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AIAA 96-0088

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34th Aerospace Sciences Meeting & Exhibit
January 15-18, 1996 / Reno, NV

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DEVELOPMENT OF AN AGILITY ASSESSMENT MODULE FOR PRELIMINARY FIGHTER DESIGN

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Abstract

A FORTRAN computer program is presented to perform agility analysis on fighter aircraft configurations. This code is one of the modules of the NASA Ames ACSYNT (AirCraft SYNThesis) design code. The background of the agility research in the aircraft industry and a survey of a few agility metrics are discussed. The methodology, techniques, and models developed for the code are presented. FORTRAN programs were developed for two specific metrics, CCT (Combat Cycle Time) and PM (Pointing Margin), as part of the agility module. The validity of the code was evaluated by comparing with existing flight test data. Example trade studies using the agility module along with ACSYNT were conducted using Northrop F-20 Tigershark and McDonnell Douglas F/A-18 Hornet aircraft models. The sensitivity of thrust loading and wing loading on agility criteria were investigated. The module can compare the agility potential between different configurations and has the capability to optimize agility performance in the preliminary design process. This research provides a new and useful design tool for analyzing fighter performance during air combat engagements.

Introduction

Agility

Agility and flight in expanded maneuvering envelopes have been considered as ways to improve aircraft combat effectiveness, which is a combination of survivability and mission effectiveness.[1] Traditional aircraft performance provides a good indication of maneuverability. The most maneuverable aircraft is the one that has the highest turn rate or can pull the most g's. The performance of fighter aircraft is increasing while the human is becoming the limiting factor. The measure of merit has to evolve from how many g's the aircraft can pull to how quickly it can achieve this limit. Agility is a measure of how quickly the aircraft can be maneuvered. It relates to minimizing the time required to perform some tasks or to the transient dynamics which occur in changing from one set of steady-state conditions to another.[1] The simplest definition of agility is the ability to move quickly in any direction or to perform a specific task. Future "superagile" vehicles will greatly expand the flight envelope with new longitudinal acceleration/deceleration capabilities, lateral and vertical direct force application, increased control authority in all axes, and increased sustained and instantaneous turning ability. The design which performed a set of maneuvers quickest would have the highest potential agility. Different sets of maneuvers will represent different versions of agility metrics. The need to define, measure, and quantify aircraft agility has been driven primarily by the inadequacy of traditional aircraft measures of merit and the emergence of advanced aircraft technologies and capabilities.[2]

Aircraft agility is a highly complex and integrated problem involving aerodynamics, propulsion, structures and controls. However, there are very few concrete definitions of what agility is. There are as many definitions of agility as there are researchers in this area. This has

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made it difficult to compare the results of one investigator with those of another.[3] As of today, the absolute definition of agility is still a subject of debate. Each of the definitions of agility proposed by the government and the industry represent different quantities measuring the performance capability of an aircraft.[4] The same aircraft could be less agile in one sense and more agile in another. The following are some of the proposed agility definitions by the government and industry in an effort to define and measure aircraft agility:

Col. J.R. Boyd[5]: "Maneuver is the ability to change altitude, airspeed or direction in any combination. Agility is the ability to shift from one maneuver to another by being able to transition from one orientation to another in minimum time."

Pierre Sprey[5]: "Agility is directly proportional to the inverse of time to transition from one maneuver to another."

Col. E. Riccioni[6]: "Agility is the ability to move from state space 1 (position, velocity, orientation) to state space 2 along an optimal path (i.e., minimum time or distance or radius)"

Northrop[7]: "Agility is the ability to rapidly change both the magnitude and direction of the aircraft velocity vector."

General Dynamics[8]: "Agility is the ability to point the aircraft quickly and get the first shot; continue maximum maneuvering for self-defense and multiple kills; and accelerate quickly to leave the flight at will."

MBB[9]: "Agility is the time rate of change of the aircraft velocity vector."

USAF Test Pilot School[10]: "Agility is the ability to shoot one's self in the 'derriere' instantly with perfect control.", "Agility is that capability of an aircraft which allows the pilot to change the aircraft present state to a desired end state with quickness and precision."

Eidetics[11]: "Agility is an attribute of a fighter aircraft that measures the ability of the entire weapon system to minimize the time delays between target acquisition and target destruction."

Kalviste, Juri[12]: "Agility is the capability to perform a specific task in the shortest time."

The existence of many definitions indicate a lack of standardization. There is little agreement on what agility is, even on the most fundamental level. Although agility is determined by a combination of performance and handling quality characteristics of the aircraft, it is very difficult to completely define and apply agility through our present state of knowledge of either flying qualities and/or maneuvering performance.[13] Agility is a function of both maneuverability and controllability. Agility of the aircraft does not have hard limiting values which means the more agility, the better. The indirect bounds on the achievable agility of an aircraft are maximum structural loads, stability and controllability limitations, and retaining the desired flying qualities characteristics.[12] The followings are some of the published agility metrics:

dynamic speed turn[8]: plot of P_S vs. turn rate.

pitch agility[11]: the time to pitch to maximum load factor plus time to pitch from maximum to zero load factor.

pitch agility criteria[11]: coefficient of pitching moment due to control surface deflection scaled with wing area, aerodynamic chord, and pitch axis inertia.

