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Fighter Agility Metrics, Research and Test

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This paper presents the results of an analysis of proposed metrics to assess fighter aircraft agility. A novel framework for classifying these metrics is developed and applied. A set of transient metrics intended to quantify the axial and pitch agility of fighter aircraft is evaluated with a high fidelity, nonlinear generic simulation of the F-18 Hornet. Test techniques and data reduction methods are proposed, and sensitivities to pilot introduced errors during flight testing is investigated. Results indicate that the power onset and power loss parameters are promising candidates for quantifying axial agility, while maximum pitch-up and pitch-down rates are for quantifying pitch agility.

Nomenclature

g = gravitational acceleration, ft/s^2
P_s = specific excess power, ft/s
P_{s_f} = P_s at maximum value of thrust minus drag, ft/s
P_{s_i} = P_s at minimum value of thrust minus drag, ft/s
t_f = time at which thrust minus drag is maximum, s
t_i = time at which thrust minus drag is minimum, s

Introduction

FIGHTER flying qualities and combat capabilities are currently measured and compared in terms relating to vehicle energy, angular rates, and sustained acceleration. Criteria based on these measurable quantities have evolved over the past several decades and are routinely used to design aircraft structures, aerodynamics, propulsion, and systems. Although these criteria, or metrics, have the advantage of being well understood, easily verified, and repeatable during test, they tend to measure the steady-state capability of the aircraft and not its ability to transition quickly from one state to another.

Although fighters engaged in close or within-visual-range (WVR) combat spend little time in steady-state flight, the requirement to be able to maneuver for a stable, rear-quarter firing advantage has generally led to extended engagements for which the standard measures of merit are useful. However, the need for maneuvers of this type has been dramatically reduced with the advent of lethal, reliable, all-aspect, short-range missiles of the AIM-9L class.[1] Engagement times have been decreased by nearly an order of magnitude because pilots now need only to point their weapons at the target in order to achieve a high probability of kill. Measures of merit or metrics are needed to quantify the short time scale capabilities that are now exploited during WVR all-aspect combat. A wide variety of measures have been proposed by pilots and researchers and are generally grouped under the catch-all of *agility metrics*. Agility metrics are intended to quantify and influence the way fighters maneuver in conventional flight while engaged in air-to-air combat. This quantifying is obtained through comparative advantage studies of the transient capabilities of similar and dissimilar aircraft engaged in air-to-air combat. The work in this paper was obtained from the simulation of a single aircraft in order to illustrate metric behavior and evaluation techniques. The promise of lethal point-and-shoot weapons has also prompted interest in controlled flight at angles of attack well beyond that for maximum lift. Poststall maneuvering in the low-speed, high angle-of-attack portion of the flight envelope, popularly referred to as *supermaneuverability*[2] is motivated by the same new weapons technology. While an agile airplane is also desirable in this flight regime, supermaneuverability is not addressed in this paper.

Published Agility Metrics

Although numerous papers[1,3–5] have discussed the need for new ways of measuring the characteristics of fighter agility, only a few authors have actually proposed new metrics that could be used to develop a quantitative measure of agility. A list and brief definition of each of the metrics that have been proposed in the open literature are presented below.

1) *Dynamic speed turn*[5]—Plot of P_s vs turn rate
2) *Pitch agility*[6]—The time to pitch to maximum load factor plus time to pitch from maximum to zero load factor
3) *Pitch agility criteria*[6]—Coefficient of pitching moment due to control surface deflection scaled with wing area, aerodynamic chord, and pitch axis inertia.
4) T^6_{90}—The time to roll to and capture a 90-deg bank angle change
5) *Torsional agility*[6]—Turn rate divided by T_{90}
6) *Axial agility*[6]—The difference between minimum and maximum P_s available at a given flight condition divided by the time to transition between the two levels
7) *Relative energy state*[7]—Ratio of aircraft velocity to corner speed after a 180-deg turn
8) *Combat cycle time*[7]—Time to complete a maximum acceleration turn and regain lost energy
9) *Pointing margin*[7]—Angle between the nose of an adversary and the line-of-sight when the friendly fighter is aligned with the line-of-sight
10) *Roll reversal agility parameter*[8]—Product of time required to reverse a turn and the cross-range displacement that occurs during the turn
11) *Agility potential*[9]—Thrust-to-weight ratio divided by wing loading

Because the pilots, engineers, and researchers now involved in agility have not yet reached a commonly accepted definition of the term, it is not surprising that the proposed agility met-

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rics deal with many different aspects of fighter capability. The various metrics proposed to measure agility deal in units of time, velocity, angular rate, distance, and combinations of time, rate, and distance. Some framework for organizing the metrics that have emerged from different points of view is now needed.

