F-14A High-Angle-of-Attack Characteristics

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The F-14 has demonstrated that fighter aircraft can be designed to have no lift curve break or angle-of-attack limitation. The maneuver flight envelope, therefore, has been expanded beyond what had traditionally been considered possible. The value of this high alpha capability in the dogfight arena has been convincingly demonstrated in flight. The importance of slats and an ARI system for enhancing this capability has also been demonstrated. The development from concept through flight test of this high alpha capability is presented by candidly reviewing the design philosophy, the background that dictated it, and the results of experimental and analytical studies.

Nomenclature

Æ	= aspect ratio
g	= acceleration due to gravity
L/D	= lift-to-drag ratio
M	= Mach number
RN	= Reynolds number
T/W	= thrust-to-weight ratio
W/S	= wing loading
$Y/b/2$	= semispan fraction
α	= angle of attack
β	= sideslip angle
Λ	= leading-edge wing sweep
C_{D_X}	= cross flow drag coefficient
C_L	= lift coefficient
C_{ℓ_β}	= static lateral stability derivative
C_m	= pitching moment coefficient
C_{n_β}	= static directional stability derivative
$C_{\ell_{\delta_a}}$	= rolling moment due to lateral control deflection derivative
I_x, I_z	= moment of inertia about x and z body axis, respectively
i_S	= stabilizer incidence

Introduction

THE F-14 supersonic, air superiority fighter was designed to U.S. Navy specifications as a long-range, carrier-suitable aircraft versatile enough to meet fighter escort, combat air patrol, and both subsonic and supersonic intercept mission requirements. The wide-spaced twin nacelle, variable sweep configuration selected fulfilled the mission requirements and permitted a conformal palletized armament system.

This paper presents the high angle-of-attack characteristics of the basic F-14 by tracing its development from concept through flight test. This is accomplished by *candidly* reviewing the design philosophy, the background that dictated it, and the results of experimental and analytical studies. In addition, the correlation obtained between some calculated, wind tunnel, and full-scale results are reviewed as well as pilot-developed air combat maneuvering (ACM) techniques for capitalizing on high α agility. Also, the introduction of an automatic flap/slat/glove vane and aileron/rudder interconnect (ARI) system on future production aircraft to further enhance high α maneuvering capability is discussed.

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Selection of Basic Configuration

Since the ability to fly at high α is dependent on the aerodynamic configuration selected, a quick review of what dictated the F-14 configuration is in order. The configuration selected and submitted[1] to meet the VFX mission requirements employed a variable wing sweep. Variable sweep was chosen since it permitted a significant degree of flexibility in designing for conflicting requirements, and, thereby, substantially reduced the inevitable compromises associated with meeting different mission requirements. The requirements were: 1) take-off and land on a carrier deck; 2) escort attack aircraft to target areas at subsonic speeds; 3) defend the carrier against enemy attack (i.e., extended loiter time on Combat Air Patrol), an overload mission; 4) intercept enemy aircraft at high supersonic speed; 5) provide maximum fighter capability on minimum carrier space; and 6) dogfight at transonic and subsonic speeds. Obviously, requirements 1-3 are best accomplished with an unswept, large span wing having a thick airfoil. On the other hand, requirements 4 and 5 are best served with a highly swept, short span wing having a thin airfoil section. Requirement 6 calls for everything in between. That is, the wing should be continuously unsweeping from 68 to 22 deg as the speed decreases.

Although the advantages of variable Λ in meeting requirements 1-5 were well-known and not seriously questioned by anyone in the aerospace industry by late 1968, the advantages in meeting requirement 6 were not fully appreciated. Since then, it has been shown that the key to effective use of variable Λ in combat is a Mach-Sweep Programmer which automatically selectes the optimum Λ for the airspeed of the moment and protects against any wing structural overload condition during pull-up maneuvers. In this manner, maximum turning performance is assured with safety and without pilot distraction.

Also, the fact that the configuration selected to meet the above requirements would permit unrestricted α flight in the subsonic-transonic speed regime was even less widely recognized, nor was the need for this capability clearly demonstrated. However, Langley Research Center (LRC) wind tunnel data existed for a TFX variable Λ configuration which indicated such superior high α characteristics. It was shown that lift could be generated up to $\alpha = 30$ deg with no lift curve break. These results demonstrated that the potential and vortex lift contributed by the moveable wing panel and a highly swept, low Æ body, respectively, could be combined to generate a desirable lift curve. A high level of lift could be produced, therefore, with no autorotative rolling moments generated beyond maximum lift. The selected F-14 configuration was also expected to exhibit the same characteristics, since these attributes are a function of maintaining the proper relationship (in area and relative location) between high and low Æ lifting surfaces.

It was known, also, that the configuration would have a stable pitching moment curve throughout the $\alpha = 0$–90 deg range. In addition, the aerodynamic characteristics responsible for producing departures and consequently spins had been identified under studies[2,3] sponsored in 1966 by the Naval Air Systems Command (NASC). In spite of this knowledge and the observation that pilots rapidly exploit a new capability in an optimum fashion, a formal commitment to exploit the inherent high α capability of the F-14 configuration was not forthcoming during the early stages of the program.

Early High Alpha Efforts

Background

Grumman was to conduct the classical full-scale spin demonstration program to determine the "spin message," which informs the pilot of the type of spins to be encountered and the recommended spin recovery procedure. The gist of these messages is that the spinning motion is violent and disorienting and, therefore, spins should not be entered intentionally. Since spin demonstration programs are expensive, dangerous, and are usually terminated because the test aircraft is lost, the wisdom of pursuing this effort, from a cost effectiveness point of view, was raised on two grounds. First, spins are indeed encountered inadvertently since they serve no useful flight function. When encountered, it will be for the first time, unanticipated, and under physical stress. The expectancy is high, therefore, that the aircraft and often the pilot will be lost if a spin is entered during combat, or below 15,000 ft at any other time—regardless of the spin recovery characteristics. Second, the reputation and combat effectiveness of an aircraft really depends on its "honesty" at its maximum maneuvering boundaries and not on the existence of a spin recovery procedure from a fully developed spin which, incidentally, can be specified during the preliminary design phase on the basis of the mass distribution and the type of aerodynamic controls available.