T_{90}[11]: the time to roll to and capture a 90° bank angle change.

torsional agility[11]: turn rate divided by T_{90}.

axial agility[11]: the difference between minimum and maximum Ps available at a given flight condition divided by the time to transition between the two level.

relative energy state[14]: ratio of aircraft velocity to corner speed after a 180° turn.

combat cycle time[14]: time to complete a maximum acceleration turn and regain lost energy.

pointing margin[14]: angle between the nose of an adversary and the line-of-sight when the friendly fighter is aligned with the line-of-sight.

roll reversal agility parameter[12]: product of time required to reverse a turn and the cross range displacement that occurs during the turn.

agility potential[15]: T/W divided by W/S.

ACSYNT Background

The ACSYNT (AirCraft SYNThesis) program for aircraft conceptual design was developed at NASA Ames Research Center during the 1970's to study the effects of advanced technology on aircraft synthesis. ACSYNT is a conceptual design code that is designed in a modular fashion, with each discipline of aircraft design analysis assigned to a different module or structured group of routines intended to handle that particular phase of analysis. Current ACSYNT analysis modules include Geometry, Trajectory (mission profile and performance), Aerodynamics, Propulsion, Stability and Control, Weights, Supersonic Aerodynamics, Economic, Agility, and Takeoff and Landing. Using these modules, the code can analyze supersonic or subsonic transports, fighters, and bomber aircraft. ACSYNT's modular structure lends itself to optimization techniques. The optimization program COPES/CONMIN is coupled with the current version of ACSYNT. COPES (Control Program for Engineering Synthesis)/CONMIN (Constrained Minimization) gives users the ability to perform sensitivity analysis, optimization, two-variable function space analysis, and approximate optimization using ACSYNT variables and analysis methods for up to 128 constraints and/or objective functions. The ACSYNT-COPES package performs trade studies and evaluates the impact of technologies on configurations. Improvements in materials, propulsion and other technologies can be incorporated and their effect on aircraft configurations can be readily determined.

The importance of agility is to provide a combat advantage over other aircraft. The goal for the agility study is to develop a methodology for inclusion of agility based requirements in aircraft conceptual design decisions. The design method is to provide quantitative estimates of aircraft agility characteristics and to be applied as a part of the optimization loop in future fighter aircraft design. The agility module in ACSYNT provides analysis of agility metrics and agility criteria. Implementation of technologies to improve aircraft agility are analyzed and optimized in ACSYNT while their penalty and impact on other design constraints are determined. This analysis provides some insight into the utility of agility technologies and the combat effectiveness of an aircraft configuration.

Agility Metrics

The general character of the agility module is to operate on the upper boundary of what is frequently referred to as the doghouse plot. This is a graph of turn rate versus speed of Mach number at a specified altitude. Figure 1 illustrates a typical doghouse plot. The peak in the upper boundary represents the highest turn rate for any Mach number. The Mach number corresponding to the peak is usually called corner speed. The aircraft's turn rate is limited by different constraints depending on which side of corner speed it is flying. Above corner speed, the aircraft can aerodynamically generate a higher load factor than the aircraft's structure can withstand. The aircraft is said to be "load limited" with the maximum turn rate determined by the maximum designed load factor. Below corner speed, the aircraft is operating at its maximum lift coefficient and cannot aerodynamically generate the design load factor. This region is said to be "lift limited." The definition of corner speed can be said as the Mach number that produces the maximum design load factor at maximum lift coefficient. Two specific metrics are discussed because they are being developed as part of the ACSYNT agility module.

Combat Cycle Time (CCT)

The combat cycle time metric measures the time it takes to turn through a specified heading change and then accelerate to regain the energy lost during the turn. The exact maneuver is as follows: roll into turn, pitch to specified load factor, hold turn through specified heading change, pitch back down to unity load factor, roll to wings level and accelerate back to original speed. The objective is to complete this maneuver in the least amount of time. In this maneuver the aircraft operates along the upper boundary of the doghouse plot. Figure 2 illustrates the path the aircraft follows on this plot over the course of the maneuver.

Pointing Margin (PM)

The pointing margin metric measures how fast an aircraft can point his nose at an adversary aircraft. This parameter is a function of flight condition, mach number, altitude, and heading angle of the turn. The two aircraft begin at the same Mach number and nearly the same location in space but pointed in opposite directions. The maneuver is shown in Figure 3. At the start of the metric both aircraft begin a maximum acceleration turn toward one another. The aircraft that first brings his line of sight upon the opposing aircraft's position is considered the most agile. The measure of merit is the pointing margin or the angle between the two aircrafts' lines of sight just as the inferior aircraft is captured. The greater this angle the longer it takes the losing aircraft to acquire the winning aircraft's position. This provides the winning aircraft a longer missile flight time and a better chance of a kill.

The metrics discussed illustrate the differences of opinion on what agility is. Some analyze how efficiently aircraft use energy to achieve an objective and how quickly they can regain lost energy. Other metrics analyze the quick-action nose pointing capability of a configuration. The agility module developed is adaptable enough to accommodate several philosophies and their respective metrics.

