Agility as a Contributor to Design Balance

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Successful fighter aircraft must achieve a high degree of balance in the design process where a wide range of potentially conflicting technologies must be brought together to achieve the highest level of combat effectiveness. Many attributes of a fighter aircraft influence its combat effectiveness, including mission (payload/range) performance, speed, lethality, maneuverability, flying qualities, and stealth. Agility is a fighter aircraft attribute that can make a significant contribution to the degree of design balance that is achieved. A new definition of agility is introduced that includes pilot, avionics, and weapon elements along with the usual airframe maneuverability and controllability elements, and the framework of an analysis methodology is discussed that could be used to measure the overall agility of the complete weapon system. Within the airframe agility element, the most important types of agility are identified and measures of merit are proposed for their quantification. The results of tactical utility simulations are presented, which show agility payoffs even in high-speed air combat. The need to include agility in the evaluation process of new fighter aircraft is discussed.

Nomenclature

D = drag
Fn = net thrust
g = acceleration due to gravity
M = Mach number
P_s = specific excess power
$\dot{P}_s$ = rate of change of P_s
T/W = thrust-to-weight ratio
t = time
V = velocity
W = weight
γ = flight-path angle
ΔD_i = delta drag due to induced drag
Δt = time to pitch down from maximum lift to zero lift
$\Delta t_{RC90°}$ = time to roll and capture 90-deg bank angle
τ_0 = time delay

I. Background

HISTORY has recorded many examples of air-to-air combat where differences in the agility characteristics of the opposing aircraft were decisive in determining the outcome of aerial engagements. History has recorded many other examples of air-to-air combat where other aircraft attributes, such as payload/range, dive speed, firepower, or stealthiness, were equally decisive in determining the outcome of an air battle. In most examples of highly successful fighter aircraft, analysis will show that an excellent blending of capabilities, a balanced design, has been achieved. Three famous examples of design balance are the Supermarine Spitfire, the North American P-51 Mustang, and the General Dynamics F-16.

Spitfire

The Supermarine Spitfire is, arguably, the most famous fighter aircraft in history (see Fig. 1). This aircraft combined speed, maneuverability, and firepower with excellent flying qualities and pilot visibility. Its transient agility characteristics, specifically in the roll axis, however, were not optimum against its most capable adversary.

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During engagements over France in 1941, the maneuvering superiority of the Spitfire over the Focke-Wulf Fw-190 was seen to be effectively negated on many occasions by the high roll rates that were attainable by the German aircraft. Even when in an offensive position against the Fw-190, the Spitfire pilots were unable to maintain a maneuver long enough to establish a guns-tracking solution.[1] This was because the German pilots continually utilized the superior roll agility of the Fw-190 to rapidly skew the maneuver plane into an orientation that was different from its adversary. The Spitfire was unable to match these roll rates, and on many occasions, an offensive situation became a neutral one.

The roll performance of the Spitfire was not deficient when compared to the military specification in use at the time. In fact, its roll performance was quite good. The important point is not how the Spitfire roll performance compared to the military specification criteria, but rather, how did it compare to its adversary? In the face of a situation where an agility deficiency was clearly affecting the outcome of critically important aerial engagement, a specialized Spitfire (the Mk XII) was designed by Supermarine to specifically counter the Fw-190 threat; it incorporated the Griffon engine to enhance low-level performance, along with clipped wingtips to enhance the transient roll agility. The clipped tips were first evaluated on the Mk III experimental test program.[2] Later, the Royal Air Force (RAF) modified many Spitfire Marks (beginning with production of Mk V and Mk IX) with the clipped wingtips, abandoning the elegant elliptical wing platform that gave the Spitfire its distinctive appearance (see Fig. 2). Figure 3 shows the roll performance of the Mk IX Spitfire compared to the Fw-190 and other WWII aircraft.

If we analyze this modification from a design balance standpoint, it is clear that several combat attributes were sacrificed to allow the roll agility of the Spitfire to be increased. Maneuverability was degraded due to the increase in wing loading and span loading. Payload/range performance was reduced due to the reduction in the aspect ratio of the wing and, of course, the modification cost money to implement—a consideration that must be accounted for in peacetime or in war.

A judgment on design balance must take into consideration the mission dependence of an aircraft's combat attributes. In the case of the Spitfire, its mission was local air defense early in the war and, as such, the RAF did not place a high weighting factor on payload/range performance. The tradeoff between maneuverability and transient agility was, however, critically important. The fact that a decision was consciously taken by the RAF to degrade the maneuverability of the

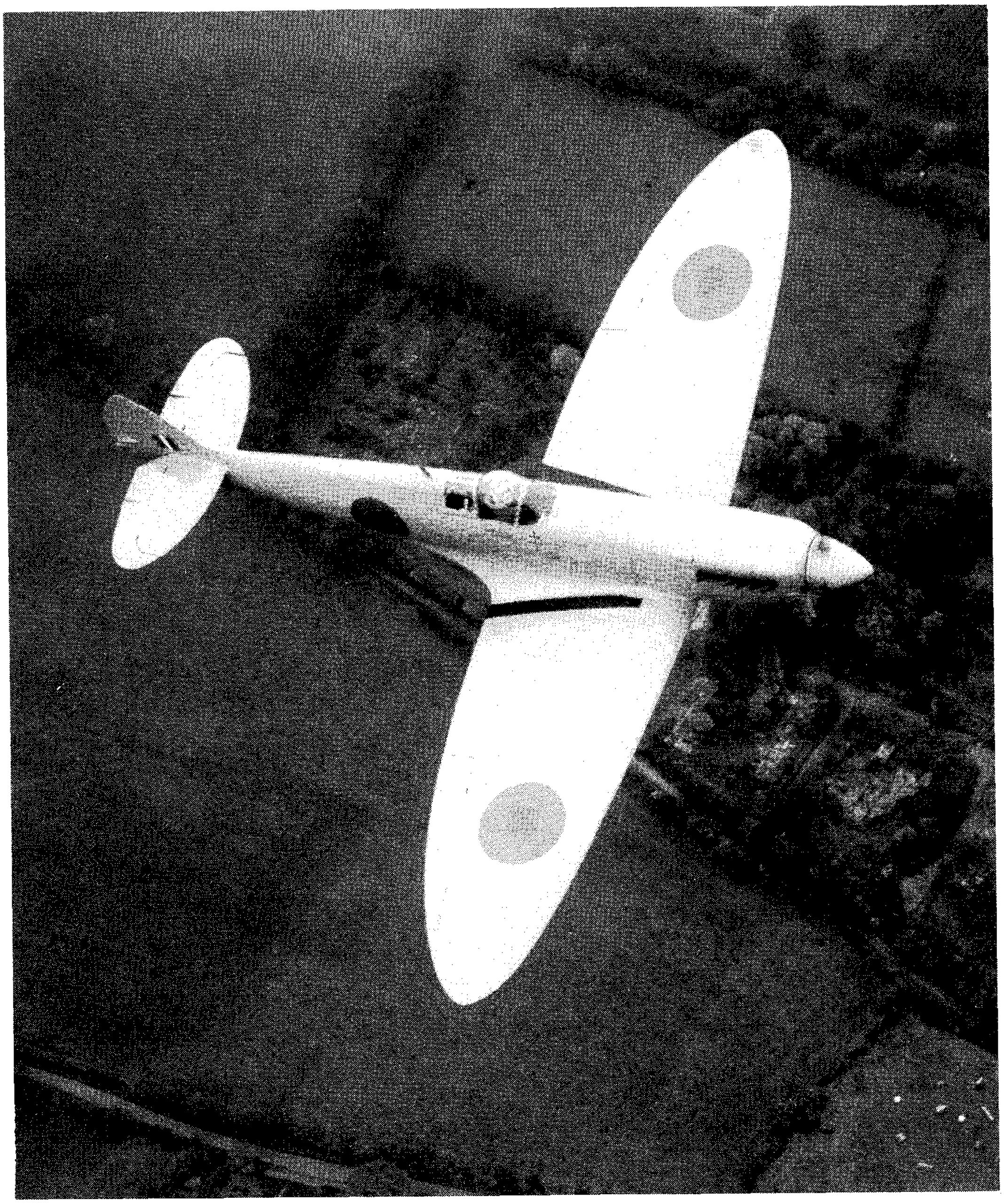

Fig. 1 Spitfire Mk XI clearly showing original elliptical wing planform.

Spitfire in favor of an increase in transient roll agility shows the critical importance that agility can have on air combat.

P-51 Mustang

The North American P-51 Mustang has been called the finest fighter aircraft produced in significant numbers during WWII. The Mustang possessed all of the attributes of the Spitfire and was able to take advantage of some advanced technologies, such as NACA high-speed airfoil technology that was developed after the design of the Spitfire.