Consequently, a presentation was made to NASC in early 1970 entitled "Spins—A new Approach to an Old Problem." Besides reviewing the state-of-the-art, possible solutions, and the level of risk involved, it stated that the objective of the F-14 design philosophy are that the aircraft possess good handling quantities [stability augmentation system (SAS)off] up to and beyond maximum lift and be spin resistant or spin proof. These objectives were to be met without interfering with the longitudinal control authority so that the aircraft could be statically trimmed at an α of 38 deg and overshoot to an α of approximately 65 deg during an accelerated maneuver. Since meeting these objectives would have the greatest "payoff" relative to the usage of the aircraft, it was recommended that the objective of the classical spin effort be officially reoriented to demonstrate that the aircraft did not depart and enter a spin.

Initial Predictions

By April 1970, tests conducted with a 1/16-scale model in the Ames Research Center (ARC) 12-ft pressure tunnel up to 90 deg α and over a β range of 30 deg at a RN of 6.6×10^6/ft, showed the F-14 configuration at Λs of 22, 35, and 50 deg to have the desirable lift and pitching moment characteristics discussed in the previous section. In fact, a 40% increase in lift was experienced in going from 16 to 25 deg α as a result of the body-glove vortex flow lift.

These data were also examined to determine if the configuration was susceptible to departure from controlled flight at high αs. This was accomplished by reviewing the test data in light of the information presented in Refs. 2 and 3. These references had indicated that the two most important aerodynamic parameters involved in the spin phenomenon were the yawing moment characteristics associated with the lateral control and the effective dihedral. A negative value (adverse yaw) for the $C_{n_{\delta a}}/C_{\ell_{\delta a}}$ ratio, or a low negative value of C_{ℓ_β} very effectively promoted spins.

The ARC data showed that a negative value of $C_{n_{\delta a}}/C_{\ell_{\delta a}}$ was realized above 20 deg α; reaching a maximum negative value at an α of 55 deg. An ever-increasing value of effective dihedral was obtained up to an α of 16 deg such that the desired high level was realized. A reduction in this parameter between 16 and 30 deg α, however, was greater than was desired. Also C_{n_β} was shown to be maintained to an α of 16 deg. These data indicated, therefore, that the aircraft was susceptible to departure if the lateral control was employed in the 30 deg α region. It was also noted during the ARC tests that around an α of 55 deg large values of yawing moment could be measured at $\beta = 0$ deg; the sign of which could vary during a repeat test. This observed phenomenon on other aircraft models had been attributed by some researchers to asymmetric vortices being shed from the nose. For various reasons, it was felt that in this instance the measurement was peculiar to the testing technique and, therefore, not indicative of the "real world."

It was predicted in July 1970, based on LRC 20-ft free spinning facility tests, that only one spin mode existed for all Λs. Unfortunately, this spin was fast, flat, and unrecoverable. Of course, the prediction of full-scale spin modes and especially the acceptability of the associated recovery characteristics requires a considerable amount of agonizing interpretation of the experimental results by applying various criteria which attempt to correlate past spin tunnel predictions with observed full-scale results. Also, this facility cannot predict if the fully developed spins observed in the tunnel can be attained in flight through some usage of the available flight controls. There is always a need, therefore, for employing other techniques, both experimental and analytical, to verify the spin tunnel predictions and to gather additional information. Radio-controlled free-flight drop models have been one experimental technique used in recent years to explore the departure, incipient spin, and developed spin characteristics.

In light of the unpleasant spin tunnel predictions, NASA was requested by the Navy to expedite the preparation and testing of such a model and Grumman initiated an analytical spin study with the reservation discussed in the next paragraph. The conventional analytical technique used in this study involved the simultaneous solution of the equations of motion and associated formula in which the aerodynamics were represented by static forces and moments and dynamic derivatives. In this instance, the aerodynamic model was based on the data obtained in the ARC 12-ft pressure tunnel. It was shown during this study that the aircraft could be flown into a flat spin whose rate of rotation was approximately one-half of the predicted spin tunnel value.

It was noted during the analytical study, as discussed in Refs. 4 and 5, that the analytical technique conventionally used does not include the aerodynamic moments acting on a spinning airplane due to steady rotational flow nor does it limit the contribution of the rotary derivatives to the oscillatory component of the total angular rates. Since fighter aircraft spin about a vertical axis which is near the center-of-gravity location, β actually varies along the length of the aircraft, and is of opposite sign forward and aft of the axis of rotation. This condition would indicate that the aerodynamic moments generated in a spin due to rotational flow would indeed be significant. It was thought, therefore, that the aerodynamic and mathematical model used in the analytical spin studies were improper and, consequently, could not be expected to predict the developed spin. (This belief has recently been verified[6] to a large extent.) However, it was also felt that the calculated incipient spin, which is mainly a function of static aerodynamic forces and moments, would be