Method

General Methodology

The overall structure of the code is a time-stepping routine that tracks pertinent parameters over the course of the agility maneuver. This is basically a simulation technique. Since CCT and PM were selected as archetypes for the simulation package, there exists separate subroutines dedicated to analyzing those metrics. There are two options to evaluate the other agility metrics. The user may input the desired maneuver segments into an existing agility subroutine or may create a different agility subroutine with different maneuver segments and parameters.

Constant Altitude

A constant altitude assumption was made throughout the development of the flight mechanics because most of the agility metrics involve maneuvers that occur at constant altitude. However, the aircraft was not constrained to fly level. The vertical excursions were ignored in this analysis to simplify the resulting equations. It is the user's responsibility to ensure maneuvers are substantially level during the simulation.

Maneuver Segments

The agility metric maneuvers were divided into separate segments. Figure 4 illustrates the four types of maneuver segments: rolls, pitches, turns, and accelerations. Segments are further divided into functional and transient categories which are explained in a later section. Turns and accelerations actually represent quasi-steady turns and straight line accelerations. The term "quasi-steady turn" refers to a steady, level turn maneuver where the velocity may be changing. If a turn cannot be sustained, the aircraft loses air-speed. In order to maintain the load factor, the angle of attack must gradually increase. If the aircraft is lift-limited and cannot sustain the load factor, the bank angle must gradually decrease to maintain the level turn. These changes in angle of attack and bank angle occur slowly so that the steady turn equations of motion can be used and the perturbation equations need not be employed. It is this type of turning maneuver that is termed quasi-steady.

Tracked Variables

In order to evaluate agility metrics, nineteen parameters must be tracked. For each time step these parameters are calculated and stored. The primary output of the agility module is a time-stepped array of these parameters. The nineteen tracked variables are listed in Table 1.

Flight Dynamics

Agility metrics are categorized by time scales (transient, functional) or by the type of motion involved (lateral, pitch, axial). Functional maneuver segments deal with long-term changes

(>5 seconds) in aircraft energy state, position and attitude. They quantify how well the fighter executes rapid changes in heading or rotations of the velocity vector. Emphasis is on energy lost during turns through large heading angles and the time required to recover kinetic energy after unloading to zero load factor. Equations of motion for the functional segments were steady-state equations for turns and rectilinear flight. Transient maneuver segments deal with short-term changes (1-5 seconds) in aircraft accelerations, positions and orientation. They quantify the fighter's ability to generate controlled angular motion and to transition quickly between minimum and maximum levels of specific excess power. Equations of motion for the transient segments were standard longitudinal and lateral-directional perturbation equations.

Equations of Motion for Functional Maneuver Segments

The turn subroutine is designated as quasi-steady since the turns are not assumed to be sustained, which makes Mach number a variable. Thus, the aircraft thrust and lift/load limit properties vary through a turn. The acceleration subroutine returns the thrust vector to the horizontal, throttles up to full power and simply accelerates the aircraft through a user specified mach number range while maintaining straight and level flight.

Equations of Motion for Transient Maneuver Segments

Pitch and roll subroutines maneuver the aircraft to a user designated load factor and bank angle, respectively. The pitch equations of motion were standard two degree of freedom short-period approximation equations. The roll segments were modeled with a single degree of freedom, lateral equation of motion.

Engine Thrust Segment

The engine transient model was based on non-dimensional data for a 1990 era low-bypass turbofan fighter engine. This data did not contain time responses for thrust changes from any thrust level to any thrust level, but consisted of six particular throttle responses as shown in Table 2. At any time step, the commanded power level may be changed by code logic. When this occurs the proper throttle response curve is enacted to provide a time history of the engine transient. Figure 5 illustrates the time histories of one of the six throttle responses. Unfortunately, throttle changes do not always fit one of the six throttle responses. For example, the throttle change may start or end at a partial throttle setting. In this case, the code begins its time history in the middle of the appropriate response curve. The main drawback of this approximation is that the power increases rapidly right from the beginning of the throttle change instead of an initial lag.

Note that the present module is best suited for functional type metrics because ACSYNT's stability module is not fully operational and the flight control module is not yet incorporated. Once those modules are fully operating, the transient maneuver analysis capabilities will be improved. Currently, the transient metrics may be analyzed, but the analytical models are not as robust as for the functional type segments.

Code Options and Features

The agility operating code contains some options and features for the users to customize the maneuvers by manipulating the input parameters. These features include the angle of attack limiter, throttle control and turning speed capture, thrust vectoring, air brake, and external stores release and weight/moment of inertia control.

Code Verification

Code verification consisted of three phases. The first phase was to test code logic and to ensure continuous, believable time histories of the tracked variables. All the code features and options were tested thoroughly as well.

The second phase was to compare the agility module's maneuver analysis with the combat analysis in ACSYNT's trajectory module. This phase would ensure that the agility module was retrieving aerodynamic and propulsive data properly and that the physical equations used for maneuverability are consistent with an independent performance package NASA has used for years. The agility module's sustained and instantaneous turn rates, radii, excess powers, angles of attack and lift and drag coefficients were compared with those of the trajectory module over a range of Mach numbers. The greatest deviation was found to be three percent. The source of error was attributed to roundoff error. The combat analysis in the trajectory module conducts its analysis at a frozen instant in time. The agility module performs these calculations for consecutive time steps and calculates the resulting kinematics between these time steps. This validation phase indicated that the agility module performs time dependent maneuverability analysis properly and the time-stepping simulation technique is effective in tracking an aircraft's performance throughout a maneuver.