The Mustang's agility characteristics were excellent, although, in the case of roll agility, the P-51 could not match the Fw-190 or the clipped-tip Spitfire. The Mustang's mission, however, was quite different from the Spitfire. The P-51 was used consistently during WWII on long-range bomber escort missions. On these missions, the Mustang amassed an enviable record in air-to-air combat against all threat aircraft, including the Fw-190, Me-109, and even the jet-powdered Me-262. However, until the P-51s were fitted with external fuel tanks, they did not possess the payload/range capability to even arrive at the air combat arena. Without adequate range, the agility characteristics of the Mustang had no combat value whatsoever. Had the Spitfire been pressed to perform the bomber escort mission rather than the P-51, it is clear that not only would external fuel tanks have been required, but the wingtips would surely have been quickly returned to their original span. In fact, just as the fuel tanks were designed to be jettisonable on the P-51, the wingtip extensions of the Spitfire were made field removable to allow a certain amount of mission tailoring to be done as the Spitfire was employed in different theaters later in the war.

F-16

The General Dynamics F-16 Fighting Falcon is an excellent example of a present day fighter aircraft that has achieved a high degree of design balance. It is illustrative to recall the fact that the F-16 was selected as the U.S. Air Force (USAF) light-weight fighter (LWF) as a result of a flyoff between prototype aircraft, the YF-16 and YF-17. During this flyoff, many parameters that are known to affect combat performance were rigorously measured and analyzed. Several performance attributes (such as payload/range) were seen to be

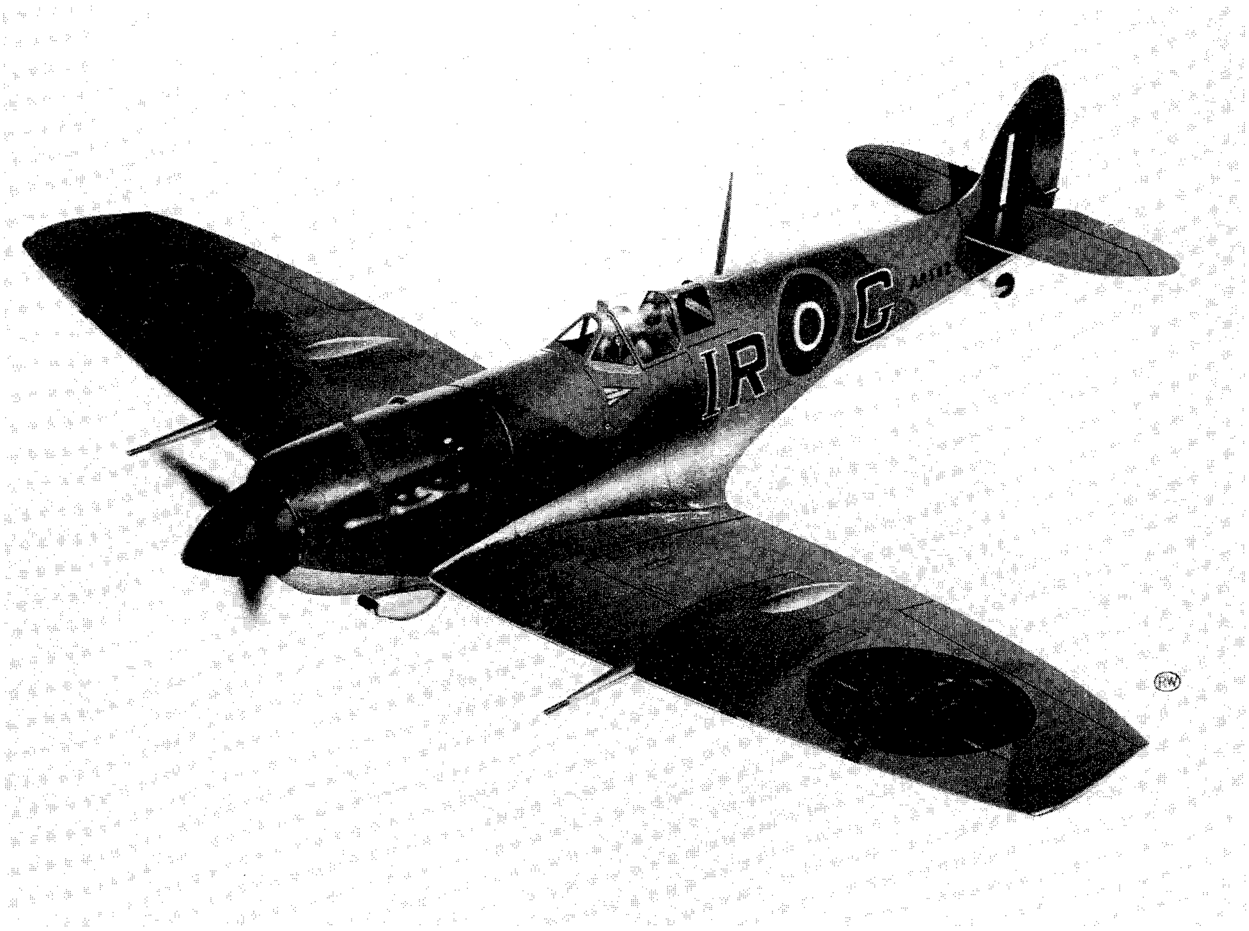

Fig. 2 Spitfire Mk VB modified with clipped wingtips.

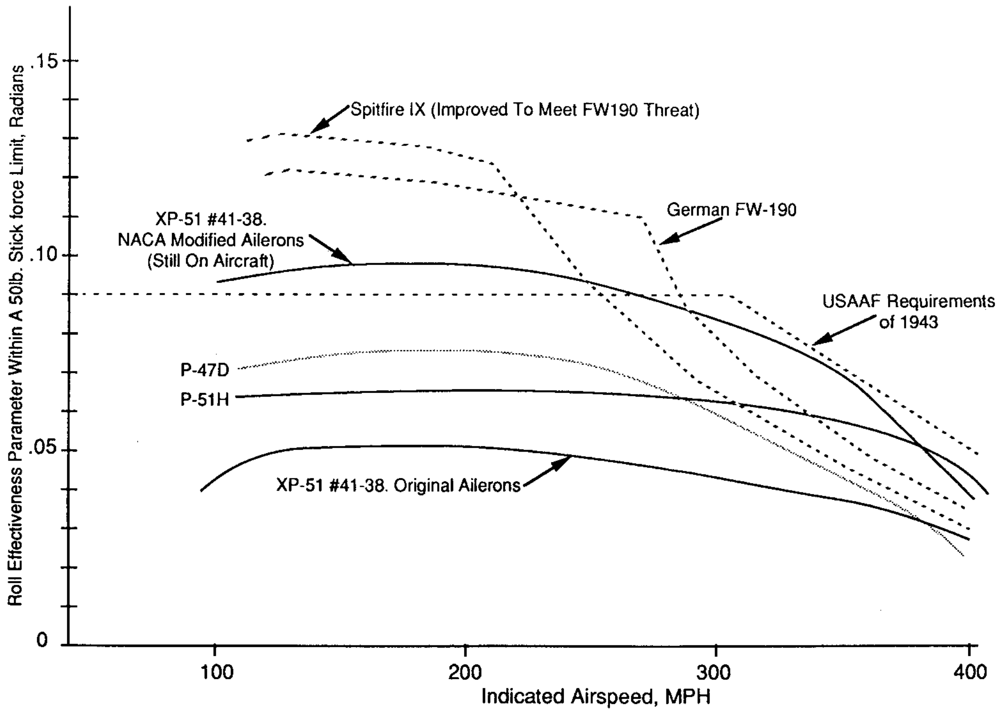

Fig. 3 Comparison of roll effectiveness of WWII fighters.

substantially in favor of the YF-16, but from a maneuverability standpoint, the analysis showed a "mixed bag." An analysis methodology developed by John Boyd and Tom Christie in the later 1960s, called energy-maneuverability (E-M), was utilized to compare the air combat performance of the prototype aircraft against various threats. When compared against the same adversary aircraft, the YF-16 showed advantages at some conditions; the YF-17 showed advantages at other equally important conditions. But when mock air combat engagements were flown, a completely different story unfolded, with the YF-16 demonstrating clear superiority over the adversaries at all conditions.

In an effort to understand this apparent discrepancy, Boyd conducted in-depth interviews with the pilots of both of the LWF prototypes as well as with the pilots of the adversary aircraft.[3] What resulted was a consistent story whereby the superior transient agility characteristics of the YF-16 were seen to be the dominant factors. In the areas of the flight envelope where the YF-16's static (E-M) performance was deficient (when compared to the threat), its superior dynamic agility was able to overcome. Conversely, in the areas of the fight envelope where the YF-17's static (E-M) was superior to the threat, its deficiencies in dynamic agility penalized its overall performance. The static, (E-M) comparisons were not wrong, just incomplete.

The main points to be drawn from this brief review of history are the following:

1) As seen with the Spitfire, transient agility can become so important in air combat that other critically important performance attributes can be sacrificed and the resultant design balance of the aircraft can still be increased.

