COMBAT AIRCRAFT AGILITY METRICS - A REVIEW

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Abstract

With changing combat environments, traditional measures of merit for fighter aircraft performance have largely proved insufficient to analyze combat capability. Combat experience has shown that the upper hand lies with an aircraft that has superior maneuverability across a large part of the flight regime. Agility metrics have come to provide a tool that would be capable of evaluating aircraft maneuverability over a wide range of conditions representative of combat, as well as provide aircraft designers the ability to design for superior maneuverability. Agility metrics have been shown to be sensitive to control laws and strategies, and aeroelastic phenomena, which means that they do not provide a parochial view of aircraft performance. In this review, agility metrics have been suitably classified, and some illustrative cases have been studied. The effects of advanced controls, such as thrust vectoring, and optimal maneuvers on combat performance, as suggested by agility metrics, have been investigated. The use of agility metrics for design has been discussed with examples of some well-known fighter aircraft.

Nomenclature

A = Agility
C_L = Coefficient of lift
j = Torsion
k = Curvature
N_z = Normal load factor
P_s = Specific excess power
S = Reference area
T = Thrust
t = Time
t_{Nz} = Time to attain load factor
t_{90} = Time to roll through 90 deg.
V = Velocity
W = Weight

Superscripts and Subscripts

$(\dot{a})$ = Time derivative of some quantity, a
$(\ddot{a})$ = Double time derivative of a
$(a)_{\max}$ = Maximum value of a

Acronyms

AOA = Angle of attack
AFFTC = Air Force Flight Test Centre
CCT = Combat Cycle Time
DST = Dynamic Speed Turn
EFM = Enhanced Fighter Maneuverability
ITR = Instantaneous Turn Rate
MBB = Messerschmidt-Boelkow-Blohm
POP = Power Onset Parameter
PSM = Post Stall Maneuverability
PST = Post Stall Technology
STR = Sustained Turn Rate
TV = Thrust Vectoring

Introduction

Agility metrics are measures of merit used to quantify the short-timescale maneuvering capabilities of aircraft, as proposed by pilots and researchers [1]. They are intended to quantify and influence the way fighter aircraft maneuver in conventional flight while engaged in air-to-air combat, and are realized through a comparative study of the transient capabilities of similar and dissimilar aircraft subjected to certain predetermined maneuvers. With this definition in mind, it is instructive to consider some trends of modern combat which prompted the development of agility metrics as a tool for analyzing combat capability and performance, and for fighter aircraft design.

The need for improved agility arises from modern combat requirements. Short range combat (or Within Visual Range, WVR, combat) is an important component of

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air-to-air combat today, and may be a result of either deliberate engagement or prolonged, multiple-engagement Beyond Visual Range (BVR) combat. This mode of combat was previously dominated by quick sustained turns, and aircraft design was governed by traditional parameters, such as the Thrust/Weight ratio. However, with the development of all-aspect weapon systems, which required the point-lock-fire-disengage type of maneuvering, the importance shifted to attained unsteady performance [2, 3]. The traditional means of evaluating performance, which were mostly limited to steady-state performance metrics, therefore proved inadequate, prompting the development of agility metrics.

One of the events that brought agility to the attention of combat analysts was the superior performance of the American F-86 in Vietnam against the Soviet MiG-15. The latter had a much better performance as per the traditional evaluation schemes, but the F-86 proved superior in combat. It was observed that this was on account of better maneuvering capability of the F-86, what we now call agility [4].

Table 1: Traditional versus Agility metrics

Axis of Motion → Metric ↓	Longitudinal	Lateral	Axial
Traditional	$N_{z_{max}}$	STR	T/W
Agility	Pitch rate Time to a fixed AOA	90 deg roll capture time	$\dot{P}_s$

Table 1 summarizes some traditional performance evaluation parameters and their corresponding recent agility metrics. It is quite apparent from the table that temporal variance is a common element of all agility metrics and, indeed, they are typically designed to determine how quickly aircraft can transit from one state to another. The traditional metrics reflect such fundamental parameters as T/W, W/S, aspect ratio, and so on [5]. However, their inability to deal with transient attained performance, on account of their very definition, means that they cannot capture a combat scenario very accurately.

For instance, consider an aircraft that has an excellent turn rate at a given speed. Another aircraft, on account of, say, an inferior T/W, may not be able to achieve such high rates. However, it may have excellent abilities to point quickly, perhaps through Post Stall Maneuverability (PSM) and Thrust Vectoring (TV). In combat, where aircraft turn into each other and seek firing positions by pointing at the adversary, the second aircraft may actually have a greater chance of winning, although it may not turn as quickly as the first aircraft. This suggests that a superior performance rating in terms of traditional metrics does not immediately translate into combat superiority, which has to be evaluated using agility metrics.

Agility metrics can be employed gainfully in the early stages of aircraft design provided a reasonably accurate estimate of stability and control derivatives is available to the designer. Agility influences fighter aircraft design as much as other performance requirements and what is usually sought is an appropriate balance of agility and other conflicting requirements based on the types of mission the fighter aircraft is sought to fulfill [6].

This review paper will first look at some of the agility metrics that have been developed to date. An attempt has been made to highlight the strengths and limitations of these metrics. The effect of improved control strategies on agility metrics has been discussed, followed by a discussion on the utility of agility metrics in aircraft design, and the design of the flight control system. The effect of avionics and weapons systems on agility has been discussed. Conclusions and recommendations for future work are listed in the final section of this paper.