After collecting and reviewing the metrics available in the literature, it is apparent that they may be categorized in two ways. First, the new metrics can be grouped by time scale into classes referred to by some authors as *functional* and *transient*.[1,10] Second, the new metrics may be classified according to type of motion involved; i.e., translational (axial), longitudinal, and lateral. Each of these two schemes of metric classification are discussed below and the resulting framework is then presented in a matrix format.

Time-Scale Classification

Regardless of the motion variables involved or the units chosen to measure the result, all of the proposed new metrics that deal with actual aircraft maneuvers can be grouped into one of two time scales. Short time-scaled agility, on the order of 1–3 s, is frequently called transient agility.[1,6] The transient agility metrics are new ways to quantify the fighter's ability to generate controlled angular motion and to transition quickly between minimum and maximum levels of specific excess power.

A second group of time-dependent metrics called large amplitude metrics[1] or functional agility metrics[10] deals with a longer time scale of 10–20 s. This class seeks to quantify how well the fighter executes rapid changes in heading or rotations of the velocity vector. Emphasis is on energy lost during turns through large heading angles and the time required to recover kinetic energy after unloading to zero load factor. Many of these functional metrics involve maneuvers made up of a sequence of brief segments that could each be evaluated with a transient agility metric. For example, the combat cycle time metric consists of a maximum load factor level turn to some specified new heading angle, a pitch-down to zero load factor and acceleration to the original airspeed. The net effect of combining a sequence of maneuvers and flight segments into a single metric is that conventional aircraft performance, that is, thrust-to-weight ratio and sustained load factor or turn rate capability, dominates the metric. The transient agility characteristics have only a minor impact on the numerical value of the functional metrics.[10] In addition to measuring the aircraft capability, these long-term metrics also depend heavily on complex pilot inputs, which in turn are influenced by the pilot's skill and experience, the aircraft's flying qualities, and the effect of cockpit displays and cues.

A third group of metrics has appeared that are independent of time and so are neither transient nor large amplitude. They deal not with the aircraft characteristics demonstrated via flight test or simulation but with the agility potential that results from sizing and configuration choices. These agility potential metrics serve to highlight the (sometimes obvious) relationships between thrust, weights, inertias, control power, and agility. While they have the advantage of using data available early in the aircraft design cycle, they do not reflect the impact of cross axis nonlinearity or flight control system response characteristics.[9]

Motion Variable Classification: Lateral, Pitch, Axial

Agility metrics may also be classified according to the type of aircraft motion being studied, independent of time scale. Lateral metrics include those that deal primarily with rolling motion, especially rolling at high angles of attack. Longitudinal metrics involve only pitching motion and normal acceleration. Additionally, a number of metrics have been proposed to quantify the ability of the aircraft to transition between energy states or P_s levels. These are commonly referred to as axial metrics and involve only translational motion.

When these two approaches to agility metric classification are simultaneously applied, the result is a matrix, as seen in Fig. 1. With two exceptions, each metric can be uniquely placed within this classification matrix. The first exception, torsional agility, is deliberately formulated to mix pitching and rolling characteristics and is the ratio of turn-rate to the time to roll and capture a 90-deg bank angle change.[6] The second exception, agility potential, is the ratio of two conventional performance measures, thrust-to-weight ratio and wing loading.[9]

Metric Evaluation

The transient agility metrics shown in Fig. 1 better reflect the agility of the aircraft, and it is this set that is evaluated via high-fidelity, nonlinear simulation. This paper examines only the axial and pitch transient metrics; the lateral transient metrics are discussed in detail in other works.[11,12]

