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STATUS OF AGILITY RESEARCH AT McDONNELL AIRCRAFT COMPANY AND MAJOR FINDINGS AND CONCLUSIONS TO DATE

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ABSTRACT

Agility research has been ongoing at McDonnell Aircraft Company for many years. The objective of this research has been to develop advanced capabilities that enhance the tactical effectiveness of fighter aircraft. Recent agility research, reported herein, has focused on defining the regions of the flight envelope where airframe agility requires improvement and determining the required level of agility to give pilots a significant tactical advantage. Flying qualities criteria have been developed and different command systems have been investigated for high angle of attack maneuvering. Ways to attain increased agility have been studied, along with studies of the pilot's ability to perform effectively in an agile motion environment. An agility working group has been formed at McDonnell Aircraft Company which has created a beneficial synergy and accelerated research efforts.

NOMENCLATURE

N_L - Normal load factor, g's
$N_{z/\alpha}$ - Body axis normal load factor change per α change, g/rad
p_{max} - Maximum stability axis roll rate, deg/sec
Ps_B - Probability of survival for Blue aircraft
Ps_R - Probability of survival for Red aircraft
$\bar{q}$ - Dynamic pressure, lb/ft^2
t_{RC90} - Time-to-roll and capture a 90 degree bank angle change, sec
t_{RT90} - Time-to-roll through a 90 degree bank angle change, sec
α - Angle of attack, deg
ΔTA - Increment in Torsional Agility metric, deg/sec^2
ζ_{SP} - Short period damping
τ_R - Roll mode time constant, sec
ω_{SP} - Short period frequency, rad/sec

INTRODUCTION

Total aircraft agility is a function of the airframe, avionics, weapons, and the pilot.[1] Agility research at McDonnell Aircraft Company (MCAIR) has focused on airframe agility and the man/machine dynamics and the use of avionics, sensors, data processing, and displays to increase agility. This paper will review the results from the airframe and man/machine dynamics agility studies and discuss the major findings, new agility criteria/concepts, and conclusions to date.

MCAIR has been researching fighter agility for many years to develop advanced capabilities that enhance the tactical effectiveness of fighter aircraft, Figure 1. Recently, government and industry researchers in the United States and Europe have increased their agility research efforts to keep pace with the need to achieve high levels of agility for future survivable aircraft. MCAIR's researchers

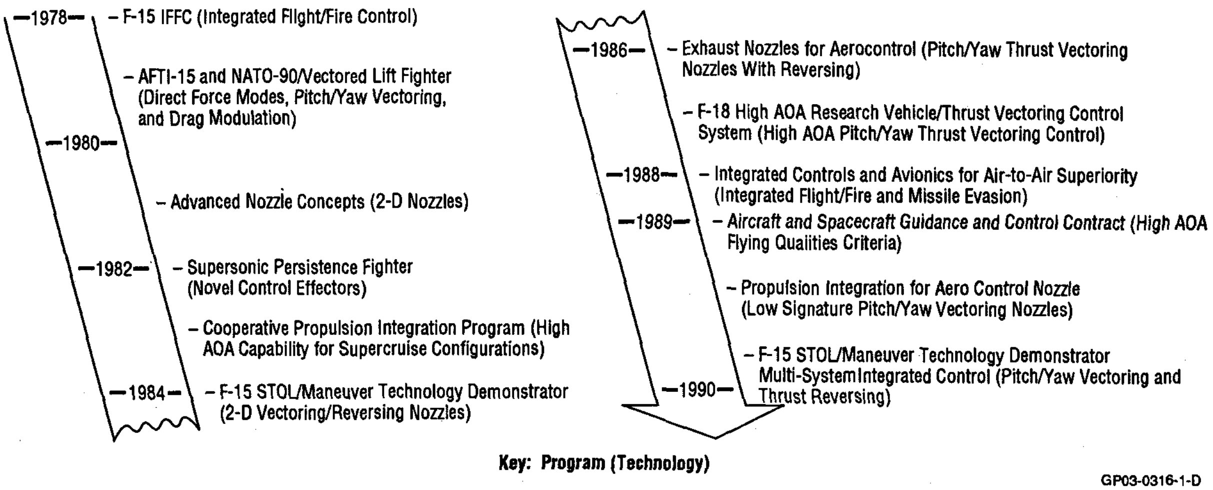

Figure 1. Agility Research and Development Programs at McDonnell Aircraft Company

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have: investigated measures of merit, called metrics; studied relationships between agility metrics and flying quality parameters; researched unconventional aerodynamic and propulsion control effectors for increased control power; enhanced off-line air battle simulation programs to model agility; and studied the effect of pilot disorientation in an agile environment.

MCAIR airframe agility research is focused on the regions of the flight envelope where airframe agility requires improvement. Analytical studies and comments from tactical pilots suggest that most fighter aircraft have sufficient airframe agility in the heart of the flight envelope, Figure 2. However, more pitch, roll, and axial agility are needed at the edges of the envelope. For example, increased nose down pitch authority is needed at high load factors and high angles of attack. Enhanced roll capability is needed at low and high speeds and for high load factors. Increased axial (deceleration) capability is needed in the high and low speed regions. This research is defining the required level of agility to give the pilot a significant tactical advantage, and finding ways to attain increased agility.

FLIGHT DYNAMICS, FLYING QUALITIES, AND AGILITY RESEARCH

Flight dynamics, flying qualities, and agility are being researched through ongoing Independent Research and Development work at MCAIR. Flight dynamics research has shown that an aircraft's maneuverability can be determined with conventional flight mechanics analysis methods, but flying qualities criteria must be used to determine the aircraft's controllability. Since an aircraft must be both maneuverable and controllable to be agile,[1] flight mechanics and flying qualities must be considered when determining an aircraft's agility.

Flying qualities research has concentrated on criteria development for superagile aircraft maneuvering at high angles of attack (AOA). Manned simulations have been conducted to determine what response characteristics a pilot needs to attain desired performance with minimal compensation (Level 1 flying qualities) at high AOAs. (Level 1 flying qualities are most desirable and are clearly adequate for the mission flight phase.) This research has demonstrated that high AOA flying qualities tasks can be developed, and the high AOA Level 1 response characteristics differ significantly from the low AOA Level 1 criteria in the flying qualities specification.[2] (A comparison between high and low AOA Level 1 response characteristics will be shown below.)

Several agility metrics have been studied to determine if they do a better job of capturing an aircraft's transient maneuverability than traditional measures. Metrics for the roll and pitch axes have been investigated through analytical studies and manned simulation. This research has concentrated on determining which agility metrics are tactically relevant and what level of agility is required to give the pilot a significant tactical advantage in Within Visual Range (WVR), air-to-air combat.