The last phase of validation was to compare agility analysis with the existing maneuver data of an inventory fighter. The only flight test maneuver data available was from one of the NASA Dryden Flight Research Facility's F/A-18 HARV flight tests. The flight test data contained a very comprehensive list of parameters except for the positional tracking, namely, XYZ positions. The positional comparison could not be completed in light of the lack of data. The parameters being compared are time, mach number, heading angle, roll rate, bank angle, load factor, angle of attack, and turn rate. The technique that is used for the validation is called simulation matching in which the real data is being tested in the code to see if it produces similar result.

A test was performed to ensure the code was working properly for the individual segments, such as roll, pitch, etc. This was done by testing piecewise segments. The piecewise test proved that the code provides acceptable result for each individual segment. Theoretically speaking, a complete maneuver should be performed the same way as when different segments are added together, if each piece is performed as expected. The flight test data was composed of many different random segments of maneuvers, and it was not in any easily identified classical maneuvers. Each segment has its own boundary conditions, therefore it was very difficult to mix and match them to create a classical maneuver. The next task was to simulate the whole maneuvers. The major problem was to decompose a continuous maneuver into the appropriate discrete segments. As expected, there is always deviation between theory and reality. The pilot may be doing a roll and a pitch simultaneously instead of performing a discrete pitch after a discrete roll. Another problem was not knowing exactly when did one maneuver begin and one end. The fighter was maneuvering with a combination of different segments in a short time and data was recorded in an interval of 0.5 sec. A test run was finally generated with a maneuver that is very similar to the CCT (roll-pitch-turn-pitch-roll-accel). As stated above, it was extremely difficult to identify where and each segment begins and ends. It is a matter of judgment concerning the identification of the different segments in the test data. It is done by looking at the maneuver characteristics such as maintaining a constant AOA for a turn, constant roll rate and bank angle for a pitch, or constant load factor for a roll. The predicted maneuver is obviously not what the fighter was actually doing, but it was believed to be close enough for our purposes. It is understood that a continuous reality can not be simulated completely by discrete simulation. With the above information, the appropriate parameters were supplied and initialized in the code according to the test data. It was found that controlling these boundary conditions was critical, since the original code initialized those parameters to be zeros, changes had to be made in the appropriate subroutine. Other than these necessary inputs, the code was not changed in any way.

While results were very good, there are several factors that introduce errors in this validation. Any difference between the simulated maneuver and the actual maneuver is going to cause the error in the analysis. One source of error is a discontinuity between segment boundary conditions. Figure 6 shows mach number vs. time for a typical maneuver. As seen on this graph, the matching is quite good. The average percentage error between the actual and the ACSYNT curve is 0.21%. The discontinuities in the graph can be seen more clearly in Figure 6a. This figure shows actual, ACSYNT, and ACSYNT-Modified curves. The discontinuity is located at the transition from one segment to another. The ACSYNT-Modified curve is generated by assuming that the curve is continuous instead of discrete. It shows how the curve should be without the discontinuity between each segment. The difference between the ACSYNT and the ACSYNT-Modified results due to the fact that the boundary conditions between segments are not forced to be the same in the code. If the boundary conditions of the beginning of a segment is the same as the end of the previous segment, then a piecewise continuous analysis can be obtained. When there is only one boundary condition, the analysis is continuous. Another source of error has to do with simulation vs.

reality. As shown in Figure 7, the curves clearly distinguish the behavior of a real and a simulated maneuvers. For a real maneuver, the flight is very smooth with a gradual increase in the load factor. Conversely, the simulated flight jumps to the designated g's for each segment. This would certainly contribute errors into the validation. Comparisons between heading angle, bank angle, load factor, turn rate, and angle of attack with time and mach number were made. For all of these comparisons, the percentage errors are shown in Table 3 and the percentage error is acceptable for this kind of analysis. Again, the discontinuity in the curve is caused by not forcing boundary conditions to be the same in the discrete analysis. Thus it can be concluded that this validation is satisfactory and the existing computer code is valid.

Trade Studies

Effect of Thrust Loading and Wing Loading

Thrust Loading (T/W) and Wing Loading (W/S) are the two most important parameters affecting aircraft performance. An aircraft with a higher T/W will accelerate more quickly, climb more rapidly, reach a higher maximum speed, and sustain higher turn rates. However, the larger engines will consume more fuel throughout the mission, which will drive up the aircraft's takeoff gross weight to perform the design mission. W/S affects stall speed, climb rate, takeoff and landing distances, and turn performance. Wing loading determines the design lift coefficient, and impacts drag through its effect upon wetted area and wing span. Wing loading has a strong effect upon sized aircraft takeoff gross weight. If the wing loading is reduced, the wing is larger. This may improve performance, but the additional drag and empty weight due to the larger wing will increase takeoff gross weight to perform the mission.