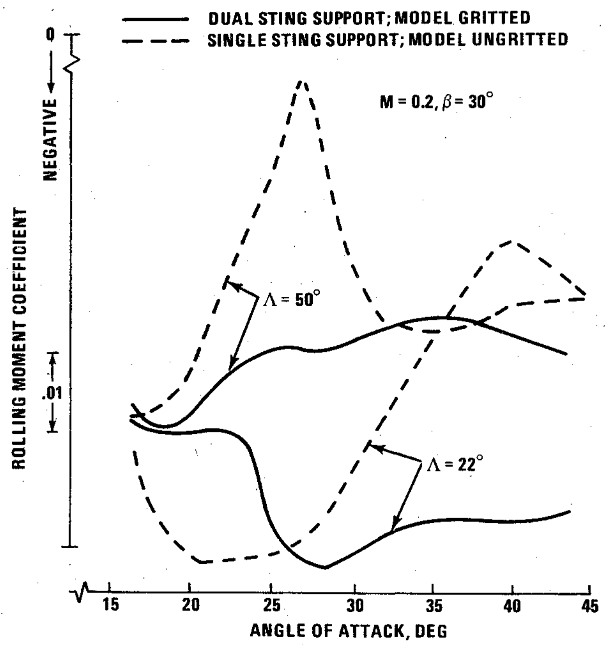

Fig. 1 Lateral data obtained for different model setups.

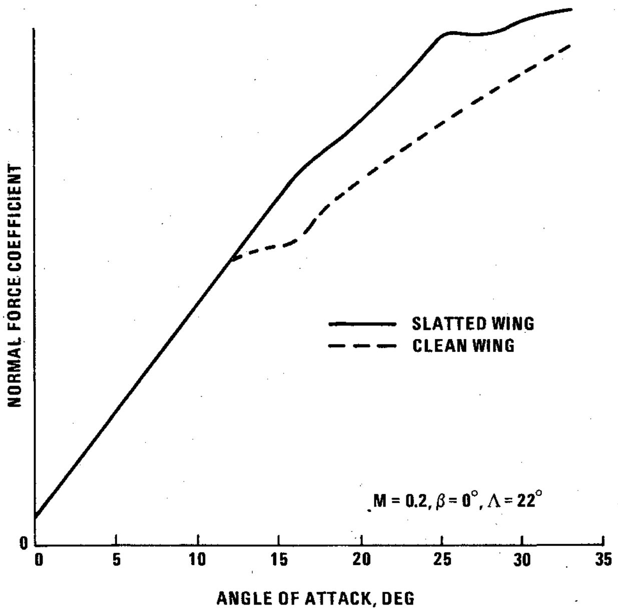

Fig. 2 Effect of slat on normal force characteristic.

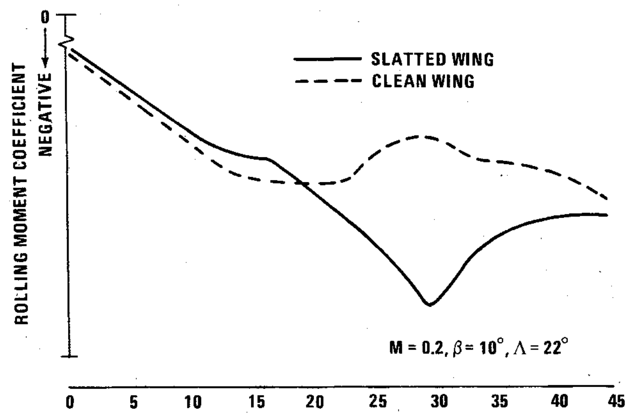

Fig. 3 Effect of slat on rolling moment characteristic.

representative of full-scale results. On this basis, it was concluded that a flat spin could be attained and that the severe spin predicted by the spin tunnel could not be proven incorrect. It was also believed that the spin tunnel testing technique and criteria employed to predict no recoveries were in this instance unduly severe. This belief, however, would have to be substantiated through radio-control model tests.

Confronted with these predictions and the fact that many fighter aircraft had been lost due to uncontrollable departures and ensuing spins, it is not surprising that some individuals strongly advocated the use of a stick pusher or an automatic maneuvering boundary limiter system. Fortunately, these recommendations were discarded and the attitude prevailed that the inherent high α capability be exploited, not suppressed. The spin predictions did act as an effective catalyst for implementing the new approach presented to the Navy earlier in the year. Consequently, a spin avoidance/prevention program was submitted to the NASC in September of 1970 which was approved by November.

Spin Avoidance/Prevention Program

This program included a wind tunnel and analytical investigation and flight demonstration. The purpose of the wind tunnel investigation was to: completely establish the F-14 lateral-directional characteristics and the phenomenon responsible for these characteristics; and investigate aerodynamic methods for improving the handling qualities at high lift coefficients using fixed and variable geometry devices.

The purpose of the analytical investigation was to demonstrate: the susceptibility of the aircraft to enter a spin, and the influence that possible variations in mass, inertia, and aerodynamic characteristics, as well as lateral-directional control authorities, control rates, SAS inputs, and control manipulations might have on this susceptibility. It was also to demonstrate the lateral-directional control techniques for avoiding and/or preventing spins. Some of the conclusions and observations gained from these investigations[7] are presented next.

Wind Tunnel Investigation

In March 1971 tests were conducted up to 45 deg α in the ARC 12-ft pressure tunnel. The first test was performed with an ungritted model mounted on a single-sting support in order to repeat the setup used during the April 1970 tests. The single-sting support had required the fuselage contour to be modified from the back of the model to an appreciable distance forward of the root leading edge of the vertical tails. Grit was then applied to the body and lifting surfaces for the next test and mounted on a dual-sting support which entered the model through each of the exhaust nozzles without affecting the external lines. This change in testing technique was found to influence the lateral-directional characteristics. For instance, the drop in lateral stability previously observed between 16 and 30 deg α was considerably minimized, as shown in Fig. 1. The airplane was obviously better than early tests had indicated.