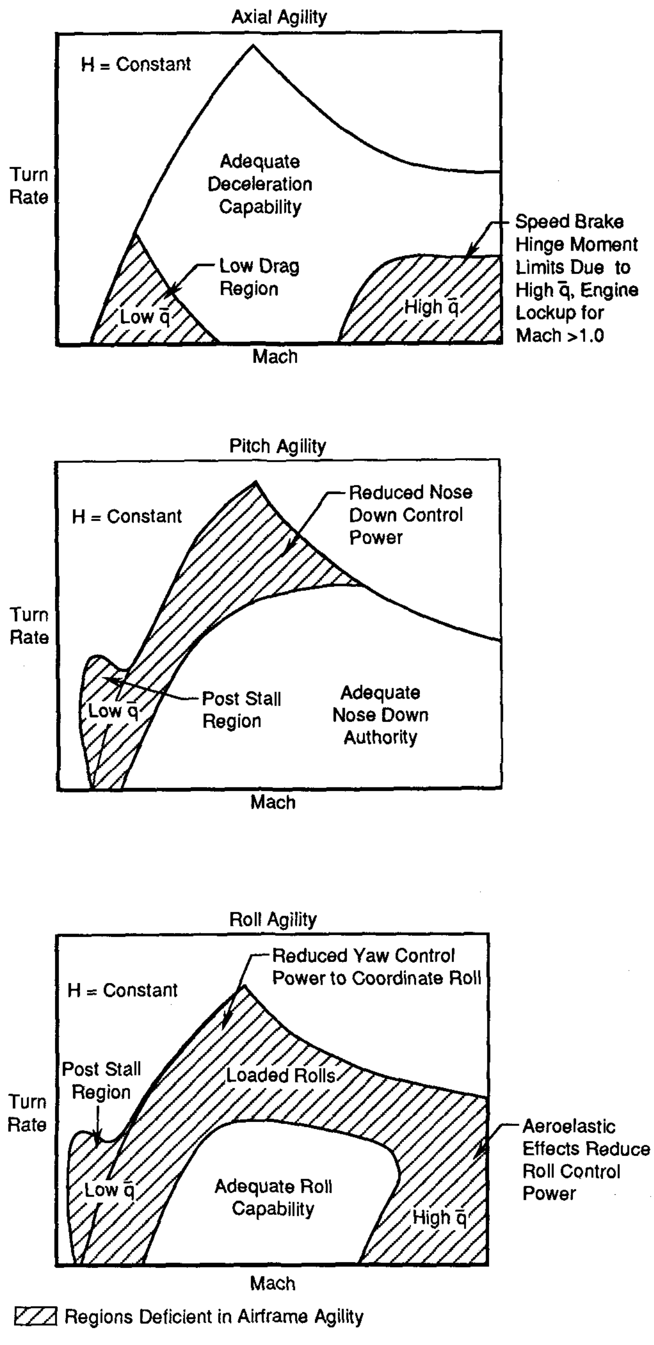


Figure 2. Regions of the Flight Envelope That Are Deficient in Airframe Agility

We have found strong correlations between proposed agility metrics and standard flying qualities parameters (as have other agility researchers).[3,4] The results from a manned simulation suggest that roll axis agility can be defined by standard flying qualities parameters. These results indicate that flight dynamics, flying qualities, and agility are all interrelated.

HIGH ANGLE OF ATTACK FLYING QUALITIES RESEARCH

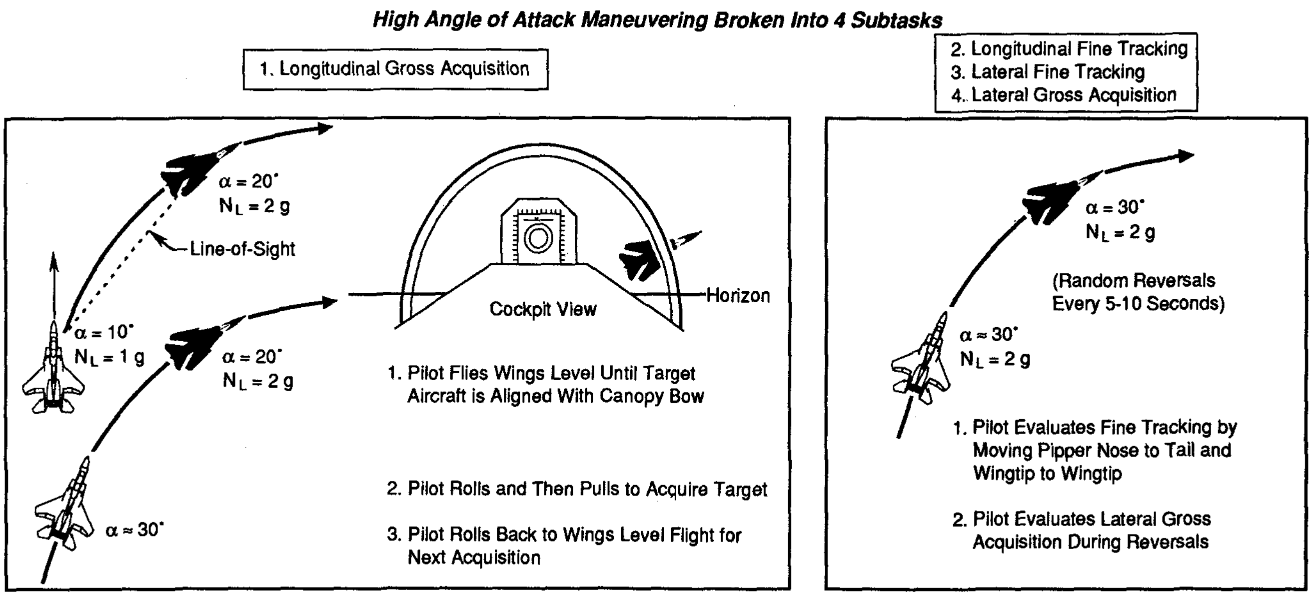
High angle of attack flying qualities research has been ongoing for over four years at MCAIR to determine what aircraft dynamics are required by pilots for good maneuverability and controllability at high AOAs. Previous high AOA flying qualities research[2] dealt primarily with departure/spin resistance, stalls, and departure cues, because low pitch and yaw control power at high AOA precluded high maneuverability. With the introduction of new control effectors, such as deflectable forebody strakes[5] and thrust vectoring[6], increased maneuverability and therefore increased agility at high AOA is now possible. However, to fully utilize this increased high AOA agility, flying qualities criteria are needed to ensure that good controllability is maintained as maneuverability is increased.

MCAIR has been developing moderate to high AOA flying qualities criteria using fixed-base simulators. Multiple simulations have been conducted to investigate longitudinal and lateral flying qualities for high gain tasks with highly maneuverable aircraft, in the moderate to high AOA flight regime. Flying qualities associated with gross acquisition to fine tracking tasks have been studied.

High AOA Task Development

High AOA tasks were developed to assess flying qualities for transient point-and-shoot type maneuvers. The tasks were structured to maximize the test pilot's evaluation time, to isolate the axis being evaluated, and to minimize changes in flight condition. The point-and-shoot maneuver was broken down into four subtasks: longitudinal gross acquisition and fine tracking and lateral gross acquisition and fine tracking. Gross acquisition is the initial large amplitude maneuver the pilot performs to acquire the target followed by fine tracking to fire the gun or a missile.

Figure 3 shows the longitudinal and lateral gross acquisition and fine tracking tasks and performance standards that were used successfully for the 30 degree AOA range.[7] These air-to-air tasks gave the



	Evaluation Task	Desired Performance Standards	Adequate Performance Standards
Performance Standards	**Gross Acquisition**	Aggressively Acquire Aim Point Within 25 mils of the Pipper With No Overshoot	Aggressively Acquire Aim Point Within 25 mils of the Pipper With No More than One Overshoot
	Fine Tracking	No PIO Pipper Within ± 5 mils of Aim Point, 50% of Task, Within ± 25 mils Remainder of Task	Pipper Within ± 5 mils of Aim Point, 10% of Task, Within ± 25 mils Remainder of Task

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Figure 3. High Angle-of-Attack Flying Qualities Tasks and Performance Standards

pilot adequate evaluation time and minimized changes in flight condition. The pilots were given the performance standards for each task and asked to use these standards in assigning a Cooper-Harper Rating[8] (CHR) for each configuration.

Flying Qualities Criteria for 30 Degrees AOA

Longitudinal criteria[9] for the gross acquisition and tracking tasks were developed using an angle of attack command system with a longitudinal stick sensitivity of 8.0 deg/in. Pilot comments and CHR from three simulations were used to determine the desired response characteristics. Lateral and directional dynamics were held fixed throughout the longitudinal variations.

The 30 degree AOA Level 1 regions are plotted against the MIL-STD-1797A[2] and Moorhouse-Moran[10] Level 1 regions in Figure 4. Note that an upper limit on damping ratio for Level 1 tracking was not identified. With the exception of the low frequency boundary of 1 rad/sec, the 30 degree AOA data does not correlate with the low AOA criteria. In Reference 9, the 30 deg AOA data are compared to other "second tier" criteria. These criteria show that at high AOA, pilots prefer configurations for which the combination of short period frequency and damping ratio minimized the open and closed loop resonance of the pitch rate frequency response.

