High Angle of Attack Flying Qualities Criteria for Longitudinal Rate Command Systems

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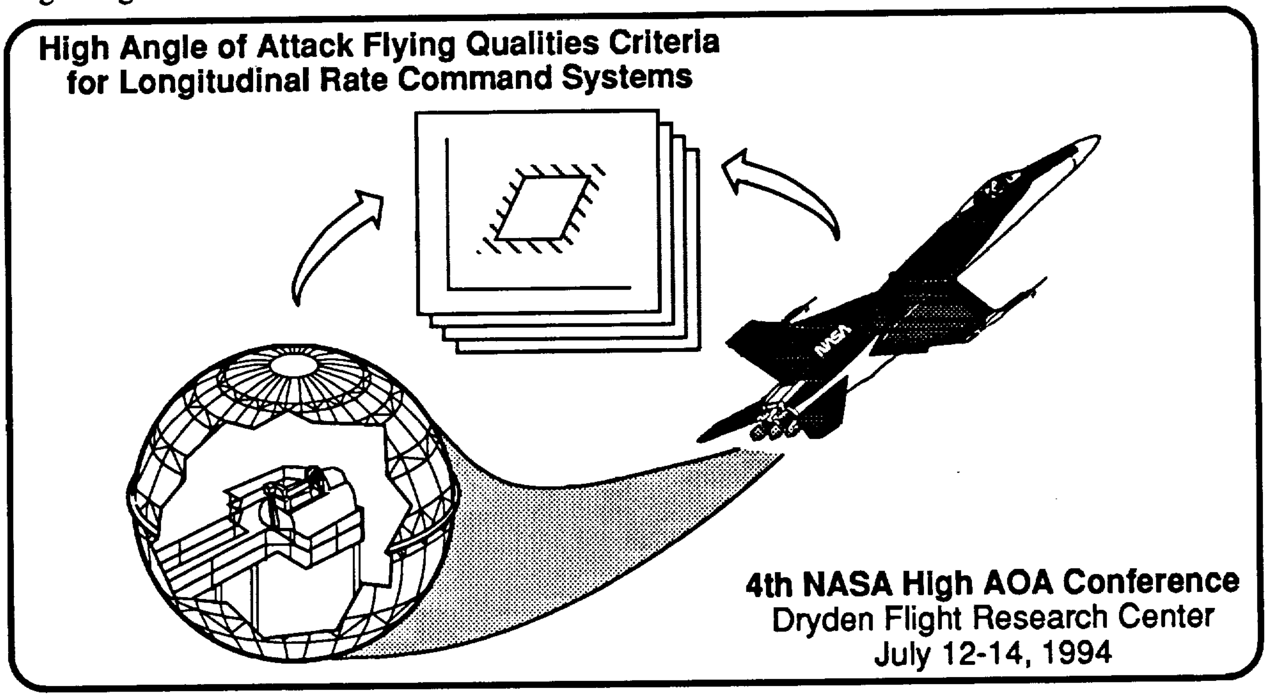
Abstract

This study was designed to investigate flying qualities requirements of alternate pitch command systems for fighter aircraft at high angle of attack. Flying qualities design guidelines have already been developed for angle of attack command systems at 30°, 45°, and 60° angle of attack, so this research fills a similar need for rate command systems. Flying qualities tasks that require post-stall maneuvering were tested during piloted simulations in the McDonnell Douglas Aerospace Manned Air Combat Simulation facility. A generic fighter aircraft model was used to test angle of attack rate and pitch rate command systems for longitudinal gross acquisition and tracking tasks at high angle of attack. A wide range of longitudinal dynamic variations were tested at 30°, 45°, and 60° angle of attack. Pilot comments, Cooper-Harper ratings, and pilot induced oscillation ratings were taken from five pilots from NASA, USN, CAF, and McDonnell Douglas Aerospace. This data was used to form longitudinal design guidelines for rate command systems at high angle of attack. These criteria provide control law design guidance for fighter aircraft at high angle of attack low speed flight conditions. Additional time history analyses were conducted using the longitudinal gross acquisition data to look at potential agility measures of merit and correlate agility usage to flying qualities boundaries. This paper presents an overview of this research. Complete documentation will be available in late 1994 through the NASA Contractor Report entitled "Flying Qualities Criteria for Longitudinal Rate Command Systems at High Angle of Attack."



Acknowledgements

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Introduction

NASA Langley Research Center sponsored the development of flying qualities design guidelines for longitudinal rate command systems at high AOA. McDonnell Douglas Aerospace (MDA) conducted this research by studying AOA rate and pitch rate command systems. Three piloted, fixed-base simulation entries were used to investigate requirements at 30°, 45°, and 60° AOA. Flying qualities tasks which are representative of high AOA fighter aircraft air combat maneuvering were used during these simulations. Specifically, longitudinal gross acquisition and tracking tasks, similar to those used during AOA command system testing, were also adequate for the evaluation of rate command systems. Pilot evaluations were conducted for several variations in longitudinal dynamics. Testing was designed to isolate differences in desired dynamics between rate command system types, isolate effects of AOA on desired dynamics, and identify the sensitivity of pilot opinion to higher order dynamics. Both rate command system types were evaluated at various angles of attack. The AOA rate command system was tested with response orders of 0/1, 0/2, and 1/2 to determine the impact of low order and higher order responses. Pilot comments, Cooper-Harper Ratings (CHR), and Pilot Induced Oscillation (PIO) ratings were gathered. The resulting criteria can be used for longitudinal design guidance of rate command system control laws at high AOA.

