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Functional Agility Metrics and Optimal Trajectory Analysis

George W. Ryan III* and David R. Downing†
University of Kansas, Lawrence, Kansas 66044

This paper examines several functional fighter agility metrics using optimal and nonoptimal maneuvers for a generic F-18-type aircraft to investigate the sensitivity of these metrics to the control strategy used to test them. The maneuvers tested are 180 deg heading changes. The metrics tested are the combat cycle time, the dynamic speed turn agility plots, and the relative energy state metric. Significant improvements in the measured agility metrics are possible if an optimal control strategy is used to test them. For example, reductions in combat cycle time of 60% with subsequent reductions in speed bleed rate of 80% are possible if an optimal maneuver is flown instead of a typical flight test maneuver. The specific agility improvements are vehicle airframe and control system dependent. However, the techniques used in this study are applicable to any aircraft and could provide insight into flight control system design and design tactics for maximizing performance during air combat engagements.

Nomenclature

M = Mach number
R_t = turn radius
V_c = corner speed
α = angle of attack

Introduction

FIGHTER performance and air combat tactics have been studied since aircraft were first used as military weapons to predict air combat effectiveness. The methods used to evaluate performance have changed to meet changes in technology from simple point performance measures, such as rate of climb, used as early as World War I,[1] to complicated mathematical formulas derived to predict the performance of modern fighters.[2] Each innovation in technology has caused a subsequent change in fighter performance evaluation methods and combat tactics.[3]

For example, the introduction of the all-aspect infrared missile has made traditional point performance measures inadequate measures of aircraft effectiveness in air-to-air combat. The all-aspect infrared missile has eliminated the need to achieve a rear aspect firing position in an air combat engagement. Turn rate and radius performance have become more important in surviving air combat for taking advantage of the "safe zone" that exists between minimum missile range and maximum gun range.[4] As a result, air combat has shifted from a series of sustained maneuvers to short, point-and-shoot maneuvers. The resulting shift in time scales for air combat has made traditional performance measures inadequate for measuring combat performance because they do not measure transient maneuvering capabilities.[3] This has prompted the development of many new performance measures, collectively called *agility metrics*.

These metrics are classified into several categories based on the time scale involved with the maneuver measured or the axis in which the maneuver takes place. One category of agility metrics is the functional agility metrics, which measure a time-dependent maneuver of a duration greater than about 5 s. An example is the time needed to turn to a specific heading angle and accelerate back to the energy level present before the initiation of the turn.

Previous tests of some of the functional agility metrics have shown that they are sensitive to the control strategy used to test them,[5] possibly making some comparisons between aircraft unintentionally biased. This is simply an illustration of how, in addition to airframe and control system characteristics, control strategy can greatly influence how effective a given fighter will be in a combat situation. This makes the determination of the best control strategy for testing a given agility metric for a given aircraft important. If the optimal control strategy is used to test a metric for each aircraft, comparisons can be made between two aircraft with bias significantly reduced or eliminated. This procedure would reduce the effects of pilot technique, allowing the true agility of a given airframe and control system to be determined.

This paper examines several fighter agility metrics for a generic F-18-type aircraft. An optimal trajectory program called Optimal Trajectories by Implicit Simulation (OTIS)[6] is used to determine the "best" control strategy that yields the smallest value of each metric. These optimal control strategies are used as inputs into a six-degree-of-freedom (6DOF), high-fidelity, nonlinear simulation for the generic F-18-type aircraft. This allows realistic comparisons to be made between optimal and nonoptimal maneuvers. The metrics examined are the combat cycle time (CCT), dynamic speed turn (DST) plots, and relative energy state (RES).

Combat Cycle Time Metric

The CCT[7] agility metric measures the time it takes for an aircraft to turn through a specified heading angle and regain the energy lost during the turn. The metric attempts to relate a combat-relevant task to a measure of time and do so in a way that is useful to pilots. This metric can be thought of as the time it takes to cycle around the limits of the turn rate vs Mach number plot, or "doghouse" plot, shown in Fig. 1. The times involved with the CCT metric include

t_1 = time to roll 90 deg and load up to maximum normal load factor
t_{21} = time to reach corner speed or maximum turn rate
t_{22} = time to reach new heading angle
t_3 = time to unload to 1 g normal load factor and roll-out
t_4 = time to accelerate back to original energy level

The CCT is the sum of these times:

$$\text{CCT} = t_1 + t_{21} + t_{22} + t_3 + t_4 \tag{1}$$

The goal is to achieve the lowest CCT possible.