The lateral criteria[9] for the gross acquisition and tracking tasks were developed using a stability axis roll rate command system. The rudder pedals were not used in general because of the good roll coordination with lateral stick. A lateral stick with a maximum displacement of 4.0 in and a stick gradient of 4.0 lb/in was used for this testing. Again, pilot comments and CHR from three simulations were used to determine the desired response characteristics. Longitudinal and directional dynamics were held fixed throughout the lateral evaluations.

The 30 degree AOA Level 1 regions are plotted against the MIL-STD-1797A[2] and Moorhouse-Moran[10] Level 1 regions in Figure 5. The 30 deg AOA lateral tracking criteria, MIL-STD-1797A, and Moorhouse-Moran do not correlate well. At 30 deg AOA, the Level 1 region from MIL-STD-1797A was too sensitive for tracking and prone to Pilot Induced Oscillations (PIO). A slower roll response may be required at high AOA because of the coning motion resulting from a velocity vector roll response.[7] The gross acquisition Level 1 region is shifted to slightly lower roll rates compared to MIL-STD-1797A requirements and the more restrictive Moorhouse-Moran requirements.

The differences in the 30 degree AOA data and the flying qualities specification, MIL-STD-1797A, illustrate the need for high AOA flying qualities research. Designers need flying qualities criteria to design control laws for superagile aircraft maneuvering at high AOA to ensure that they are maneuverable and controllable. Criteria for higher angles of attack are being investigated under a NASA Langley Research Center task order contract to determine how the desired response characteristics shift with increasing angle of attack.[11]

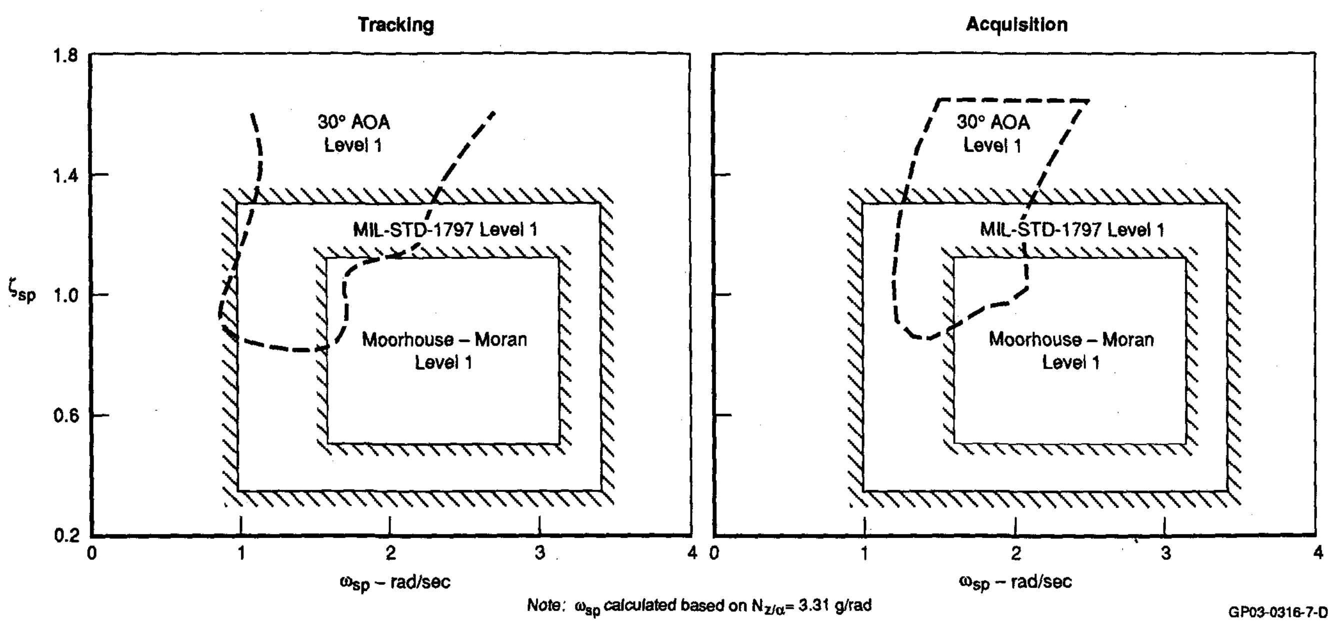

Figure 4. Comparison of Longitudinal High Angle-of-Attack Criteria to Low Angle-of-Attack Criteria

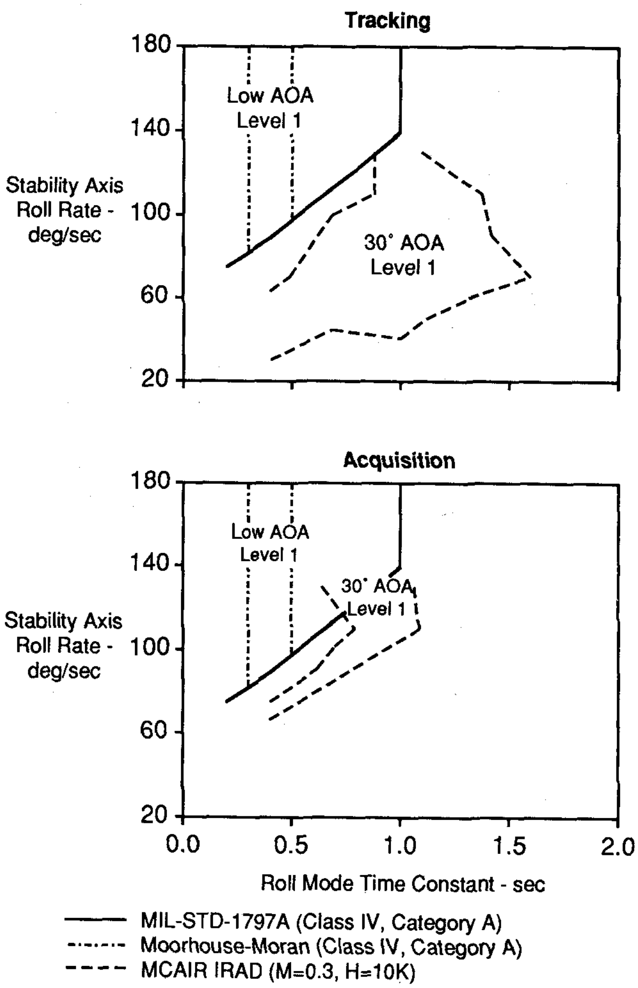

Figure 5. Comparison of Lateral High Angle-of-Attack Criteria to Low Angle of Attack Criteria

AGILITY RESEARCH

Aerodynamics Department agility research has primarily focused on the study of agility metrics to determine which metrics are tactically relevant and what level of agility gives the pilot a significant tactical advantage. Initial agility studies focused on the roll response. This research showed that a pilot can use only a limited amount of maneuverability for closed loop tasks, which confirmed the importance of controllability in executing air combat maneuvers. This research is leading us to the study of minimum agility requirements rather than maximum agility capabilities.

Torsional Agility Metric

A metric entitled Torsional Agility[12] (TA) is the ratio of the aircraft's horizontal turn rate to the time-to-roll and capture a 90 degree bank angle change. (The time-to-roll and capture a 90 degree bank angle will be referred to as t_{RC90}.) The TA metric measures how well the aircraft rolls while loaded. The turn rate is a function of normal load factor and true airspeed, while t_{RC90} is a function of the aircraft's lateral dynamics.