The studies performed are intended to illustrate how the agility module may be used to ascertain and optimize an aircraft configuration's agility potential. The two parameters were chosen because they are fundamental in classical energy maneuverability analysis as discussed earlier. The new agility metric analysis shows aircraft that appear to have similar energy maneuverability performance levels can have quite different levels of agility. The baseline aircraft used for the studies were the Northrop F-20 Tigershark and the McDonnell Douglas F/A-18 Hornet aircraft models. The weights, external dimensions and installed thrust were matched to obtain a representative fighter model. The maneuver used was a 7g turn through 180 degrees at an altitude of 15,000 feet. The aircraft began the maneuver in straight and level flight at Mach 0.9. Combat cycle time (roll-pitch-turn-pitch-roll-accel) and pointing margin (roll-pitch-turn) maneuvers were performed for the test runs. The effects on T/W and W/S on both CCT and PM are discussed.

Effect of Thrust Loading on Combat Cycle Time and Pointing Margin

The baseline fighter along with four other configurations were flown through the same maneuver. These configurations were altered only in the available level of thrust specified as a percentage of the baseline configuration's available thrust (80%, 90%, 110%, 120%).

Figure 8 illustrates the time differences for each segment of the CCT maneuver for all five configurations. The maneuver times steadily decreased with increased available thrust and the highest thrust aircraft performed the maneuver in the least amount of time. This is because the reduced velocity deficit coupled with the more powerful engine created significantly shorter acceleration times for the higher thrust configurations. However, The lower thrust aircraft completed the turn segment slightly quicker than the higher thrust aircraft which is the case for the pointing margin maneuver as shown in Figure 9.

Turning speed determines an aircraft's highest turn rate. It is understandable why the lower thrust aircraft completed their turns sooner. Their higher decelerations placed them in speed regimes with higher turn rate than the greater thrust aircraft and thus were able to achieve superior turns. If the starting velocity were below the turning speed, the higher thrust aircraft would be better able to accelerate to and maintain the turning speed. It is situations like this that make the development of agility criteria so difficult. The configuration can be entirely dependent on the specific situation. Figure 10 showes pointing margin vs. thrust loading. A better pointing margin can be obtained for a lower thrust loading which is consistent with the turning speed effect that was discussed. The aircraft that reaches the turning speed and completes the turn sooner can always obtain a better positional advantage. Figure 11 illustrates the turn profile in the horizontal plane of both maneuvers. The lower thrust configurations turn tighter and possess a positional advantage over the course of the turn segment. However, as the aircraft accelerate back to the starting velocity the lower thrust aircraft take longer. They have lost their positional advantage by the time the maneuver is completed.

The impact of thrust loading is entirely dependent on what is considered most important. For CCT type of maneuver, the higher thrust aircraft has a time advantage and appeared to win. For PM type of maneuver, a lower thrust aircraft would be a better choice because lower thrust configurations possessed a positional advantage up to the end of the turn segment. The conclusion of this study is there is a tradeoff of what type of performance is most crucial and what are its costs.

Effect of Wing Loading on Combat Cycle Time and Pointing Margin

The baseline fighter along with four other configurations were flown through the same maneuver. These configurations were altered only in the wing loading and all other input parameters were held constant. The selected wing loadings were 65, 70, 85, and 90 psf with a baseline wing loading of 78.4 psf. Figure 12 illustrates the time differences for each segment of the CCT maneuver for all five configurations. The total time to complete the maneuver was very similar for all configurations, but there was a difference in the times for each maneuver segment. The higher loaded aircraft completed the turn segment slightly faster than the less loaded configurations. This is because a higher loaded aircraft produces higher lift coefficients, thus increases induced drag and results in greater deceleration and velocity deficit. The higher loaded aircraft required longer accelerations times than did the less loaded aircraft because they had to make up the energy lost in the turn. Similar to the thrust loading results, the quicker approach to turning speed provided higher turn rates and resulted in a shorter time for a turn. Figure 13 plots the turn profile in the horizontal plane of the maneuver. This graph shows the higher loaded aircraft has a turn advantage both in time and in space.

The points discussed above are also well illustrated in Figures 14 and 15 for the pointing margin maneuver. Figure 15 shows a better pointing position can be obtain with a higher wing loading which correspond to the fact that a higher wing loading has a turn advantage.

It was illustrated that the results of this study were highly dependent on the particular type of maneuver. If the turn was extended to 270 or 360 degrees, the higher loaded aircraft would have lost its turning advantage and created an excessive velocity deficit that would lengthen the acceleration phase. This shows the difficulty in developing robust agility criteria that provide the best overall performance for a variety of situations and tasks.

Aircraft Optimization with Agility Parameter as One Constraint

The agility module can be used in configuration optimization. This capability is the real power of ACSYNT and it is the optimization studies that will be used to determine the impact of agility technologies and constraints on the overall aircraft configuration.

The basic optimization method used by COPES in conjunction with ACSYNT consists of an objective variable, design variables and constraint variables. The objective variable is the parameter being optimized and can be either maximized or minimized. Design variables are the parameters whose values are varied to provide a design space. These design variables are given upper and lower bounds. The constraint variables are parameters that further limit the design space. Typical constraints in ACSYNT are overall aircraft density or a sustained turn requirement at altitude. Only the design variable space that satisfies all constraints can provide possible solutions. The optimizer evaluates aircraft configurations over this design space and attempts to find the design point that produces the best value of the objective variable.