Dynamic Speed Turn Plots

Though maneuver time is an important consideration for combat effectiveness, measuring the transient energy level during a maneuver is equally important. One metric that measures transient energy levels is the DST plots.

The DST[8] plots relate energy state rate of change to spatial state rate of change. Two plots are created by cross plotting the load factor/lift limit lines of the doghouse plot and the 1-g acceleration line along the bottom of the doghouse. Figure 2 shows the conceptual development of these plots. The first plot, turn rate vs speed bleed rate,

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*Graduate Student, Department of Aerospace Engineering. Member AIAA.

†Professor and Chair, Department of Aerospace Engineering. Associate Fellow AIAA.

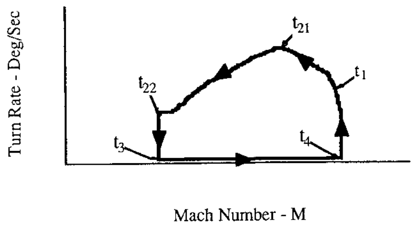

Fig. 1 Conceptual plot of CCT metric.

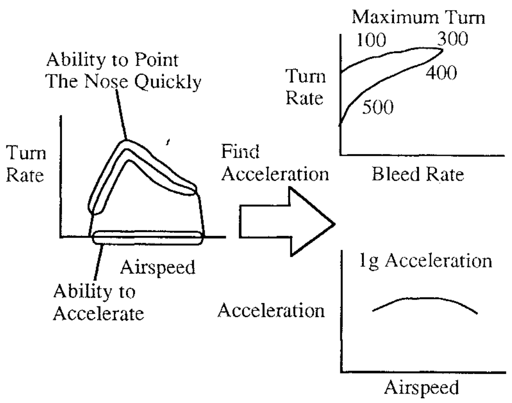

Fig. 2 Development of DST plots.

is produced by measuring the turn rate and speed bleed rate at each point along the turning portion of the doghouse plot Points along the load factor limit line and the lift limit line are plotted to yield a representation of the turning potential of the aircraft. Airspeed flags can be added to the plot to show the airspeed that corresponds to each speed bleed rate during the maneuver. The second plot is obtained by taking points along the bottom of the doghouse to determine the 1-g acceleration capability of the aircraft.

These plots can be used to compare the turning or acceleration capabilities of different aircraft or to compare maneuvers for the same aircraft to see where increases in speed bleed rate do not yield significant increases in turn rate. The plots add another tool to the traditional energy maneuverability (EM) approach to analyze aircraft performance by studying acceleration and deceleration. This time differentiation of traditional EM analysis techniques can expose differences between the efficiency of different maneuvers or different aircraft because the transient maneuver is looked at rather than a steady-state condition.

Relative Energy State

Since aerial combat is not always a first-shot-only phenomenon, it is important to maintain maneuvering capabilities after the state of the aircraft has been changed during an initial defensive or offensive maneuver.[8] This capability is needed to be able to get a first-shot opportunity, continue to maneuver for a second-shot or defensive maneuver, and to be able to accelerate quickly to leave the engagement or attack of another aircraft. However, engagement studies have revealed that fighters designed on the basis of superior first-shot performance alone can suffer unacceptable levels of energy loss, which results in degraded maneuverability.[9] Therefore, a metric is needed that can measure turning capability while taking energy into account. The RES[8] is such a metric.

The RES metric is a measure of the speed of the aircraft relative to the corner speed of the aircraft. The ratio of aircraft speed during the maneuver to the corner speed of the aircraft (V/V_c) is plotted as a function of heading change. The plot shows the capability of the aircraft to turn its flight path while flying a certain control strategy. The point at which the line on the plot crosses the $V/V_c = 1$ line is where the aircraft has lost its ability to continue turning at high turn rates because the available energy has been depleted. Figure 3 shows a conceptual plot of this metric.