2) As seen with the P-51 Mustang, agility is not everything! Weighting factors applied to combat attributes change for different missions. This goes for agility too. A methodology to help achieve this mission-dependent design balance is needed.

3) As seen with the F-16, transient agility should be a part of the evaluation process in competitive aircraft selection. Agility differences influenced the USAF's choice of the YF-16 over the YF-17, even though these differences were subjective in nature and not analytically quantifiable at that time. Agility differences between the YF-22 and YF-23, if any, should influence the USAF choice of the better advanced tactical fighter (ATF). Excellent agility contributed to the design balance of the F-16 and agility can make a positive contribution to the design balance of the ATF as well.

The extension of these historical lessons to the future and to advanced aircraft is clear. Unlike the Spitfire example, we will not be able to wait until we see the results of a few months of air-to-air engagements before we undertake a modification program to enhance the agility of our aircraft. We must deal with agility proactively in the design process. Like the P-51 example, we must carefully balance agility with other critically important combat attributes. Like the F-16 example, we must include agility in the evaluation process of any advanced air craft if we are to have a clear picture of the design balance that has been achieved. This requires 1) a clear definition of agility; 2) standardized agility measures of merit; 3) a proven agility quantification methodology applicable in design, test, and operational contexts; and 4) mission dependent weighting factors for agility as it contributes to design balance.

II. Agility Definitions

The clear definition of agility must precede any discussion of the subject. During the past few years, as a direct result of the increased interest in agility and supermaneuverability, several experts have put forward various definitions of agility.

Col. J. R. Boyd: "Maneuver is the ability to change altitude, airspeed, or direction in any combination. Agility is the ability to shift from one maneuver to another." (Ref. 4)

Pierre Sprey: "Agility is inversely proportional to the time to transition from one maneuver to another." (Ref. 4)

Col. E. Riccioni: "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)." (Ref. 5)

Northrop: "Agility is the ability to rapidly change both the magnitude and direction of the aircraft velocity vector." (Ref. 6)

General Dynamics: "Agility is the capability 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 fight at will." (Ref. 7)

MBB: "Agility is the time rate of change of the aircraft velocity vector." (Ref. 8)

USAF Test Pilot School: "Agility is the ability to shoot one's self in the 'derrierre' instantly with perfect control." (Ref. 9)

Eidetics: "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." (Ref. 10)

The reader can clearly see that, from a philosophical point of view, there is a substantial amount of agreement between the different definitions; all involve time, and all seek to minimize the time required to achieve some desired outcome. Eidetics' definition is the broadest, encompassing all elements that influence the agility of the weapon system. Airframe agility makes up a critical portion of the overall system, but is positioned in context with the other critical elements so that the tendency to analyze the airframe in isolation is countered.

Even though the focus of this paper is airframe agility, it is important to remember that the motivation for the study of agility is combat. Combat success requires more than an agile airframe. It requires an agile weapon that can successfully control the launch transient pitchover while maintaining target lock; it requires agile avionics systems with agile sensors that can collect and process multiple target information; and it requires an agile pilot that can utilize agile displays and cueing systems to maintain a high level of situational awareness in a highly dynamic engagement with multiple adversaries. It is just as important for a pilot to know when not to use his agility as it is for him to know when to use it. An agile airframe, by itself, is useful only in airshow aerobatics. An agile weapon system is needed for air combat. Hence, Eidetics' definition of agility establishes an overall weapon system frame of reference.

In response to the same desire to broaden the application of the agility theory to all elements of a weapon system, Boyd[11] expanded his definition of agility in 1988: "Agility is the ability to shift from one unfolding pattern of ideas and actions to another by being able to transition from one orientation to another." This definition can be applied to the aircraft, to the pilot, or to the avionics suite with equal clarity. This definition, in combination with Boyd's "observe, orient, decide, act" (OODA) loop concept for the pilot/avionics element of the weapon system is utilized in Fig. 4 to illustrate how the overall concept of weapon system agility can be used to identify six individual time delays that interconnect each of the elements in the sequence of events between target identification and target destruction.

The six individual time delays are the following:

1) τ_1 is the delay between the time that the threat can be observed and the time that the pilot is conscious of its presence. It can be a function of many parameters, including visual acuity, sensor detection range, cueing and display formats, etc.

2) τ_2 is the delay between the time the pilot is consciously aware of the threat and the time he correctly orients himself mentally to this knowledge. This time delay is cognitive in nature and can be influenced by many factors, the most im-

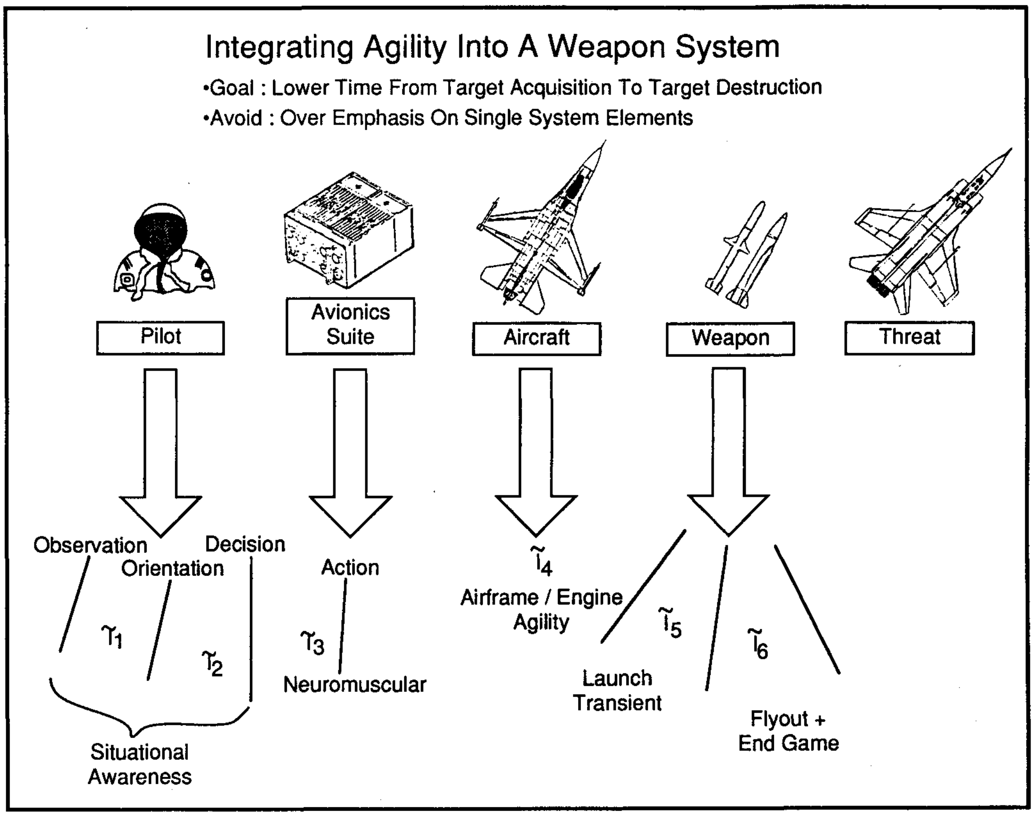

Fig. 4 Weapon system agility concept.

portant being pilot situation awareness, which can be enhanced by training. Cockpit cueing and display system formats can enhance situation awareness as well, and current research in artificial intelligence could lead to significant reductions in this time delay.

3) τ_3 is the delay between the pilot's decision to take an action and the actual movement of the control stick, rudder, pedals, throttle, or a switch. This time delay is dependent only on neuromuscular effects and typically is <300 ms.

4) τ_4 is the time required for the aircraft to shift from one maneuver state to another. Aircraft airframe agility is a function of both the maneuverability of the aircraft and of its transient controllability.

5) τ_5 is the time required for the weapon to successfully transition from its stored position on the aircraft to a trajectory toward the target. For a gun, this time delay is effectively zero. For an externally carried rail-launched missile, this is the time between missile firing and the time where the missile has completed its launch transient and is successfully guiding toward the target. For an internally carried missile, the delay may include additional time.

6) τ_6 is the time delay between the successful launch transient and weapon impact. For a gun, this time delay is influenced by the caliber and type of round, and for a missile, is influenced by motor impulse/burn times or by missile endgame agility.

Designers of agile fighters must seek to minimize each of these time delays while taking care not to suboptimize any individual one. It is possible that overemphasis on any one single time delay could cause other time delays to be increased, reducing the overall system agility. For instance, if poststall maneuvering is used to decrease τ_4, it is possible that τ_5 could increase to infinity due to missile launch transient problems. Also, increasing the load factor onset rate to reduce τ_4 could cause the pilot to experience g-induced loss of consciousness, causing τ_3 to increase to infinity because the pilot is asleep. Adding more sensors to the aircraft can decrease τ_1, but unless the information from them is properly displayed or communicated to the pilot, sensory saturation can occur, driving τ_2 up.