In this case study, the objective variable was gross takeoff weight. The constraint for this optimization was to complete the same CCT maneuver within twenty seconds. The design variables were the wing area and the engine size. Figure 16 illustrates the design variables bounds, the constraint variable value, and the pertinent parameters of the starting configuration and the optimized configuration.

The tradeoff is wing loading versus thrust loading. A decrease in wing loading allows a decrease in thrust loading and vice versa. A larger wing and a larger engine both add weight to the vehicle. Some combination of wing and engine size will satisfy the agility constraint and provide the overall lowest takeoff weight. It can be seen on Figure 16 that the trends drive the wing to as small a value as possible. This results in only a moderate increase in engine size. It is shown that the agility criterion is much more sensitive to engine size than wing loading.

Conclusions and Recommendations

FORTRAN programs were developed for two specific metrics, CCT (Combat Cycle Time) and PM (Pointing Margin), as part of the agility module in ACSYNT design code. This is an effective design tool in analyzing an aircraft configuration's agility potential. The integrity of the code was proved by comparing with existing flight test data. Example trade studies or the effect of thrust loading and wing loading illustrate how the module can be used to perform trade studies on parameters important to agility metrics that are based on flight test maneuvers. The module is capable of providing constraints for ACSYNT's optimization analysis. Once agility criteria has been developed the module can be used to optimize an aircraft configuration for agility requirements as well as contemporary mission requirements.

The present module is best suited for functional type metrics, particularly combat cycle time, pointing margin, and dynamic speed turn. Although the transient metrics may be analyzed and the architecture is well suited for transient maneuvers, the analytical models are not as robust as for the functional type segments. Once ACSYNT is capable of generating stability derivatives and the flight control module is incorporated, the transient maneuver analysis capabilities will be improved. The agility module's architecture has an important characteristic for future improvements. Since industry and government have not yet settled on a single definition of agility, an accepted group of metrics, or quantifiable requirements, the adaptable architecture will allow future metrics and requirements to be incorporated with the least amount of work. The simulation's time-stepping technique of analysis and list of maneuver segments should provide the necessary adaptability.

Combat Cycle Time and Pointing Margin are the two dedicated subroutines. Future work effort should involve development of subroutines dedicated to performing other agility metrics. Many of the metrics discussed in the introduction section are appropriate for inclusion in the agility module.

The goal for this agility study is to develop a methodology for inclusion of agility based requirements in aircraft conceptual design decisions. This is accomplished by using the agility module to provide quantitative estimates of aircraft agility characteristics and to apply as a part of the optimization loop in future fighter aircraft design.

Acknowledgments

The authors are grateful to Mr. Jeffrey Samuels, Mr. Paul Gelhausen, Mr. George Kidwell of NASA Ames, and Mr. Al Bowers of NASA Dryden for their guidance and support throughout this study. This research was funded by NASA Grants NAG2-743 and NCC2-834.

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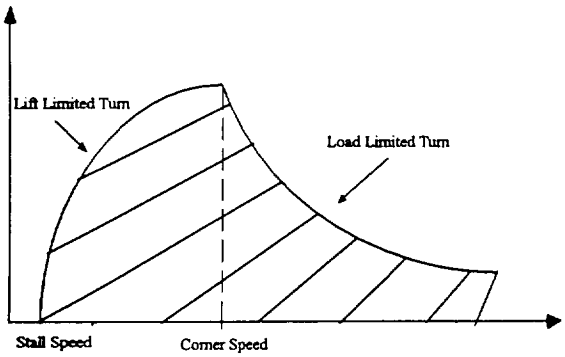