Classification of Agility Metrics

As stated previously, agility metrics are measures of merit used for evaluating short timescale maneuvering capabilities of aircraft. Evaluation of capabilities involves executing certain maneuvers, and that provides one way of ordering the agility metrics in terms of the maneuver performed. Another way of classifying agility metrics is in terms of the timescales of these maneuvers. Agreeably, we are looking at short timescales, but how short? We will first look at the two classification schemes suggested above, following which we look at some alternative definitions proposed for agility, and see how they correlate with those suggested earlier.

Firstly, maneuvers can be classified into three classes based on the axis about which they are carried out. Agility metrics fall into three classes accordingly:

1. Axial: Along the velocity vector.
2. Longitudinal: Rotation of the velocity vector in the pitching plane.
3. Lateral: Rotations about the velocity vector, i.e., predominantly roll.

This is the classification that has been followed in Table 1. Another classification is based on the timescale of the maneuver. There are three types of agility metrics then [1, 7]:

1. Transient: The maneuvers analyzed are of a timescale of 1 - 3 seconds, typically. This is also regarded as the capability to generate quick angular motions and transit quickly between extreme levels of specific excess power.
2. Functional: Maneuvers last for a longer time, typically 10 - 20 seconds. This class quantifies how well a fighter aircraft can generate rapid changes in heading or rotation of the velocity vector, with emphasis on the energy lost during the maneuver and the time to recover it.
3. Potential: These metrics are largely independent of time and have nothing to do with quick transitions during combat maneuvers. They deal with agility that results from sizing and configuration of the airplane, and are of particular interest in the early phases of aircraft design. For additional information on these metrics, the reader is referred to Ref. [1]. This paper will discuss only transient and functional metrics in detail.

Table 2: Classification of Agility Metrics

Axis of Motion → Agility Metric ↓	Longitudinal	Lateral	Axial
Transient	Average pitch rate	t_{90}	POP
Functional	Pointing Margin	Roll Reversal Parameter	CCT, DST

Table 2 gives examples of some transient and functional agility metrics, classified on the basis of the maneuver axis, which will be examined closely in the following section. Before proceeding to study some results obtained for the above metrics, it is instructive to look at definitions of agility proposed by the industries and the U.S. Air Force. According to Bitten [8], the various conferences organized by and between the U.S. government and the industries have yielded a general agreement on the importance of agility and a general disagreement on what constitutes agility. According to Dorn [9], there are two different schools of thought that define agility in their own ways. One group suggests agility to be an experimental metric that can be evaluated through flight tests and can be meaningful to aircraft designers. Another school of thought argues that agility is a scientific term which identifies a unique characteristic of flight dynamics. Inevitably, different organizations choose to define agility metrics in a manner that best suits their needs, and perhaps even their resources. In the remainder of this section, some of these definitions, obtained from Refs. [8, 10] have been briefly described.

Table 3: Eidetics and AFFTC Agility Metric Definitions

Axis of Motion →	Longitudinal	Lateral	Axial
Eidetics	Time to Δg	t_{90}	POP
AFFTC	Pitch capture time	Roll capture time	Time to final speed from given speed and N_z

The definitions provided by Eidetics International and Air Force Flight Test Center (AFFTC) [11] have been listed in Table 3. Time to Δg is the time to attain a final load factor starting from some initial load factor. The t_{90} metric measures the time required for an aircraft to roll through 90 deg starting from a zero initial bank angle. Power Onset Parameter (POP) measures the average rate of change of specific excess power as it is increased from the minimum to the maximum value, starting from a given flight altitude and Mach number. These metrics have been discussed in greater detail later in this paper. Pitch and roll capture metrics indicate the times required to capture a final pitch angle and bank angle, respectively, starting from a given velocity and load factor.

General Dynamics defined agility as being the ability to point the nose quickly, continue pointing it, and accelerate [8]. Agility is governed by maneuverability and controllability. Their concept of agility is captured in the Dynamic Speed Turn, which plots the turn rate versus acceleration or bleed rate. A typical DST plot has been shown in Fig. 1. Messerschmidt-Boelkow-Blohm (MBB) [8] and Avanzini [10] have essentially defined agility in the same manner - mathematically - using the Frenet-Serret system. They have both defined agility as the second

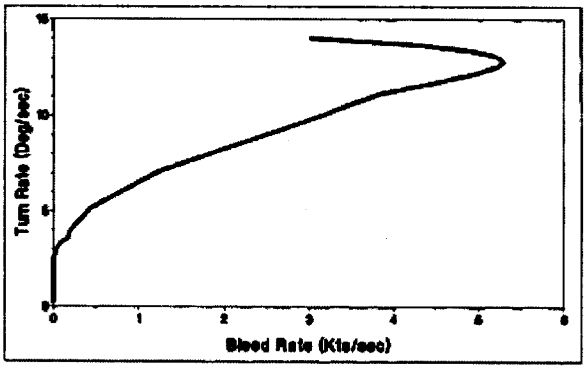


Fig. 1 General Dynamics DST Plot [8]

time derivative of the steady state variables in the Frenet-Serret system. Avanzini [10] has stated the agility metric as the following vector:

$$\boldsymbol{A} = [\ddot{V} - V^3 k^2, 3V\dot{V}k + V^2 \dot{k}, V^3 k j] \qquad (1)$$

Here, k and j are curvature and torsion, respectively.