III. Agility Metrics Revisited

During the past several years, many measures of merit or metrics for agility have been suggested.[13-19] Recently, several studies have been published that evaluated the relative merits of some metrics.[20,21] Additionally, Dorn[22] reviewed several metrics and categorized them according to the time scales appropriate to their application. Working groups for the study of agility (including ways to define and measure it) have been established by the USAF, the Navy, and by AGARD. Clearly, work on agility metrics is ongoing, and government and industry have not, as yet, adopted standardized parameters to be used for agility quantification.

The principal motivation that is propelling the research into agility metrics stems from the fact that current aircraft performance measures of merit do not adequately capture the important transient characteristics of an aircraft. Researchers in the operations analysis community are attempting to augment, or supplant, the traditional metrics that they use to compare aircraft, such as E-M and payload/range performance, with new metrics that more completely account for the dynamics of air combat. Researchers in the flying qualities community are attempting to determine whether the current military standards relating to flying qualities and flight control systems (MIL-STD-1797 and MIL-STD-18372) adequately define the transient characteristics of an aircraft in an agility context or whether any of the proposed metrics do a better job (see Ref. 23). Since the transient response of a fighter aircraft is multidimensional, researchers in both of these areas (operations analysis and flying qualities) have a great deal of work ahead of them before a complete list of standardized metrics can be defined and accepted by the community.

Prioritized Metrics

In order to potentially accelerate the process of defining metrics for agility, it is proposed that certain metrics be given priority, based on their importance in air combat. Multiple surveys conducted since 1984 with USAF and U.S. Navy (USN) Fighter Weapon School instructors and operational pilots (i.e., Ref. 24) have noted that metrics are critically needed in two specific agility areas:

1) Differences in the capabilities of two opposing aircraft to roll while executing a high angle-of-attack turning maneuver must be measured.

2) The capability of a aircraft to pitch down from a high load-factor maneuver at high angle of attack/high drag to an unloaded, low angle of attack/low drag condition in order to accelerate to a higher airspeed must be quantified.

The survey pilots gave special emphasis to the requirement that metrics to evaluate both of these important transient agility effects must be presented in a format that can clearly communicate tactically relevant information to an operational pilot. Many pilots pointed to the Boyd/Christie E-M measures of merit as an example of a methodology that is mathematically precise and, at the same time, is usable to a fighter pilot without a mathematics background. Historically, pilots have always understood the importance of speed and maneuvering to air combat success. They have also understood that hard maneuvering often resulted in a rapid loss of speed, requiring an acceleration at lower angles of attack to regain the speed. Engineers have always understood these same relationships and have, in fact, developed sophisticated computational schemes to achieve optimized maneuvers or to achieve minimum time-to-climb profiles, such as the Rutowski energy-climb profile concept from the 1930s. What the Boyd/Christie E-M methodology provided was a format on which known, mathematically correct parameters (P_s and turn rate) could be displayed and be readily used by pilots. Rutowski did the math in the 1930s; Boyd/Christie translated it into a usable format in the 1960s.

The development of a transient agility methodology that describes the dynamic elements of air combat that are not captured by E-M parameters must take a similar approach. Pilots intuitively understand the importance of fast maneuver transients in air combat. Engineers can rigorously define the transient response of any aircraft motion that the pilot wants. What is needed is a set of meaningful agility metrics and an analysis methodology that is mathematically correct and tactically usable by fighter pilots. The following parameters are proposed as standard metrics for the definition of the two highest priority agility characteristics.

High Angle-of-Attack Roll Agility Metrics

The pilot of a highly agile fighter aircraft utilizes the roll axis at high angles of attack to 1) point the normal-force vector (lift and thrust terms included), and/or 2) point his weapons (body axis roll/yaw orientation). Pointing of the normal-force vector while maneuvering allows the pilot to change the orientation of his plane of maneuver relative to his opponent. In an offensive situation, the pilot of a superior maneuverable aircraft must continually align his plane of maneuver relative to that of his target to allow his turn-rate (TR) advantage to be used to bring his weapons to bear. In a defensive situation, if a pilot can continually change the relationship between his plane of maneuver and that of his opponent, he can effectively negate some of the TR advantage of the opponent.

Weapon pointing through high angle-of-attack body axis roll/yaw orientation can be of value in some special circumstances, even if the normal-force vector of the aircraft is weak due to low airspeed and thrust/weight <1. This type of roll agility does not change the plane of maneuver necessarily, but can be used to achieve an offensive advantage especially when employing guns at short range.

In order to capture the important maneuver dynamics and control transient effects embodied in the normal-force-pointing element, the torsional agility (TA) parameter is proposed:

$$\text{Torsional agility} = \frac{\text{Turn rate}}{\text{Time to roll and capture } 90^\circ \text{ bank}} \tag{1}$$

$$TA = \frac{TR}{\Delta t_{RC90^\circ}} \left(\frac{\text{deg}}{\text{s}^2}\right) \tag{2}$$

Low values of TA are given to an aircraft that is highly maneuverable but has very sluggish roll/yaw axis controllability. Likewise, low values of TA are given to an aircraft that can roll very rapidly (to reposition the plane of maneuver) if the maneuverability of the aircraft is low. In other words, TA is a parameter that can be used to achieve a balance between high maneuverability and fast roll/yaw axis transient response. The value of high maneuverability is lessened when the ability to orient the plane of maneuver is low. The value of fast transient roll/yaw axis response is lessened when the maneuverability of the aircraft is low.

For the case where the pilot's objective is weapon pointing, irrespective of the normal-force vector's orientation, an appropriate metric could be called lateral agility and would be inversely proportional to the denominator of the TA parameter:

$$LA = \frac{1}{\Delta t_{RC90^\circ}} \left(\frac{1}{\text{s}}\right) \tag{3}$$

For both of these parameters, the choice of 90 deg for the roll-capture bank angle is somewhat arbitrary. Alternate bank angle capture targets can be substituted without affecting the validity of the parameters. In air combat, a wide variance in actual bank angle captures would be seen in any engagement. However, interviews with a large sample of current operational pilots resulted in the selection of 90 deg as the most representative. The pilots felt that 30 deg bank angle change was too small and 180 deg was too long. To a certain extent, 90 deg was a compromise.

Torsional Agility Variations in Current Aircraft

To illustrate the utility of the TA metric, a comparison of five current fighter aircraft was made utilizing transient roll/yaw axis response data from high fidelity, piloted simulations.[10] All simulations were flown with each aircraft in an appropriate air-to-air weapon loading, at a mid center-of-gravity position with 50% internal fuel. Figure 5 presents the comparative data at $M = 0.60$/15,000 ft. As can be clearly seen, a wide variation in the TA characteristics is evident. At higher Mach numbers, the variation was less due to the lower angles of attack required to generate the turn rates. At lower Mach numbers, the variations increased.

Aircraft A and C exhibited the widest disparity in TA and also exhibited a large difference in conventional E-M. Figure 6 illustrates how a TA comparison between these two aircraft can be used in conjunction with an E-M comparison to communicate a more complete picture of the relative air combat capability than would be given by a comparison of E-M alone. From the E-M comparison (Fig. 6a), it can be seen that Aircraft C has superior 1 g P_s, superior sustained turn rate and superior instantaneous turn rate when compared to Aircraft A. From the TA comparison (Fig. 6b), it can be seen that Aircraft A has significantly higher TA than Aircraft C when both aircraft are maneuvering at turn rates high enough to cause the specific excess power to be negative. From a tactics standpoint, the pilot of Aircraft A would know (if he reviewed the E-M and TA characteristics of his own aircraft and that of his adversary prior to the fight) that, in a hard maneuvering engagement where he is positioned defensively, if he rapidly skews the plane of maneuver of his aircraft, his opponent will

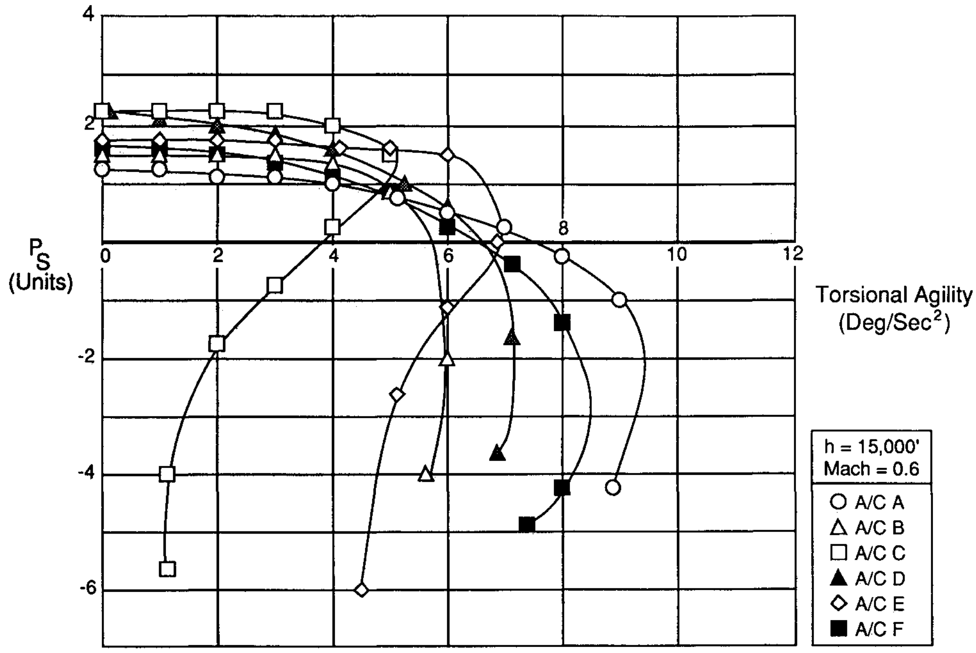

Fig. 5 Torsional agility comparison of current fighters.