Figure 6 shows how TA varies with normal load factor and t_{RC90} for a constant Mach and altitude.[13] Note that the same level of TA can be obtained for two dissimilar flight conditions: A) low load factor and small t_{RC90} value; and B) high load factor and large t_{RC90} value. In example A, an outside observer would see an aircraft rolling rapidly about the velocity vector without making a significant change in heading. In example B, an outside observer would see an aircraft turning sharply while rolling very slowly. This example shows that the TA metric does not differentiate between dissimilar flight conditions and indicates that TA may not be a tactically relevant metric.

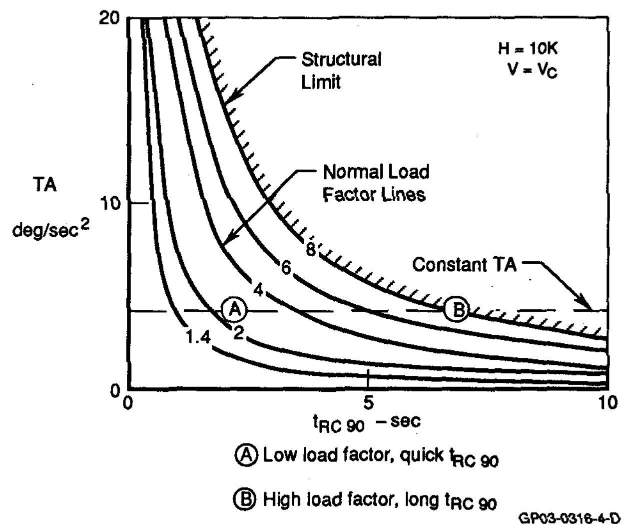

Figure 6. Torsional Agility Metric Measures an Aircraft's Ability to Roll While Loaded

One of our first tasks in studying the TA metric was to determine the relationship between the t_{RC90} metric and lateral dynamics. To establish this relationship, we gathered t_{RC90} values in a fixed-base, domed cockpit using MCAIR's Generic Aircraft simulation program (GENAIR).[14] We took t_{RC90} data for multiple pilots over a wide range of maximum roll rate (P_{max}) and roll mode time constant (τ_R) values.

The average t_{RC90} values are presented in Figure 7 as a 3-D plot for varying lateral dynamics.[13] The regions where decreased maneuverability or decreased controllability increase the piloted t_{RC90} values are noted on the surface. A lack of maneuverability increases the t_{RC90} at low roll rates, while at high roll rates, the aircraft is very maneuverable but controllability suffers. An increase in roll mode time constant reduces maneuverability at low roll rates and contributes to the loss of controllability at high roll rates. The minimum t_{RC90} occurs around 200 deg/sec roll rate for a fast roll mode time constant. This was the optimum point for our model where the best balance between maneuverability and controllability was achieved. Previous roll rate studies have shown that roll rates around 200 deg/sec are most desirable for fighter aircraft in air-to-air combat.[15] This gave us confidence that our model was valid and properly reflects the pilot's ability to maneuver and control the aircraft.

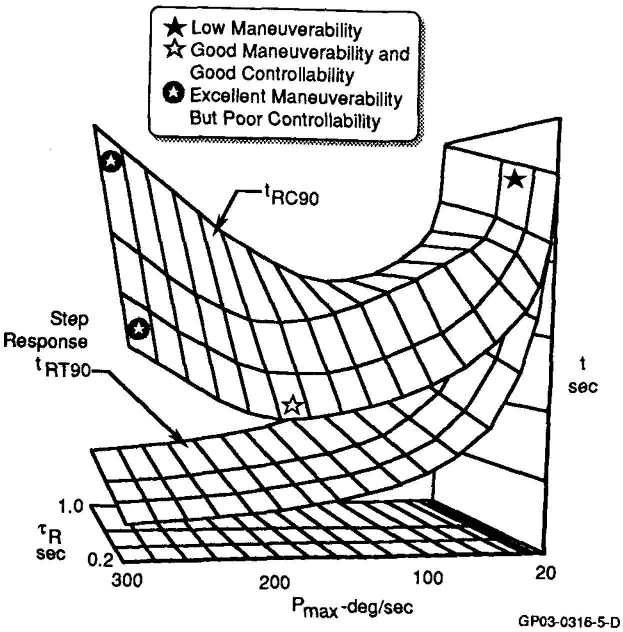

Figure 7. t_{RC90} and t_{RT90} Vary Differently With P_{max} and τ_R

Roll Agility Simulations to Study TA Metric

A manned simulation was conducted in October 1988 to see if the TA metric is tactically relevant and what level of incremental TA (ΔTA) is required to give the pilot a significant tactical advantage. The simulation setup is discussed in detail in Reference 13. The results from this initial simulation showed an increase in exchange ratio with increased ΔTA for 1 vs 1, WVR, air-to-air combat.[13] However, a large amount of variability in the data reduced our confidence in the result, so a second simulation was conducted to try and obtain a more statistically significant result.

The second simulation was conducted in March 1989 to: 1) better define the effect of ΔTA by gathering more data; 2) study variations in P_{max} and τ_R; and 3) compare the relative effects of ΔTA and increased specific excess power, P_s. Two of the three tests and experimental variables are shown in Figure 8. The simulation and experimental setups and run procedures are discussed in detail in Reference 16.

The results from the second roll agility simulation are shown in Figure 9. The statistical significance levels for seventeen combat performance measures are shown for the first two tests. The change in combat performance measures was calculated along with an associated significance level. The significance level indicates if the change in combat performance was due to the change in the experimental variables or if the change was due to chance alone.[17] At the 95% significance level, the probability of chance alone generating this effect is only 1 in 20. A measurand change is considered to be statistically significant if it shows up at the 95% significance level or greater.[17] Therefore, the effects at the 90% level are marginally significant and the effects below the 90% level are not significant.

The increase in exchange ratio with increased ΔTA from the first simulation was not supported by this simulation, as can be seen in Figure 10. Time to first weapon hit for Red was the only measurand that was significant at the 95% level or better, but the data did not show a consistent trend with increasing ΔTA. More combat performance measures were significantly affected by P_{max} and τ_R than by ΔTA. Increased P_{max} and decreased τ_R led to earlier Short Range Missile (SRM) and gun shot opportunities for the Blue aircraft. See Figure 11. Two measurands each were significant for

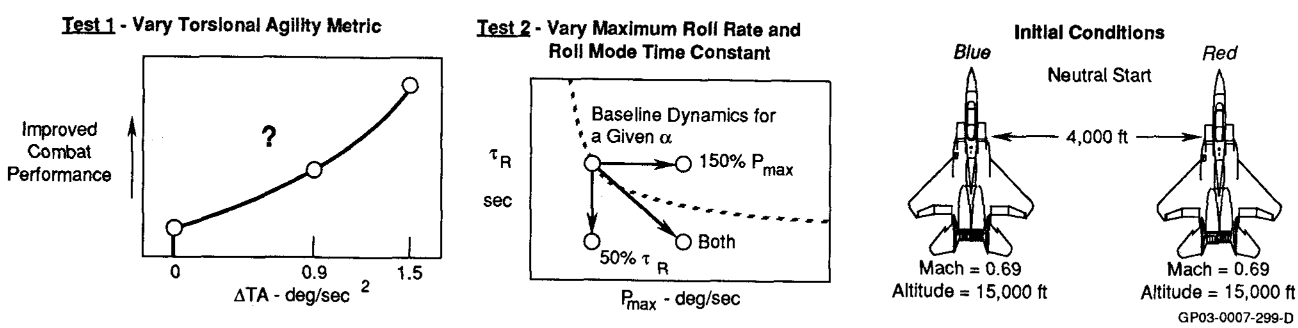

Figure 8. The March 1989 Roll Agility Simulation Evaluated the Torsional Agility Metric, Maximum Roll Rate, Roll Mode Time Constant, and P_s in a 1 v 1, WVR, Gun and SRM Scenario

variations in P_{max} and τ_R. Even though more combat performance measures were significantly affected by variations in P_{max} and τ_R than by ΔTA, these variations did not give the pilot a significant tactical advantage for a 1 vs 1, WVR scenario.