The flight simulation computer program used to evaluate the proposed agility metrics in this paper is the University of Kansas Flight Research Laboratory's version of Sim-II.[13] The Sim-II computer program is a high-fidelity nonreal-time, nonlinear 6-degree-of-freedom aircraft simulation. The particular version of Sim-II used in this analysis simulates an F-18 Hornet-type aircraft. It contains full flight control system, engine, and aerodynamic models. The flight control system model is representative of the type used on the F-18 and runs multirate with gain scheduling. All limiters and nonlinearities in the flight control system are present. The aerodynamic database contains nonlinear, steady aerodynamic data for up-and-away flight at angles of attack up to and including 70 deg. The aerodynamic database was obtained from wind-tunnel testing and is corrected to flight-test data. The engine model is nonlinear. User interface to Sim-II is through input and output files. The input files contain initial attitude and flight condition, and pilot commands in the form of longitudinal and lateral stick position, rudder, and throttle time histories. Output files consist of tabular time history data, which is plotted using standard plotting routines. Any special processing such as filtering or estimation is performed within the simulation itself, when possible.

The procedure used to evaluate the metrics in this paper was first to obtain a sequence of pilot commands by trial and error that provided the desired trajectories and responses. The simulation was rerun, the output was collected, postprocessed if necessary, and plotted as time histories. Provided careful attention is paid to pilot inputs and the resulting aircraft responses, non-real-time simulation using this technique is feasible without a real-time pilot-in-the-loop because the limiters embedded in the flight control system and control surfaces prevent overstressing and inhibit departure.

Simulation of agility metrics testing using an unmanned aircraft simulation is intended to be only a precursor to thorough testing and flying qualities evaluation using a manned aircraft simulator. The authors recognize that flying qualities are an important aspect of agility testing and are beyond the capability of the methods of this paper. The reader is directed to another work that addresses this particular aspect.[14]

	TRANSIENT (1 - 5 SECONDS)	FUNCTIONAL (> 5 SECONDS)	POTENTIAL
LATERAL	T_{90}	ROLL REVERSAL PARAMETER	LATERAL AGILITY CRITERIA
	TORSIONAL		
LONGITUDINAL	$T_{MAX\,G}$ T_{UNLOAD} LOAD FACTOR RATE	POINTING MARGIN	PITCH AGILITY CRITERIA
			AGILITY POTENTIAL
AXIAL	POWER ONSET POWER LOSS	COMBAT CYCLE TIME DYNAMIC SPEED TURN RELATIVE ENERGY STATE	

Fig. 1 Proposed classification framework.

Axial Agility

The axial agility metrics measure the rate of change of P_s. Instead of knowing only what level of P_s an aircraft possesses at a particular point, axial agility reflects how effectively the aircraft can *transition* to another P_s level. Both the magnitude of the P_s change involved in transitioning from minimum to maximum levels and the time required to make that transition are important. The aircraft with superior axial agility will be able to generate large positive and negative P_s quickly at a given flight condition. The axial agility metrics measure the combined effects of engine spool time, maximum thrust, and drag due to speed brakes. Thus, an aircraft having greater axial agility possesses superior velocity control (both acceleration and deceleration). For instance, a standard comparison using energy maneuverability methods on two dissimilar aircraft having different engine spool times might indicate that both possess nearly identical P_s levels at a particular flight condition. This comparison would indicate incorrectly that no clear advantages or disadvantages exist because the difference in engine spool times is transparent to the method.

Two parameters have been proposed to quantify axial agility. The first, the power onset parameter, is defined as the increment of specific excess power (ΔP_s) in going from a minimum power/maximum drag condition, to a maximum power/minimum drag condition, divided by Δt, the time in seconds required to complete the transition.[6] The aircraft begins the maneuver in level flight decelerating at flight idle power with speedbrake extended. At the test Mach number, the throttle is advanced to the maximum power setting while the speedbrake is simultaneously retracted. The resulting acceleration is maintained until the maximum net axial force (thrust minus drag) is attained for that flight condition.