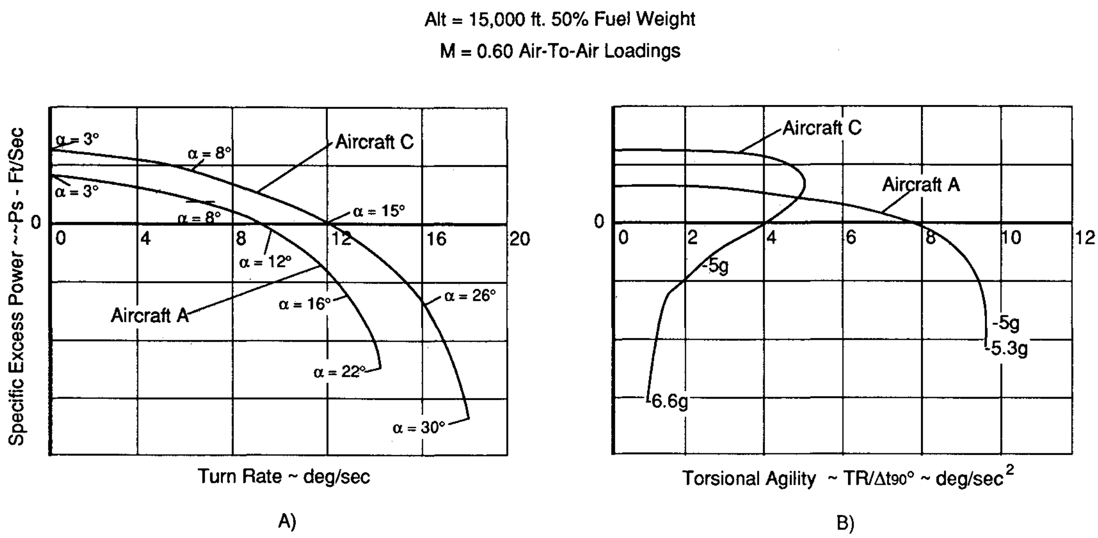

Fig. 6 Maneuverability and torsional agility comparison.

not be able to follow. He may be able to use this knowledge to turn a defensive situation into (at least) a neutral one.

Subjective analysis of multiple engagements between these aircraft in training indicates that the superiority of Aircraft C over Aircraft A is less than might be expected from a comparison of E-M alone. Analysis of the comparative TA levels of the two aircraft helps to explain the difference between the expected and the actual air combat effectiveness results.

Lateral Agility Variations in Current Aircraft

Figure 7 illustrates the variation in lateral agility for the same five aircraft discussed previously. It can be seen from the figure that all of these aircraft exhibit similar lateral agility at low angles of attack but show significant differences as angle of attack approaches that for maximum lift. The lateral agility similarities at low angle of attack are due to the fact that the military specification for flying qualities (MIL-F-8785) requires category IV fighters to roll through 90 deg in <1 s. Early versions of this specification required compliance with this requirement only at 1-*g* conditions. The latest version (MIL-F-8785C) requires compliance up to 80% of the limit load factor and varies the requirement with airspeed. All of the comparison aircraft were designed to the earlier specifications.

High Angle-of-Attack Pitch Unload Metric

In an aggressive engagement against a highly maneuverable adversary, maximum load factor or maximum lift maneuvering may be required for survivability. The high values of turn rate that are achieved at these maximum conditions come at the expense of energy. Since maximum rate maneuvering bleeds energy rapidly, it can only be continued for short durations. When the pilot decides to terminate a maximum rate maneuver that has caused his airspeed to be bled to a low value, he needs to accelerate quickly. In order to minimize his vulnerability during the straight line acceleration, he may only budget a short time segment to regain as much energy as possible. Maintaining a predictable flight path for longer than 10–15 s rapidly reduces combat survivability in a dense, many vs many (MvN) air battle.

Only two factors influence the ability of the aircraft to accelerate rapidly: thrust minus drag and gravity. Gravity, of

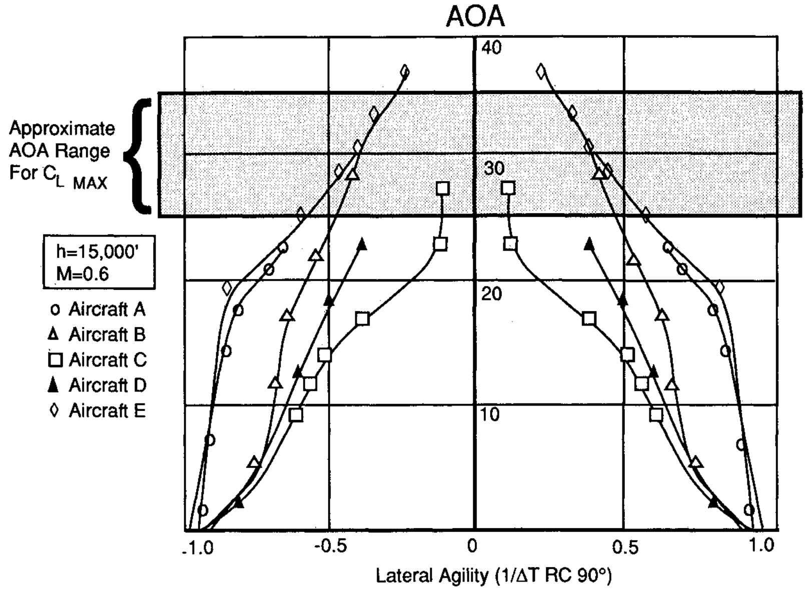

Fig. 7 Lateral agility comparison of current fighters.

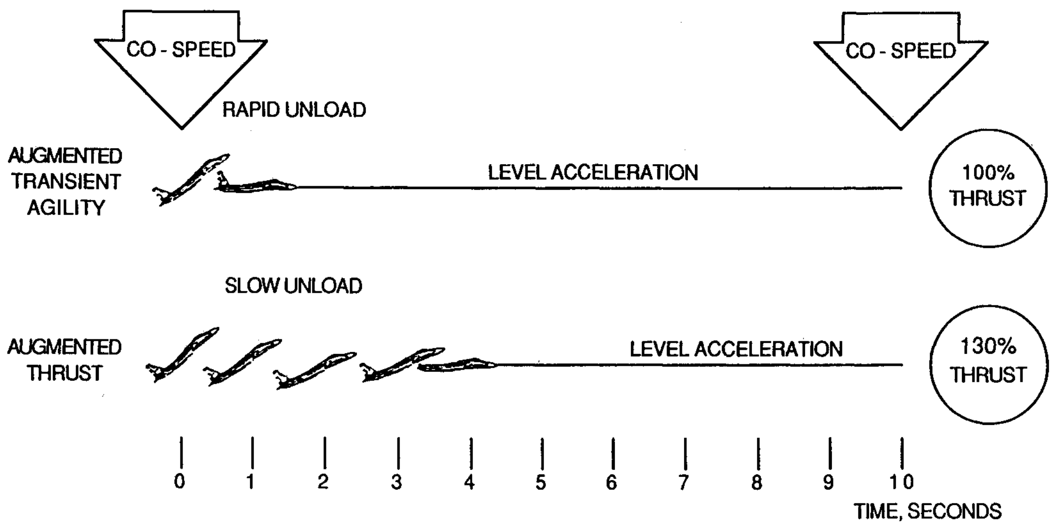

Fig. 8 Effect of slow pitch unload time on a 10-s acceleration.

course, can help or hurt, depending on the flight-path angle γ. If we assume that negative flight-path angles are not an option (due to terrain avoidance), then we are left with thrust and drag. For a high thrust/weight fighter, the rate at which thrust increases after a movement of the throttle can have an important effect on the energy addition achieved during a short acceleration. However, the rate at which drag is reduced can have a substantially greater effect. For instance, for modern, high-thrust/low-wing loading fighters of the F-15/Su-27 class, installed thrust/weight in combat can exceed 1:1. The lift-to-drag ratio for these types of aircraft can be as low as 1.2:1 at subsonic Mach numbers and at maximum lift angle of attack. Taking an example condition of $M = 0.6/15{,}000$ ft/7 g, the maneuver drag can be as high as 160,000 lbs while the maximum installed thrust will be approximately 40,000 lb. The majority of the maneuver drag comes from induced drag or drag-due-to-lift. Therefore, it is clear that, from a transient agility standpoint, the time required to reduce drag due-to-lift is at least four times as important as the time required for the engine to spool up from idle power to maximum power.