Combat Performance Measures	Test 1	Test 2		
	ΔTA 0, 0.9, 1.5	P_{max} Baseline and 150% Baseline	τ_R Baseline and 50% Baseline	P_{max} and τ_R Interaction Effects
Exchange Ratio				
Probability Blue Wins				
Probability of Survival for Blue				
Probability of Survival for Red				
Survival Ratio (Ps Blue / Ps Red)	90% to 95%			
Survival Advantage (Ps Blue - Ps Red)				
Time to 1st Weapon Hit for Blue				
Time to 1st Weapon Hit for Red	95% to 99%	90% to 95%		
Time 1st Weapon Hit Advantage: $t_{1stHITRED} - t_{1stHITBLUE}$		95% to 99%		
Probability 1st SRM Shot Available to Blue			95% to 99%	
Total Gun Envelope Time for Blue		90% to 95%	90% to 95%	
Total Gun Envelope Time for Red				
Gun Envelope Time Advantage: $t_{GUNBLUE} - t_{GUNRED}$				
Probability 1st SRM Shot Available to Blue		95% to 99%		
Total SRM Envelope Time for Blue			95% to 99%	
Total SRM Envelope Time for Red				
SRM Envelope Time Advantage: $t_{SRMBLUE} - t_{SRMRED}$				

Not Significant | 90% to 95% | 95% to 99% | 99% or better

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Figure 9. Statistical Significance Levels for Combat Performance Measurands

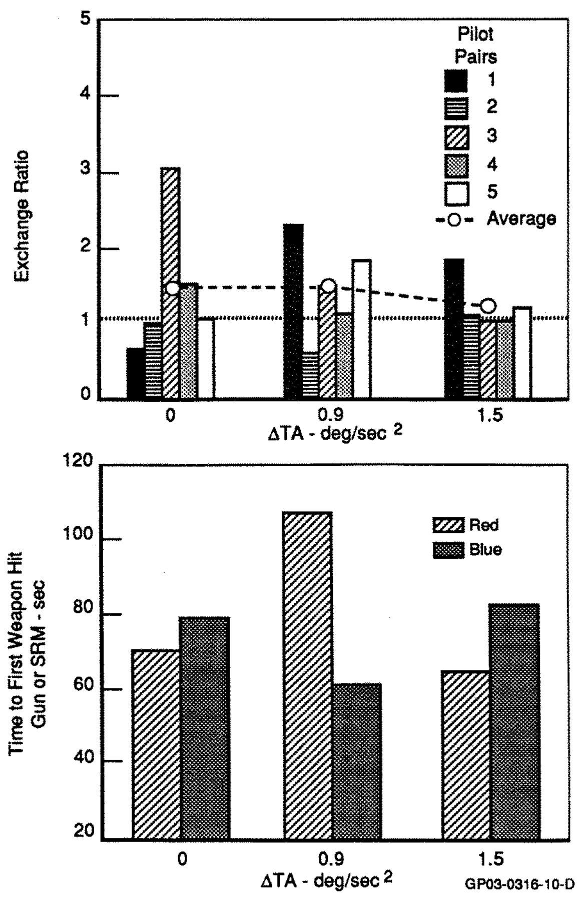


Figure 10. Exchange Ratio and Time to First Weapon Hit for Red and Blue vs ΔTA

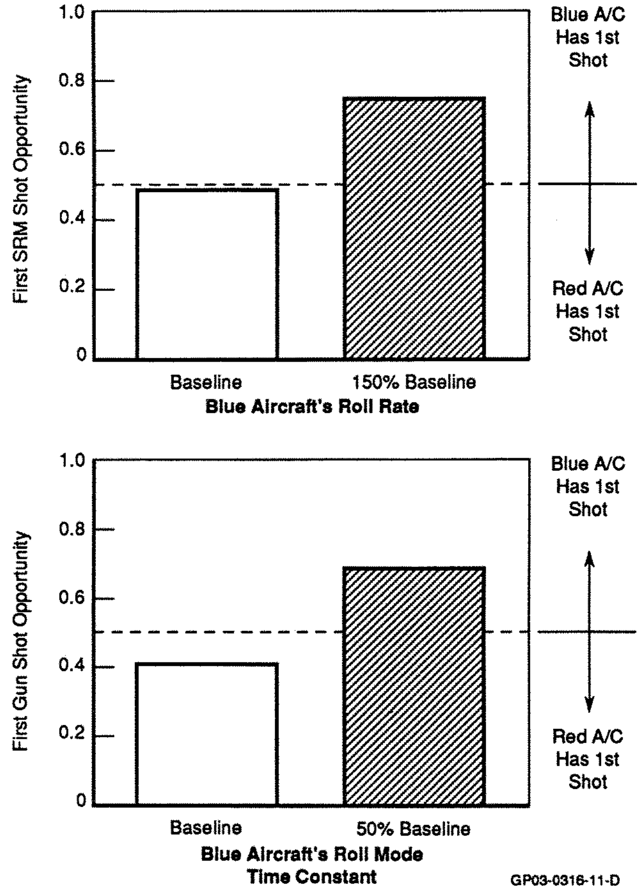


Figure 11. Blue Aircraft's First SRM Shot Opportunity and First Gun Shot Opportunity for Roll Rate and Roll Mode Time Constant Variations

Flying Qualities as an Agility Metric

Flying qualities is defined by George Cooper and Robert Harper[6] 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." To quantify flying qualities, Cooper and Harper jointly developed the Cooper-Harper Rating (CHR) scale shown in Figure 12. Three levels were later assigned to the CHR scale where Level 1 is most desirable and Level 3 is least desirable. The CHR associated with each level is shown in Figure 12 and general flying qualities level descriptions are given in Figure 13.

The pilot is able to achieve desired task performance with minimal compensation in a Level 1 aircraft, and adequate task performance with an increase in workload in a nominal Level 2 aircraft. Therefore, a Level 2 aircraft has lower agility than a Level 1 aircraft, but the agility is not seriously degraded. A pilot flying a Level 3 aircraft cannot achieve adequate task performance, even through maximum workload compensation, due to poor controllability and poor maneuverability. This means the degradation in agility between Levels 2 and 3 is much more severe than between Levels 1 and 2.

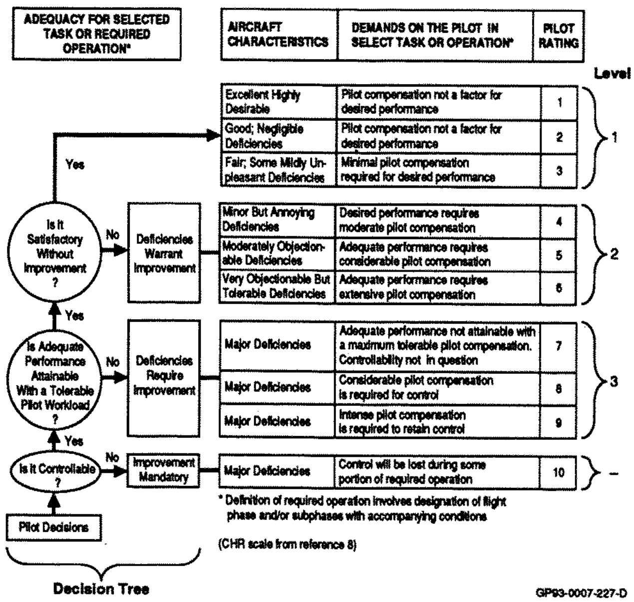


Figure 12. The Cooper-Harper Rating Scale

Level 1	• Pilot Can Attain Desired Performance • Minimal Pilot Compensation • No PIO • Satisfactory Without Improvement
Level 2	• Pilot Can Attain Adequate/Satisfactory Performance • Increase in Pilot Workload • Degradation in Mission Effectiveness • Deficiencies Warrant Improvement
Level 3	• Pilot Cannot Achieve Adequate / Satisfactory Performance • Pilot Workload Excessive • Controllability Problems • Mission Effectiveness is Inadequate • Deficiencies Require Improvement

Figure 13. General Flying Qualities Level Descriptions

Tactical Relevance of Flying Qualities Levels

Figure 14 shows the hypothetical increase in combat effectiveness with lateral flying qualities variations[18] using the Figure 13 flying qualities level descriptions. This hypothetical result is for two aircraft that are identical except for roll axis flying qualities. Note that the increase in effectiveness is greatest between Levels 2 and 3 because of the large change in workload and performance between these levels. The change in effectiveness between Levels 2 and 1 is minimal because a pilot with a Level 2 aircraft can almost achieve Level 1 performance with a moderate increase in workload. The hypothetical combat effectiveness trend with flying qualities was substantiated in a January 1990 roll agility simulation and has been duplicated with an off-line fighter battle simulation program.