Figure 1 Illustration of the Doghouse Plot

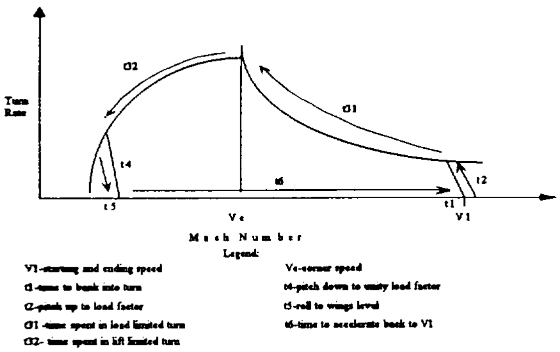

Figure 2 Combat Cycle Time Maneuver Circuit

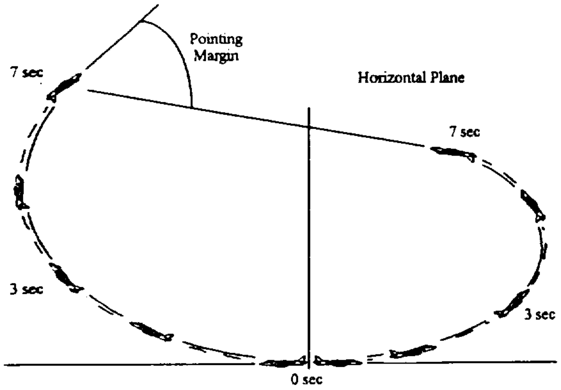

Figure 3 Pointing Margin Agility Metric

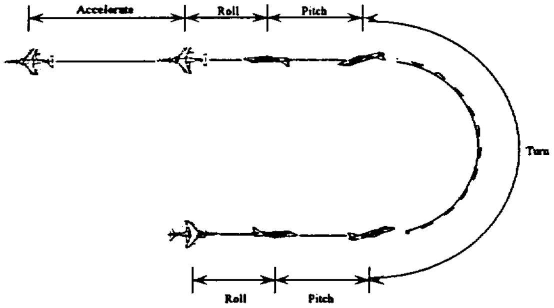

Figure 4 Breakup of Metric Maneuvers into Maneuver Segments

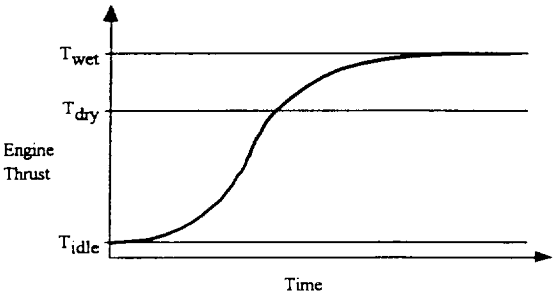

Figure 5 Throttle Transient Response from Flight Idle to Maximum Afterburner

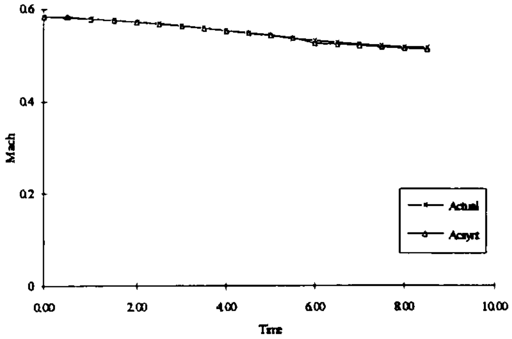

Figure 6 Comparison of Simulated and Actual Maneuvers - Mach vs. Time

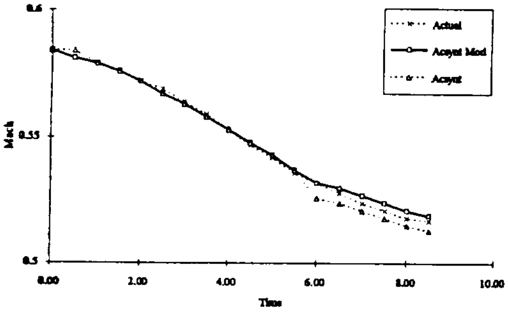

Figure 6a Comparison of Simulated and Actual Maneuvers with Modification - Mach vs. Time