The power loss parameter is the second metric. It is intended to measure the effectiveness and response times of the engine and drag producing devices of the aircraft, and is also defined as $\Delta P_s/\Delta t$, but here ΔP_s is the increment of specific excess power in going from a maximum power/minimum drag configuration to a minimum power/maximum drag configuration. Prior to the start of the maneuver, the aircraft is accelerating in level flight at maximum throttle setting with speedbrake retracted. The throttle is then reduced to flight idle while the speedbrake is simultaneously extended. Thrust reversers would also be deployed if the test aircraft were so equipped. The deceleration is maintained until the minimum net axial force (i.e., thrust minus drag) is attained for that flight condition. Testing can be easily extended to aircraft with thrust vectoring or thrust reversing nozzles. Pitching maneuvers that generate drag to decelerate the aircraft may also be viewed as axial agility. However, such maneuvers are not addressed here because pitch agility is studied in a later section.

Both the power onset parameter test and the power loss parameter test were simulated at sea level, 15,000 ft, and 30,000 ft and at Mach numbers from 0.4 to 0.9. The Mach numbers and altitudes were selected to be representative of the range of speeds at which aircraft would most likely be engaged in close air combat. The data reduction method used postprocessing of the time history tabular output. The equation used is

$$\frac{\Delta P_s}{\Delta t} = \frac{P_{sf} - P_{si}}{t_f - t_i} \tag{1}$$

Figure 2 displays the power onset parameter in curves of constant altitude for different Mach numbers. At lower altitudes, the generic F-18 possesses a greater acceleration capability. This is due to the larger difference between flight idle thrust and maximum thrust at these altitudes. As expected, the acceleration capability is proportional to the test Mach number for a given altitude.

The computation of the power loss parameter is completely analogous to that of the power onset parameter. The power loss parameter is plotted vs Mach number for curves of constant altitude in Fig. 3. The greatest deceleration capability is seen to be at lower altitudes, due again to the larger difference between flight idle thrust and maximum thrust. The deceleration capability is again proportional to Mach number for a given altitude. The axial agility parameters seem to be an important addition to the standard point performance methods for determining axial capabilities.

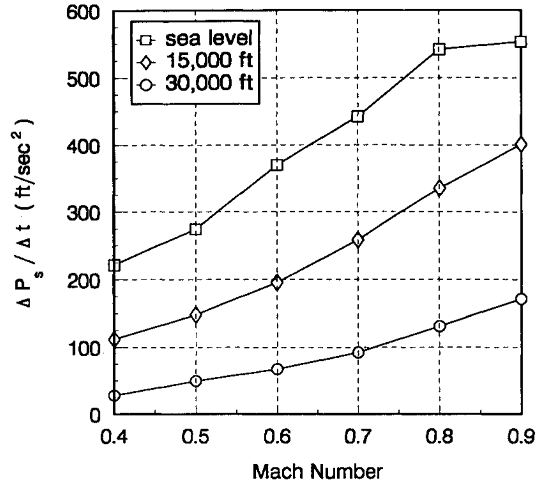

Fig. 2 Power onset parameter.

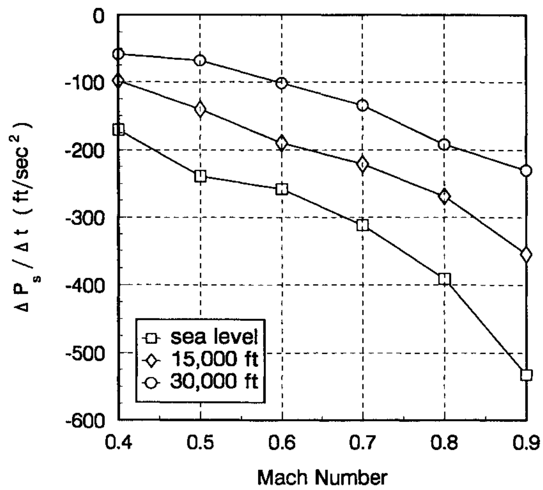

Fig. 3 Power loss parameter.