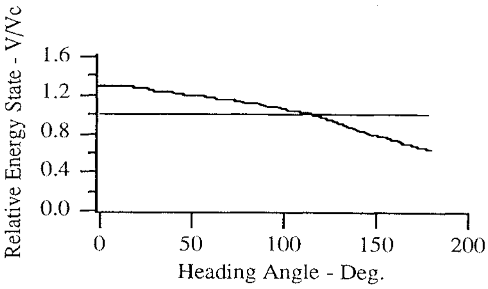

Fig. 3 Relative energy state concept plot.

Experiment Design

Previous analysis of these functional agility metrics has shown that the metrics are very sensitive to the control strategy used to test them.[5] For example, if a metric is tested using maximum aft stick deflection during the turning portion of the maneuver, an aircraft with angle-of-attack limiters in the flight control system will have a superior CCT by avoiding high-angle-of-attack, high-drag flight conditions. This avoids large energy losses, which in turn require a large amount of time to regain. This sensitivity to control inputs indicates that an optimal control strategy exists that would maximize the performance of a given airframe-flight control combination.

To test this, optimal control strategies were calculated for the CCT maneuver using an optimal trajectory program called OTIS. The resulting optimal maneuvers were compared to a maximum angle-of-attack maneuver to determine the possible performance improvements for optimal maneuvers. A total of three control strategies were used to test the CCT maneuver, with all the other metrics being calculated from the resulting data.

The three control strategies tested include a maximum-angle-of-attack CCT maneuver, a CCT maneuver with the turning portion optimized, and a CCT maneuver with the whole maneuver optimized. The maximum-angle-of-attack test case was tested for comparison to the optimal maneuvers.

The maximum-angle-of-attack CCT maneuver was tested at a starting condition of Mach 0.8 by rolling the aircraft to capture a 90 deg bank angle. Next, the turn was initiated by pulling and holding full aft stick until the desired heading was reached. This is similar to test techniques used in other studies.[5,10] After the new heading was reached, the aircraft was unloaded to a 1-g normal load factor condition and rolled back to a zero-degree bank angle. Finally, the aircraft accelerated back to the original energy level present before the turn was started, completing the maneuver. An altitude constraint of ± 200 ft was used during the acceleration phase of the maneuver to ensure that aircraft was not trading altitude for airspeed and energy.

The optimal-turn CCT maneuver was tested by first running the OTIS program to determine the optimal-angle-of-attack schedule for a minimum-time 180 deg turn. The test conditions were a starting Mach number of 0.8 at an initial altitude of 15,000 ft. No specifications were placed on the final Mach number for the OTIS runs for this test case. The resulting optimal-angle-of-attack schedule was then used as a model for testing the maneuver on the 6DOF simulation of the generic F-18. This was done by rolling the aircraft to a 90 deg bank angle as in the last test case, and then following the optimal angle of attack schedule through the turn to the new heading. The aircraft was then rolled to a wings-level condition and allowed to accelerate back to the original energy level, completing the maneuver as in the previous case.

The optimized total CCT maneuver was tested by first running the OTIS program to calculate the optimal control strategy for a minimum time 180 deg turn at Mach 0.8 with the final speed specified to be equal to the starting speed. This yields control inputs that optimize the whole CCT maneuver. The corresponding optimal-angle-of-attack time history was then used as a guide for the inputs into the 6DOF simulation of the generic F-18. The maneuver was tested by the same methods as the previous test cases by following the optimal-angle-of-attack schedule. However, the angle-of-attack values output by OTIS caused the aircraft to reach the desired heading at the same instant that the original energy level was recovered, eliminating the 1-g level acceleration phase for this test case.

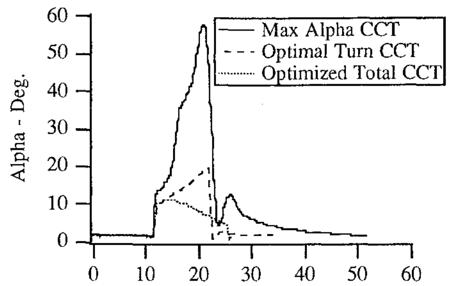

Fig. 4 Angle-of-attack comparison.

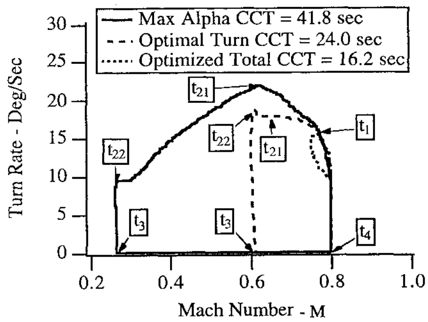

Fig. 5 Combat cycle time results.

