocities) and the helicopter response dynamics. The helicopter response dynamics were varied through the command model of the model-following control system. For these tests, a decoupled rate command attitude hold (RCAH) command model was implemented. For this command model, the approximate roll response was given by the following transfer function:

$$\frac{p}{\delta_y} = \frac{L_{\delta_y}}{.05s^2 + s - L_p} e^{-0.11s}$$

Bandwidth was changed through variations in the damping derivative, L_p, along with associated changes in sensitivity, $L_{\delta y}$. For the tests, no additional time delays were used. A rate of climb response was defined for the collective input and sideslip command was defined for the pedals. In principle, pilot inputs were fully decoupled, except for the terms governing turn coordination and roll attitude thrust compensation. The model-following control system was optimized for 60 kt forward flight, so that some deficiencies could be expected at off-design speed. These were very mild at 80 kt, but turned out to be more severe at 40 kt, which is why only a few data points were collected at this velocity.

During two weeks of testing, a total of 40 configurations were evaluated. For each evaluation, the pilot performed a few practice runs through the course, followed by two evaluation runs. For each configuration flown, the pilot completed a comprehensive questionnaire and assigned a handling qualities rating using the Cooper-Harper scale (Ref. 1). Since almost all configurations were rated by at least two pilots, this resulted in a total of 80 data points. Five test pilots participated in the tests: one NASA pilot, one Royal Navy/DERA pilot, one US Army pilot, one WTD-61 pilot and one DLR pilot. The NASA and the Army pilot also participated in the VMS tests.

Discussion of the Results

This section will describe the results from the ground-based and in-flight simulations. Initially the results are presented against the bandwidth requirements from ADS-33D and then in terms of two frequency-domain task-characterization metrics. Finally the results are shown against the ADS-33 attitude quickness requirements and an attitude quickness-type task-characterization metric is explored.

Vehicle bandwidth requirements from the VMS tests
Figure 8 shows the averaged handling qualities ratings (HQRs) against the vehicle's roll-axis bandwidth for the three slalom tasks plus the ADS-33D slalom. Of all slalom tasks, the tracking slalom appears to require the highest bandwidth, whereas the symmetrical slalom appears to be the least demanding of all the tasks. The 80 kt tasks were generally found to be the most demanding, but the 40 kt task is not clearly less demanding than the 60 kt task. It should be pointed out that many of the evaluations are based on the opinion of only one pilot, and that individual pilot differences may have contributed to the differences in ratings between tasks.

From Fig. 8, the Level 1-2 and Level 2-3 crossing points for the VMS tests were obtained and replotted along with the ADS-33D requirements (see Fig. 9). Roughly four groups of tasks can be distinguished: (1) a task with a Level 1-2 bandwidth requirement of about 1 rad/sec (gate slalom at 40 kt); (2) tasks with a bandwidth requirement of about 2 rad/sec (tracking and gate slaloms at 60 kt and the symmetric slaloms at 40, 60 and 80 kt); (3) tasks with a bandwidth requirement of about 2.5 rad/sec (tracking slalom at 40 kt and the ADS-33D slalom); and (4) a task with a bandwidth requirement of more than 4 rad/sec (tracking slalom at 80 kt). It should also be noted that the gate slalom at 80 kt did not receive a Level 1 rating even at the highest bandwidth evaluated.

In general, the slower speeds and the symmetric tasks at moderate speeds seem to require less bandwidth than the tracking type tasks at higher velocities. Nevertheless, the bandwidth requirement for the tracking slalom at 80 kt (4.2 rad/sec needed for Level 1) seems very high. Conversely, at the other end of the spectrum it is interesting to observe that for some tasks a Level 3 rating was not obtained, even at bandwidths below 0.5 rad/sec. Compared to the ADS-33D boundaries (shown at the top of Fig. 9), the HQRs from these tasks circumscribe both the Air Combat and All Other MTE requirements from Ref. 2 on the high and low end.

Vehicle bandwidth requirements from the flight tests
Figure 10 shows the averaged HQRs against the roll-axis bandwidth for the slalom tasks evaluated on ATTHeS. The differences between the tasks are

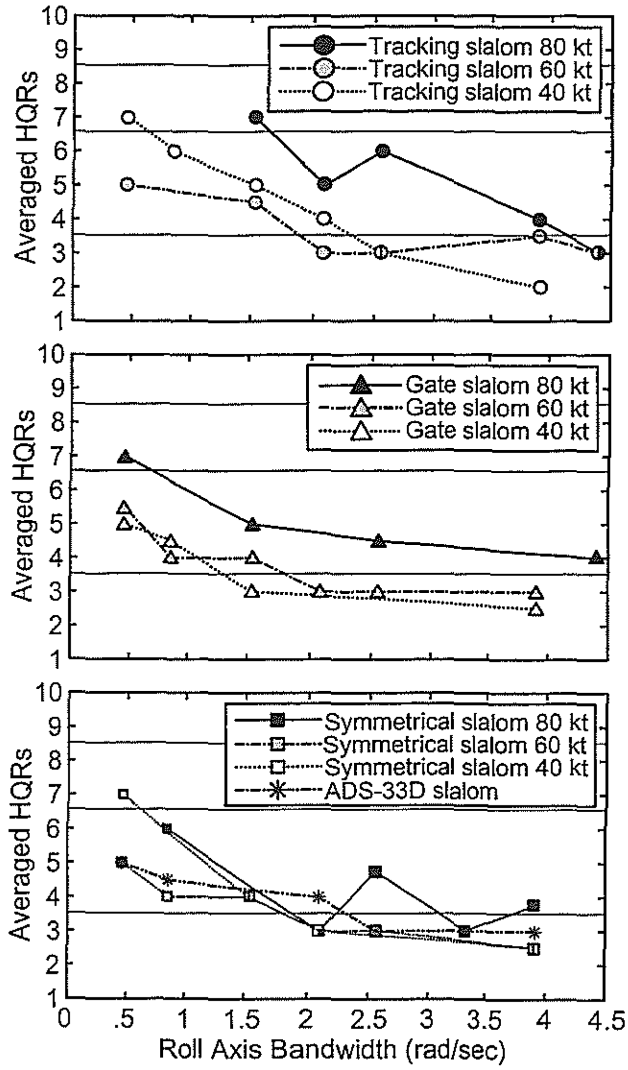


Fig. 8. Averaged handling qualities rating versus roll-axis bandwidth (VMS tests).