The next test examined the effect of the leading-edge slats that are presently a part of the power approach configuration. It was found that deflecting the slats resulted in the following: 1) a 20% increase in normal force at 25 deg α (see Fig. 2); 2) A 90% increase in the α range over which $-C_{\ell_\beta}$ is increasing with increasing α. Consequently, a 100% increase in the maximum level of $-C_{\ell_\beta}$ is attained at an α of 30 deg (see Fig. 3); and 3) a 45% increase in the α range over which C_{n_β} is maintained (see Fig. 4).

As shown in Fig. 5, the consequence of 2 and 3 was a 100% gain in the α range over which the $C_{n_{\beta}}$ dynamic parameter is increasing in a positive direction with increasing α, which is thought to be indicative of a departure resistant airframe by some investigators. In general, the beneficial effects obtained

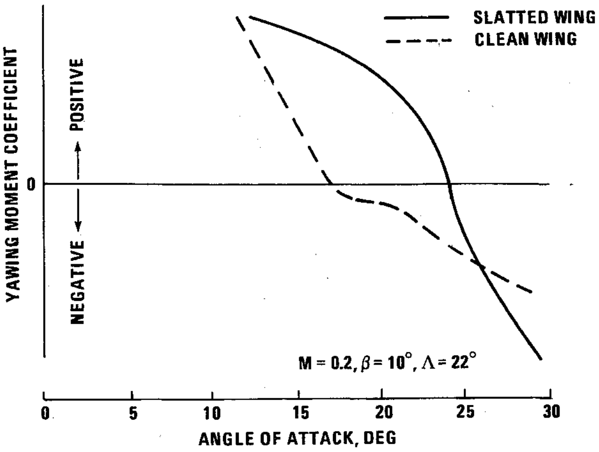

Fig. 4 Effect of slat on yawing moment characteristic.

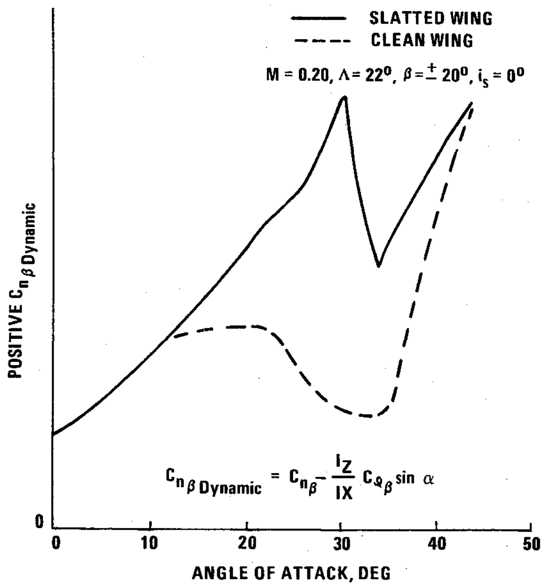

Fig. 5 Effect of slat on $C_{n\beta_{\text{Dynamic}}}$.

for the 22 deg Λ were evident at the higher Λs, but, as would be expected, the influence and importance of the slat decreases with increasing Λ although still effective at a 50 deg Λ position. The use of a five-component balance precluded an examination of the beneficial effects on drag; nor was the effect on buffet onset explored. The beneficial slat effects demonstrated during this program triggered additional slat investigations, as discussed later under development of ACM control systems.

The benefical effect of the slat on directional stability was not anticipated nor understood. The initial thought was that the vortex off the inboard edge of the slat was responsible. This belief was immediately found to be in error, since no change in slat influence was detected when the in-board section of the slat was extended up to and under the glove area. To establish the flow mechanism responsible for the static directional stability characteristics, additional force tests were conducted in the LRC 12-ft and Grumman 7 × 10-ft low speed tunnels in June and July of 1971, respectively. During the Grumman tests, the twin vertical tails were also instrumented, relocated, and tested individually, and tuft screens were installed behind the model and on the model in the area of the vertical tails for flow visualization studies.

Since the LRC 12-ft tunnel is a very low *RN* (0.34×10^6/ft) facility, a comparison was made between directional data measured in this facility and the high *RN* (6.6×10^6/ft) ARC 12-ft facility. The correlation between the data was extraordinarily good considering the widely different types of tunnels, balances, measurement techniques, and models employed. As would be expected, however, *RN* was important when the high lift configuration was tested. It was found that with the slat deflected, good correlation was obtained below an α of 15 deg. Above this α the low *RN* data were effectively worthless. It was thought, therefore, that the slats delayed flow separation over the moveable wing panel to a higher α when tested at high *RN* and this attached flow apparently influenced the flow in the area of the vertical tails. To substantiate this belief, the geometrically scaled slat was replaced with a slat having an exaggerated large nose radius to insure attached flow to a higher α. With this modification, directional stability was also maintained at this very low *RN* up to and beyond 30 deg α. (This point will be discussed again later.)

It was also discovered during these tests that the directional stability was a function of stabilizer deflection. Deflecting the stick forward of neutral significantly increased the stability, whereas the reverse was the case when the stick was deflected aft.

The tests at Grumman conclusively established that any change in measured yawing moment above 16 deg α is due to an increasing loss in vertical tail effectivenss because of adverse sidewash and a reduction in dynamic pressure. This was established to be the result of a vortex emanating from the windward inlet which, for $\beta \leqq 20$ deg, is located in the region of the windward vertical tail. The location of this vortex is influenced by the pressure fields generated by the adjacent vertical tail, the stabilizer, and the moveable wing panel. The windward moveable wing panel sucks the vortex outboard and downward relative to the windward vertical tail, whereas a downward load on the leeward stabilizer panel sucks this vortex inboard and onto the windward vertical tail. The favorable influence of the windward wing is the dominent effect when the moveable wing panel is lifting. Consequently, directional stability can be maintained to a high α by deflecting the slat regardless of stabilizer setting.