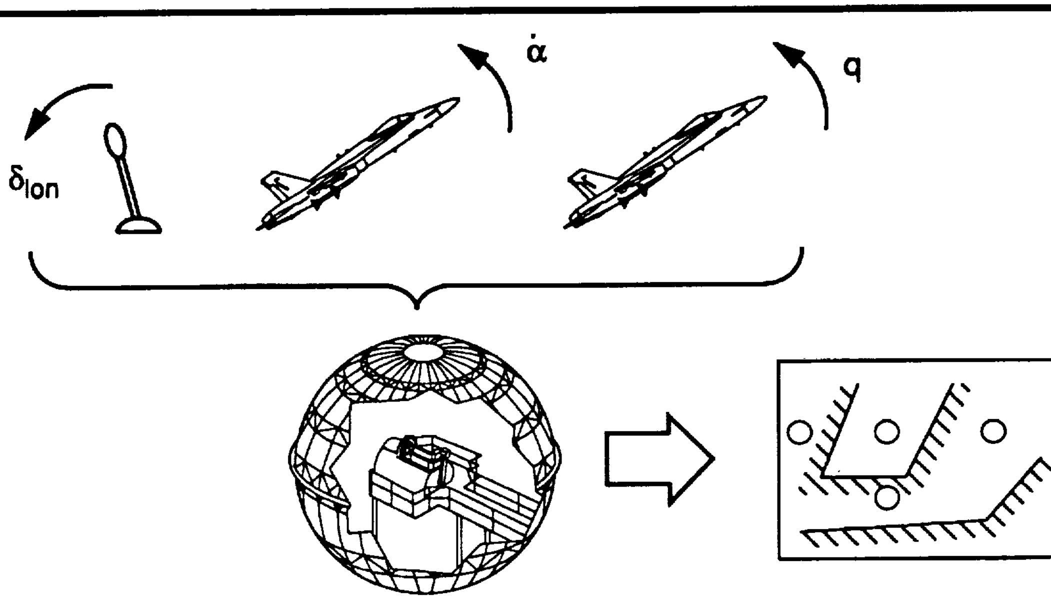


Figure 1. Flying Qualities Criteria for Rate Command Systems

Simulation Setup

Three simulation entries were conducted in the MDA simulation facility during this research. A fixed-base, 40 foot domed simulator with F-15 hardware was utilized. This cockpit contained primarily F-15C hardware; however, the stick spring cartridges were replaced with cartridges similar to those on the F-15 STOL and Maneuvering Technology Demonstrator (S/MTD). The F-15 S/MTD cartridges consist of a single longitudinal and a single lateral gradient. A single longitudinal gradient was desired for the rate command system testing. A Gould SEL 32/97 computer with dual processors was used to drive the simulation at a 60 Hz update rate. The total time delay from stick input to visual scene update was approximately 100 msec.

Visual cues were provided by a Compuscene IV computer image generation system. The Compuscene image was projected on the forward 180° of the dome with a high resolution inset projected directly in front of the pilot. A video projected F-15 was used to represent an air-to-air target. The visual and aural cues in this simulation were of high fidelity; however, motion cues were not simulated. Due to the unique motion environment of high AOA flight, motion-based simulation and/or flight testing is needed to confirm the criteria presented in this paper.

Aircraft Model

This study was designed to isolate and test a fighter aircraft's primary response characteristics. There are many non-linearities associated with any particular aircraft at high AOA. However, this study was meant to be generic and applicable to both current research aircraft and future aircraft designs. As a result, a low order, closed-loop aircraft model was used during the simulation tests. This model allows the user to quickly and easily specify the performance and dynamic response to be simulated. The closed-loop dynamics can be directly specified and hence, multiple variations in dynamic responses can be investigated quickly. The lift and drag characteristics of the simulated aircraft were similar to modern fighter aircraft. Maximum lift occurred around 38° AOA. Aircraft-specific control effectors and stability characteristics were not modeled.

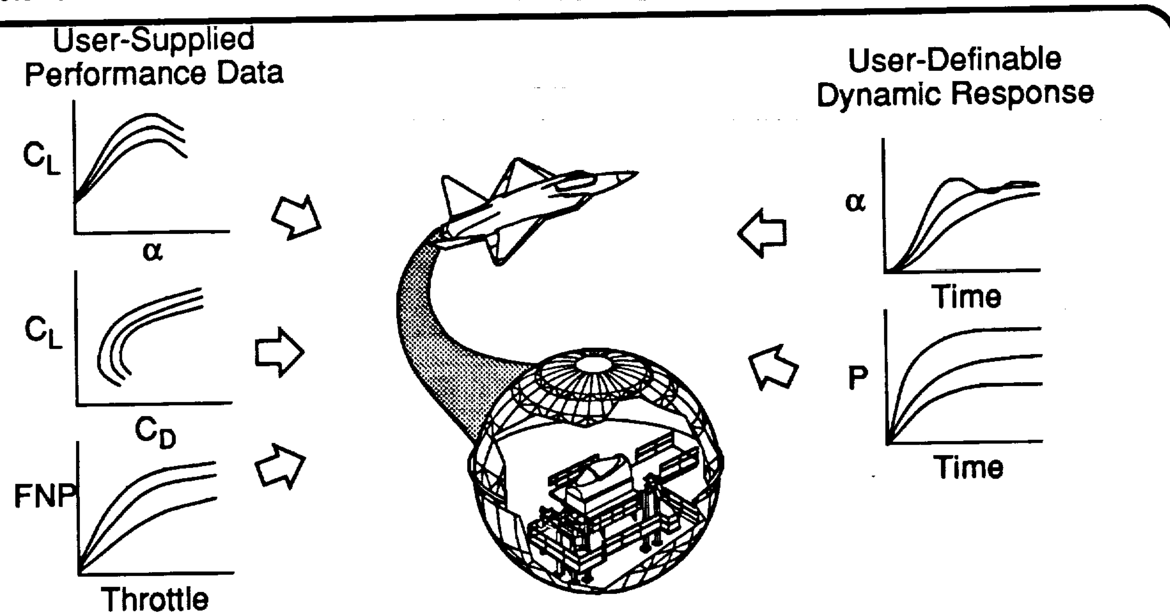


Figure 2. A Generic Aircraft Model was Used to Conduct Fixed-Base Testing

Longitudinal Gross Acquisition Flying Qualities Task

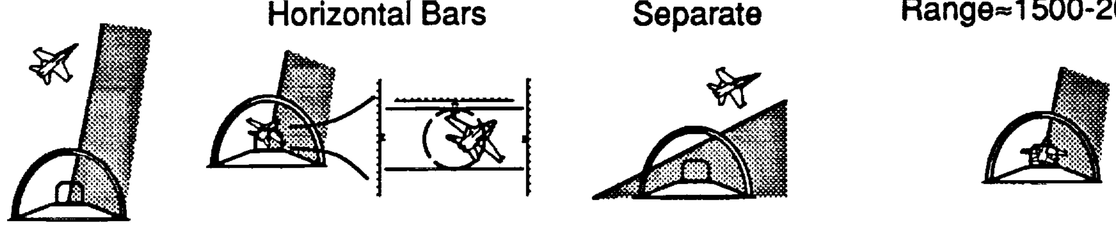
Gross acquisition and tracking tasks were tested to isolate different maneuvering requirements and pilot inputs for air-to-air combat. These tasks were structured to provide repeatable flying qualities data while testing phases of tactically relevant maneuvering such as would be experienced during rapid point and shoot or low speed scissors maneuvers. These tasks were originally designed for simulator use but have been modified for a flight test environment.

The gross acquisition task was designed to exercise rapid, large amplitude maneuvering. During this task, the pilot expects to use a large longitudinal stick input and wants to be able to command a high pitch rate to minimize the time required to get to the target. Such maneuvering exists when a pilot pulls through a large nose angle change to engage a target. As a result, this task focuses on desired pitch rates and the overall time to accomplish the task. Another important aspect of the gross acquisition task is the ability to stop the pipper near the target and transition to tracking. To isolate the acquisition and capture characteristics from tracking, the pilots terminated the task when the target was stabilized within error bars displayed on the HUD.