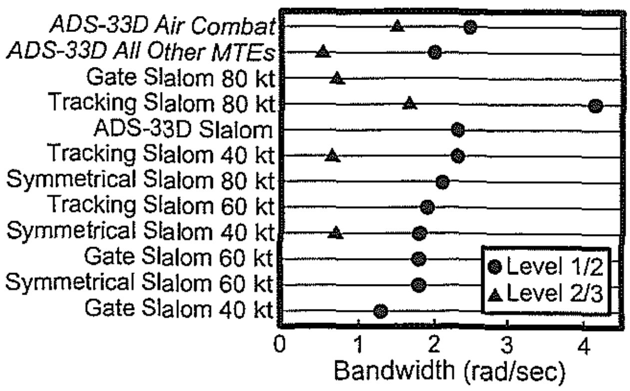


Fig. 9. Vehicle bandwidth requirements (VMS).

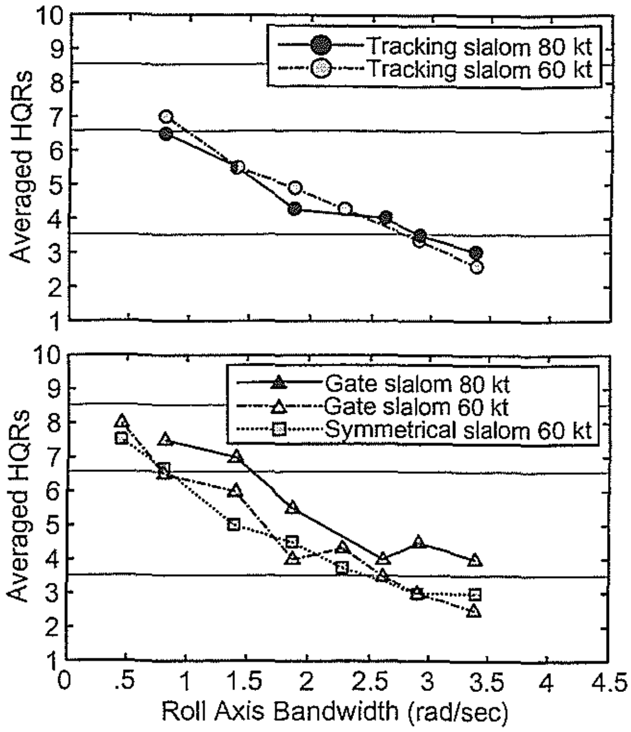


Fig. 10. Averaged handling qualities rating versus roll-axis bandwidth (ATTHeS tests).

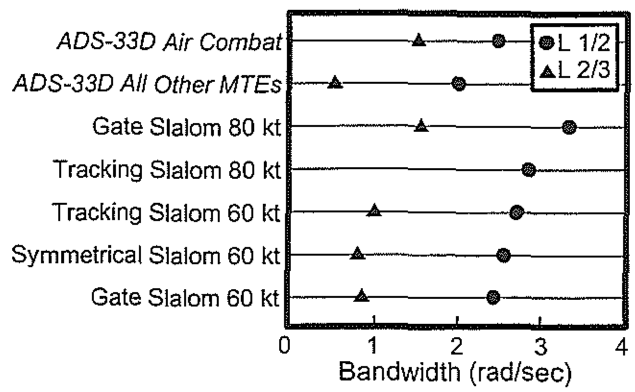


Fig. 11. Vehicle bandwidth requirements (ATTHeS).

obviously much smaller than for the VMS tests. From this diagram, the most demanding task is clearly the gate slalom at 80 kt, although it must be noted that the pilots complained about too little sensitivity for the baseline (L_p=-8, $L_{\delta y}$=0.130) case. When the sensitivity for this case was increased to $L_{\delta y}$=0.153, an HQR of 3 could be obtained. The same results can be read from Fig. 11 which shows the Level 1-2 and Level 2-3 crossing points for the five flight tested slalom tasks. Here, the differences in task demands appear smaller than for the VMS, e.g., the Level 1-2 ATTHeS boundary spans a frequency range from around 2.4 to around to 3.3 rad/sec whereas, the VMS results span a range from just over 1 up to 4.2 rad/sec. The Level 2-3 ATTHeS crossover points span a frequency of around 0.8 rad/sec, for the least demanding tasks, to around 1.5 rad/sec for the more demanding gate