To verify that the path of the vortex as a function of α and β had been identified, a more favorable tail location was selected with regard to directional stability. The existing vertical tails were displaced laterally, out to the edge of the fuselage, and then canted outboard 25 deg. This vertical tail configuration, which is possible on a wide-bodied fuselage, was shown to have directional stability at 32 deg α. However, since the unslatted aircraft was found to be relatively departure free (as discussed later) and activating the available high lift slats improved not only the directional stability but all of the aerodynamic characteristics, repositioning the vertical tails was not considered for the production aircraft.

In August 1971, predictions from testing a 1/10-scaled dynamically ballasted free-flight model at low *RN*($\approx 0.6 \times 10^6$/ft) in the LRC 30 × 60-ft tunnel were obtained.[8] It should be noted that this facility, as well as the free-spinning facility, must interpret its tests to predict full-scale characteristics because of testing technique limitations and the possible influence of *RN*. The fact that this facility has correctly predicted the flying qualities of many aircraft, as has the free-spinning facility relative to spins, is attributed to the experience, the astute observations, and intuitive reasoning of the investigators. However, in this instance the superb flying qualities to be realized with the clean wing were not completely appreciated, nor could the improvement due to slats be demonstrated. The latter was probably due to the fact that the lateral-directional characteristics were affected by the moveable wing panel flow which, as mentioned previously, was found to be critically dependent on *RN*. This phenomenon, in particular the effect on directional stability, had never been observed in the past. At present, free-flight models are first force tested in the 30 × 60 ft tunnel at the free-flight *RN*. In the future high *RN* data should also be obtained and compared with these data. If significant differences are detected, geometric modifications should then be developed on the free-flight model which produce the high RN characteristics at low RN.

In November 1971 an LRC uninstrumented radio control model verified that by using the differential tail the flat spin predicted by the spin tunnel could be obtained. However, recoveries were always realized when conventional recovery procedures were employed.

Analytical Investigation

The analytical portion of the spin avoidance/prevention program provided the following information relative to all Λs: 1) The existing F-14 configuration would not diverge due to external disturbances throughout the α range. 2) Snap roll departures could be experienced if the differential tail was fully engaged by the pilot or roll SAS above 20 deg α during an accelerated maneuver. 3) To avoid a control induced departure and, thereby, permit an expansion of the offensive maneuvering envelope beyond what had been traditionally considered possible, a spin avoidance system was recommended which would null the lateral stick input via the roll SAS and mechanize the lateral stick to engage the rudder rather than the differential horizontal tail (i.e., ARI system) above 20 deg α. 4) Since the leading edge slats had an appreciable beneficial effect on all of the aerodynamic characteristics, it was strongly recommended that the existing slats be activated at high lift coefficients. The gist of these observations was presented at the Air Force Flight Dynamics Laboratory (AFFDL) spin symposium held in December 1971.[5]

Initial Flight Demonstrations

In October 1972, an instrumented LRC radio control drop model demonstrated that no combination of control inputs or maneuvers could induce departures or spins if the differential tail was neutralized above an α of 20 deg. Also, no yawing moments at $\beta=0$ deg were experienced throughout the α range. These results were immediately verified on the full-scale test aircraft. Consequently, pilots were instructed to turn off the roll SAS before engaging in air combat maneuvers, and to use restraint when employing the roll control above an α of 20 deg. This procedure, of course, puts the burden on the pilot to avoid a control induced departure with the present production configuration.

Development of ACM Control Systems

Maneuver Slat Program

As shown in Fig. 6, the present production configuration employs a trailing edge flap and a wing glove vane to allow the aircraft to maintain a higher g level. The original function of the vane was to reduce the supersonic static margin, but it also reduces the required horizontal tail download and trim drag associated with extension of the maneuvering flap at transonic and subsonic speeds.

As mentioned previously, the beneficial slat effects demonstrated at $M=0.2$ for $\Lambda \leq 50$ deg in March 1971 triggered additional slat investigations. Consequently, in December of 1971, the clean (unslatted) wing and a 8.5 deg slat deflection were investigated at a RN of 3.0×10^6/ft up to 28 deg α through the transonic Mach/sweep range on a 1/16-scale model installed in the Cornell Aeronautical Laboratory (CAL) 8-ft tunnel. The beneficial slat effects were shown to exist up to and beyond $M=0.8$. In addition, drag was reduced and an improvement in C_L for buffet onset was obtained. Additional tests were therefore performed in this facility in July of 1972 for different slat deflections as part of a slat optimization study[9] which included flight tests to determine: 1) the effects of maneuver slats, maneuver flaps (10 deg only) and glove vane on aircraft combat maneuverability; 2) the optimum maneuver slat deflection for future production and retrofit considering the aerodynamic benefits and impact on

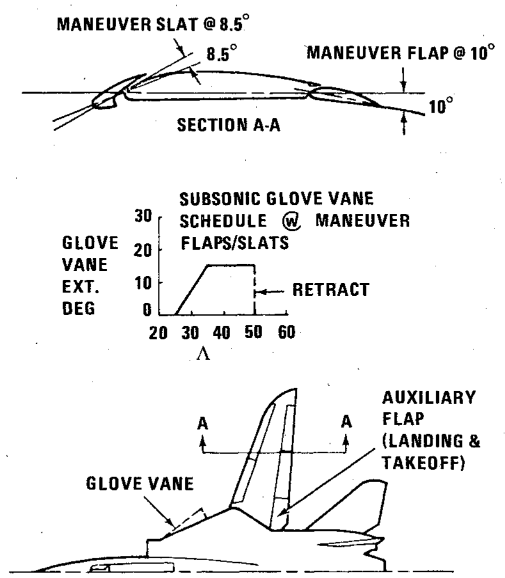

Fig. 6 Maneuver flaps/slats/glove vane.