In the context of Avanzini's metric, Bitten [8], and Kutschera and Render [12] have defined the following terms:

1. Performance: A measure of the steady state or the point performance of an aircraft.
2. Maneuverability: A measure of the time derivative of the performance.
3. Agility: A measure of the time derivative of the maneuverability.

With these definitions in place, the following comparisons can be made:

1. The MBB and Avanzini metric is purely agility metric.
2. The Eidetics metric, t_{90}, uses roll rate, which is a maneuverability term. The other terms are all agility terms.
3. The General Dynamics DST metric is a purely maneuverability metric.
4. The AFFTC metric uses steady state at both ends, and the time to transit incorporates the initial conditions, accelerations, as well as their derivatives. Thus, the AFFTC metric is a measure of the point performance, maneuverability, as well as agility. Functional agility is the sum of transient agility and maneuverability.

Bitten [8] noted that the results obtained using the metrics proposed by the various organizations mentioned above were mutually consistent for a particular type of metric (viz., axial, longitudinal, or lateral).

The above discussion points out the vagueness of the definitions of some terms, such as agility and maneuverability, and their interconnections. One can choose to be pedantic about the usage of these terms, or else use them without distinction, but with the understanding that there exist mathematical differences between the definitions of these terms. These terms have been used more or less interchangeably from hereon.

Some Illustrative Agility Metrics

In this section, we look at some agility metrics applied for analyzing aircraft performance. Each type of agility metric has been considered with one example. The discussion here follows Refs. [1, 7]. In all the cases in these references, the aircraft models analyzed, using non-real time simulations, were those of F-5, F-16 Falcon, and F-18 Hornet. The inputs provided for obtaining the metrics have also been discussed.

Axial Agility Metric - Power Onset Parameter

Power onset parameter is defined as follows:

$$POP = (P_{s,max} - P_{s,initial})/\Delta t = \Delta P_s/\Delta t \qquad (2)$$

where P_s is the specific excess power.

This metric measures the combined effects of the aircraft thrust and engine spool time, which denotes the time taken by the aircraft engine to bring about the required change in thrust. The flight test Mach number is first held at idle throttle and the speed brakes are deployed so that the initial condition corresponds to the minimum value of specific power. Thereafter, simultaneously, the throttle is raised to its full value and the speed brakes are retracted. This testing can be carried out for different aircraft at different initial Mach numbers for a comparative study as shown in Fig. 2 which indicates that the POP of the F-18 is largely superior to that of the F-16. A similar analysis carried out at different altitudes showed that it is only at high altitudes and higher Mach numbers that the F-16 compares favorably [7]. A sensitivity analysis performed for this metric indicated a significant error in the final result when the initial conditions were changed by 10 percent [13].

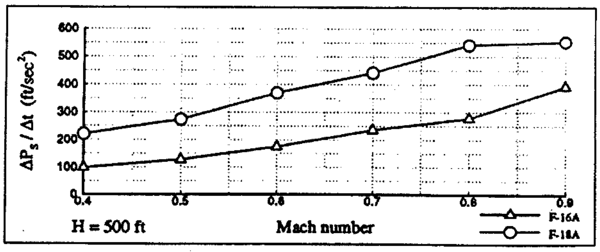


Fig. 2 Power Onset Parameter Comparison [7]

Longitudinal Agility Metric - Average Pitch Rate

This is a very common metric used to analyze the pitch agility of an aircraft. It is defined as the time-averaged integral of pitch rate for a given maneuver. The maneuver used in Ref. [7] was a two-second full aft stick deflection, after which it was brought back to the initial condition of zero deflection. The results obtained for this metric have been given in Fig. 3. It can be observed that the F-5 has the poorest pitch performance, especially at higher Mach numbers, whereas the F-16 is superior at Mach numbers higher than 0.6, the F-18 being superior at lower Mach numbers. This metric was shown to be sensitive to an aft stick magnitude error. Further sensitivity analysis showed that the metric is relatively insensitive to errors in initial pitch rate [13].

Lateral Agility Metric - t_{90}

This metric measures the time required for an aircraft to roll through 90 deg starting from zero initial bank. The input commanded is a full lateral stick in the direction of the roll. Time required to roll through 90 deg is obtained for different Mach numbers and angles of attack. Figure 4 shows the time to roll through 90 deg taken by the F-5, F-16 and F-18 at various angles of attack at 0.5 Mach and 15000 ft altitude. It can be observed from Fig. 4 that the F-16 and F-18 interchangeably show superior roll performance, while that of the F-5 is the poorest at the assumed Mach number and altitude. This metric was found to be relatively insensitive to small initial stick deflection errors. A similar metric, with a roll through 45 deg, was analyzed in Ref. [13], and it was shown to be insensitive to initial condition errors in velocity, roll moment of inertia, and the roll damping derivative.

Although this metric provides a good way of measuring the roll performance of an airplane, it does not consider the final state attained by the aircraft, or the arrest of the roll beyond 90 degrees. An alternative suggested is 90 deg roll angle capture, which makes more sense in principle, but lacks the relative simplicity of the inputs required for the other metric. It is finally the choice of the analyst to decide the metric that best suits his/her needs and resources.