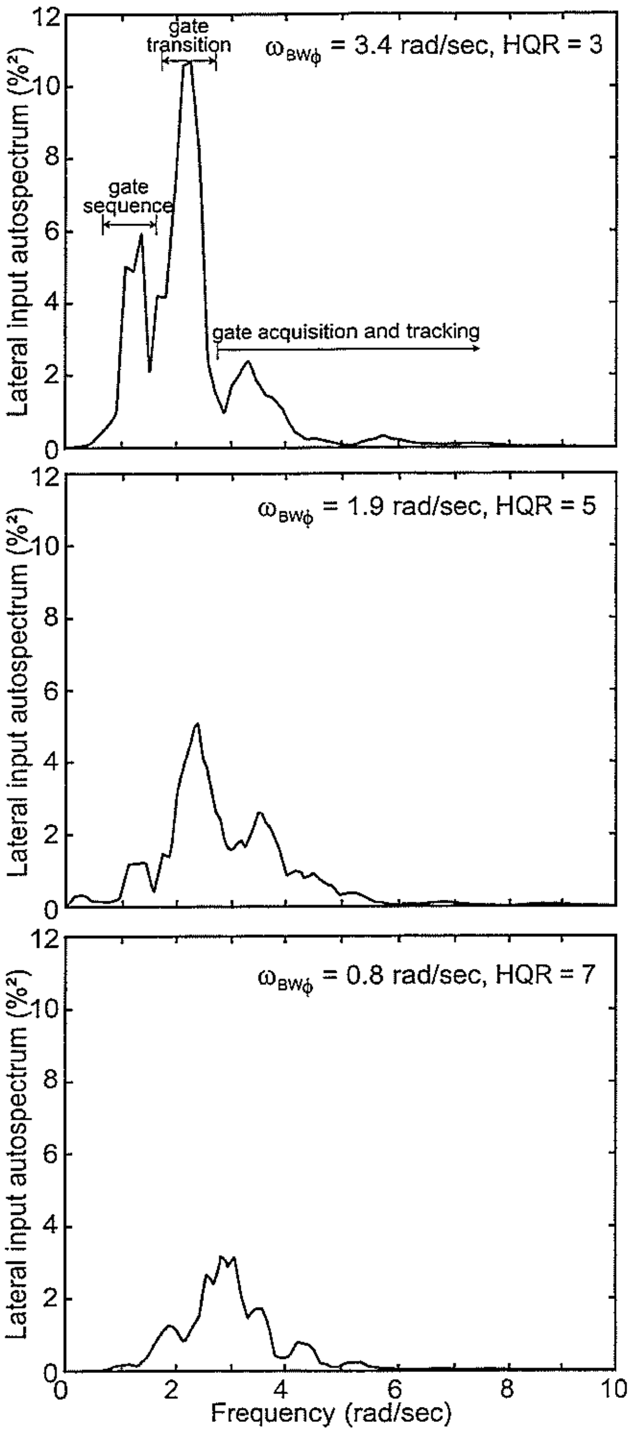


Fig. 12. Lateral control autospectrum of 60 kt tracking slalom (ATTHeS).

slalom task at 80kt. Except for this gate slalom at 80 kt data, the ADS-33D Air Combat Level 1-2 requirements of 2.5 rad/sec is fairly well supported by this data. On the other hand, these same data support lowering the ADS-33D Air Combat Level 2-3 requirements from 1.5 rad/sec to around 1.0 rad/sec. Coincidentally, Whalley (Ref. 8) also recommended a reduction in these Level 2-3 requirements to 1.0 rad/sec.

Frequency-domain tasks metrics

A number of frequency-domain parameters were explored as task-characterization metrics. Two of these will be discussed and are referred to as: the task bandwidth; and the aircraft-task frequency ratio.

Task Bandwidth. One method explored was an examination of the pilot's control activity to try to quantify differences in the task demands and the impact on handling qualities. The autospectrum of the pilot's control inputs shows the frequency content of the control inputs throughout the entire task. Shown in Fig. 12 is the autospectrum of the pilot's lateral cyclic from the ATTHeS in-flight simulation for the tracking slalom task at 60 knots. Note that as the vehicle handling qualities degrade, the control inputs will generally shift towards higher frequencies while, at the same time, the amplitude decreases.

The pilot cut-off frequency, $\omega_{c\text{-}o}$, is used as a means to quantify the information contained in the autospectrum. That is, the $\omega_{c\text{-}o}$ can be thought of as a measure of the pilot's control activity bandwidth and is defined as the frequency at which 70% of the control input energy (the integral of the input power) is reached. This metric was first proposed by Tischler, and applied to a fidelity assessment of a UH-60 simulation (Ref. 9). It was postulated that when the aircraft's control response bandwidth exceeds the task demands such that the pilot can achieve desired task performance with minimal compensation, this pilot cut-off frequency gives a good approximation of a so-called task bandwidth, ω_{BWt}.

Figure 13 shows ω_{BWt} for each of the tasks evaluated in the VMS. Note how the tracking and gate slaloms are grouped together at a higher frequency (1.7 to 2.7 rad/sec) than the symmetric and ADS-33 slaloms (0.7 to 0.9 rad/sec). Also placed on this figure are the evaluated Level 1-2 roll-axis bandwidth boundary (i.e., $\omega_{BW\phi}$ where HQR=3.5) for each of the tasks. One might suspect that for satisfactory handling qualities, the control response bandwidth, $\omega_{BW\phi}$, should be greater than ω_{BWt}, i.e., the pilot should have some vehicle response margin at least equal to or preferably greater than the demands of the task. Heffley introduced this idea in a comprehensive helicopter roll control study (Ref. 10). We call this difference between the vehicle response bandwidth and the task bandwidth, ($\omega_{BW\phi}$ - ω_{BWt}), a task margin. Indeed, Fig. 13 shows for the symmetric and ADS-

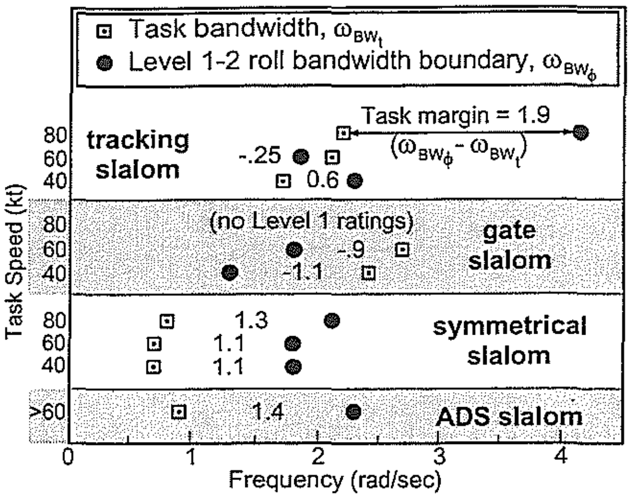


Fig. 13. Task bandwidths and Level 1-2 roll-axis bandwidth required from VMS.