A description of the longitudinal gross acquisition task is shown in Figure 3. Both aircraft are initialized at 15,000 ft altitude in a tail-chase condition. The target aircraft was digitally controlled to execute a descending right-hand spiral turn. The evaluation pilot was asked to roll to match the maneuver plane of the target, hesitate, and time his pull so that the capture portion of the maneuver occurred near the test AOA. After completing the capture, the pilot unloaded and partially rolled out to allow the target to increase separation. The pilot could then perform another acquisition by rolling, stabilizing, and pulling to the target. The pilots performed many aggressive acquisitions of the target aircraft to evaluate the gross acquisition capabilities. Each pilot attempted various control strategies to determine the pitch rate and capture performance of each configuration. The pilots evaluated their ability to capture the target within the error band, and they judged the time that was required to perform the acquisition. A specific value of time was not chosen for the "desirable time" or the "adequate time" in the CHR performance standards so that the pilots could base that decision on their experience.

Task Description:

Roll and Hesitate	Pull and Capture Target Within Horizontal Bars	Unload, Roll Out, Allow Target to Separate	Repeat Acquisition Several Times, Maintain Range≈1500-2000 ft



Performance Criteria:

Desired Aggressively acquire aim point within the 80 mil error bars (±2.29°) with no overshoot and within a desirable time to accomplish the task.

Adequate Aggressively acquire aim point within the 80 mil error bars (±2.29°) with no more than 1 overshoot and within an adequate time to accomplish the task.

Note: 50 mil error bars (±1.43°) used for the 30° AOA Task

Figure 3. Longitudinal Gross Acquisition Task and Performance Criteria

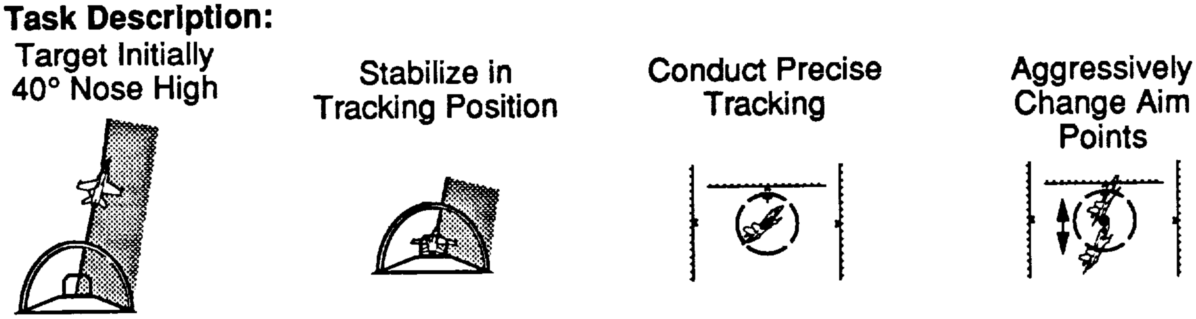
Longitudinal Tracking Flying Qualities Task

The longitudinal tracking task was developed to test precise pipper control. Fine tracking will probably not occur for a long duration at post-stall angles of attack, but some degree of precision will be necessary for weapon delivery. During tracking, the pilot expects to use only slight control stick inputs to generate small corrections in pitch. The ability to precisely control the aircraft's pipper while following a maneuvering target is a highly desired tracking feature. The tracking task was implemented with a steady target and no turbulence, so the pilot also evaluated his ability to move the pipper to new aim points on the target. The advantage of a steady target is that a pilot is able to easily discern the aircraft response to stick input from any independent target motion. Reticles of 10 mil and 50 mil diameter were drawn around the gun pipper as a measure of tracking performance.

Both aircraft are initialized in an 80° banked turn for the tracking task. The target started above, to the right, and ahead of the evaluation aircraft. The target was also initialized with a heading difference as would occur in a turn. This setup was developed to decrease the amount of time required to achieve stabilized tracking. The tracking task also was started at a higher altitude than the acquisition task to provide a longer evaluation time. The setup used during this research was optimized for simulator testing. A modified setup has been developed for in-flight testing.

A description of the longitudinal tracking task is shown in Figure 4. During the tracking task, the target aircraft performed a descending spiral turn. The evaluation pilot was asked to establish a stabilized tracking position on the target. The acquisition was not done aggressively and was not done for evaluation. The pilots tested their ability to tightly track a desired aim point, make precise corrections, and aggressively move the pipper to a new aim point. The pilots were using a 10 mil diameter reticle as a performance standard when they were performing point tracking. They were making aim point changes of approximately 50 mils when they were exercising nose-to-tail and tail-to-nose corrections. Each pilot was allowed several runs to identify deficiencies in the configuration and attempt various control strategies.

Task Description:



Performance Criteria:

Desired No objectionable PIO.
Pipper within ±5 mils (±0.29°) of aim point 50% of the task and within ±25 mils (±1.43°) the remainder of the task.

Adequate Pipper within ±5 mils (±0.29°) of aim point 10% of the task and within ±25 mils (±1.43°) the remainder of the task.

Figure 4. Longitudinal Tracking Task and Performance Criteria

Rate Command System Models and Dynamics Tested

Combinations of AOA rate, pitch rate, 0/1 order, 0/2 order, and 1/2 order command systems were used during the pilot evaluations. Various response orders were tested to determine an acceptable range of high AOA rate responses. A 1/2 order response was tested because it represents the classical, low AOA, heart-of-the-envelope pitch rate response that results from a load factor or AOA command system. A 0/1 order system was tested because research within MDA has identified control law design approaches which achieve this response at high AOA, and this research indicates that a 0/1 order response may be preferred for rate systems. Finally, a few 0/2 order responses were included to test a rate response order that is the same as the classical AOA response order tested in previous AOA command system research at high AOA. These models were used to determine desired ranges of pitch time constant ($\tau_{\dot\alpha}$ or τ_q), rate sensitivity/maximum attainable rate ($K_{\dot\alpha}$ or K_q), short period frequency (ω_{sp}), short period damping (ζ_{sp}), and lead time constant (τ_L).

A nose-down bias was added to the pilot command because other research has shown the desire for nose-down rate resulting from neutral longitudinal stick. The nose-down bias was only desired at high AOA, so it was blended in between 15° and 20° AOA. Variations in the amount of bias were tested using the gross acquisition task prior to the criteria development testing. This initial testing showed that 15 deg/sec was adequate for the acquisition task. The nose-down bias was set equal to the stick sensitivity ($K_{\dot\alpha}$ or K_q) during the tracking testing. This was done so that a 1 inch stick deflection resulted in zero rate regardless of the dynamics being tested. As a result, the pilot was able to avoid the stick breakout forces while tracking.

An Euler compensation term was added to the pitch rate command system so that the aircraft would generate additional pitch rate in a turn rather than hold a constant nose position. Flying qualities experience on existing aircraft with pitch rate command systems has shown the need to use Euler-compensated pitch rate. Some qualitative evaluations were conducted prior to the first simulation to compare Euler-compensated pitch rate to pure pitch rate. The evaluation pilot preferred Euler-compensated pitch rate, so it was used during all three simulations.