Figure 4 contains the angle-of-attack time histories for the three test cases with 10 s of steady flight shown before the maneuvers.

All the test cases were restricted in altitude to isolate the effect of angle of attack on turning performance. Optimal-bank-angle inputs were generated by the optimization program but resulted in three-dimensional turns that involved large altitude changes. Because air density changes would invalidate the propulsion model used, the turns were kept within 1500 ft above or below the starting altitude of 15,000 ft to ensure the accuracy of the model. Restricting the maneuvers to essentially level turns only increased the CCT for the test cases by about 0.7%, which indicates that the maneuvers are dominated by the angle-of-attack schedule flown during the maneuvers.

Combat Cycle Time Results

Figure 5 contains the CCT plots for the three test cases. The maximum-angle-of-attack test case looks like a typical doghouse plot, with the aircraft turning first along the load factor limit line to corner speed (t_1 to t_{21}), then along the lift limit line until the new heading is reached (t_{21} to t_{22}). The Mach number at the end of the turn shows that a large amount of speed was bled off during the turn, showing that a large amount of time is needed to accelerate back to the original energy level (t_3 to t_4). The CCT for this case was 41.8 s, 28.7 s of which was spent accelerating back to the starting energy level.

The CCT maneuver with the turning portion optimized is also shown in Fig. 5. The plot of turn rate vs Mach number is flattened for this case because the aircraft turns at almost a constant turn rate by reducing the angle of attack to match the optimum schedule found by the OTIS program. The resulting plot is similar to the results for an aircraft with angle-of-attack limiters.[5] The CCT for this control strategy is 24.0 s. This represents a 43% reduction over the maximum-angle-of-attack test case.

The last control strategy tested yielded further reductions in the total CCT for the generic F-18. For the optimized total CCT test case, Fig. 5 shows a significant change in the shape of the plot of turn rate vs Mach number. The turn is performed with very little speed loss. This is because the angle of attack is decreasing during the turn. This allows the aircraft to accelerate through the last half of the maneuver. The CCT for this case is only 16.2 s. This is a 61% improvement over the maximum-angle-of-attack test case. This illustrates the significant effects of using different control strategies for the CCT maneuver.

Table 1 contains the times for each segment of the three CCT maneuvers tested. By looking only at the times involved, the optimized total CCT case is the best maneuver for finding the lowest total CCT for the generic F-18 aircraft, as the optimization routine predicted. Using the proper control strategy can therefore result in a large reduction in the time it takes to perform a given CCT maneuver.

Table 1 Combat cycle time results for test cases, s

Test Maneuver	t_1	t_{21}	t_{22}	t_3	t_4	Total CCT
Optimized total CCT	2.4	1.8	11.3	0.7	—	16.2
Optimal turn CCT	2.9	6.6	2.05	1.2	11.25	24.0
Maximum alpha CCT	3.65	2.65	3.05	3.7	28.7	41.75

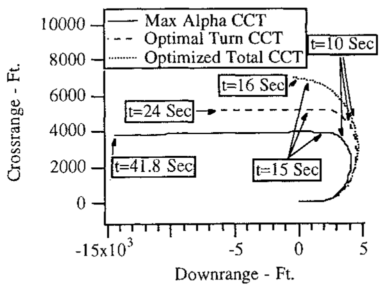

Fig. 6 Downrange and crossrange plot.

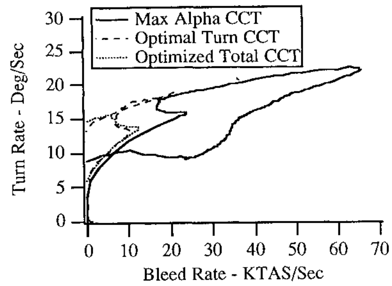

Fig. 7 Bleed rate DST plot.

However, because the optimized total CCT maneuver was designed to preserve the energy of the aircraft during the turn, it takes longer to reach the new heading. This is evident from looking at the times for each test case up to time t_{22}. This indicates that the improvements in energy efficiency and total maneuver time associated with the optimized total CCT do not come without a penalty. The reduced angle of attack lowers the maximum turn rate and increases the speed through the turn, which increases the time needed to turn to the new heading.