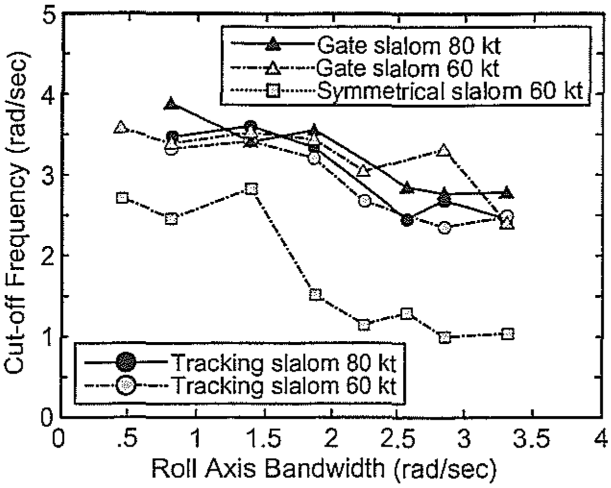


Fig. 14. Averaged cut-off frequencies versus roll-axis bandwidth (ATTHeS).

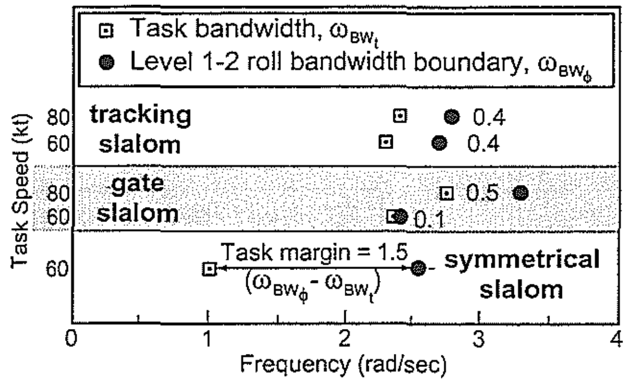


Fig. 15. Task bandwidths and Level 1-2 roll-axis bandwidth from ATTHeS.

ADS-33 slaloms there is a task margin between 1.1 rad/sec and 1.4 rad/sec. Curiously, the task margin is near zero for the tracking slalom at 60 kt. and even negative for the gate slalom at 40 and 60 kt. The 1.9 rad/sec margin for the 80 kt tracking slalom performed on the VMS seems exceptionally high, and is primarily due to the seemingly high bandwidth (4.2 rad/sec) required for Level 1. It appears there is more task margin for the larger amplitude maneuvers and less (even negative margins) for the smaller amplitude more precise slaloms. This difference could be influenced by more open-loop low-frequency control inputs for the larger amplitude maneuvers.

Figure 14 shows $\omega_{c\text{-}o}$ versus $\omega_{BW\phi}$ from the in-flight simulation for the different slalom tasks evaluated. For all tasks, the pilot cut-off frequency increases with decreasing bandwidth (and degrading handling qualities). This trend is most pronounced for the symmetrical slalom case, and least pronounced for the 60 kt gate slalom. Following the same procedure used above, one can determine the approximate task bandwidth for each task. Figure 15 shows the task bandwidths and the Level 1-2 roll-axis bandwidths from the in-flight simulation data. The numbers adjacent to data points show the task margins, i.e., $\omega_{BW\phi} - \omega_{BWt}$. Comparing the $\omega_{BW\phi} - \omega_{BWt}$ data between the in-flight and ground-based simulation for the larger amplitude symmetrical and ADS-33D slaloms (Fig. 15 to 13), one observes that the task margin is essentially the same for each simulator (between 1.1 to 1.5 rad/sec) even though the handling qualities Level boundaries are different. For the smaller amplitude more precise tracking and gate slaloms, the ATTHeS results show task margins which are smaller or almost zero (between 0.5 and 0.1 rad/sec). The VMS results had these same trends of smaller (or even negative) task margins for the tracking and gate slaloms. Unfortunately, the task margin appears to be different for different tasks and thus may not be well suited toward a universal or generic task-characterization parameter. It appears that some account of the maneuver amplitude must also be considered.

Aircraft-task frequency ratio. Another frequency-domain characterization investigated was a combination of parameters first introduced in 1994, by Padfield et. al. and referred to as the aircraft-task frequency ratio. The authors presented in a paper (Ref. 11) the results of their work to characterize pilot control activity and its relation to an aircraft-task characterization. In addition to the analytical and numerical simulations, a flight test was conducted to corroborate the theoretical results from the simulations. The analytical simulation showed how the pilot's control strategy was "likely to change with