Functional Agility - Combat Cycle Time (CCT)

This is a very popular metric for measuring functional agility, and highlights several important features of the models used for testing. CCT is defined as the time taken to complete the maneuver shown in Fig. 5. The goal of the maneuver is to accomplish a 180 deg heading change and then return to the same Mach number. As shown in Fig. 5, CCT evaluates the sum of five time periods. The individual maneuvers have been tabulated in Table 4, along with the inputs needed to obtain them. It may be noted that CP

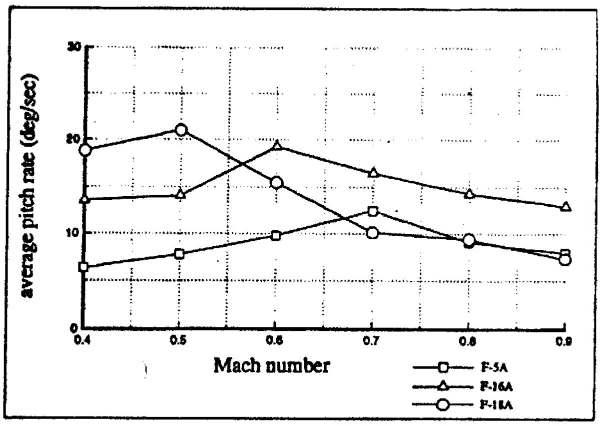


Fig. 3 Average Pitch Rate Comparison [7]

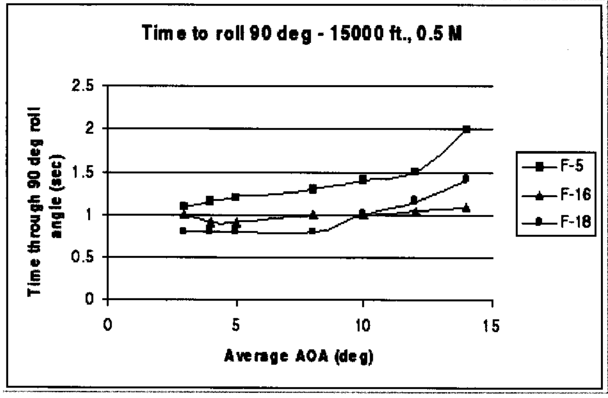


Fig. 4 Roll capture time comparison [7]

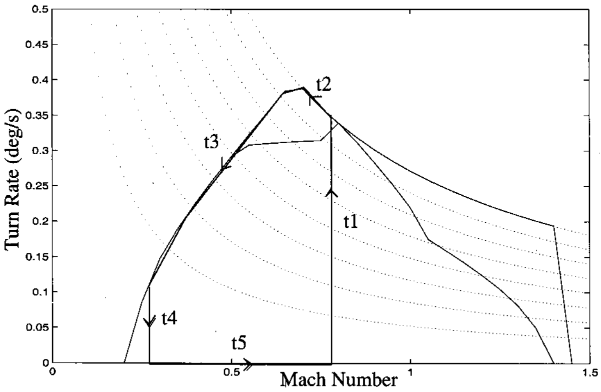


Fig. 5 Conceptual CCT Plot

Table 4: CCT Metric

Maneuver Points	Maneuver	Input needed	Time
A-B	Roll to Nz, max	Lateral stick doublet	$t1$
B-CP	Pitch to $C_{L_{max}}$, turn	Full longitudinal stick	$t2$
CP-C	Roll out at $C_{L_{max}}$	Lateral stick removed	$t3$
C-D	Roll out to 0g/1g level	Lateral and longitudinal stick	$t4$
D-A	Accelerate at 0g/1g	Full throttle	$t5$

Table 5: CCT Comparison

Maneuver Stage	F-5	F-16	F-18
$t1$	2.31	2.97	2.45
$t2$	–[b]	6.10	3.85
$t3$	20.49	2.93	5.15
$t4$	1.45	1.45	2.05
$t5$[a]	11.81 (0.57,0.80)	9.90 (0.60,0.80)	30.20 (0.25,0.80)
CCT	36.06	22.73	43.70

[a] Bracketed numbers in $t5$ indicate Mach number range of acceleration.

[b] $t2$ for F-5 was not given explicitly; instead $t3$ for F-5 represents $t2 + t3$.

is the corner point, where the aircraft attains the maximum instantaneous turn rate.

The results obtained for the F-5, F-16, and F-18 using the CCT maneuver have been tabulated in Table 5. The CCT indicates that the F-16 is superior to F-5, which is superior to F-18. F-16 has fared well in all five regimes, and this is on account of its aerodynamic characteristics and design, as well as the fact that it incorporates AOA and load factor limiters which prevent large energy losses during the maneuver. In case of F-5, the maximum load factor, between 4 and 5, is much lower than that of F-16 and F-18, and this aircraft does not fare very well in the ($t2$ + $t3$) region. F-16 shows a better performance than F-5 in the $t5$ region on account of a better specific excess power.

The case of F-18 is an interesting one. The F-18 model does not incorporate AOA limiters, and consequently it goes to very high AOA by the time it enters the $t4$ phase. Until this point, its performance in terms of time to maneuver has bettered even that of the F-16. However, on account of the high drag associated with high angles of attack, it bleeds a lot of speed, and starts accelerating only at a speed corresponding to Mach 0.25. It is in the $t5$ phase that F-18 spends a lot of time, and thus, its overall CCT worsens despite good maneuverability characteristics.