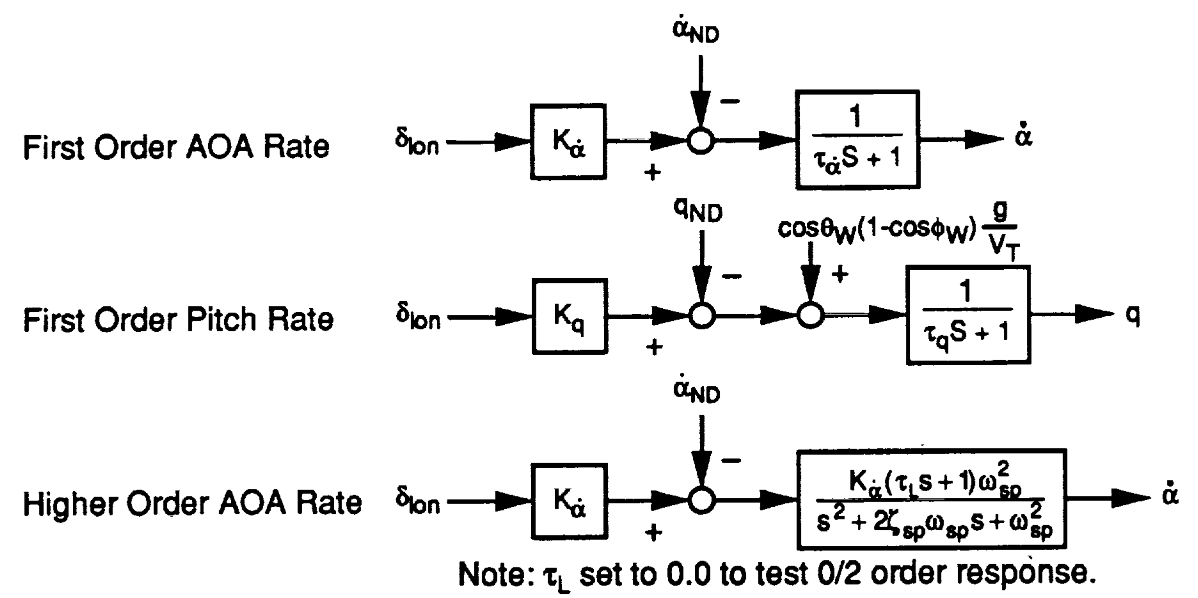


Figure 5. Longitudinal Response Models Tested

Rate Command System Test Approach

This research was designed to test longitudinal rate command systems at high AOA and develop design guidelines that can be used on future fighter aircraft. In particular, AOA rate and pitch rate command systems were tested at 30°, 45°, and 60° AOA. These test conditions were selected to correspond with previous AOA command system research. The order of the response was also varied to determine allowable ranges of dynamics for different response orders. Results were organized as "first order" and "higher order" testing to simplify documentation. However, the actual testing was not segregated by type, and the pilots were not informed of the order of dynamics being tested. In this paper, first order testing will refer to the 0/1 order AOA rate and pitch rate systems, and higher order will refer to the 0/2 and 1/2 order AOA rate testing.

A great deal of simulation time would have been required to fully test all combinations of command system types for both the gross acquisition and tracking tasks at all three angles of attack. Therefore, a more efficient experiment was designed to isolate each effect of interest. The overall simulation test approach used is shown in Figure 6. Each of the oval elements indicates a test matrix consisting of variations in dynamics. The lines connecting test matrices indicate data comparisons which can be made to isolate effects of response order, angle of attack, and response type. This test approach was used with both the gross acquisition and tracking testing except that tracking was not conducted at 45° AOA due to time limitations.

The primary testing was conducted at 60° AOA with 0/1 order AOA rate command systems. The remaining test matrices were designed to identify trends with respect to this primary matrix. The low order AOA rate command system testing at 60° AOA was selected as the primary matrix for several reasons. First, the 0/1 order model required only two dynamic parameters to be varied thereby greatly reducing the total test time. Additionally, pilot comments from the first simulation indicated that the 0/1 order response was desirable. The 60° AOA test condition was selected as the primary condition so that the results could be compared to the most recent AOA command system work where additional agility analyses had been conducted. Also, 60° AOA represents the largest amplitude and most aggressive of the tasks.

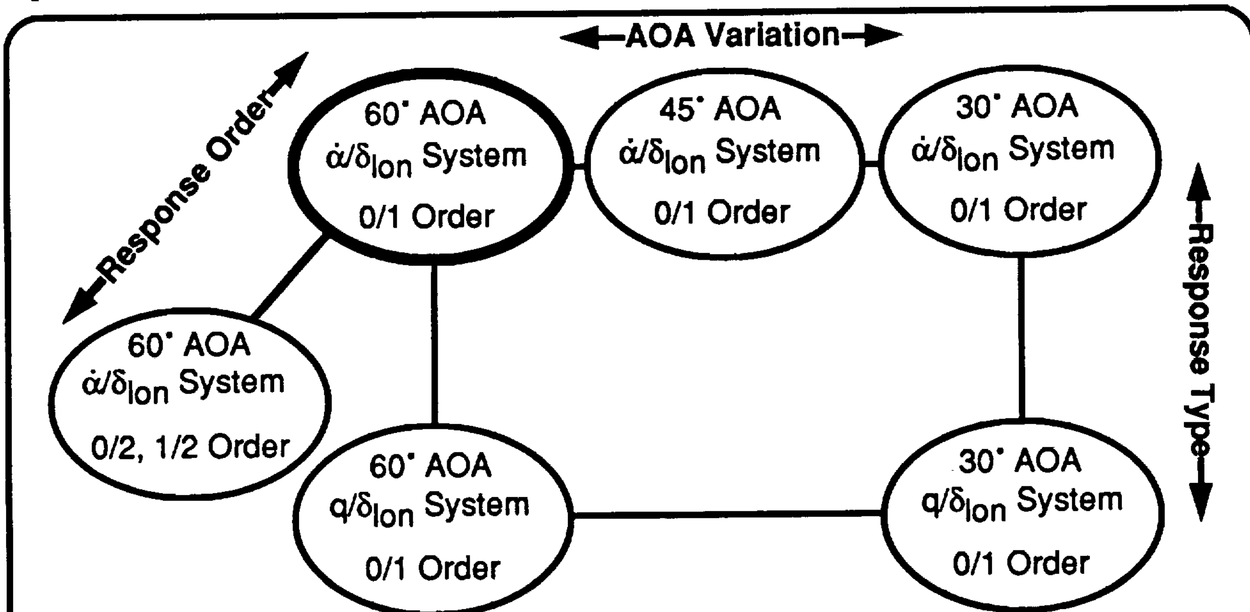


Figure 6. Longitudinal Rate Command System Test Matrix Overview

Comparison of Test Data Across AOA

The test matrix overview shown in Figure 6 was designed to isolate any AOA dependency of the gross acquisition and tracking Level 1 regions. Longitudinal acquisition testing was conducted at 30°, 45°, and 60° AOA with AOA rate command systems and with pitch rate command systems. Tracking testing was conducted at 30° and 60° AOA. The flying qualities of both command system types were examined for any dependency upon AOA. No significant AOA dependency was identified for either acquisition or tracking using either AOA rate or pitch rate command systems. The following is a brief example showing a comparison of pilot ratings for the tracking task. Pilot comments were compared in a similar fashion but will be omitted in this paper for brevity.