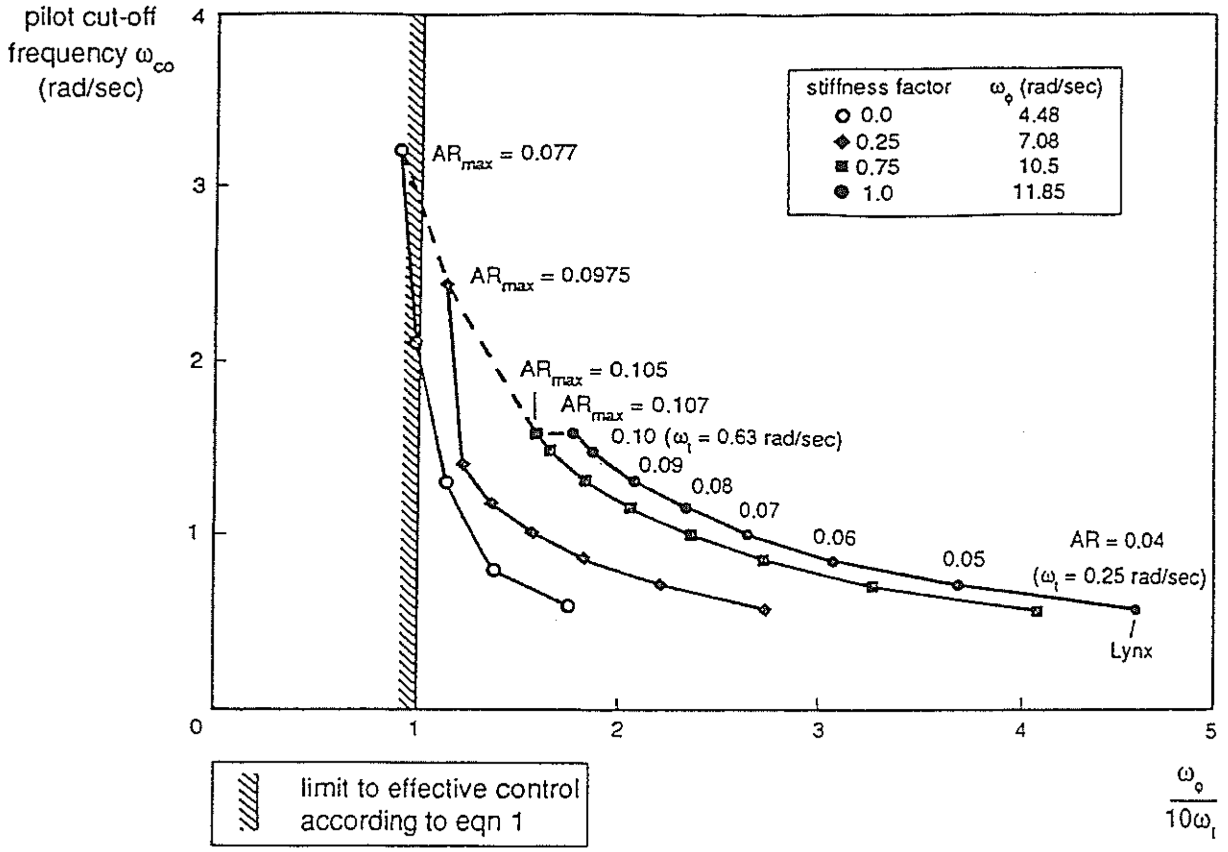


Fig. 16. Pilot cut-off frequency as a function of frequency ratio for HELINV slalom flights (from Ref. 11).

the temporal and spatial demands of a mission task element." For quantifying the pilot's control activity, one method investigated was also the use of the pilot cut-off frequency, $\omega_{c\text{-}o}$. For the aircraft-task characterization, the helicopter was characterized using a frequency-domain parameter, ω_ϕ, defined to be equal to the natural frequency of the roll-flap regressive mode. This means ω_ϕ is highly influential on and closely related to the attitude response bandwidth. The task was also characterized in the frequency domain through a parameter defined as the task natural frequency, ω_t. For a simple two-sided slalom, i.e., from wings-level through one sinusoidal motion of the ground track and back to wings-level, the value of ω_t was very closely related to the inverse of the task time. The authors suggested that there is a limit to this aircraft-task frequency ratio which represents an effective control limit:

$$\omega_\phi/\omega_t > 2\eta_v \quad \text{or} \quad \omega_\phi/2\eta_v\,\omega_t > 1 \qquad (1)$$

where η_v = number of flight path changes required in a given task.

For the simple two-sided slalom, η_v equals five and hence $\omega_\phi/10\omega_t > 1$ to avoid this limit. In the paper, a parametric variation of the task width-to-length (aspect ratio) for the simple slalom along with several vehicle natural frequencies, ω_ϕ, representing a teetering, articulated, hingeless, and Lynx rotor are shown for an airspeed of 60 knots, see Fig. 16. If above the effective control limit, one observes for constant aspect ratio tasks that the pilot cut-off frequency, $\omega_{c\text{-}o}$, remains relatively constant as $\omega_\phi/10\omega_t$ decrease due to decreases in ω_ϕ. It was observed from the ATTHeS in-flight simulation data (Fig. 14) that the pilot cut-off frequency increases as the vehicle bandwidth decreases for each of the tasks evaluated. That is, as the helicopter control response bandwidth decreases, the pilot must modify his control strategy by adding compensation to try to achieve "Desired" and then "Adequate" task performance. This has the overall effect of making his control activity smaller in amplitude and higher in frequency, e.g., recall Fig. 12.

Figure 17 from the Ref. 11 shows the analytical results and flight test results for the Lynx helicopter. Although the same general trends exist between the