Functional Agility - Roll Reversal Parameter

Roll reversal parameter is defined as Y^nT, where Y is the cross range generated during the maneuver described below, T is the time required to perform the maneuver, and n is the weighting factor on the distance parameter, Y. The maneuver used consists of an initial steady, level turn at constant velocity with a certain bank angle, followed by a roll through zero bank angle to reach (not capture) the initial bank angle, but with an opposite sign. Y and T are measured when the initial heading is achieved. Angle of attack should be held constant during the maneuver. Higher agility is indicated by a smaller value of this metric. Reference [7] refers to this metric as the defensive roll reversal parameter, although it can also be used for evaluating offensive maneuvers. The weighting factor, n, is obtained empirically, although as a first approximation, it is assumed to be unity for *defensive* maneuvers. It is less than 1 for offensive maneuvers, since the advantage due to a reduced cross range is less than that offered by point-and-shoot capability.

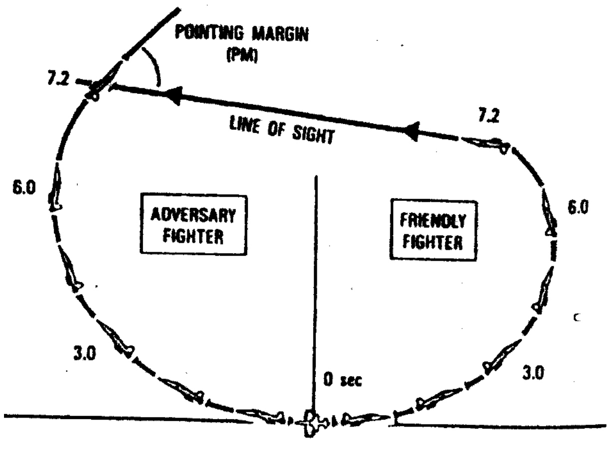
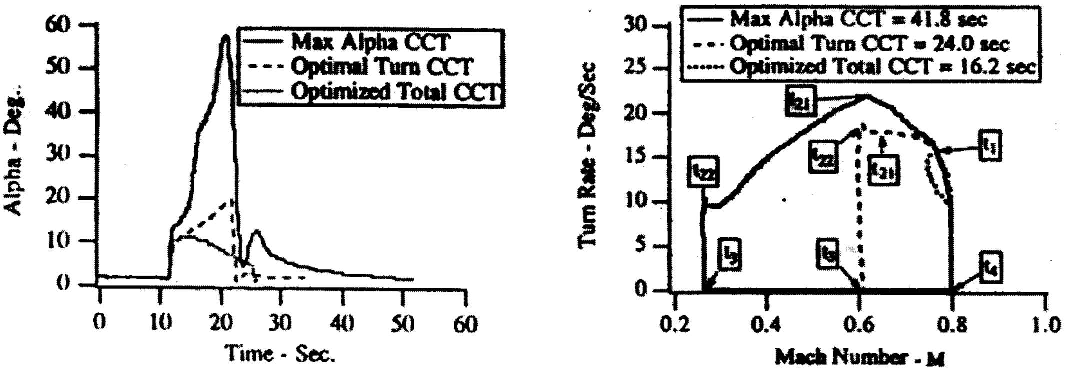


Fig. 6 Pointing margin metric [12]

Functional Agility - Pointing Margin Metric

Ability to point quickly at an adversary offers a significant advantage in combat, and this metric addresses this capability [7, 12, 14]. The metric is evaluated by getting two aircraft to start turning in the same plane starting from the same initial heading, but in opposite directions, towards each other. Pointing margin metric measures the angle between the line of sight of the friendly aircraft and the nose of the adversary at the moment the friendly fighter is aligned with the line of sight as shown in Fig. 6 [12]. A higher value of this metric indicates better agility. This metric incorporates the effects of pitch rate, thrust and drag transient characteristics, but the long term performance (7 - 10 s) tends to have a greater impact than transient capabilities.



(a) AOA history (b) Maneuver Profile

Fig. 7 Parameter Schedules

Optimal Trajectories and PSM

Functional Agility

Recall that the CCT metric required the aircraft to turn through a heading of 180 deg, and then accelerate back to the initial Mach number. To achieve this, the maneuver was flown as described in Table 4 in the previous section. CCT was seen to be dominated by the acceleration phase. It is likely that an alternative maneuver could achieve the same final state in terms of heading and velocity by better managing the velocity bled during turning and minimizing the acceleration needed, thereby reducing the CCT. Ryan and Downing [15, 16] did this by optimizing the maneuver for minimum CCT, and the results were astounding.

The need for optimization generally arises when the maneuver is spread over a considerable period of time, and there are several variables simultaneously affecting it. Clearly, it is the functional metrics that render themselves to optimization, rather than the transient ones. Optimal maneuvers for evaluation of agility metrics have an additional benefit that they are not biased towards a particular aircraft or control system, but help extract the best possible performance out of every aircraft [16].