Cooper-Harper ratings for the AOA rate command system tracking tests are compared at 30° and 60° AOA in Figure 7. The three configurations used for comparison represent a slice through the primary test matrix. These configurations include a Level 1 configuration, an overly sensitive configuration, and an overly sluggish configuration. The individual and average Cooper-Harper ratings agree very well for configurations 454 and 465. The average CHR for configuration 457 shows a change between 30° and 60° AOA. However, less variation is observed if individual ratings for each pilot are compared. The only rating that is significantly different is the rating of 6 given by Pilot C at 30° AOA. However, the repeat evaluations of 4 and 3 given by Pilot C agree exactly with the ratings given at 60° AOA. Pilot comments for the configurations shown in Figure 7 were also compared to search for AOA dependency. In summary, the pilot comments for each of the three configurations are very similar between the two test angles of attack. This indicates that the pilots perceived a very similar response at 30° AOA and 60° AOA for each set of dynamics.

Comparisons similar to this were made using the pitch rate command system data and data from acquisition testing. Overall results indicate that the flying qualities of rate command systems at high AOA are independent of angle of attack.

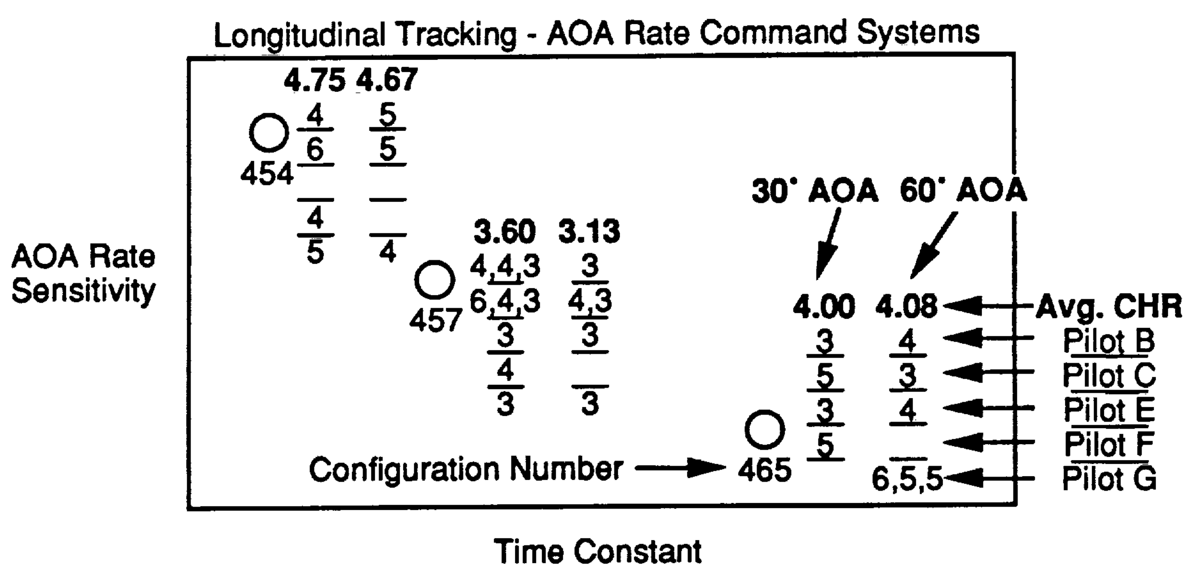


Figure 7. Example Comparison Across AOA Test Points

Comparison of AOA Rate Versus Pitch Rate Command Type

The test matrix shown in Figure 6 was also designed to isolate any differences between AOA rate and pitch rate command systems at high AOA. Comments and ratings at each test AOA were examined for any dependency upon command system type. No significant differences were identified for either acquisition or tracking. The following is a brief example showing a comparison of pilot ratings for the tracking task.

Cooper-Harper ratings for the tracking testing at 60° AOA are compared in Figure 8. The three configurations used for comparison represent the same slice through the primary test matrix as was used to search for AOA dependencies. The individual and average pilot ratings for each configuration compare very closely. The consistency observed in pilot ratings between command system types indicates very similar performance and workload between the AOA rate command system and the pitch rate command system. The pilot comments for each of the three sets of configurations were also quite similar. The different rate command system types were often tested back-to-back during the simulation. The pilots tended to noticed subtle differences and expressed minor preferences between the command system types but, in general, the flying qualities characteristics were very similar.

Comparisons similar to this were made for both tasks and all test angles of attack. In summary, the AOA rate and pitch rate command system data agreed closely for all test conditions indicating that the flying qualities are generally independent of the type of rate command system. This does not imply that AOA rate and pitch rate command systems would work equally well for all tasks and maneuvering. Pilots may be able to achieve better performance or prefer a certain implementation for other aspects of ACM.

The fact that the flying qualities data is independent of response type and AOA simplifies the design guidelines because it means that one set of criteria can be developed for rate command system control law design at high AOA. The same criteria can be used for AOA rate and pitch rate command systems and the dynamics do not need to be scheduled with AOA.