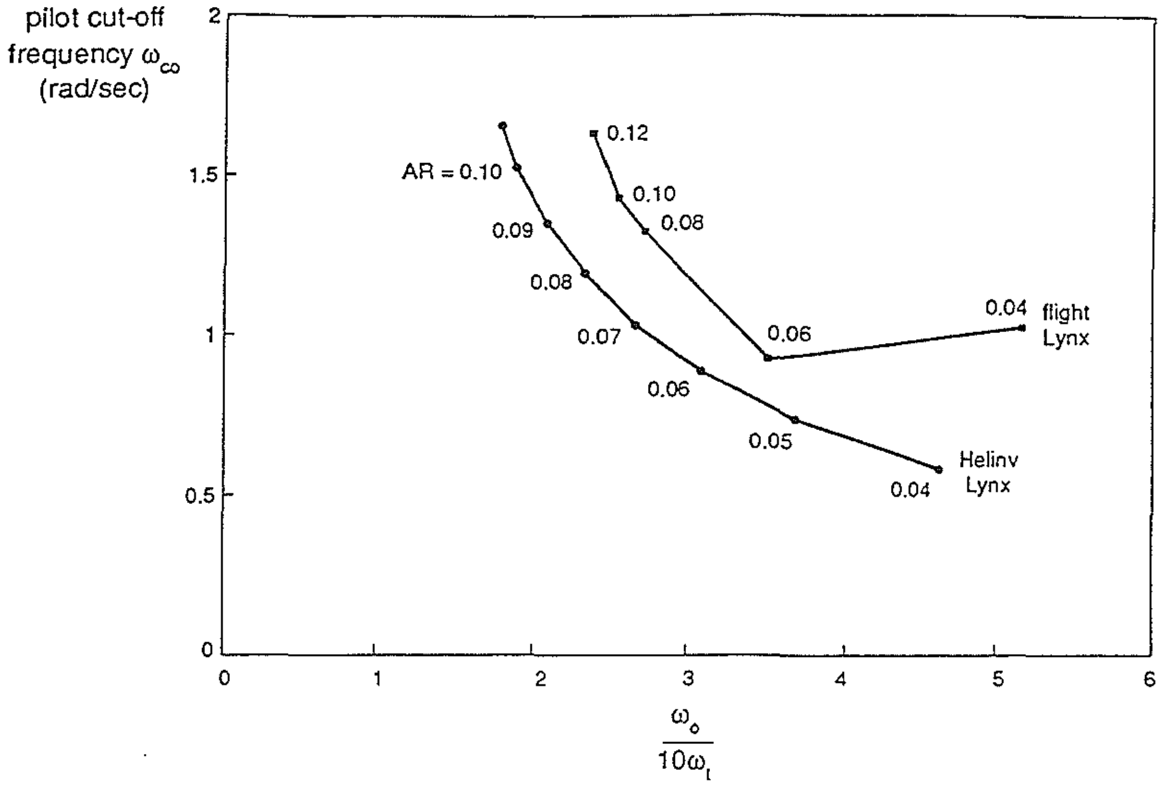


Fig. 17. Comparison of pilot cut-off frequency for Lynx-flight vs. HELINV (from Ref. 11).

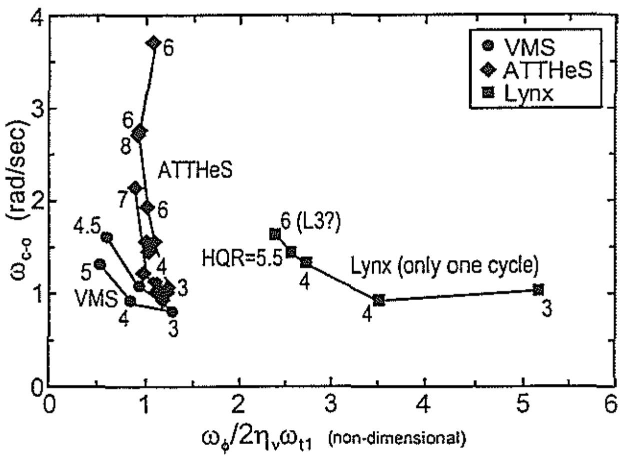


Fig. 18. Pilot cut-off frequency as a function of frequency ratio for Lynx, ATTHeS, and VMS.

two cases, the flight data are shifted to the right due to longer flight times (caused by flight outside the course markers and non-constant airspeeds).

Results from the VMS simulation and the ATTHeS in-flight simulation were analyzed using this aircraft-task frequency ratio, $\omega_\phi/2\eta_v\ \omega_t$, metric. Figure 18 shows these results for the 60 kt symmetrical slalom along with the Lynx flight data. Note that the VMS and ATTHeS results are grouped not only at a much lower aircraft-task frequency ratio, but also in a fairly small range or variation. The multiple-cycle slalom task had a big influence on these results (a larger number of flight path changes, η_v) and for the lower values of ω_ϕ the task times (and hence ω_t) were also affected such that the overall effect on aircraft-task frequency ratio ($\omega_\phi/2\eta_v\omega_t$) may have been relatively small.

For the Lynx flight data, the task frequency was varied through different aspect ratio slaloms and the aircraft characterization (ω_ϕ) remained constant. For the VMS and ATTHeS data it was just the opposite, i.e., the task frequency remained about constant and the vehicle characterization was varied. The two groups of data look quite different and raise questions. For example, it is not clear how the effects of multiple-cycle slaloms impact the interaction between the task aspect ratio, task time and natural frequency, and the HQRs compared to a single-cycle slalom.

Vehicle attitude quickness requirements
As an alternative to the frequency-domain metrics discussed above, time-domain metrics were also explored. One such metric was the attitude quickness parameter from ADS-33D (Ref. 2). Note, only data from the ATTHeS in-flight simulation will presented here.

The background and the initial supporting data for the attitude quickness requirement came from a helicopter roll control study by Heffley (Ref. 10). The basis for the requirement was extracted from "maneuver performance" diagrams that were constructed from a number of discrete lateral maneuvering tasks. For a maneuver that requires discrete control inputs, the ratio of peak angular rate to change in attitude for the entire maneuver describes a "task signature" related to the pilot's demands on the vehicle. For small attitude changes, the value of attitude quickness is dominated by the bandwidth criteria. For large attitude changes, the attitude quickness is dominated by the large amplitude requirements. The attitude quickness requirements in Ref. 2 effectively connect the frequency-domain bandwidth limits at small amplitudes with the time-domain peak angular rate limits at large amplitudes. Because of this link between a small-amplitude frequency-domain parameter and maneuver amplitude, the application of attitude quickness-type parameters was examined for this pilotage task maneuver metric study.

Figure 19 shows a control response time history and the parameters needed to compute the attitude quickness. Also shown are the forward flight roll-axis attitude quickness boundaries from ADS-33D for Air Combat and All Other MTEs. These attitude quickness boundaries, shown in Fig. 19, were established from ground-based simulation and flight test results and are based upon what was generated or used by the pilot in performing a task. For compliance, one only needs to demonstrate points above the boundary lines, therefore it is not necessarily a measure of the vehicle's ultimate capabilities. Like the task margin examined in the previous section, to ensure satisfactory handling qualities one could imagine that some margin must exist between the vehicle's attitude quickness capabilities and those demanded by the task. Both the attitude quickness capability of the vehicle and the attitude quickness used by the pilot while performing the task were investigated.