Table 6: CCT Comparison for Optimization

Maneuver Stage	Routine CCT	Optimized turn	Optimized maneuver
$t1$	3.65	2.9	2.4
$t2 + t3$	5.70	8.65	13.1
$t4$	1.2	1.2	0.7
$t5$	28.7	11.2	-
CCT	41.75	23.95	16.2

Ryan and Downing investigated the effect of optimization for the CCT metric using an optimization routine called Optimal Trajectories by Implicit Simulation (OTIS). Optimization was employed separately for the turn ($t2$ + $t3$) phase in Fig. 5 and the entire maneuver. The results were compared to those obtained using the more routine approach. The F-18 model was used. Figure 7 plots the angle of attack history, and the maneuver profile on the turn rate versus velocity plot, for all three cases, viz., maximum AOA, optimum turn, and optimum total CCT. Table 6 gives the time segments for these cases. The common feature for the optimized cases is the relative avoidance of the high angle of attack regions, which are chiefly responsible for the high CCT. In fact, the total maneuver optimization case avoids this part completely. Heading change takes place until the last moment at which the aircraft also returns to the initial velocity. It is interesting to note that the F-16 CCT of 22.73s is still better than that of the turn-optimized F-18.

Furthermore, the two models, F-16 and F-18, show nearly the same values for all time segments. This suggests the overriding importance of a good control system, and the use of better control strategies using optimization to partly compensate for the absence of the appropriate limiters.

Thrust Vectoring

Herbst [3] has pointed out the importance of PSM for enhanced combat capability. Costes [17], Gal-or [18], Anderson [19], and Tamrat [4, 20] have shown that TV and PSM improve the chances of victory in a head-to-head combat by improving the agility of the aircraft. It is of interest to know how PSM and TV, together or separately, help to do so.

Kutschera and Render[12] developed a new metric which is primarily a maneuverability metric, as per the definition given earlier. It is a modified version of the CCT metric and starts from the point at which the aircraft has rolled to N_{zmax}. Thereafter, the aircraft turns along the N_{zmax} and C_{Lmax} curves until the pointing margin (defined earlier) to the adversary aircraft, which is assumed to be stationary, has become less than the maximum angle of attack of the aircraft. At this point, the aircraft pitches up to maximum post-stall angle, and points to the adversary for a firing which marks the end of the maneuver. This metric evaluates the time to complete the maneuver, the final SEP, the energy change, and the turn diameter. Using this metric, they have shown how TV and PSM improve agility.

Three F-18 configurations were tested by them using the above metric: standard (no TV, AOA for ITR of 20 deg, and maximum AOA of 30 deg), advanced (TV, AOA for maximum ITR of 20 deg, and maximum AOA of 70 deg), and super-advanced (TV, AOA for maximum ITR of 35 deg, maximum AOA of 70 deg). It may be noted that stall AOA for F-18 is around 35 deg. The metric was evaluated for a variety of initial Mach number and altitude combinations. As expected, the advanced aircraft showed better agility as compared to the standard configuration. The time to complete the maneuver was lesser for the advanced aircraft, especially at higher initial altitudes, which constitutes a significant advantage. The turn diameter was smaller and the turn rate was higher as well. The final SEP, though, was smaller due to the fact that it ended up at a post stall AOA. The energy bled by the two aircraft was almost comparable for various initial conditions. With this information in mind, it is left to the strategist to decide when to employ TV.

A similar comparison between advanced and super-advanced aircraft presented an unexpected surprise. The advanced aircraft actually completed the maneuver in a shorter duration of time, although the super-advanced aircraft had a higher maximum ITR because it was allowed to fly to the AOA for maximum C_L. The reason for the reduced performance is the higher drag experienced below the corner velocity where the aircraft flies close to stall, and poststall for final pointing. This results in a rapid decrease of velocity, and an accompanying loss of turn rate. The more time the aircraft spends at velocities less than the corner speed, the more pronounced this difference becomes. This indicates that PSM provides significant advantage in combat when it is used for short periods of time. Longer periods of PSM may lead to greater energy losses, which is detrimental to the performance of the aircraft.

Another demonstration of the advanced capability of TV and PSM was observed when the X-31 was tested against the F-18 in combat scenarios. X-31 is an experimental aircraft being developed and tested jointly by the U.S. and Germany [21]. The X-31 program is intended to highlight the tactical utility of Extended Fighter Maneuverability (EFM) at low cost [4]. It was observed that the F-18 had a better success rate when the X-31 was own in conventional configuration. However, when PSM was enabled, X-31 emerged as the winner. TV was provided for pitch as well as yaw control in X-31. X-31 actually has an inferior T/W ratio as compared to the F-18. Further, the maximum turn rate is lesser than that of the F-18. PSM, however, provided X-31 with a better pointing ability, and also helped it pull tighter turns. Interestingly, the winning maneuver of the X-31 was mostly what is called the ‘Helicopter Attack Maneuver,’ wherein the X-31 yawed rapidly in order to point at the adversary which was turning around it. The yaw control for this maneuver came from the yaw thrust vectoring.

F-16 Falcon - The Classic Case

Alarmed by the superior combat performance of Soviet-made aircraft, especially the MiG-21, the United States Air Force (USAF) decided that a fighter was needed to supersede its maneuverability. What emerged in the mid-seventies, through a competition between General Dynamics (GD) and Northrop, was the F-16 developed by GD. The reader is referred to References [5, 22] for an extensive account of the development of F-16.