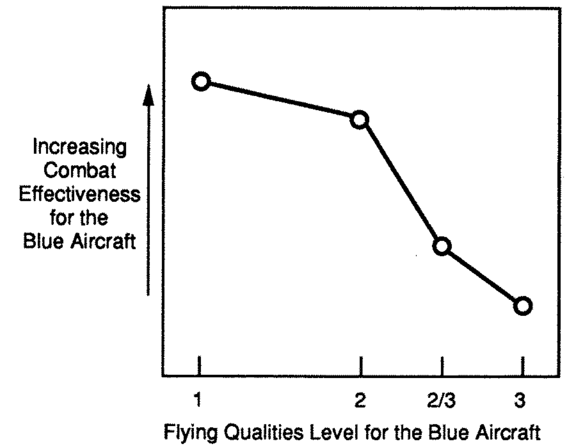


Figure 14. Hypothesized Combat Effectiveness for Blue Aircraft Flying Against Level 3 Adversary

The January 1990 roll agility simulation investigated the tactical relevance of lateral flying quality level variations. The lateral gross acquisition dynamics for the Red aircraft were varied from Level 3 to Level 1 and the Blue aircraft's lateral gross acquisition dynamics were fixed at Level 1. See Figure 15. Four initial conditions were tested: 1 vs 1, neutral head-on; 1 vs 1, neutral abeam, 1 vs 1, Blue defensive; and 1 vs 2, neutral head-on. The pilots had the same weapons as for the March 1989 roll agility simulation which are discussed in Reference 16. Six pilots with varied experience were grouped into four pilot pairs. Approximately 160 engagements were flown for each initial condition with each pilot flying both the Red and Blue aircraft against his paired opponent.

The composite probabilities of survival for the Blue (Ps_B) and Red (Ps_R) aircraft are shown in Figure 16 with 95% confidence intervals for the four initial conditions. The variation in composite probability of survival was significant at the 99% level for both the Blue and Red aircraft. The Ps_B is essentially constant between Levels 1 and 2 while the Ps_R increases slightly between Levels 1 and 2. The Level 1 dynamics may have given the pilot too much maneuverability and caused the increase in Ps_R between Levels 1 and 2. However, the average Ps_R between Levels 1 and 2 is within the 95% confidence intervals so this shift may not be significant.

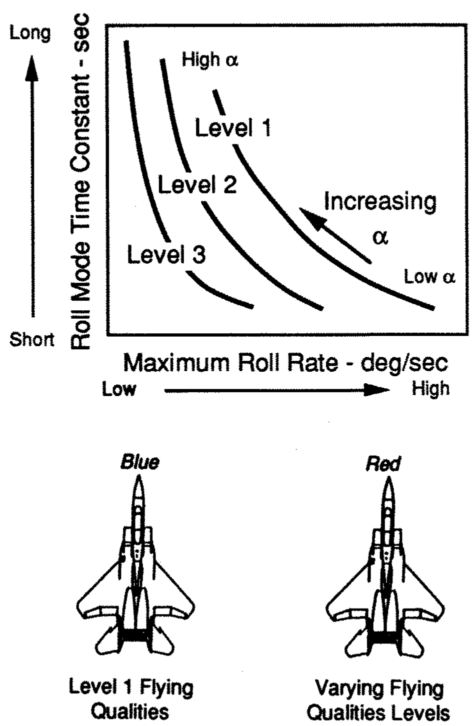


Figure 15. Dynamic Variations for January 1990 Roll Agility Simulation

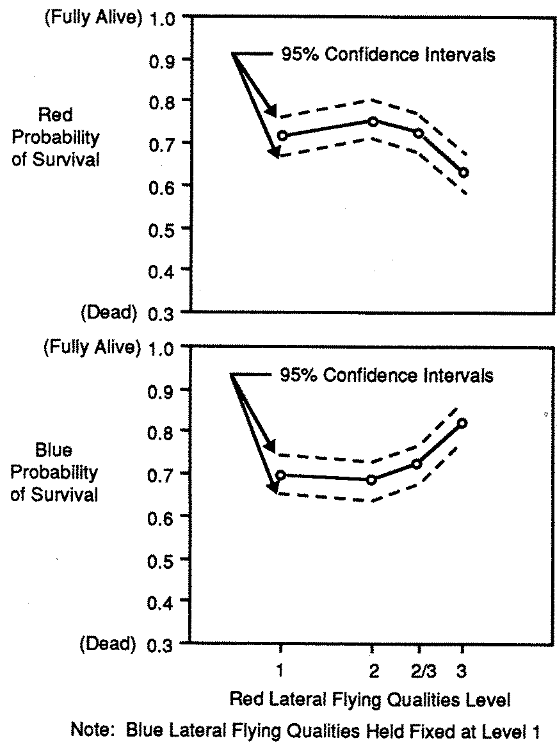


Figure 16. Average Red and Blue Probabilities of Survival for All Initial Conditions

The general shape of the probability of survival plots is similar to the hypothetical exchange ratio curve in Figure 14. The change in probability of survival between Levels 1 and 2 is minimal compared to the change between Levels 2 and 3 in Figure 16. This supports our hypothesis about the relationships between flying qualities, pilot performance, and agility for the roll axis.

Figure 16 shows that tactical effectiveness only degrades for very low agility levels. This preliminary result suggests that minimum agility guidelines rather than maximum agility levels are needed to help designers weigh the increased cost and complexity of enhanced agility against the increase in tactical effectiveness. This is especially important for modern fighter aircraft for which numerous design tradeoffs must be made.

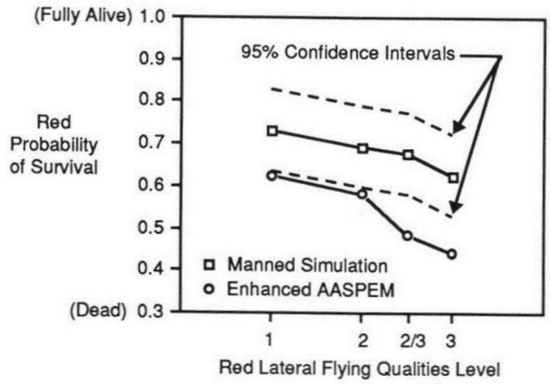
TOOLS TO EVALUATE OPERATIONAL EFFECTIVENESS

DIGITAL FIGHTER BATTLE SIMULATION PROGRAM

The Advanced Air-to-Air System Performance Evaluation Model (AASPEM), an off-line fighter battle simulation program,[19] has been modified at MCAIR to accurately model a pilot's ability to control the roll axis. Aerodynamics engineers worked closely with operations analysis engineers to enhance the program. The AASPEM program now accurately predicts an aircraft's achievable roll dynamics with varying flight conditions. Data from manned simulation agility testing was used to model the pilot's ability to maneuver and control varying levels of roll agility in the program. This improved prediction tool will allow us to study the effect of roll agility on different engagement scenarios at a considerable cost and time savings compared to manned simulation studies.