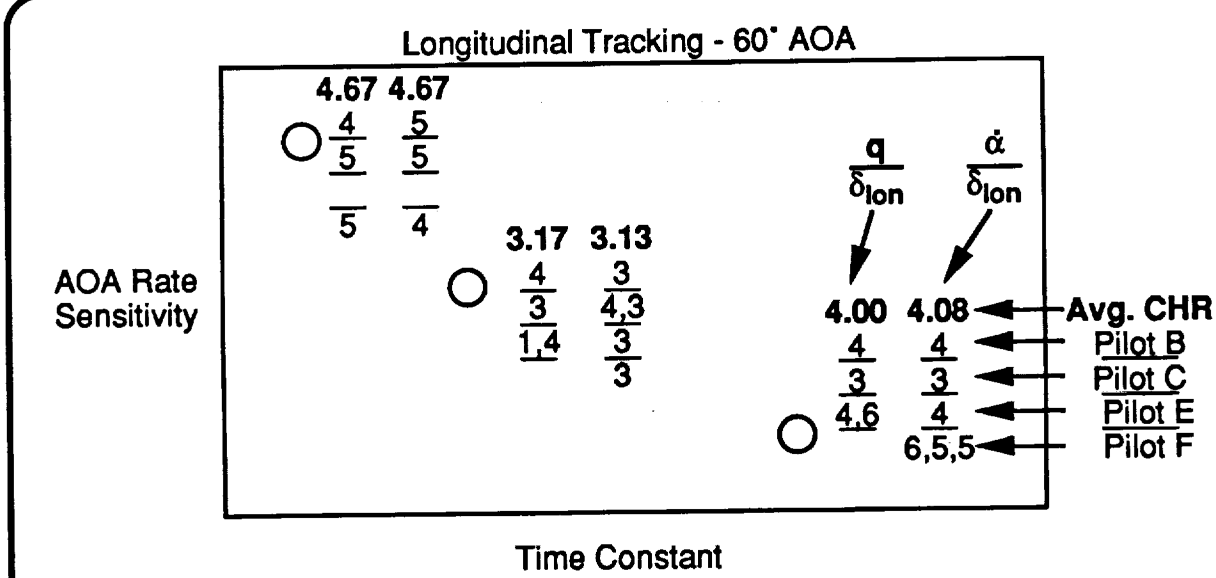


Figure 8. Example Comparison of Rate Command System Types

Gross Acquisition Flying Qualities Criteria for First Order Systems

The first order AOA rate command system data gathered at 60° AOA was used to define a region of Level 1 dynamics. The maximum attainable AOA rate and the time constant were varied over a wide range during testing. Figure 9 shows the results of the evaluations, typical pilot comments, and defines criteria boundaries for the Level 1 region.

The longitudinal gross acquisition Level 1 region is characterized by comments indicating a predictable, controllable capture of the target and a desirable time to accomplish the task. Configurations that were on the high side of the Level 1 region bordered on overly sensitive responses and some pilots experienced bobbles during the capture. The overall time was still good even though some pilots had to reduce their gains to avoid the bobble tendency. As a result, the upper Level 1-2 boundary indicates an increase in the pilot workload or a degradation in capture precision. The right-hand Level 1-2 boundary tended to indicate configurations that had more of an overshoot tendency.

The lower Level 1-2 boundary was typically determined by the pilot's perception of a tactically desirable time to accomplish the acquisition task. When a low maximum rate was combined with a quick time constant, then the pilot had enough acceleration to perform an accurate and predictable capture. However, the pilots considered these configurations deficient from the consideration of time required. Configurations with low rate and long time constant had a large lag in initial response and the attainable rate was too low. If a slow time constant was tested with a high maximum rate, the pilot had an overshoot tendency. This is because the pilot could develop a fairly high rate but the maximum acceleration was deficient, and it took too long to stop. The pilots tended to use less than full stick or take it out very early to compensate. The configurations with quick time constants and high maximum rates resulted in very sensitive responses that have a PIO potential. These configurations have a higher maximum acceleration capability than desired for this closed-loop flying qualities task.

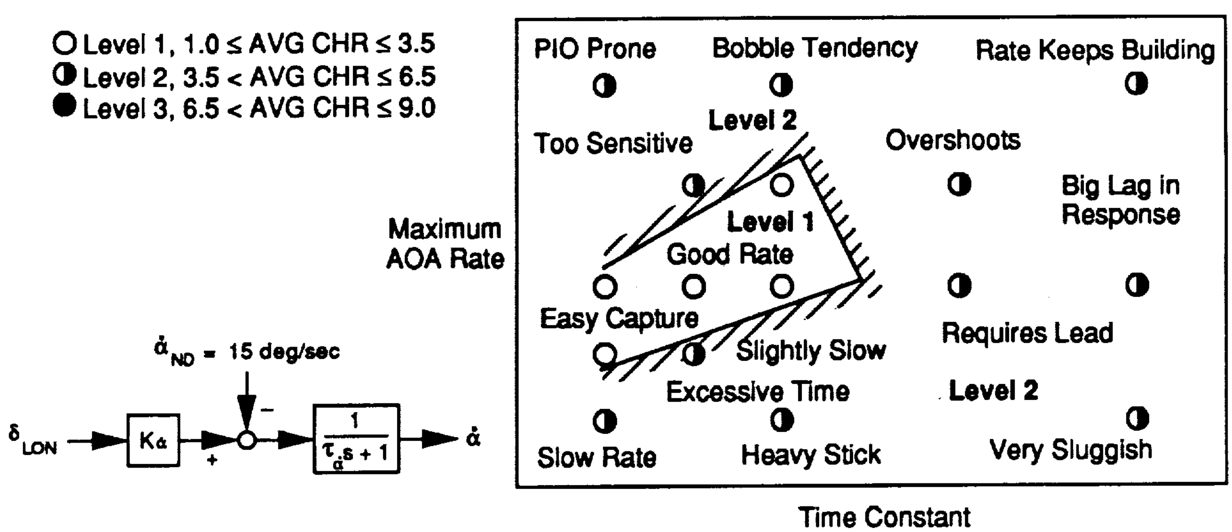


Figure 9. First Order Longitudinal Acquisition Criteria

Gross Acquisition Flying Qualities Criteria for Higher Order Systems

Variations in higher order dynamics were also investigated. Preliminary guidelines have been developed from this data; however, there was not enough test time available to develop a complete set of higher order criteria. Response orders of 0/2 and 1/2 and variations on the lead time constant, short period frequency, and short period damping were tested. The 0/2 order systems were found to be very undesirable because of the large lag in initial response. The 0/2 order response was improved by significantly increasing the short period frequency, but pilot comments indicated that the response was still not desirable. The 1/2 order testing was accomplished by taking two slices through the three-dimensional test space. The first slice was conducted by fixing short period damping. The second slice was tested by fixing the lead time constant. In both test matrices, the variations were made relative to a first order system to determine pilot acceptance of increasingly non-first order responses.

Figure 10 shows the results of the Cooper-Harper evaluations, typical pilot comments, and defines tentative guidelines for the Level 1 regions. The Level 1 boundary was based on the average CHR 3.5 line and the pilot comments but should be treated as a preliminary guideline because of the limited number of configurations evaluated. The pilots were able to achieve the desired time to acquire and were able to stop precisely on the target within the Level 1 regions. Configurations with a low short period frequency resulted in a sluggish initial response regardless of the lead time constant that was selected. If the short period frequency was too high, the response was too quick and bouncy. As the short period frequency and the lead time constant were simultaneously increased beyond Level 1 values, the pilots had increasing difficulty with overshoots. Finally, the response was PIO prone at extreme values of either short period frequency or lead time constant. The data indicates that the damping must be increased with increasing frequency to maintain Level 1 flying qualities. Configurations with low damping resulted in less precise captures. The severity of the response also depends upon frequency. If a low damping is combined with a low frequency, the response tends to be sluggish and imprecise. However, a sensitive and bouncy response occurs if a low damping is combined with a moderate to high short period frequency.