Pitch Agility

Pitch agility as originally postulated consists of "time required to pitch-up to maximum lift or to unload to 0 g or to rapidly change to any desired angle of attack."[6] Alternate ways of measuring pitch agility are: 1) the time to capture an angle of attack[10]; 2) the time to change pitch attitude[10]; 3) the time derivative of load factor[15]; 4) curvature agility[15]; and 5) maximum nose-up and nose-down pitch rates.[6] During subsequent discussion of pitch agility time to capture a specified angle of attack was generally rejected as a useful metric.[16] Its primary disadvantages are that time to capture angle of attack is not an appropriate quantity for comparison among dissimilar aircraft, and accurately capturing specified angles of attack during flight test is difficult. This metric also neglects the lift curve (lift vs angle of attack) characteristics of the aircraft, and is not studied further in this report.

Reference 10 reported flight test results of time to change pitch attitude. During that study, pitch angle changes of −45 to 45 deg and −30 to 30 deg were flown. Pilots and flight test engineers involved in that evaluation concluded that time to change pitch attitude was unsuitable as a pitch agility metric due to the large changes in airspeed and altitude that occurred during the maneuver.

The time derivative of load factor, although difficult to measure directly, can be extracted from flight test or simulation time histories. Because both pitch-up and pitch-down capability are tactically important, the rate of change of load factor during both types of maneuvers are investigated in this report. It has been shown that time histories of load factor derivative and the curvature agility metric are virtually identical when scaled to account for different units.[15]

Based on this discussion, three of the published metrics that quantify pitch agility are investigated here: 1) time to load to maximum load factor and to unload to zero load factor; 2) positive and negative load factor rate; and 3) pitch rates during maximum authority pitch-up and pitch-down maneuvers. All three measures of agility are extracted from the same simulation runs. At each flight condition investigated the aircraft was trimmed to straight and level flight. Step inputs of 5 in. (maximum aft deflection) were applied to the longitudinal stick and held for two seconds. Forward stick was then applied to pitch-down to zero load factor. In the following paragraphs each of the three published metrics is evaluated in both the nose-up and nose-down directions. Results are shown at three representative altitudes over a range of subsonic Mach numbers.

First, time to attain maximum load factor and time to unload from maximum load factor are plotted against Mach number for altitudes of 0, 15,000, and 40,000 ft in Figs. 4 and 5. These two figures show that pitch agility, as measured by the time to achieve maximum load factor and the time to unload from maximum load factor, is a strong function of Mach and altitude. At any altitude, the aircraft's normal acceleration due to angle of attack increases with Mach number so the resulting time to both load and unload is smaller, even in cases where the pitch rates at each Mach number are nearly the same.

The 15,000-ft line in Fig. 4 illustrates a shortcoming of the time to maximum load factor metric. Contrary to the indications from Fig. 4, the generic F-18 is not slower to achieve positive load factor at Mach 0.7 than it is at Mach 0.6. Load factor onset is actually faster at Mach 0.7 but the maximum peak load factor is higher, so the time to reach that peak is slightly longer. If the time to maximum load factor is used to compare the agility of dissimilar aircraft, or even the same aircraft at different flight conditions, misleading results could occur at flight conditions where the maximum load factors of the aircraft are different. For example, consider two dissimilar aircraft, one with a 5-*g* limit and the other with a 9-*g* capability at the same flight condition. If each were equally agile in terms of load factor rate, the first aircraft would have a smaller time to maximum load factor since the maximum is lower.

A comparison of Figs. 4 and 5 suggests that the generic F-18 is significantly more agile in nose-up than in nose-down pitching motion. At lower Mach numbers, the aircraft requires about twice as long to unload from maximum load factor as it does to pitch from straight and level flight to maximum load factor. An analysis indicated that all of several current fighter aircraft studied possess much less nose-down than nose-up pitch agility.[6] If pitch agility in both directions is important to an operational pilot, then nose-down authority; that is, the ability to recover from a high *g* to an unloaded flight condition, is a promising candidate for improvement.