The F-16 was designed with the following requirements: Cruise Mach number between 0.6 and 1.6, flight at altitudes between 30000 and 40000 ft, 9 g at full fuel load (USAF only required 7.33 g at 80% internal fuel load). The emphasis was on rapid acceleration, turn rate, and specific excess power (those were the traditional measures of merit). There were trade-offs involved in the design, such as the value of W/S that had to be chosen to give suitably high values of both, range and turn rate. Finally, the configuration of F-16 gave a leading edge wing sweep of 40 deg, an aspect ratio of 3, and a wing loading of 25 N/m^2. The weight of the aircraft, with external fuel tanks, was a little below 10 tons, and is still one of the lightest in its category. The aircraft's small size reduces the moments of inertia, and improves angular rates for maneuverability. External fuel tanks are used for take off, and before a dog fight, they are dumped. This produces a 5% increase in turn rate and 30% increase in acceleration. F-16 has a T/W ratio greater than unity, and the aircraft can accelerate to supersonic speeds while climbing upwards. The low aspect ratio of the wings gives the aircraft good maneuvering capability, such as higher roll rates. The CG is located aft of the aerodynamic center to reduce longitudinal stability in favor of maneuverability, and help the horizontal tail add to the lift while maintaining longitudinal trim. The F-16 FCS was designed with rate and maximum AOA limiters to ensure superior handling qualities. Tamrat [4] and Hodgkinson et al. [23] noted that there is a direct correlation between superior handling qualities and agility, which makes handling qualities an important design issue for agility.

The above case study, although specific to the F-16, gives a general make up of agile fighters. It has to be noted, though, that the concept of agility that has been discussed earlier in this paper did not exist in the days when the F-16 was designed. Only steady state performance parameters were used to design the F-16. Nonetheless, the characteristics such as high T/W, low aspect ratio, optimized wing loading and longitudinal instability in the open loop, are common features of most agile fighters even today.

Many agility metrics require a detailed knowledge of the aerodynamic coefficients of the airplane for testing [12]. These agility metrics will typically be used after a series of flight tests for improving the existing variant and for designing future variants. Reference [24] presents an agility assessment module meant for the preliminary design stage of an aircraft. It may be noted that such modules would utilize metrics which require a small number of the most rudimentary aerodynamic data, and these metrics are usually what have been referred to earlier as maneuverability metrics and potential agility metrics.

Agile Falcon

Agile Falcon was studied as a variant of the F-16 in a project undertaken by General Dynamics Fort Worth Division to incorporate advanced technology in the existing variants of F-16, in order to help it regain the original F-16's agility that was lost in the subsequent variants because of additions to payload and fuel weight, and improve agility at high angles of attack [25]. It was primarily tested with larger wings with the same trapezoidal shape. Agile Falcon integrated wing, strake, and the fuselage with a view to improving agility. Wing and strake tailoring was seen as a key ingredient of good performance in both, the subsonic as well as transonic, regimes.

A three-tier study covering aerodynamics, controllability, and aeroelasticity was performed. The former was centered on improving maneuverability by studying effects of wing twist and camber. Agility metrics such as high-g turn rate and 1-g acceleration were used. Controllability studies looked at handling qualities at high angles of attack and low speeds. Aeroelastic studies to design strategies that would best complement the two requirements of maneuverability and structural stability were conducted. An interesting outcrop of the aeroelastic studies was the development of the washout wing. It led to a 23 percent reduction in induced drag and concentrated aerodynamic load at the fuselage-wing interface, which resulted in a wing heavier at the root and a subsequent reduction in the aircraft roll moment of inertia, enhancing the roll performance. This is an excellent illustration of how agility metrics can be gainfully employed to bring about an all-round improvement in the design of an aircraft.

Agility and FCS

It was seen earlier that the flight control system affects the aircraft agility. FCS plays a major role in reducing pilot workload by providing the appropriate handling qualities in the closed loop [26]. This section investigates the agility improvements that could result from a well-designed FCS, as well as some of the features that such an FCS should possess.

Actuators limit the deflections of various control surfaces as well as their rates. This, in turn, restricts the maneuverability of the aircraft in some or all of the flight regimes. In order to improve it, one or more of the above parameters may need to be changed, and their effects will have to be studied. One example that can be cited is the improvement in lateral agility of the F-18, defined by the 90 deg roll capture metric, as suggested by Eggold et al. [27]. It may be noted that this metric is similar to the t_{90} metric described earlier, except that in this case, a 90 deg bank angle has to be captured, not just reached. They determined that the three factors that affected this metric the most were rudder saturation, rudder actuator rates, and the roll control surface deflection limiting at high AOA. It was seen that increasing the three quantities helps reduce

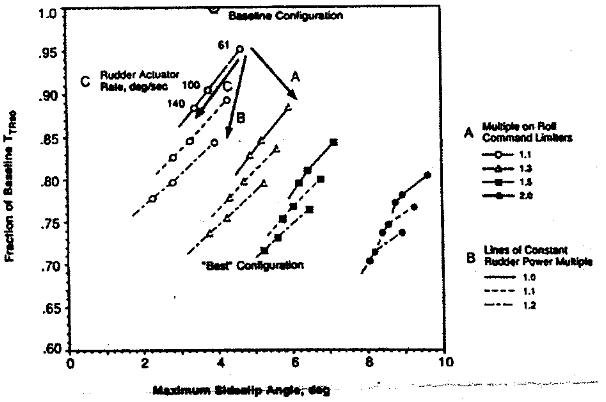


Fig. 8 Lateral Agility improvements by increasing rudder limits

the time to capture a 90 deg bank angle change. However, an optimal combination of the three has to be chosen to ensure that the increase in sideslip does not get very adverse. Their results have been shown in Fig. 8. This figure plots the time required to capture a roll angle of 90 deg, as a fraction of the baseline value, with improved limits on rudder power and roll command limiters. The improvement in time to capture a 90 deg roll angle is evident from the fact that its ratio with respect to the baseline value is always less than unity.