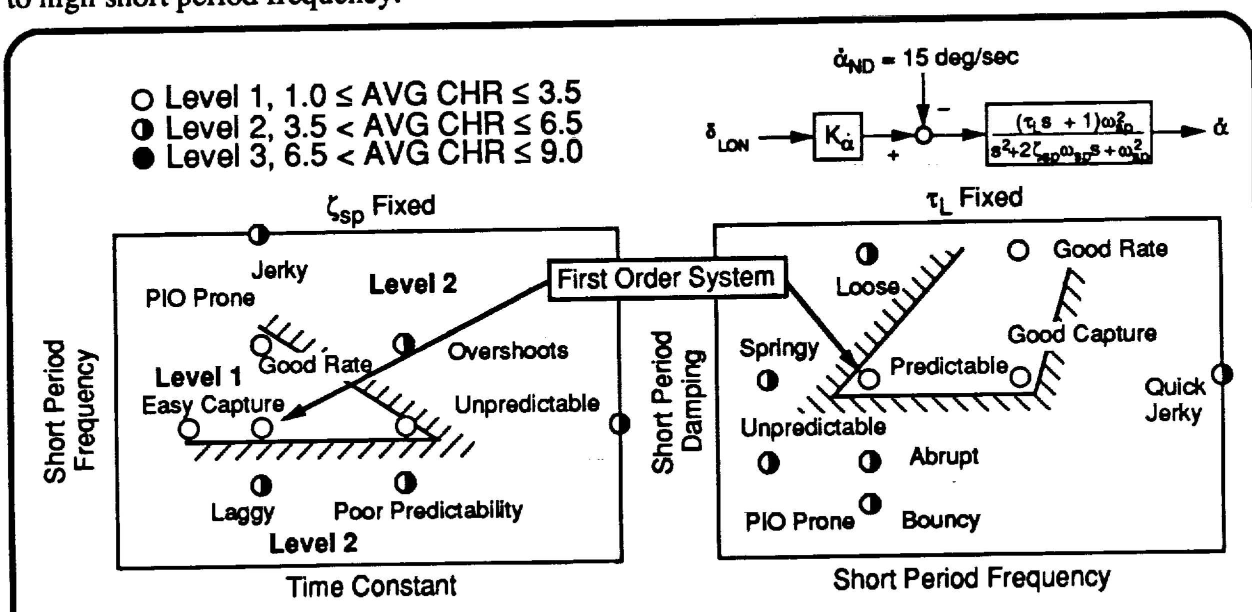


Figure 10. Higher Order Longitudinal Acquisition Criteria

Tracking Flying Qualities Criteria for First Order Systems

Longitudinal tracking Level 1 flying qualities regions were developed in a similar manner as that used for the acquisition criteria. Data gathered at 60° AOA with the AOA rate command system was used to develop the region shown in Figure 11. For the tracking testing, the AOA rate sensitivity and the time constant were varied over a wide range. The resulting Cooper-Harper evaluations and pilot comments were used to define the criteria boundaries.

The pilot ratings and comments for tracking indicate a large Level 1 region. However, the preferred sensitivity is dependent upon time constant. Dynamics within the Level 1 region received comments indicating solid, precise spot tracking and the ability to predictably make corrections of approximately 50 mils. A very quick, abrupt response resulted if the time constant was reduced below the minimum Level 1 boundary. Pilots had problems making small, predictable changes for these systems. Configurations around the upper Level 1 boundary had too much rate capability (sensitivity) to precisely track and pilots occasionally experienced bobbles. The pilots also had to reduce their gains during the aim point changes to avoid PIO. Therefore, the upper Level 1 boundary indicates an increase in workload and a degradation in tracking precision. The right-hand Level 1 boundary indicated too much lag in initial response. This manifested itself in a pipper response that seemed to wander during spot tracking or resulted in overshoots during aim point corrections. The lower Level 1 boundary was determined by the perception of a tactically desirable time to make aim point changes. The spot tracking tended to be good, but the pilots noted that the configuration would be too slow to track an active target.

Neither a minimum nor a maximum was identified for the AOA rate sensitivity. However, pilot comments indicated that configurations with low sensitivity would not be desirable for tracking an actively maneuvering target because of the slow response and the large stick inputs required to make corrections. It is also recommended that stick sensitivities not exceed the range tested in this experiment. The pilot comments indicate that, even with the right time constant, configurations with the highest stick sensitivity tested are on the borderline of being too sensitive and a very aggressive, high gain pilot could have PIO problems.

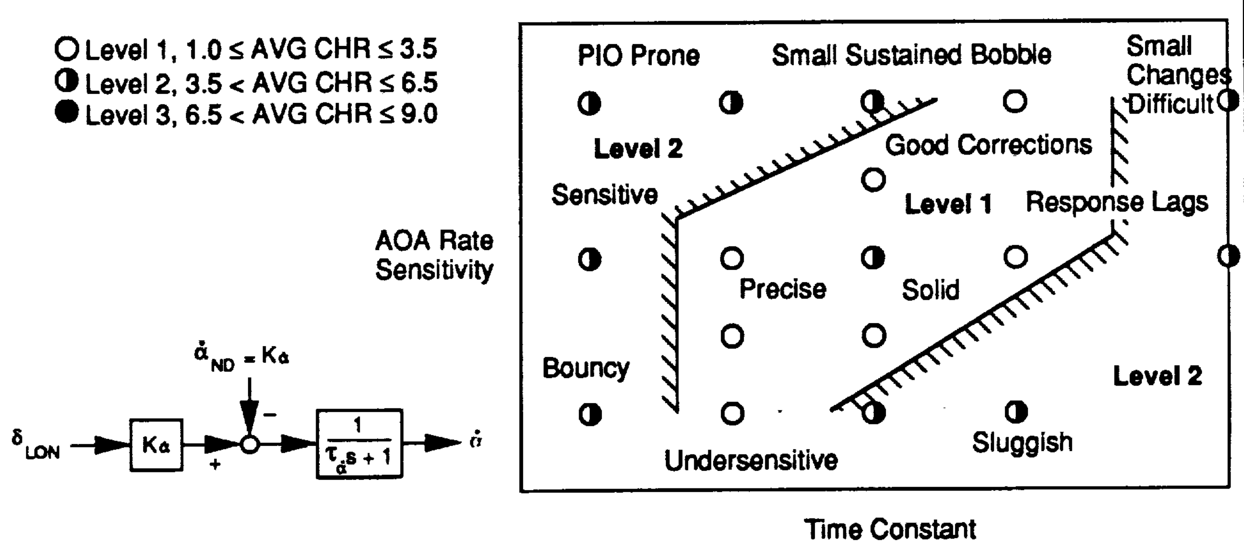


Figure 11. First Order Longitudinal Tracking Criteria

Tracking Flying Qualities Criteria for Higher Order Systems

Variations in higher order dynamics were also investigated using the tracking task. Preliminary guidelines have been developed from this data; however, there was not enough test time available to develop a complete set of higher order criteria. Response orders of 0/2 and 1/2 and variations on the lead time constant, short period frequency, and short period damping were tested. Just as with the acquisition testing, the 0/2 order systems were found to be very undesirable because of the large lag in initial response. The 1/2 order testing was accomplished by taking two slices through the three-dimensional test space. The first slice was conducted by fixing short period damping. The second slice was tested by fixing the lead time constant. In both test matrices, the variations were made relative to a first order system to determine pilot acceptance of increasingly non-first order responses.