The maximum positive load factor rate generated during pitch-up and the maximum negative load factor rate generated during an unloading maneuver are plotted against Mach and altitude in Figs. 6 and 7. Except for the lack of a peak at Mach 0.7 at 15,000 ft, these figures reflect the same dependence on Mach and altitude that was seen in the "time to load factor" results of the previous paragraph. The load factor rate data shown here were obtained from the simulation with a simple differencing scheme because load factor rate is not directly available either as a term in the dynamic model of the aircraft or as an output of a modelled sensor. A similar approach would be needed to obtain this data from a flight test maneuver. In the simulation with no random atmospheric inputs, buffet, or sensor noises applied, the differencing algorithm produced usable load factor rate data. Application of a differencing scheme to obtain load factor rate information from flight test would require extensive smoothing and might not produce acceptable results. The maximum nose-up pitch rate generated when pitching to maximum load factor and the

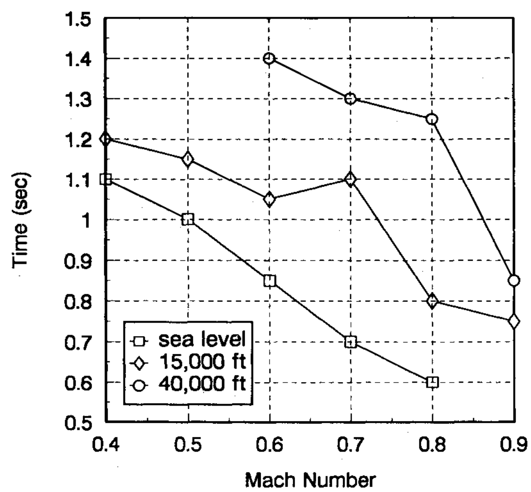

Fig. 4 Time to pitch to maximum load factor.

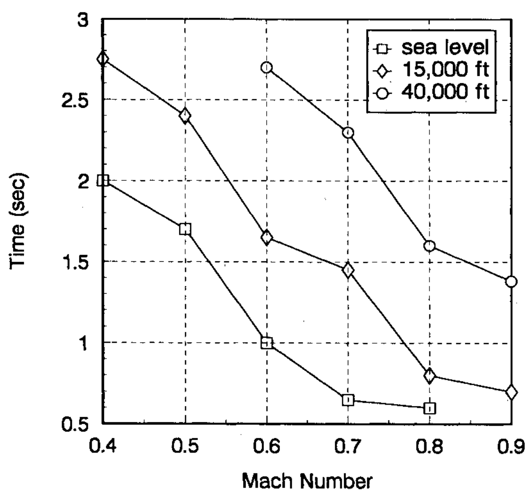

Fig. 5 Time to pitch from maximum load factor to 0 *g*.

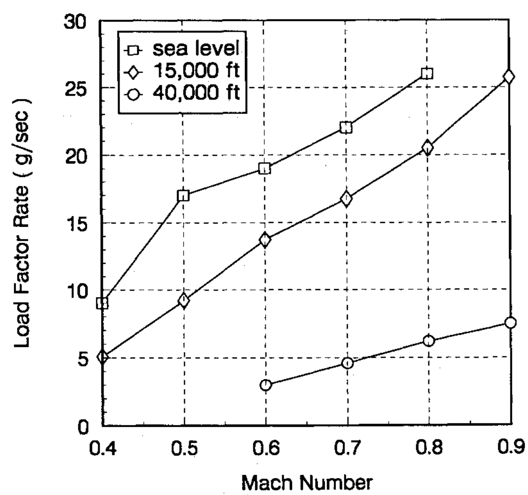

Fig. 6 Maximum positive load factor rate.

maximum nose-down pitch rate encountered while pitching down from maximum to zero load factor are plotted against Mach and altitude in Figs. 8 and 9. The effects of limiters in the flight control system are evident in these figures. Figure 8 shows that at sea level and at 15,000 ft, pitch rate is reduced above Mach 0.6 to prevent the aircraft from exceeding its limit load factor. At 40,000 ft the aircraft is restricted by available lift to less than its structural limit so no flight control limiting is needed. High positive and negative pitch capability is available throughout the subsonic Mach range at this altitude.

At many flight conditions, maximum load factor cannot be held during the two second input step. In these cases, aircraft deceleration causes load factor to decrease immediately after the peak is achieved and before the pitch-down command is initiated. Time to pitch-down as shown here is calculated from the time forward stick is input, not from the time that load factor begins to decay due to airspeed loss. This method minimizes the influence of aircraft drag characteristics on pitch agility measurements and emphasizes nose-down pitch authority.