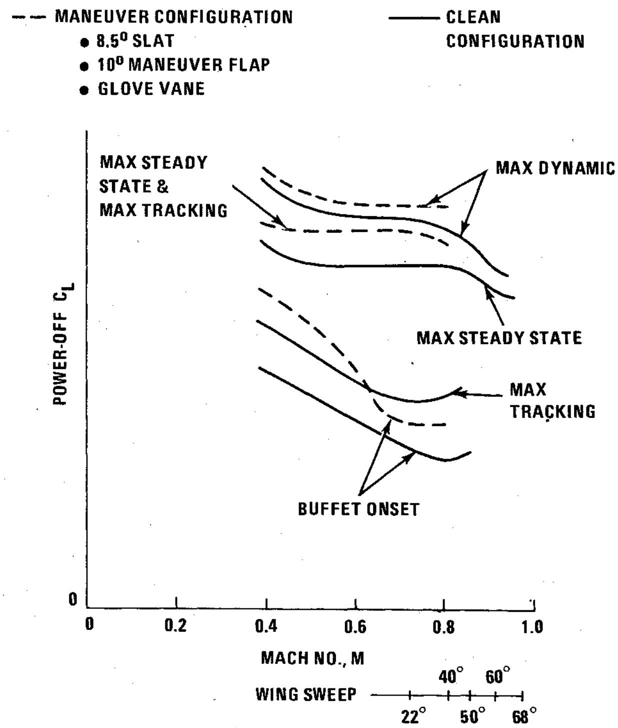

Fig. 7 F-14 aerodynamic envelope for clean and slatted wing configuration.

aircraft structure and mechanical systems; and 3) an expanded but realistic Mach/altitude envelope for deployment of maneuver devices (slat + flap + vane).

The study showed that deflecting the slats 8.5 deg (one-half maximum deflection) in conjunction with the flaps and glove vane substantially enhances the F-14 combat effectiveness by providing marked improvements in instantaneous and sustained maneuvering load factor, tracking capability, and flying qualities. This is the case since the slat: significantly increases lift and decreases drag at high C_L, improves the level of lateral and directional stability at high αs, significantly increases C_L for buffet onset, and appreciably reduces buffet intensity buildup.

The importance of the latter two effects is indicated in Fig. 7. As shown, the maximum tracking C_L established in flight (using gun camera records) for the unslatted aircraft occurred well below the maximum steady-state C_L. With the slat, however, the pilot could track up to the maximum steady-state C_L boundary.

The study also showed that slat effectiveness at high α increases with increasing deflection, especially at lower M's. For instance, the C_L for buffet onset is further increased in going from an 8.5 deg. to 11.5 deg slat deflection. Above this deflection, however, buffet intensity buildup increases. Although the 11.5 deg slat was aerodynamically optimal, the 8.5 deg deflection was chosen since most of the slat effectiveness could be realized at his deflection with no associated mechanical or structural penalty.

ARI Program

A study[10] performed on the LRC dynamic maneuvering simulator in July 1973 verified the conclusions of the analytical study[7] previously discussed as part of spin avoidance/prevention. The LRC study, of course, was more sophisticated in that it included a pilot in the control loop flying, on a fixed base simulator, several tracking and ACM tasks against an adversary using the present F-14 clean (unslatted) wing configuration. During this simulator study several control departure and spin prevention systems were also evaluated. It was concluded that an ARI system greatly improved the tactical effectivenss as well as the safety of the airplane at high α. Also, of all the departure systems studied it was found to be the most desirable. In October 1973, a flight test program was initiated to select system gains and threshold values for the ARI system. Then, with the selected values, it was demonstrated that the clean wing F-14 would not depart for all possible control inputs, external store configurations, center-of-gravity locations, and mass distributions.

Since snap-roll departures can still be generated with the slatted wing, both the ARI and maneuvering control (slat + flap + vane) system will be employed in the future to further enhance the F-14 ACM capability.

Correlation Between Calculated, Wind Tunnel, and Flight Results

Longitudinal Force and Moment Characteristics

Low speed longitudinal wind tunnel data are compared with representative semi-empirical aerodynamic predictions for $\alpha = 0\text{-}90$ deg in Fig. 8. These retrospective aerodynamic estimates were used to evaluate contemporary estimation techniques after the ARC 12-ft pressure tunnel data[11] were in hand.

As shown, the longitudinal characteristics of the F-14 can be conveniently described in terms of four α regimes. Both the wing-body and wing-body-tail normal force data rise steeply in the linear low α regime until, at $\alpha = 9$ deg, the wing begins its innocuous stall without any evidence of abrupt lift loss as confirmed by wing root bending and shear data. The continued rise in normal force throughout the designated "vortex flow" regime is almost entirely due to the high α characteristics of the low Æ glove-fuselage configuration. Beyond the vortex flow regime, the flow transitions to a fully separated state which persists up to $\alpha = 90$ deg.

Estimated normal force characteristics for the body, wing-body, and complete configuration are seen to compare reasonably well with the force data. The body-alone configuration includes the glove and overwing fairing shown in Fig. 9. The wing-body and wing-body-tail estimates were constructed using the configuration breakdown noted; i.e., forebody, glove, center-section, pancake, exposed wing panel, and exposed tail.

The body-alone estimate was a component build-up using DATCOM nonlinear estimates for the glove-centersection (treated as a round nose low Æ wing having sharp edged tips); the forebody (a circular body with a C_{D_X} of 0.7); and the pancake (a low Æ rectangular wing operating in the glove-centersection downwash with a C_{D_X} of 2.1).