Figure 12 shows the results of the Cooper-Harper evaluations, typical pilot comments, and defines tentative guidelines for the Level 1 regions. The Level 1 boundary was based on the average CHR 3.5 line and the pilot comments but should be treated as a tentative guideline because of the limited number of configurations evaluated. A relatively small range of variation was found to be allowable for short period frequency and lead time constant. The pilots were able to achieve desired spot tracking and 50 mil aim point changes within this region. Configurations with a low short period frequency resulted in a sluggish response regardless of the lead time constant that was tested. If the short period frequency was increased too much, the response was too sensitive. As the lead time constant was increased beyond Level 1 values, the pilots also perceived an increase in the sensitivity of the response. If both the short period frequency and the lead time constant were simultaneously increased beyond Level 1 values, then the response became sensitive, oscillatory, and PIO prone. A dependency between desired short period frequency and damping was identified. Just as with the acquisition task, pilots desired higher short period damping as the frequency was increased. And finally, low values of short period damping resulted in poor tracking.

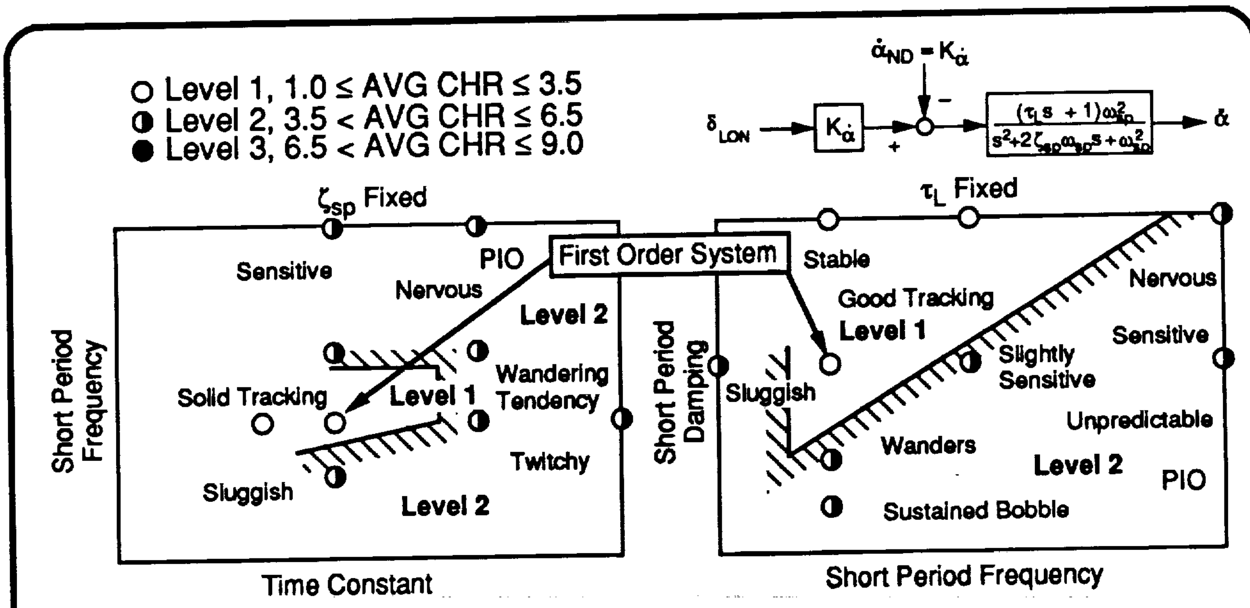


Figure 12. Higher Order Longitudinal Tracking Criteria

Summary

This investigation was conducted to determine flying qualities requirements for AOA rate command and pitch rate command systems at high AOA. Previous research had been conducted for AOA command systems at 30°, 45°, and 60° AOA. These angles of attack were also studied during this investigation. Piloted simulation verified that the flying qualities tasks used for AOA command systems could be used for rate command system criteria development. Pilot evaluations were conducted for a wide range of rate command system dynamics. Pilot comments, Cooper-Harper ratings, and PIO ratings were used to develop flying qualities criteria for longitudinal acquisition and tracking tasks.

Both AOA rate and Euler angle compensated pitch rate command systems were evaluated. The AOA rate system was tested with different response orders to determine the desirability of low order and higher order responses. Response orders of 0/1, 0/2, and 1/2 were tested. A wide range of closed-loop dynamics were tested for each of the variations in response type, response order, and AOA. Evaluation of the flying qualities data indicates that the Level 1 region of dynamics is independent of response type (AOA rate or pitch rate) and angle of attack. This simplifies the design guidelines because it means that one set of criteria can be developed for rate command system control law design at high AOA. The same criteria can be used for AOA rate command as is used for pitch rate command systems and the desired dynamics do not need to be scheduled with AOA. The primary criteria defines desired regions of maximum rate/rate sensitivity and time constant. Additional guidelines were developed for higher order dynamics. It was found that 0/2 order rate responses were not desired for the acquisition or tracking tasks. Desirable regions of dynamics were identified for 1/2 order responses. Guidelines were developed from this data to define acceptable ranges of short period frequency, short period damping, and lead time constant. However, these should be used more for trend information because they represent two-dimensional slices through a large three-dimensional design space.

The criteria presented in this paper and the previous AOA command system criteria are the result of extensive testing; however, additional research is needed for high AOA flying qualities design guidelines. Pilot comments during this testing indicated slight preferences between the AOA rate command and pitch rate command systems for the tasks investigated. A study to identify the relative merits of rate command and AOA command systems for tactical maneuvering at high AOA is needed to help a control law designer choose the best approach for a fighter aircraft design. A wider range of maneuvers and simulated air combat engagements should be used to directly compare rate command and AOA command systems at high angles of attack. Such a study would expose implementation issues for each command system for a full envelope design and would solicit pilot opinions over a much wider range of maneuvering than used in this study.

These flying qualities criteria (and the AOA command system criteria) were developed in fixed-base simulations and therefore need to be validated in flight. Aggressive high AOA maneuvering can result in large rotational and linear accelerations at the pilot's station. Therefore, flight test data is required to determine how much the flying qualities boundaries will shift with the addition of motion cues. Motion-based simulations may also provide useful correlating data for some of the tasks. In-flight testing with aircraft such as the NASA HARV, F-15 ACTIVE, X-29, and X-31 is needed to fully determine the effect of motion cues on the Level 1 regions defined in this paper.