For the computation of the maximum attitude quickness capability of the vehicle, a simplified model was evaluated which consisted of the rate-limited actuators and the command model of the ATTHeS in-flight simulator. The quickness capability was obtained from a series of single-sided full-control pulse inputs of varying duration. Figure 20 shows the vehicle attitude quickness capabilities that are necessary to obtain Level 1 and Level 2 handling

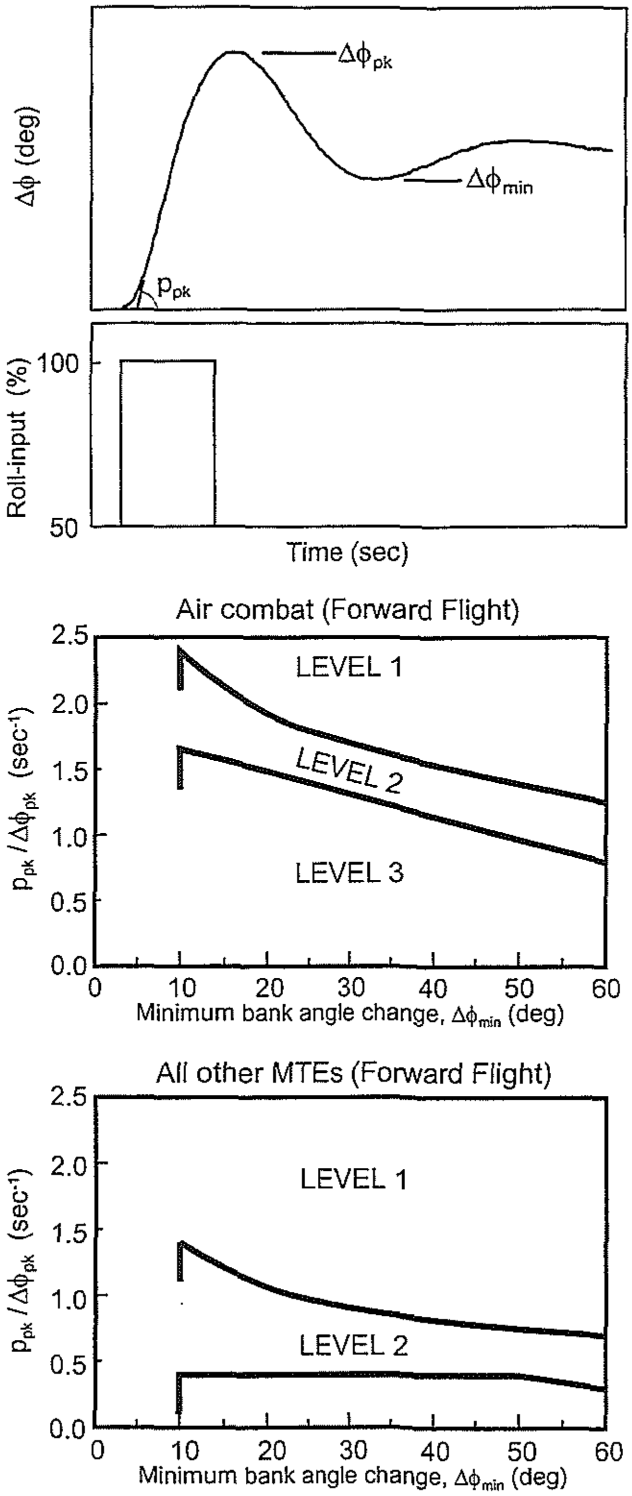


Fig. 19. Definition of Attitude Quickness and ADS-33D requirements.

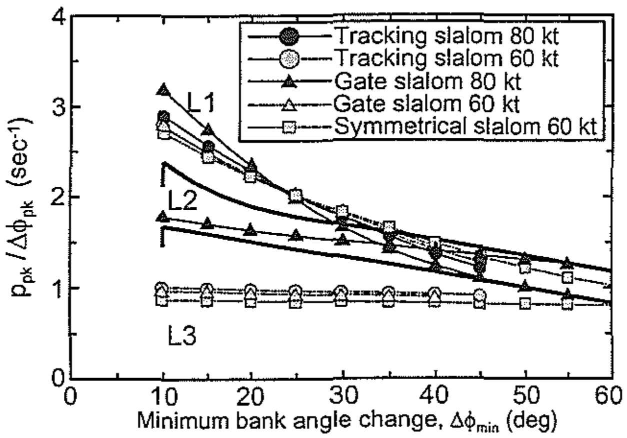


Fig. 20. Vehicle attitude quickness capability for Level 1, 2, and 3 vs ADS-33 boundaries (ATTHeS).

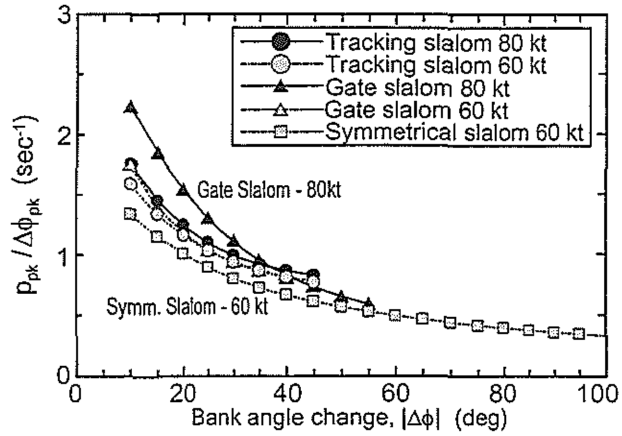


Fig. 21. Averaged attitude quickness usage from Level 1 configurations (ATTHeS).

qualities for the five flight test tasks. These vehicle attitude quickness capability Level lines were computed based upon a numerical average of configurations around the HQR=3.5 and 6.5 boundaries. Also on this figure are the forward flight roll-axis ADS-33D Air Combat Level boundaries. One can observe from the figure that if one uses the vehicle capabilities to establish minimum Level boundaries, the data suggests a raising of the Level 1-2 attitude quickness boundary for attitude changes less than about 30 degrees. In fact, the data from Whalley (Ref. 8) also support this. For larger amplitude attitude changes (> 30 degrees), the ATTHeS data agree fairly well with the ADS-33D boundary or even suggest a slight decrease may be possible. It should be noted, however, that the attitude quickness usage spectrum from this investigation is mainly below 40 degrees of bank angle change and so recommendations at the higher bank angle changes should be considered accordingly. An exception is the symmetrical slalom task, which had a fairly broad distribution over a range of bank angle changes up to a 100 degrees. Also, from Fig. 20 the ATTHeS data for all tasks except one (gate slalom at 80 knots) suggest a lowering of the Level 2-3 attitude quickness boundary. Again, this 80 knot gate slalom configuration aligns fairly well with Whalley's recommended Level 2-3 boundary for attitude changes above about 25 degrees.