In light of the shortcomings of the time to achieve load factor and the load factor rate metrics, maximum positive and negative pitch rate seem to be the most useful measures of longitudinal transient agility. Although maximum positive and negative pitch rates neglect the lift curve slope and only indirectly measure the aircraft's ability to generate normal accelerations, they are still the most useful pitch agility metrics. This is because pitch rate is a direct measure of the pilot's ability to rotate the nose of the aircraft, a significant capability particularly during WVR engagements.

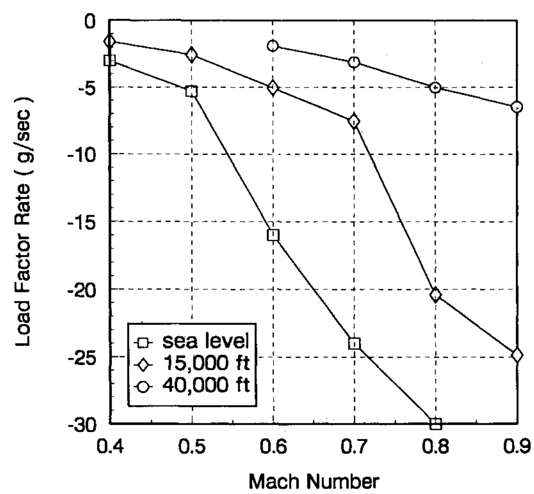

Fig. 7 Maximum negative load factor rate.

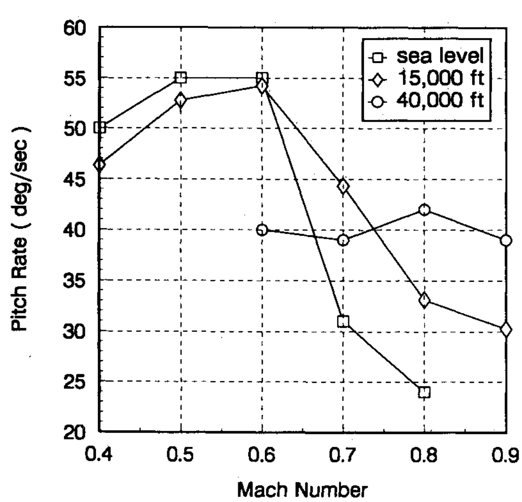

Fig. 8 Maximum nose-up pitch rate from steady level flight.

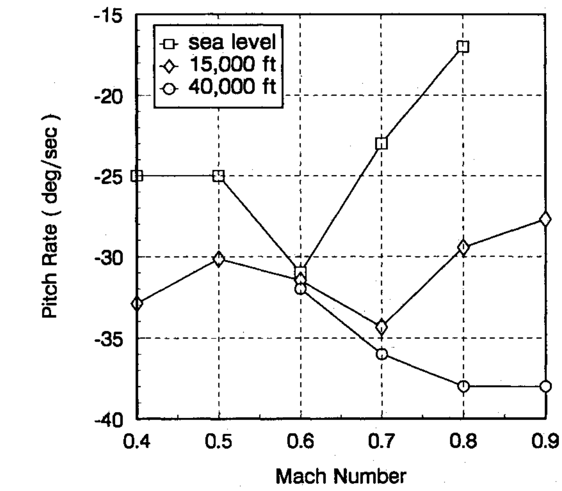

Fig. 9 Maximum nose-down pitch rate from steady level flight.

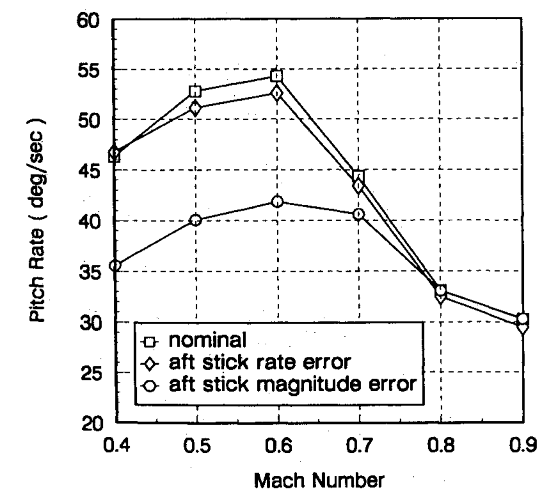

Fig. 10 Nose-up rate error sensitivity for 15,000 ft.