Figure 6 shows a second effect of using the optimized total CCT strategy to be a significant increase in the distance traveled in downrange and crossrange. The increase in downrange and crossrange is due to the increased speed through the turn and reduced maximum turn rate values for the optimal maneuvers. These factors increase the turn radius R_t.

Dynamic Speed Turn Plot Results

The DST plots offer more insight into the utility of flying lower angle of attack turning maneuvers, indicated to be superior by the optimization routine. By plotting the turn rate vs speed bleed rate for the three maneuvers, it is possible to estimate the energy efficiency of the three control strategies. This plot shows where increases in angle of attack do not yield significant increases in turn rate and are therefore less efficient. For very high angle-of-attack maneuvers, increases in angle of attack yield very small increases in turn rate but significantly increase the speed bleed rate.

For example, the maximum-angle-of-attack test case reaches very high angles of attack. This makes the drag on the aircraft very large and causes the speed bleed rate to be very high. Figure 7 shows the plot of turn rate vs bleed rate for the three test cases. As the maximum-angle-of-attack test maneuver progresses, the speed bleed rate increases dramatically. This causes the aircraft to decelerate from the initial Mach number of 0.8 to a Mach number of 0.25 at the end of the turn. The slope of the line on the plot for

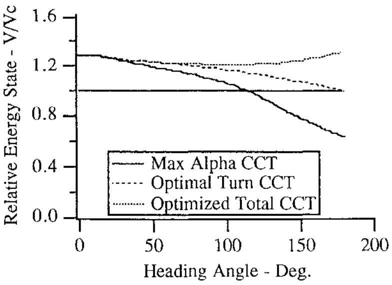

Fig. 8 Comparison of relative energy states.

this test case indicates that reducing the maximum angle of attack would cause the speed bleed rate to be lower. This would keep the aircraft from reaching the high-speed bleed rates of over 60 Knots true airspeed (KTAS) per second.

For the test case with the turning portion optimized, Fig. 7 shows that the maximum bleed rate is reduced from the values for the previous test case. However, the slope of the plot indicates that it still would be possible to reduce the maximum speed bleed rate encountered by reducing the angle of attack further. Bleed rate values over 12 KTAS/s only yield changes in the turn rate of a few degrees per second.

The speed bleed rate DST plot for the test case with the whole maneuver optimized is also shown in Fig. 7. This test case yields a maximum speed bleed rate of only 12 KTAS/s. This is 80% lower than the 60 KTAS/s rate for the maximum alpha test case. It is also evident that very little airspeed would be lost for this case because of the low bleed rates achieved and the short maneuver time found from the CCT analysis. This indicates that this control strategy is much more energy efficient than the maximum-angle-of-attack test control strategy.

The second of the dynamic speed turn plots dealing with level acceleration capability does not show any significant difference, since the F-18 maximum-level-acceleration capability is the same for all three tests. Because all three test maneuvers result in a level acceleration capability of 12 KTAS/s, the plot is not presented.

It is interesting to note that the optimized total CCT angle-of-attack strategy results in a maximum bleed rate during the maneuver that is roughly equal to the maximum-level-acceleration capability of the aircraft. This indicates that the first half of the optimized total CCT maneuver is spent bleeding energy at a rate such that the energy can be regained in the second half of the maneuver.

Relative Energy State Test Results

Next, the RES metric was analyzed for the three test cases. This test quantifies the energy efficiency of the aircraft for each control strategy. The RES plot for each test maneuver is presented in Fig. 8.

The maximum-angle-of-attack test case allows the aircraft to perform only one 90 deg heading change before the speed drops below the corner speed of the aircraft. The heading at which V_c is reached is about 110 deg. This indicates that if the pilot pulls and holds full aft stick deflection to perform a turning maneuver, he or she will only be able to complete slightly more than one turn before most of the energy is depleted and must unload to accelerate and regain energy to continue maneuvering.

If the angle of attack is limited to the values used for the optimal-turn CCT maneuver, the generic F-18 does not drop below corner speed until the heading has changed by 180 deg. This control strategy makes it possible for the generic F-18 to easily perform two 90 deg heading changes before the turning capability is reduced to below the maximum-turn-rate capabilities of the aircraft.