The modifications to AASPEM were substantiated with the results from the January 1990 manned simulation. A baseline Blue aircraft was flown in AASPEM against a Red aircraft with varying flying qualities levels. The initial condition was similar to the 1 vs 1, neutral abeam starting condition used in all three roll agility manned simulations. The Ps_R for the AASPEM study is shown in Figure 17 along with the Ps_R from the January 1990 manned simulation. The gun model in AASPEM was more lethal than the gun model in the manned simulation, which may account for the lower Ps_R from AASPEM compared to the manned simulation Ps_R.

Note that the Ps_R from AASPEM follows the same trend as the Figure 14 hypothetical curve and the manned simulation results. This excellent result indicates that MCAIR has developed a method to properly model the pilot's ability to maneuver and control varying levels of roll agility.



Note: Blue Lateral Flying Qualities Held Fixed at Level 1

Figure 17. Modified AASPEM and Manned Simulation Probability of Survival for Red Aircraft

COMBAT MONITOR PROGRAM

Our early attempts to analyze air combat engagements from manned simulations indicated the need for a tool that could produce an animated, three-dimensional representation of the engagements on a graphics terminal. The Combat Monitor Program (CBM), which runs on a color, Silicon Graphics, IRIS-4D workstation, was developed to satisfy this need. See Figure 18. The CBM allows the user to play back engagements at various speeds (forward or reverse), view the engagement from different vantage points, and view weapon employment throughout the engagement. The CBM has proved to be a useful tool in analyzing tactics and maneuvers used during the engagements.

EXTENSIONS TO CONVENTIONAL STABILITY AND CONTROL CONCEPTS USING NEW EFFECTORS

Unconventional aerodynamic and propulsion control effectors are being researched to determine their ability to provide increased control power for superagile fighters. Available yaw control power from conventional aerodynamic surfaces falls short of the yaw control power requirements for maneuvering at high angles of attack.[20] Large amounts of nose down control power are required to counteract the nose up pitching moment from inertial coupling[21] during high angle of attack rolls. Advanced flowfield control concepts, like those discussed by Murri in Reference 5, are being investigated to determine their ability to provide increased yaw and nose down control power for high angle of attack maneuvering. Pitch and yaw thrust vectoring concepts[22] are also being studied to determine how well they meet the control power, design, and cost requirements of superagile fighters.

AGILE CONTROLLER AND COMMAND SYSTEM REQUIREMENTS

The expansion of flight envelopes to high AOA may require new control concepts to avoid stick sensitivity problems and provide the pilot with good flying qualities while maneuvering in this dynamic region. Angle of attack type command systems are the conventional response type at high AOAs and directly relate to the flying qualities specification, MIL-STD-1797A. If the commandable AOA range is increased for a fixed stick throw, stick sensitivity may be a problem for tasks that require fine control, such as tracking. A larger stick throw would allow an AOA control system to distribute the large AOA range over a large stick range. However, increasing the longitudinal stick throw may introduce harmony problems between the longitudinal and lateral axes.

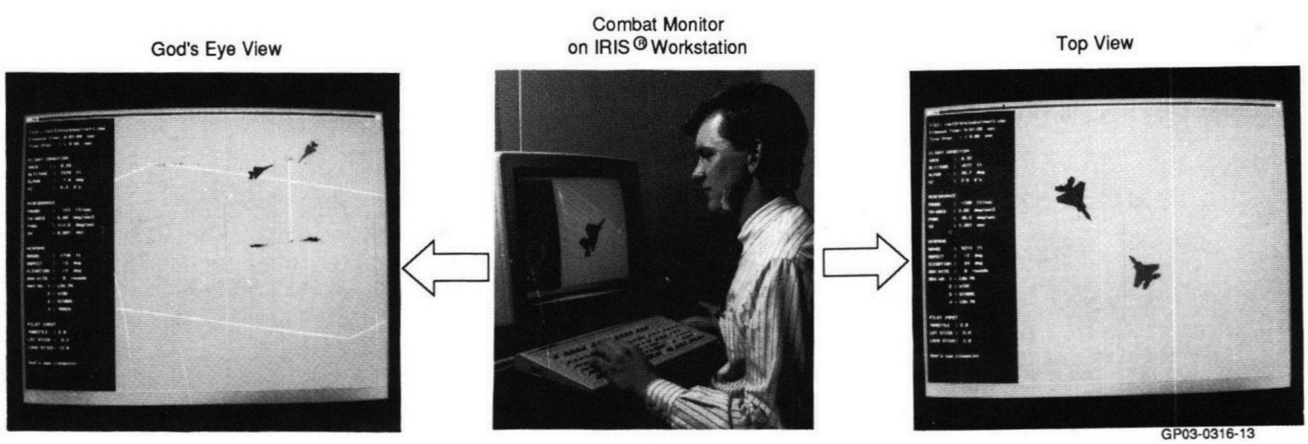


Figure 18. Combat Monitor Program

MCAIR has developed a hybrid longitudinal command system which combines an AOA command system and an AOA rate command system for high AOA tasks. This system, entitled High Alpha Command System (HACS), is discussed in Reference 7. The HACS is intended to allow rapid maneuvering at high AOAs while maintaining the precision required to capture and track a target.

Other response types, such as Rate Command Attitude Hold (RCAH) or AOA rate, may be better at high AOAs for specific tasks. RCAH command systems, that decouple the aircraft attitude from the flight path, may provide the pilot with better control for high AOA point-and-shoot type tasks. A recent high AOA, air-to-air simulation found a RCAH command system to be acceptable for high AOA maneuvering. Other types of command systems, such as angle of attack rate command systems, may be acceptable for some high AOA tasks. No matter what type of command system is utilized, control law designers must recognize that the flying qualities of the aircraft will be a function of the specialized controllers or command systems being used.

HUMAN FACTORS RESEARCH

The multi-axis maneuvering potential of agile aircraft can generate a motion environment that could potentially cause pilot disorientation and degrade mission performance.[23] Instantaneous and steady state load factors at the pilot's head, which are due to motion effects from maneuvering at 30 degrees AOA, are shown in Figure 19. Human factors engineers have been evaluating several agile maneuvers and maneuver sequences to assess the probability of disorientation occurring during agile maneuvering. Vestibular stimulation, the visual field, and the maneuvering force field experienced by the pilot are being analyzed. Means of improving a pilot's tolerance to agile maneuvers are also being studied.

MCAIR AGILITY WORKING GROUP

The MCAIR agility working group has been in place for over two years. It was formed to promote agility research at MCAIR, share technical information, provide for interchange of ideas, and support agility research in each technical area. Technologies represented in the working group include: Aerodynamics (flight dynamics and flying qualities), Guidance and Control Mechanics, Propulsion, Operations Analysis, Human Factors, plus representatives from MCAIR's Test Pilot Office. The group includes representatives from many different disciplines because we recognize that many technologies contribute to total aircraft agility. Regular meetings are held to share technical information and stay attuned to recent agility developments at MCAIR, and in Government and industry. The exchange of technical information and ideas, and mutual support has created a beneficial synergy which has accelerated MCAIR's agility research.