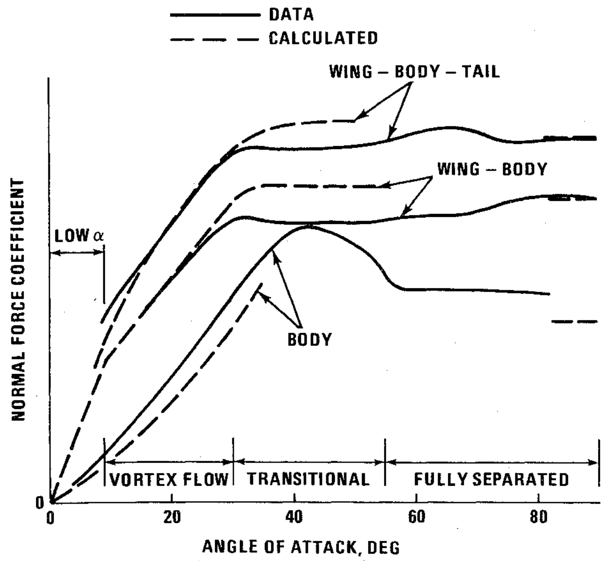

Fig. 8 F-14 normal force characteristics, low speed, $\Lambda = 22$ deg.

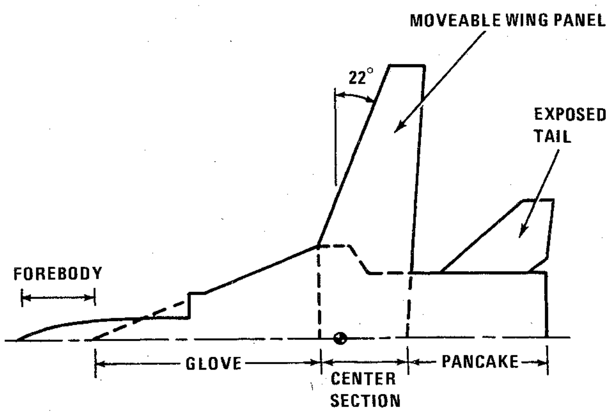

Fig. 9 Schematic: F-14 configuration.

The wing-body estimate assumes a linear lift curve for the exposed wing to $\alpha = 9$ deg and, thereafter, a slow post-stall inboard wing lift build-up due to increasing fuselage upwash with α. The horizontal tail contribution was calculated using the exposed tail normal force characteristics predicted by DATCOM procedures at the local tail alpha and including tail-body carryover.

The F-14 estimates at $\alpha = 90$ deg assume a C_{D_X} of 1.17 for the wing, tail, and fuselage area that is end-plated by these surfaces. A C_{D_X} of 0.88 was selected for the rounded glove and remaining pancake area and a C_{D_X} of 0.7 for the forebody. These values were based on C_{D_X} data.[12]

The total lift curve predicted for $\alpha = 0\text{-}90$ deg appears in Fig. 10. Despite the austere simplicity of these estimates, the predicted lift agrees well with the tunnel data.

Estimated C_m characteristics are compared with wind tunnel data in Fig. 11. Once again, one can identify the four regimes: linear low α (potential flow), vortex flow, transitional, and fully separated flow. The low α stability estimates shown are based on a detailed wing-body potential flow computer calculation used in lieu of simple DATCOM estimates which are unreliable for a configuration as complex as the F-14. In all other regards, i.e., the nonlinear contributions, the present estimates were constructed in a manner similar to that described for the normal force estimates. In general, the predicted C_m levels show reasonably good agreement with the data, with the important exception of the late prediction of wing-body pitch-down at $\alpha = 30$ deg as compared to $\alpha = 23$ deg per the data. This discrepancy carries through to the complete wing-body-tail estimate and would

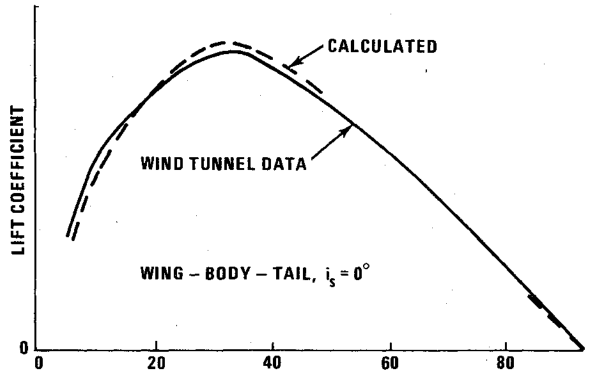

Fig. 10 Lift curve, low speed, Λ = 22 deg.

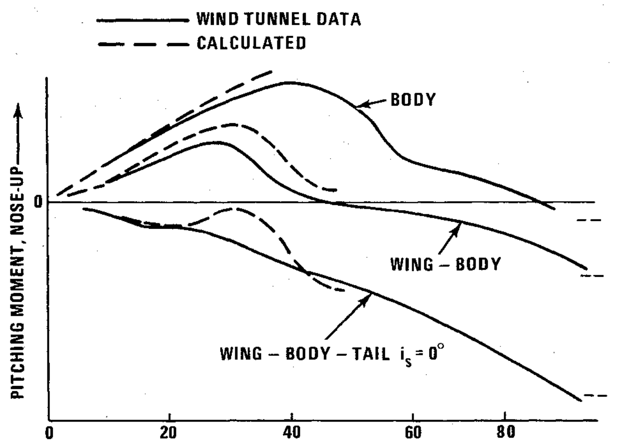

Fig. 11 Pitching moment characteristics, low speed, Λ = 22 deg.