Many modern fighter aircraft are designed to be unstable in some part or the whole of the flight regime in the open loop. Therefore, it becomes important to identify the unstable regimes, and the nature of instability in those flight zones [28]. In some cases, the instabilities might be of a relatively simple nature, such as spiral divergence, phugoid, etc., or else they could be as complex as wing rock, which is generally observed at high angles of attack [29]. Ananthkrishnan and Sinha [30] observed that the maximum steady roll rate, in open loop models, is constrained by loss of lateral stability, and this constraint dominates the constraint imposed by performance criteria and actuator limits such as aileron and rudder saturation. These instabilities have to be compensated for by the FCS [31]. In the case where it becomes too difficult to satisfactorily do so, restrictions have to be imposed on the maneuvering envelope.

Sometimes, pilots complain that the FCS often makes the aircraft response somewhat sluggish. This has to be interpreted as a case of excessive stability, which reduces maneuverability. Thus, the FCS has to be designed to ensure that it stabilizes the aircraft, but only to an extent whereby the pilot does not find it very hard to maneuver it. Agility considerations play an important role in design of the FCS, which has to go hand-in-hand with a much wider aircraft design [32, 33].

Agility, Avionics and Weapons Systems

So far, agility has been studied from the standpoint of aircraft performance. Loosely speaking, agility has been viewed as a measure of the quickness of an aircraft during a maneuver. One aspect that needs to be studied in the context of agility is the effectiveness of the avionics and weapons system.

Head-up display (HUD) and several of its advanced derivatives such as the Helmet-mounted Display (HMD) have revolutionized the way in which information is conveyed to a fighter pilot in order to create a better situational awareness. The onus is on conveying information to the pilot as *quickly* and as *effectively* as possible. The pilot is an important component of the closed-loop aircraft and has a strong influence on the agility exhibited by an aircraft during a maneuver [11]. The pilot's responses are governed by motion and visual cues, where the latter are obtained from the real-world, "outside-the-cockpit" visual environment and from the cockpit displays. A significant delay in the pilot's response to external cues can result in a severe degradation in the aircraft handling qualities [34] and ultimately affects the aircraft's agility adversely [23].

Another effect on aircraft agility arises directly from the time that the pilot takes to respond to an external stimulus such as the approach of an adversary. This information is conveyed to him by the cockpit display systems. Although an aircraft may possess agility in its ability to maneuver rapidly, a delay from the pilot's side affects the *total* time to effect a maneuver from the time the requisite stimuli are available.

Another factor affecting agility that needs to be addressed is the effect of weapons systems. Several modern all-aspect air-to-air missiles do not require direct pointing at the adversary aircraft. The adversary needs to be brought within a "firing cone," and the time taken for the missile to deploy from the time the adversary enters this cone becomes critical. This is true, however, only if the aircraft is not in a defensive position. If the aircraft starts from a defensive position, its success will depend on its maneuverability. Maneuverability is also the most critical factor when two aircraft with equally capable weapons system engage in combat.

Metrics that are capable of evaluating agility from these standpoints as well need to be developed. However, unlike most metrics described earlier in this paper, metrics that evaluate the effectiveness of avionics and/or weapons systems are highly case specific, and cannot be used to compare two aircraft, especially because the choice of weapons is not unique for a given aircraft. Further, they will require a pilot in the loop, which will elicit a need for more resources as well as time.

Conclusions

1. Traditional performance measures have proved inadequate to explain the overwhelming successes in combat of aircraft over "traditionally superior" adversaries. It was realized that rapid, controlled angular rotations and heading changes were at work, and they were termed as agility of the aircraft. The need for agility was felt on account of changing combat tactics, which in turn elicited a need for agility metrics.
2. Agility metrics can be classified on the basis of the timescale and the axis of the maneuvers being evaluated. On the basis of timescale, agility metrics were classified as transient, functional, and potential. The axis-based classification led to three types of metrics: axial, longitudinal, and lateral. Some illustrative metrics were studied to understand the test procedure, as well as metric robustness.
3. It was shown that control strategies such as optimization of maneuvers bring about substantial improvements in functional agility. Advanced controls such as PSM and TV improve transient as well as functional metrics significantly.
4. Agility metrics can be used to improve existing designs, by suggesting changes that can be readily made in the baseline configuration. The baseline configuration can be designed using some traditional rules such as high T/W, low W/S, etc., and they can be flight tested to get the necessary data for agility evaluation. Design for agility, among other things, involves efficient aerodynamics and configuration, adequate control power, and a sound, robust FCS.
5. As a recommendation for future work, it would be worthwhile to develop metrics that simultaneously evaluate agility and closed-loop stability of the aircraft.

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