Task metrics based on vehicle attitude quickness usage

For computing the attitude quickness usage, i.e. the attitude quickness actually used to perform the task, a software program was written that used the piloted time history records from each evaluation. In simple terms, the program captures the roll attitude when the roll rate passes through zero. As the roll rate varies during a maneuver, successive passes through zero rate results in discrete bank angle changes. During the time interval between these distinct bank angle changes, the peak roll rate is captured along with the corresponding bank angle change.

The effects of the task on the attitude quickness usage were examined from the usage data of the Level 1 configurations. Level 1 configurations were used because these data should be the least distorted by the effects of pilot compensation for handling qualities deficiencies. That is, for the Level 1 configurations, the pilot makes control inputs to maneuver the aircraft through the task with satisfactory or desired performance and minimal compensation. A possible advantage of using the body-state information over the pilot control inputs is that it is less influenced by the control response dynamics, e.g., consider the pilot control inputs for a rate command versus an attitude command response-type.

Figure 21 shows the average attitude quickness usage for the Level 1 configurations. These attitude quickness curves were computed from an exponential approximation through the individual attitude quickness usage data points. The average was obtained by averaging the exponential approximation over the different configurations at 5 degree intervals. The curves are only shown over the range where valid data were available. The most demanding task – in terms of attitude quickness usage – is obviously the gate slalom at 80 knots. The least demanding task seems to be the symmetrical slalom task. This task, however, requires much larger bank angle changes than the other tasks. The remaining three tasks, the two tracking tasks and the gate slalom at 60 knots, all

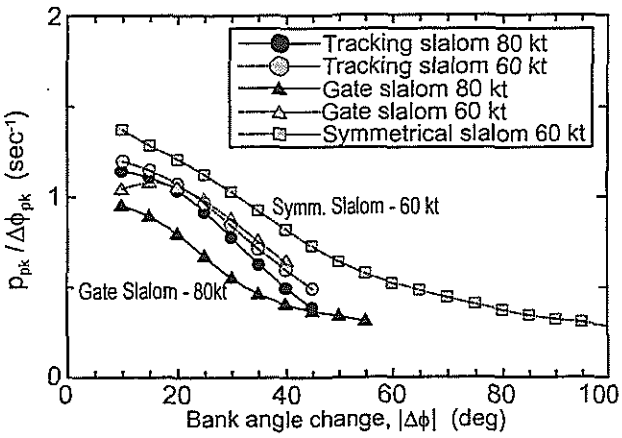


Fig. 22. Attitude quickness margin lines for Level 1-2 handling qualities (ATTHeS).

seem to require about the same amount of attitude quickness.

In a parallel effort to the task margin metric in the frequency-domain, an attitude quickness margin was assessed. This margin parameter was the difference between the attitude quickness capability of vehicle and the attitude quickness used for the task.

Figure 22 shows this attitude quickness margin from the ATTHeS data, i.e., shown are the Level 1-2 crossover boundaries for the five tasks. These boundaries represent the attitude quickness margin that must exist between the vehicles attitude quickness capabilities and those demanded by the task. The symmetrical slalom requires the largest margin, whereas, the 80 knot gate slalom requires the least. The other three tasks consolidate nicely, but the use of an attitude quickness margin metric as a means to characterize a generic task is not quite complete. If all the tasks had collapsed to a uniform margin, then one could fly through a task with a rotorcraft that possessed Level 1 handling qualities and use the attitude quickness usage data to characterize the task, apply the margin, and then obtain a good estimate of what a new vehicle's capabilities would need to be to perform the task with satisfactory handling qualities. Nevertheless, with all that said, the outlook is still promising. This study is not complete, and this paper presents only the initial results. Much progress has been made toward the understanding of pilotage tasks and their relationship with handling qualities.

Conclusions

This paper presented initial results of a comprehensive investigation aimed at characterizing the pilot's basic flying task and its impact on handling qualities. Three slalom tasks were evaluated in a ground-based and in an in-flight simulator at three different velocities and with different vehicle roll-axis characteristics. The results confirmed the existing relationship between the task parameters and the (perceived) vehicle handling qualities – even though this relationship seemed less pronounced for the in-flight simulation results than for the ground-based simulator results. This difference between the results of the ground-based and the in-flight simulation is in itself an important lesson to be learned from these tests.

When the results of this study are compared to the existing ADS-33D roll-axis bandwidth criteria, the Level 1-2 air combat boundary of 2.5 rad/sec is relatively well supported by the in-flight data. However, the Level 2-3 air combat boundary of 1.5 rad/sec seemed slightly high and the results from this study suggest it could be reduced to around 1.0 rad/sec. Comparing the results to the existing ADS-33D roll-axis attitude quickness criteria, the data for all but one task suggest a slight increase in the Level 1-2 boundary for attitude changes below 30 degrees and an overall decrease in the Level 2-3 boundary.

Attempts at quantifying the task in terms of a task margin did not produce a single universally applicable result. Several evaluated concepts – the task bandwidth, the aircraft-task frequency ratio, and the vehicle attitude quickness usage margin – produced results that were usable for a single task or for tasks that are closely related. However, none of the concepts evaluated thus far were able to provide a unified parameter that defines the relationship between the task and the (perceived) vehicle handling qualities. This effort is not complete and there is a high confidence that by the continuing work on this study, many insights will be gained into characterizing the task and its impact on handling qualities.

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