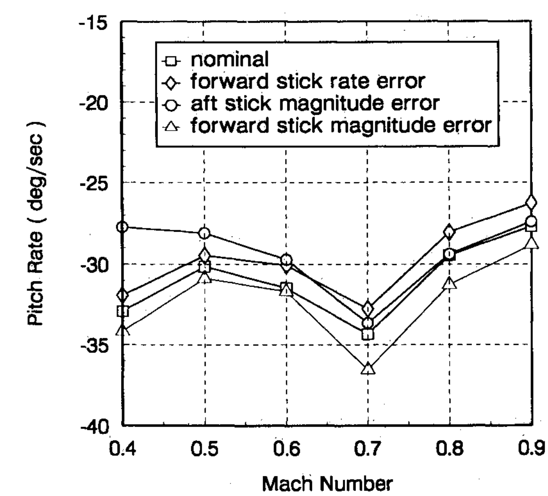

Fig. 11 Nose-down pitch rate error sensitivity for 15,000 ft.

Sensitivity of Pitch Agility Metrics

A key issue in the flight testing of agility is the accuracy required of the pilot in following cueing directions in order to produce useful data. The pitch agility metrics could be subject to errors from pilot inputs which deviate from the cues because: 1) aft stick input rate is incorrect; 2) aft stick input is less than full deflection; 3) forward stick input rate is incorrect; and 4) forward stick input magnitude is incorrect.

To determine sensitivities, each of these errors was imposed, one at a time, on the pitch agility metrics described in the section above. The tested deviations from the nominal steering commands are a 20% reduced aft stick rate; a 20% reduced aft stick deflection; a 20% reduced forward stick rate; and a 20% increased forward stick deflection. Forward stick rate was increased rather than reduced because a 20% reduction failed to achieve the zero load factor as required by the metric definitions. Only the first two errors, aft stick rate and aft stick deflection, have a noticeable impact on the pitch-up portions of the metrics. Changes in the forward stick command rates or magnitudes have no effect on the time to maximum load factor, positive load factor rate, or positive pitch rate because they occur after the pitch-up portion of the maneuver. Similarly, only the last three errors have an effect on the pitch-down portions of the metrics. The rate at which the initial nose up command is applied does not affect the pitch-down metrics. The size of the initial aft stick deflection, however, affects the attitude from which the pitch-down is initiated. Deviations in the forward stick commands clearly have an impact on the nose-down parts of the metrics.

Figure 10 shows that slower aft stick rate has little effect on the maximum pitch rate encountered during a pitch-up. However, when the maximum stick deflection (5 in.) is reduced to only 4 in., maximum pitch rate is significantly reduced at the lower Mach numbers.

The effects of changes in forward stick rate and forward and aft stick magnitudes is shown in Fig. 11. Commanding more than the nominal forward stick deflection causes slightly higher nose-down rates, while applying the stick at a slower rate reduces the resulting pitch-down magnitude. In no case, however, are the changes either large or unpredictable.

Summary and Conclusions

Fighter agility has been defined in this paper to encompass transient capabilities within the conventional flight envelope that are not emphasized in the standard approaches to fighter performance and maneuverability. Functional metrics that consist of longer term flight segments connected by periods of linear acceleration or nearly constant rate turns do not focus on transient agility, and do not provide any insight that could not otherwise be obtained with standard analysis methods. Based on the results of this work, the following conclusions were drawn:

1) Classification by time scale and axis is a useful method for studying agility metrics.

2) The power onset parameter and the power loss parameter seem to be useful candidate metrics for quantifying axial capabilities and lend themselves well to flight test.

3) Load factor rate appears to be a useful candidate pitch agility metric although extraction of useable data from flight test may require unique data reduction methods.

4) Maximum nose-up and nose-down pitch rates seem to be the most promising candidate pitch agility metrics because they apply to dissimilar aircraft comparisons, are easy for pilots to flight test, and are measureable with existing flight test instrumentation.

5) All of the candidate pitch agility metrics investigated in this paper are largely insensitive to deviations from pilot cues caused by incorrect pilot input commands.

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