The optimized total CCT control strategy causes the aircraft to stay above corner speed throughout the whole maneuver and return to the original speed ratio of about 1.2. This is because OTIS was asked to provide a control strategy that would change the heading by 180 deg and cause the final speed to equal the starting speed. This control strategy would allow the pilot to perform 180 deg heading changes back to back if the combat situation dictated this need.

The RES metric values for the three test cases indicate that the optimized total maneuver is the "best" control strategy because it yields the lowest speed loss for a given heading change. This result is consistent with the metric values for the CCT metric and the DST plots. This is an indication that the tested metrics all weigh maneuver time and energy efficiency heavily at the expense of increased turn radius values, which could be significant in a given air combat engagement.

Conclusions

The data presented for each of the agility metrics show that each metric is sensitive to the different control strategies used to test it. These sensitivities cause large changes in the measured values for each metric. This indicates that the metrics are measures of the efficiency of a given maneuver type, in addition to being measures of airframe agility. The metrics are also related to each other since they indicate the same improvements for optimal maneuvers. The sensitivities of the metrics can be summarized by the following:

1) The optimal control inputs resulted in lower energy losses and reduced total maneuver times when compared to nonoptimal inputs: CCT was reduced by as much as 60% by following an optimal α schedule for a 180 deg heading change; speed bleed rate was reduced by as much as 80% by following an optimal α schedule for a 180 deg turn; and RST also was greatly improved, allowing multiple back-to-back 90 deg turns if an optimal α schedule is used.

2) In contrast, optimizing the whole CCT maneuver results in slight increases in the time it takes for the aircraft to change heading (as expected, since optimizing the whole maneuver yielded lower angles of attack to conserve energy): 180 deg heading capture time was increased by as much as 40% by flying the optimized total CCT maneuver when compared to a maximum α maneuver and Cross-range distance traveled during a given heading change was increased by as much as 100% when the optimized total CCT maneuver was tested and compared to a maximum α maneuver.

High alpha maneuvers are therefore good for maximizing the turn rate of an aircraft but can result in unacceptable energy losses if the aircraft is in a multiple-enemy engagement. The combat situation would dictate which type of control strategy is best to achieve a desired heading change, as suggested in other studies.[11] From the data presented, the following additional conclusions can be drawn about the agility metrics studied here and how they can be applied to fighter aircraft analysis.

3) Trajectory optimization routines can provide control strategies that lead to significant reductions in the functional agility metric values for a given aircraft.

4) Optimal-turn maneuvers would be best for maneuvering in a multiple-bogey engagement or beyond-visual-range (BVR) combat to allow for continued maneuvering while still pointing the nose at high turn rates and maintaining high energy levels. This conclusion is also supported in other studies.[12]

5) Within-visual-range (WVR) combat should consist of maximum-angle-of-attack maneuvers to achieve a quick first-shot opportunity in a one-on-one engagement and take advantage of nose-pointing capabilities.

6) It is likely that these metrics will not replace traditional point measures of performance but will augment them by offering further insight into existing performance measures.[13]

Recommendations

The following recommendations are made as a result of the data presented in this paper:

1) Standardized test procedures should be developed for testing the functional agility metrics for different aircraft. One possible method is to follow the trajectory optimization methods used in this study for each aircraft, and then make comparisons.

2) The functional agility metrics studied do not take into account the turn radius of a given maneuver, which is an important consideration. A metric that combines energy efficiency, maneuver time, and turn radius values for a given maneuver would be very useful.

3) The optimal maneuvers studied in this analysis could be used to provide information for designing flight control system limiters and pilot displays to allow the aircraft to automatically fly optimal maneuvers, allowing the pilot to concentrate on other tasks during air combat.[14] In addition, the pilot may need to be able to switch between a high alpha control system and an optimal performance

control system to allow taking advantage of the high alpha nose-pointing capabilities of an aircraft in a one-on-one WVR engagement, as suggested in other studies.[11]

4) The utility of high angle of attack and post-stall maneuvers should be studied further by applying the OTIS program for optimization of high alpha maneuvers, such as the Herbst maneuver. By calculating the functional agility metrics for this type of maneuver, comparisons could be made to conventional maneuvers to study energy loss, heading capture time, and total maneuver time.

5) Studies need to be done to relate the resulting metric values for given maneuvers to actual combat effectiveness. This must be done before any of the agility metrics can be used to truly measure the combat utility of an aircraft.

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