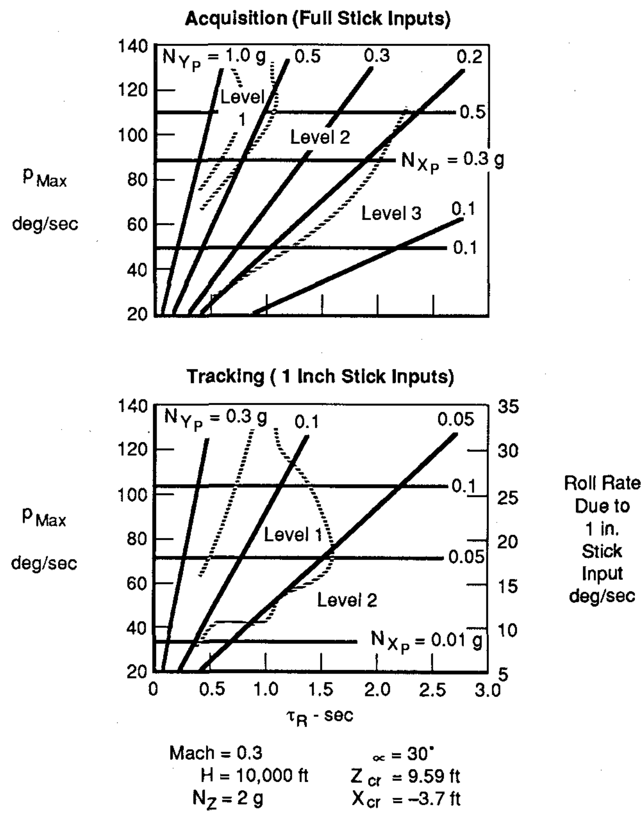


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Figure 19. Lateral and Eyeballs Out Load Factor at the Pilot's Head

CONCLUSIONS

MCAIR has been researching fighter agility for many years to develop advanced capabilities that enhance the tactical effectiveness of fighter aircraft. The agility research has focused on: 1) defining the regions of the flight envelope where airframe agility requires improvement; 2) determining the required level of agility to give the pilot a significant tactical advantage; and 3) studying ways to attain increased agility. These studies have primarily focused on airframe agility and man/machine dynamics.

The high AOA flying qualities research has demonstrated that flying qualities tasks can be developed for this dynamic flight regime and used to generate flying qualities criteria. These high AOA criteria, for an angle of attack command system, differ significantly from low angle of attack criteria. This shift in Level 1 regions demonstrates the need for task oriented flying qualities for all flight phases to provide the pilot with the most tactically effective aircraft.

New agility metrics and flying qualities levels have been researched using manned simulation studies. Initial results show that a proposed roll axis metric, Torsional Agility, did not provide the pilot with increased tactical effectiveness for the scenarios that were investigated. However, variations in lateral flying qualities levels did provide the pilot with a significant increase in tactical effectiveness.

Recent agility research has led to the study of minimum agility requirements rather than maximum agility capabilities. Manned simulation results showed that a pilot can use only a limited amount of roll rate (maneuverability) for closed loop tasks. Providing the pilot with a high level of maneuverability, without a high level of controllability, will reduce agility.

Recent roll axis, air-to-air combat, manned simulation results showed that tactical effectiveness only degrades significantly for very low agility levels. This preliminary result suggests that minimum agility guidelines rather than maximum agility levels are needed to help designers weigh the increased cost and complexity of enhanced agility against the increase in tactical effectiveness.

An off-line fighter battle simulation program has been modified to accurately model an aircraft's achievable roll dynamics with varying flight conditions. The enhanced program also models the pilot's ability to maneuver and control varying levels of roll agility. This improved prediction tool will allow agility researchers to study the effect of roll agility on different engagement scenarios at a considerable cost and time savings compared to manned simulation studies.

Unconventional aerodynamic and propulsion control effectors are being researched to determine their ability to provide increased control power for enhanced agility. Advanced flowfield control concepts and pitch and yaw thrust vectoring concepts are being studied to determine how well they meet the control power, design, and cost requirements of superagile fighters.

The expansion of flight envelopes to high AOA may require new control concepts to avoid sensitivity problems and provide the pilot with good flying qualities while maneuvering in this dynamic region. Angle of attack type command systems are the conventional response type at high AOAs, but other response types, such as Rate Command Attitude Hold (RCAH) or AOA rate, may be better at high AOAs for specific tasks. No matter what type of command system is utilized: 1) control law designers must recognize that the flying qualities of the aircraft will be a function of the specialized controllers or command systems being used; and 2) the optimum command system needs to be researched for each task and recommended for future flying qualities specifications.

The multi-axis maneuvering potential of agile aircraft can generate a motion environment that could potentially cause pilot disorientation and degrade mission performance. Human factors engineers have been evaluating agile maneuvers and maneuver sequences to assess the probability of the occurrence of disorientation during agile maneuvering. These studies also point the way to improved pilot tolerances.

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REFERENCES

1. Eidetics International, "Fighter Agility Seminar Notes," presented January 1988, Redondo Beach, CA.

2. Anon., "Military Standard - Flying Qualities of Piloted Vehicles," MIL-STD-1797A, 30 January 1990.

3. Hodgkinson, J. A., et al., "Relationships Between Flying Qualities, Transient Agility, and Operational Effectiveness of Fighter Aircraft," AIAA Paper 88-4329, August 1988.

4. Bise, M. E., Black, G. T, "Is Agility Implicit in Flying Qualities?," IEEE National Aerospace and Electronics Conference (NAECON), May 1990.

5. Murri, D. G. and Rao, D. M., NASA Langley Research Center and Vigyan Research Associates, "Exploratory Studies of Actuated Forebody Strakes for Yaw Control at High Angles of Attack," AIAA-87-2557, 1987.

6. Mace, J., et. al, "Advanced Thrust Vectoring Nozzles for Supercruise Fighter Aircraft," AIAA 89-2816, July 1989.

7. Wilson, D. J., and Riley, D. R., "Development of High Angle of Attack Flying Qualities Criteria Using Ground-Based Manned Simulators," NAECON CH2759-9/89/0000-0407, May 1989.

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

9. Krekeler, G. C., Wilson, D. J., and Riley, D. R., "High Angle of Attack Flying Qualities Criteria," AIAA-90-0219, January 1990.

10. Moorhouse, D. J., and Moran, W. A., "Flying Qualities Design Criteria for Highly Augmented Systems," NAECON, May 1985.

11. Wilson, D. J., and Riley, D. R., "Flying Qualities Criteria Development Through Manned Simulation for 45° Angle of Attack," (To be published as a NASA Langley Research Center Contractor Report in June of 1990).

12. Skow, A. M., et al., "Transient Performance and Maneuverability Measures of Merit for Fighter/Attack Aircraft," TR-86-201, USAF Contract F33615-83-C-0120, January 1986.

13. Riley, D. R., and Drajeske, M. H., "An Experimental Investigation of Torsional Agility in Air-to-Air Combat," AIAA-89-3388, August 1989.

14. Citurs, K. D., "Controller requirements for Uncoupled Aircraft Motion," AFWAL-TR-84-3060 Volume I, September 1984.

15. Holmquist, H. O., "Rate of Roll Requirements for Fighter Airplanes," Naval Air Test Center Report, June 1960.

16. Drajeske, M. H., and Riley, D. R., "An Experimental Investigation of Roll Agility in Air-to-Air Combat," AIAA 90-2809, August 1990.

17. Box, G. E. P., Hunter, W. G., and Hunter, J. S., Statistics for Experimenters - An Introduction to Design, Data Analysis, and Model Building, John Wiley & Sons, 1978.

18. Riley, D. R., and Drajeske, M. H., "Relationships Between Agility Metrics and Flying Qualities," SAE Aerospace Atlantic Conference, 901003, April 1990.

19. McDonagh, G. M., "Advanced Air-to-Air System Performance Evaluation Model (AASPEM) Analyst Manual," Boeing Document D180-29122-1, November 1985.

20. Marks, B. A., and Hahne, D. E., "Innovative Control concepts and Component Integration for a Generic Supercruise Fighter," AGARD Conference, September 1989.

21. Miller, J., The X-Planes, X-1 to X-29, Specialty Press, 1983.

22. Mace, J., and Doane, P., "Integrated Air Vehicle/Propulsion Technology for a Multirole Fighter-A MCAIR Perspective," AIAA Propulsion Conference, July 1990.

23. Whitley, P., "Human Capabilities in Highly Agile Aircraft," Invited Presentation for High Maneuverability Session of SAE Aerospace Atlantic Conference, 25 April 1990.