In order to capture this important pitch transient effect, a combined pitch/axial agility parameter is proposed which is called drag power rate (DPR):

$$\mathrm{DPR} = \left[\frac{\Delta D/\Delta t|\text{max lift to zero lift}}{W}\right] V \tag{4}$$

$$\mathrm{DPR} = \left(\frac{\Delta D_i/\Delta t}{W}\right) V \left(\frac{\text{ft}}{\text{s}^2}\right) \tag{5}$$

where

$$\Delta D_i = D_{\text{zero lift}} - D_{\text{max lift}}$$

Drag power rate is equivalent to the first derivative of the drag term in the equation for P_s:

$$P_s = \left(\frac{T - D}{W}\right) V = \left(\frac{T}{W}\right) V - \left(\frac{D}{W}\right) V \tag{6}$$

$$\mathrm{PR} = \frac{\mathrm{d}P_s}{\mathrm{d}t} = \left[\frac{\mathrm{d}T/\mathrm{d}t}{W}\right] V - \left[\frac{\mathrm{d}D/\mathrm{d}t}{W}\right] V \tag{7}$$

$$\mathrm{PR} = \frac{\mathrm{d}P_s}{\mathrm{d}t} = \mathrm{TPR} - \mathrm{DPR} \tag{8}$$

where TPR is the thrust power rate. By separating TPR and DPR effects, engine spool-up times and pitch unload times can be seen to have individual contributions to $\dot{P}_s$ in a maneuver to unload and accelerate. The same terms can be used to show the separate effects of engine thrust spool down, thrust reversing, or speed-brake deployment on deceleration maneuvers.

In order to show the applicability of the DPR metric, the following example is presented. Two aircraft in the same thrust class as the previous TA example (F-15/Su-27 class) are compared in a 10-s acceleration. Both aircraft are co-speed at the start of the acceleration at $M = 0.6$/10,000-ft altitude. Both are initialized at 7 g/30-deg angle of attack. Aircraft 1 has rapid nose-down pitch agility and is able to unload from 7 to 1 g in 1 s. Aircraft 2 has sluggish nose-down pitch performance, completing the same task in 4 s. Both aircraft are assumed to have maximum thrust available from the start of the acceleration (i.e., no engine transient effects included). In order for both aircraft to be co-speed at the end of the 10-s acceleration, Aircraft 2 requires 30% more thrust than Aircraft 1 (see Fig. 8).

Figure 9 illustrates how improvements in transient pitch agility can be equated to a traditional measure of merit, i.e., thrust. Current fighter aircraft demonstrate a significant variation in nose-down pitch agility with some aircraft requiring as much as 6 s to reduce angle of attack from maximum lift to zero lift conditions and some aircraft requiring <2 s. As seen in Fig. 9, a reduction in the time to pitch down to 1 g of 1 s can be equated to an improvement in installed thrust of 5–10%, depending on Mach number.

Figure 10 presents the same information as Fig. 9, but in this case, using DPR and P_s as the interdependent variables.

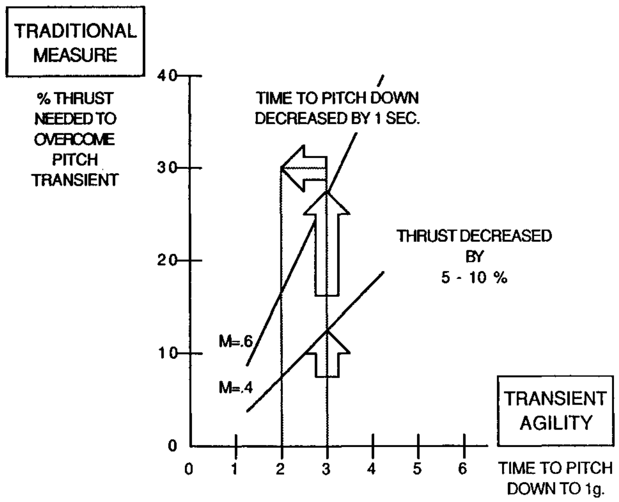

Fig. 9 Equating transient pitch agility to traditional measures of merit.

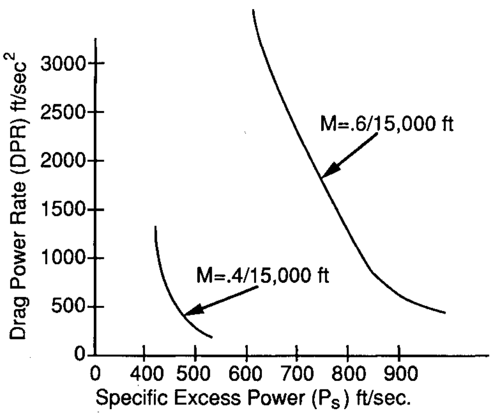

Fig. 10 Relationship between DPR and P_s for equivalent 10-s acceleration performance.

It can be seen that an improvement in DPR of −750 ft/s² (equivalent to reduction in pitch-down time of 1 s for an F-15 class fighter) translates to an increase in P_s of 64 ft/s. The operations analysis community generally considers differences in P_s between opposing fighters of >50 ft/s to be tactically significant. By inference then, differences in the time to pitch down to 1 g of >1 s should be tactically significant in engagements dominated by transients between short duration/hard turns and short duration/unloaded accelerations.

As airspeed is reduced, the relative contribution of TPR and DPR to the total airframe PR changes. Thrust power rate becomes more important since thrust is only weakly affected by dynamic pressure. Drag power rate becomes less important since drag varies directly with dynamic pressure.

IV. Tactical Utility of Agility in Air-to-Air Combat

Whereas there is universal agreement that agility in air combat is valuable, many other aircraft attributes such as acceleration, speed, maneuverability, and payload/range performance have value also. Each of these attributes has a value and a cost. There is a well-substantiated knowledge base in government and industry that quantifies the operational value of E-M and payload/range performance for an air-to-air fighter. There exists no such knowledge base for transient agility. In order for an aircraft design team to properly balance agility along with the many other competing aircraft performance and capability goals, a specific quantification of the operational value of agility is required. There have been many study results published that show significant operational value attributable to various types of agility enhancements ranging from poststall maneuvering to enhanced roll performance to thrust vectoring/reversing. Most of these studies were constrained in some manner, such as the following:

1) Air battle density constrained to 1 vs 1 or 1 vs 2 engagements due to the unavailability of multiple domed simulators.

2) Weapon technology either unevenly allocated between the friendly and threat forces [i.e., Blue has U.S. Air-to-Air Missile (AIM-9L) and Red has Soviet Air-to-Air Missile (ATOLL)] or unrealistically constrained to gun only (i.e., very short range combat).

3) Successful employment of agility technology required adaptation of a radical tactical doctrine or the precise execution of a unique maneuver (i.e., intentional, ultra-low-speed maneuvering required for supermaneuverability advantage).

Perhaps as a result of these types of constraints, which limited the acceptance of previous operational studies, the question of the potential combat value of agility remains open. In order to provide an additional input to the operational effectiveness question, a study[10] was structured with three important ground rules:

1) The combat simulations were conducted in a dense, MvN air battle in which both the friendly and threat aircraft were armed with all-aspect, infrared missiles and current technology guns.

2) The tactical employment doctrine utilized by both the friendly and threat forces was conventional in nature and was consistent with current USAF tactics. In fact, the tactics utilized were biased toward the conservative "speed is life" philosophy, whereby maneuvering below the corner speed was prohibited.

3) The study was conducted in such a way that the increments in combat effectiveness which were attributed to enhanced transient agility were equated to increments attributed to traditional measures of merit (such as P_s and TR) in order to connect agility to the existing knowledge base through a consistent analysis methodology.

The air combat simulations were conducted utilizing the Air-to-Air System Performance Effectiveness Model (AASPEM).[25] The air combat maneuvering (ACM) scenario size was varied from 1 vs 1 to 2 vs 2 and 4 vs 4 in order to assess the effect of air battle density on the tactical utility of agility.