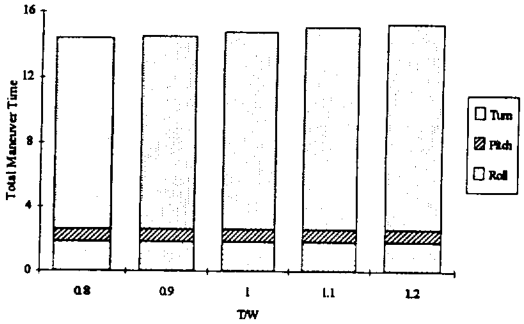

Figure 9 Pointing Margin Total Maneuver Time for Different Thrust Loadings

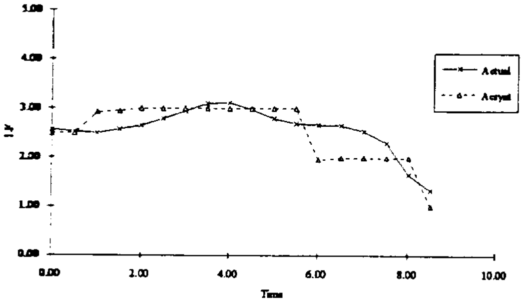

Figure 7 Comparison of Simulated and Actual Maneuvers - Load Factor vs. Time

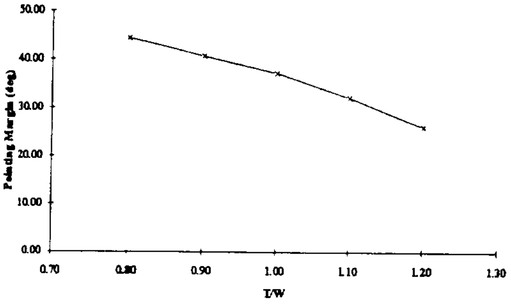

Figure 10 Pointing Margin vs. Thrust Loading

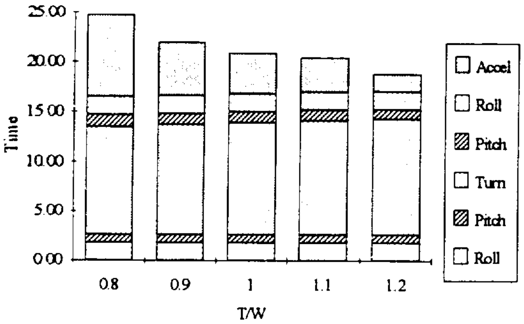

Figure 8 Combat Cycle Time Variation for Different Thrust Loadings

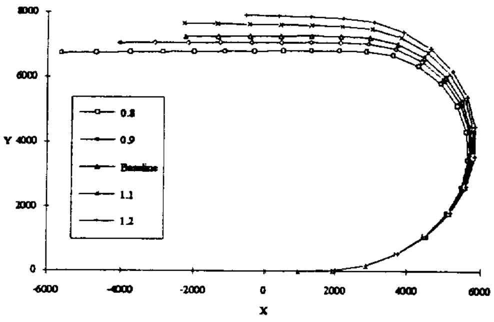

Figure 11 Horizontal Plane Turn Diagrams for Different Thrust Loadings

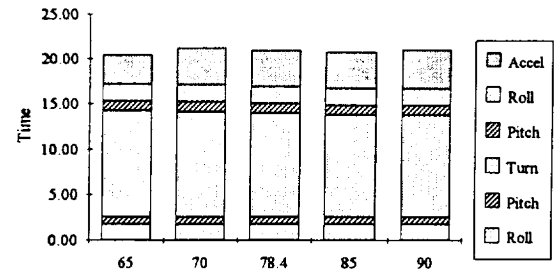

Figure 12 Combat Cycle Time Variation for Different Wing Loadings

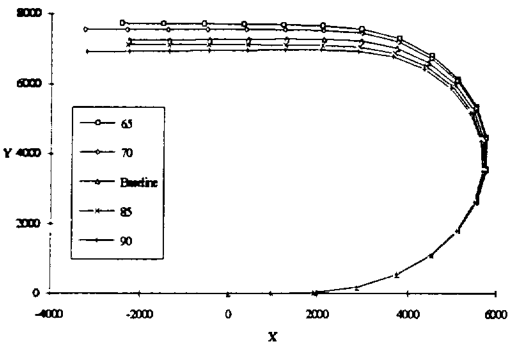

Figure 13 Horizontal Plane Turn Diagrams for Different Wing Loadings

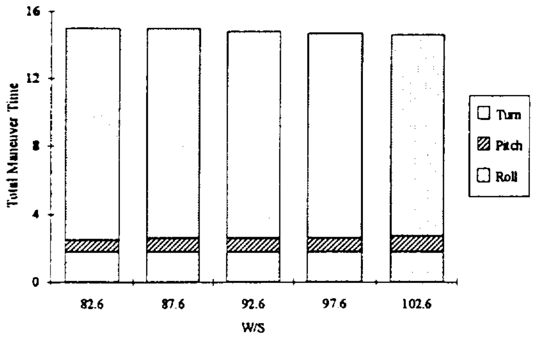

Figure 14 Pointing Margin Total Maneuver Time for Different Wing Loading

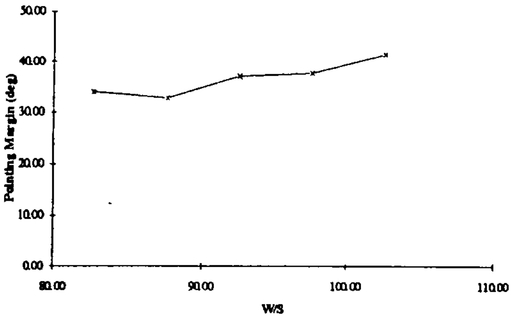

Figure 15 Pointing Margin vs. Wing Loading

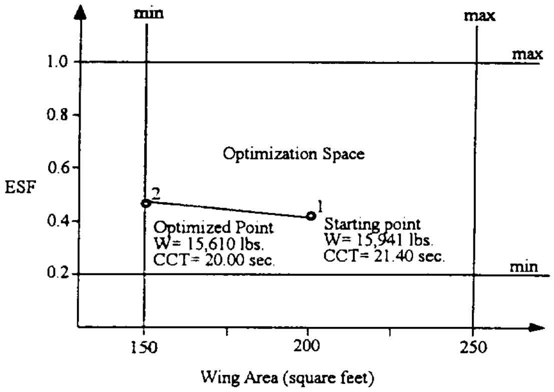

Figure 16 Optimization Path for Minimization of Aircraft Takeoff Weight

M -- mach number
$\dot{V}$ (g's) -- axial acceleration
Throttle command logic (numeric)
λ (degrees) -- thrust vector angle
T_g (pounds) -- gross thrust
T_n (pounds) -- net thrust
Engine core thrust (% thrust)
Afterburner thrust (% thrust)
α (degrees) -- angle of attack
n (g's) -- normal acceleration "load factor"
C_L -- lift coefficient
C_D -- drag coefficient
Ψ (degrees) -- heading angle
$\dot{\Psi}$ (deg/sec) -- turn rate
Φ (degrees) -- bank angle
P (deg/sec) -- roll rate
X (feet) -- downrange distance
Y (feet) -- crossrange distance
R (feet) -- turn radius

Table 1 Variables Tracked Over Time by the Agility Module

Max afterburner→ Flight idle	Flight idle → Max afterburner
Max dry → Flight idle	Flight idle → Max dry
Max afterburner → Max dry	Max dry → Max afterburner

Table 2 Throttle Response Time Histories Obtained from Contemporary Fighter Engine

	% error
Mach Number	0.21%
Heading Angle	0.58%
Bank Angle	20.70%
Load Factor	9.80%
Turn Rate	13.83%
Angle of Attack	17.44%

Table 3 Percentage Error Between the Simulated and Actual Maneuvers for the Agility Code Validation