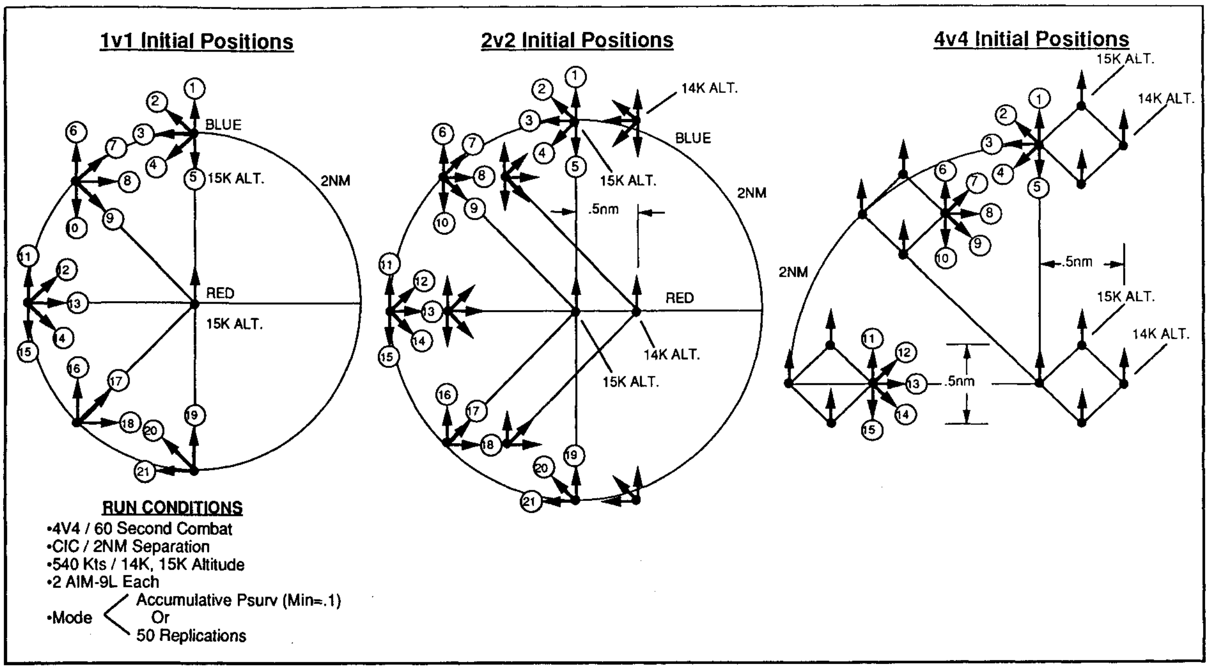

Fig. 11 Air combat maneuvering simulation initial conditions.

Sym	Enhancement Category	Δ Capability	Technology Required
○	Agility	Faster Transients In Pitch, Roll, Yaw	Conventional Controls
△	Turn Rate	30% More Sustained	23% Reduced Weight Thru Adv. Matl
□	Thrust	30% More Thrust	Engine T/W Increased From 7.5 To 10.0

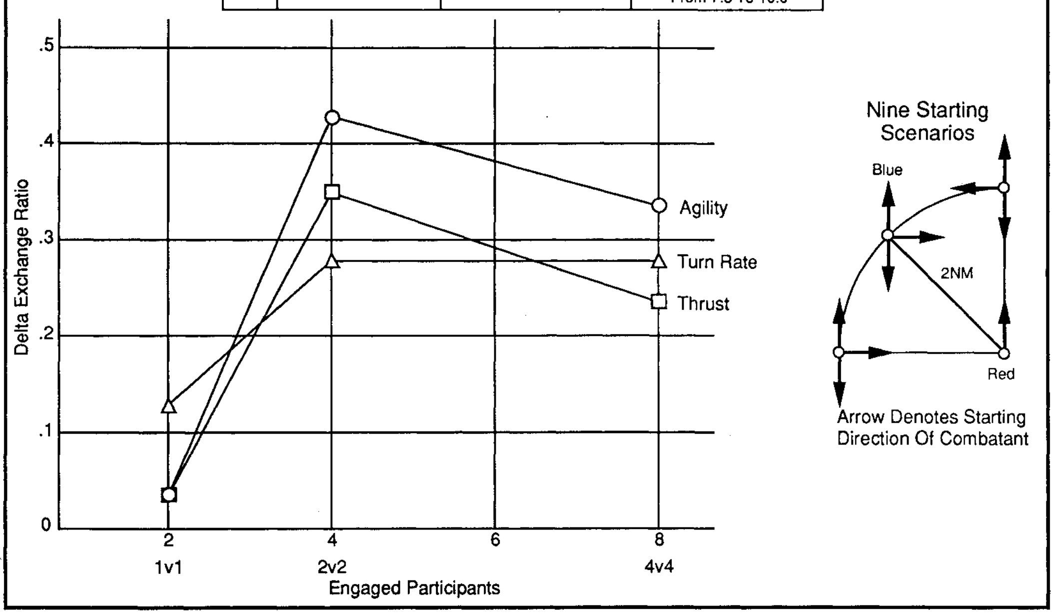

Fig. 12 Air combat maneuvering simulation results.

Agility levels of the Red aircraft and of the baseline Blue aircraft were set at levels representative of an average conventional fighter. The E-M levels of the Red aircraft and of the baseline Blue aircraft were set at levels representative of the F-16/F-18/MiG-29 class of aircraft. The baseline Blue aircraft was evaluated against the threat and then was enhanced in two separate ways:

1) Blue transient agility was enhanced. The agility level of the Blue aircraft was enhanced from its baseline, average conventional level to a level representative of excellent conventional aircraft. No poststall capability was added to the Blue aircraft. The specific changes to the relevant agility metrics are the following: axial agility—thrust rate ($\Delta Fn/\Delta t$) increased from 4,000 to 8,000 lb/s by reducing engine spool time (idle-max) from 8 to 4 s; pitch agility—maximum pitch rate (nose up and nose down) increased from 20 to 40 deg/s while maintaining typical short-period response; and lateral agility—time to bank 90 deg and stop reduced from 2.2 to 1.8 s.

2) Blue conventional performance was enhanced. Specific changes to performance are the following: thrust—installed thrust of the Blue aircraft was increased by 30% with no increase in weight (thrust loading T/W increased by 30%);

and turn rate—the wing area of the Blue aircraft was increased by 30% with no increase in weight (wing loading W/S reduced by 23%).

The simulations were structured to evaluate the tactical utility of each of the five enhancements (three transient enhancements and two conventional enhancements) separately. Combat initial conditions were set up as shown in Fig. 11. A large sample size of possible initial conditions was chosen in order to be representative of most of the situations that might be found in a dense air battle and in order to prevent the tactical outcome from being heavily dependent on the setup geometry.

The aggregate results of the simulations are shown in Fig. 12. The following principal conclusions can be drawn from the data:

1) The increment in exchange ratio that results from the combined enhancements to pitch, roll, and axial agility is roughly equivalent to the increment in exchange ratio predicted to result from a 30% increase in thrust loading or from a 23% decrease in wing loading.

2) The increment in exchange ratio from all types of enhanced performance (i.e., thrust, wing loading, or transient agility) increased as the number of engaged participants was increased from two to four (i.e., 1 vs 1 to 2 vs 2) and maintained its high level as the number of engaged participants was further increased to eight (i.e., 4 vs 4).

In order to understand the relative contribution of each individual transient agility enhancement, the 2 vs 2 scenarios were analyzed in more detail. Figure 13 presents the results that were obtained and illustrates that the enhancements to lateral agility provided the largest increment in exchange ratio (22.9%), followed by axial agility (12.5%) and pitch agility (7.7%). The combined effect of enhanced pitch, axial, and lateral agility produced an increment in exchange ratio that was greater than the sum of the individual contributions, indicating that some type of synergy was involved. Interestingly, when the two types of conventional performance enhancements were evaluated in combination, a negative synergy was seen in which the combined effect of a reduction in wing loading (34.7%) and an increase in net thrust (38.0%) produced an increment in exchange ratio that was less than the two individual increments (52.5%).

Effect of Tactics on the Combat Value of Agility

As previously stated, this simulation study was structured to utilize the existing conventional, "speed is life" tactical employment doctrine that is practiced today. This tactical doctrine was required for survival in air combat in an F-4 during Vietnam (with some notable exceptions) and is still advisable today in the F-15, F-16, and F-18, although the increased thrust-to-weight ratios and lower wing loadings of these aircraft do allow maneuvering to airspeeds below the corner speed to be utilized for short duration without a survivability penalty. This is due to the lower energy bleed rates and the rapid acceleration potential that is achievable in these newer technology aircraft. The digital pilots in the present AASPEM study, however, religiously followed the conservative tactical doctrine, never maneuvering at high-energy bleed rates long enough to cause them to lose significant airspeed. In fact, the minimum maneuvering airspeed utilized during this study was approximately 400 kt for all participants.

Previous simulation studies of agility and poststall maneuvering have concentrated on the low-speed region of the flight envelope. It is significant to find that, even when this portion of the flight envelope is not utilized due to tactical considerations, the aggregate combat value of transient agility enhancements, within the conventional flight envelope, is still seen to be large.

However, if Super Agile aircraft are built in the future, taking advantage of technology developments in thrust vectoring or advanced aerodynamic controls, it is expected that combat pilots will develop specialized new tactics to fully exploit this new capability. Figure 14 illustrates the fact that there can be, and indeed must be, an interaction between fighter aircraft technologies and the tactics that are utilized to employ them. In this figure, the technology that is shown is the controllable angle-of-attack range of an aircraft. An increase in the controllable angle-of-attack range can create an increase in the transient agility capability of the aircraft in all three axes. Also shown in the figure is the tactical employment doctrine most appropriate to the technology. During the F-4 era, the controllable angle-of-attack range was <20 deg and aggressive agility usage near that angle of attack in the F-4 often resulted in departures. Furthermore, due to the high wing loading of the F-4, maneuvering the aircraft at high angle-of-attack for very long resulted in a significant loss of airspeed and placed the pilot in an unfavorable position with limited options.

After the F-15 was integrated into the USAF inventory, some adjustment to air-to-air tactics was seen to develop. This aircraft has a controllable angle-of-attack range in excess of 30 deg and exhibits a combat thrust-to-weight ratio significantly higher than that of the F-4. With the F-15, pilots can utilize its full transient agility potential very aggressively without concern for departure. If the pilot maneuvers aggressively and decelerates to an airspeed below the corner speed, the high-thrust and low-wing loading of the Eagle give him multiple offensive and defensive options. If the pilot of an F-15 flew his aircraft exactly as he flew the F-4, the combat value of the F-15 in a maneuvering engagement would be reduced from its maximum value.

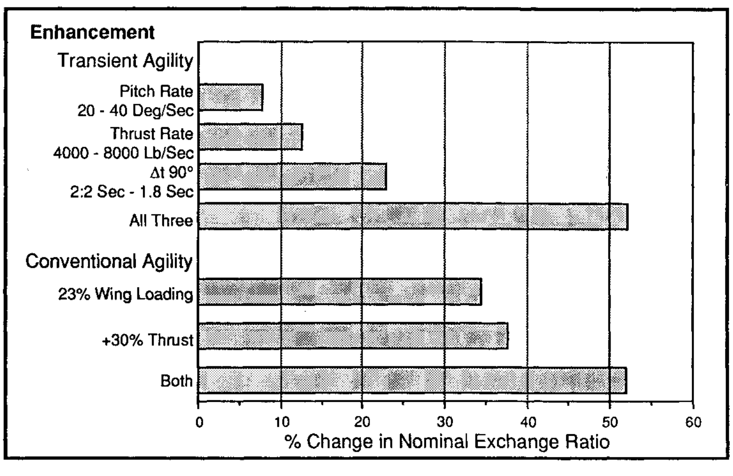

Fig. 13 Relative contribution of combat effectiveness.

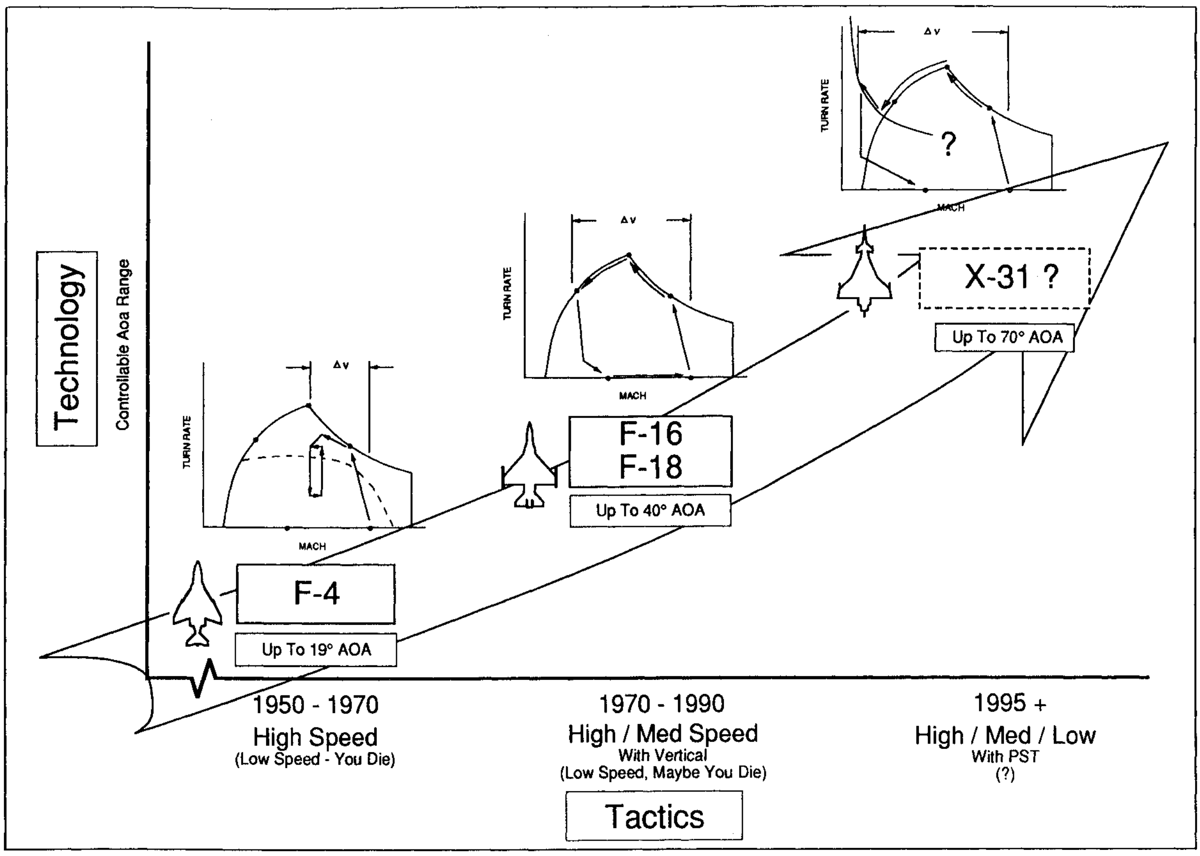

Fig. 14 Interaction between technology and tactics.

The X-31 research aircraft promises to prove that advanced control technology can extend the controllable angle-of-attack range to 70 deg. It is likely that the pilots of the X-31 will develop new tactics to take maximum advantage of this capability. These tactics, however, must mesh with the current tactics. The present study has shown that the type of transient agility enhancements that are achievable in an aircraft like the X-31 can show a high combat payoff even when constrained by a conservative, "speed is life" tactical employment doctrine. In other words, in our study, the pilots of the Super Agile Blue aircraft used F-4 tactics and still showed a payoff. It they utilized tactics more consistent with the F-15/F-16 (i.e., minimum maneuvering airspeed reduced to perhaps 100 kt below corner speed), the combat payoff from agility might increase. If the pilots utilized even lower maneuvering airspeed limits and new specialized maneuvers such as those used for poststall maneuvering, the payoff might increase more. However, studies to determine these payoffs must consider the effect of the number of engaged participants and both the friendly and threat aircraft must be equipped with equal weapon technology (i.e., all-aspect infrared missiles).

V. Summary

Differences in the agility characteristics of opposing aircraft have always been a factor in air-to-air combat. This idea has been intuitively supported by fighter pilots who continue to say "give me more." Since agility is but one of many, sometimes conflicting, combat attributes for an aircraft, the optimum design balance may not result in maximum agility. However, in the absence of a validated assessment methodology for agility, design teams may unintentionally sacrifice agility in favor of combat attributes such as speed, payload/range performance, or stealth due to the fact that these factors are more well defined and more straightforward to measure.

Differences in agility influenced the selection of the YF-16 over the YF-17, even though the agility differences were not analytically quantifiable. During the LWF flyoff, agility definitions were inadequate and agility measures of merit did not exist. The differences that were observed were valid but subjective in nature, coming from pilot evaluations against common adversary aircraft.

Since the LWF competition, substantial agility development has taken place. We now have limited agreement on a clear definition of agility, at least in philosophical terms. Standardized agility metrics have been proposed to quantify and measure the most important types of agility. An agility assessment methodology has been developed and applied to a wide variety of current fighter aircraft using high-fidelity simulators, and to a lesser extent, using the flight test aircraft. Using this methodology, wide variations in the agility characteristics of current fighter aircraft were seen. Some surprises were uncovered that were counter to the conventional wisdom but were supported by subjective evaluation of air combat engagements between several of the aircraft.

The potential for enhanced agility to increase the combat effectiveness of current and advanced fighter aircraft has been quantified and has been equated to increases in conventional, E-M performance. Simulations show that increases in transient agility levels that are fully achievable within the current state-of-the-art are equivalent to increasing thrust by about 30% or decreasing wing loading by 23%. These results were obtained in MvN engagements (not just 1 vs 1) where conservative, high-speed tactics were employed [$V_{min} > 400$ knots indicated airspeed (KIAS)]. The rank order of agility payoff functions placed torsional agility first, followed by axial agility and pitch agility.

Even though the agility methodology that was used to compare existing fighters is still developmental, significant potential exists to extract valuable information about the agility characteristics of competitive aircraft. Application of this agility methodology to the ATF aircraft could quantify the agility potential inherent in the competing prototype designs and could identify, at an early date, any agility limiting design features that could be enhanced during full-scale development.

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