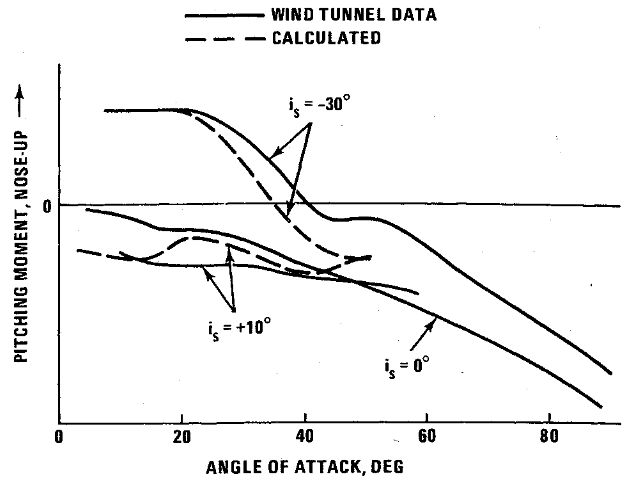

Fig. 12 Horizontal tail effectiveness, low speed, Λ = 22 deg.

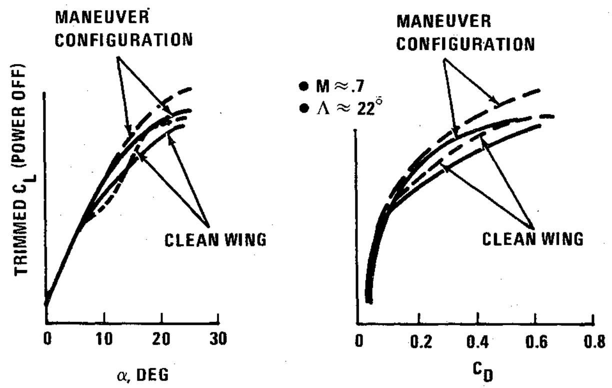

Fig. 13 Representative comparison of wind tunnel and flight test data. – tunnel; – – – flight.

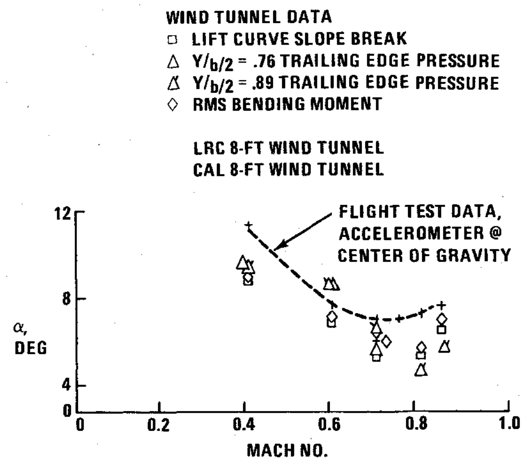

Fig. 14 Comparison of wind tunnel and flight test angle of attack at buffet onset.

indicate a pitch-up when in fact this does not materialize. It would appear that the early wing-body pitchdown evidenced by the data is an inherent feature of high Æ (wing)—low Æ (body) mutual interference not readily described in terms of existing wing-body interference factors. Comparable results [13] for a narrow fuselage NASA wind tunnel model show similar trends but less significant discrepancies since the fuselage C_m contribution is small.

Estimated horizontal tail effectiveness and wind tunnel data are compared in Fig. 12. In general, the estimated tail power is conservative for α greater than 15 deg primarily as a result of the early prediction of tail stall. Whether this is due to the inappropriateness of the aerodynamic interference factor employed for tail lift in the presence of the body or body lift in the presence of the tail or interference effects on maximum tail C_L at incidence is not clear, but it would appear that the latter effect predominates.

In summary, the low speed lift characteristics and maximum C_L of the clean wing F-14 are reasonably well-predicted by contemporary aerodynamic estimation procedures. As is to be expected, C_m estimates are more problematical and at this time any realistic prediction for a new configuration should be based on estimating differences between the proposed configuration and a related configuration for which wind tunnel data are available.

Longitudinal characteristics at Λs of 35 and 50 deg are very similar to those presented for the 22 deg Λ. Available tunnel data show little longitudinal force and moment sensitivity to RN effects for the clean configuration from $RN = 0.8 \times 10^6$ to 5.0×10^6 based on mean aerodynamic chord at all α beyond moveable wing panel stall.

Representative wind tunnel and flight data are compared in Fig. 13 for both the clean and maneuvering slat configuration. The wind tunnel lift curves and drag polars were conservative compared to flight data for both configurations. The incremental effects of slat/flap extension on lift, drag, and pitching moment were, however, correctly predicted by the tunnel data.

Buffet

Buffet is the lightly damped, random response of the aircraft structure to flow separation. The aerodynamic forces which cause buffet are a result of high α prestall flow breakdown at subsonic speeds and local shock wave and boundary-layer interaction in the transonic speed range. The degree to which one or the other causes buffet on a particular aircraft is primarily a function of airfoil section and wing design.

Preflight estimates for buffet onset were based on F-14 wind tunnel data. The wind tunnel prediction techniques employed utilized lift coefficient, axial-force coefficient, wing-root bending moment, wing trailing-edge pressure, and wing-tip accelerometer divergence characteristics with alpha to identify initial flow breakdown. Both chordwise pressure distributions across the span and oil flow photographs aided in the determination of buffet onset. Careful attention was given to the placement of transition grit[14] during these tests to simulate flight shock locations and turbulent boundary-layer conditions. The comparison of flight test α for buffet onset (defined as ± 0.05 g oscillation in normal acceleration at the aircraft center of gravity) with the wind tunnel predictions for the clean wing configuration along the Mach/sweep program is presented in Fig. 14. The data show that the predictions were conservative relative to flight results.

Importance of High Alpha Capability on ACM Techniques

The absence of a lift curve break, wing rock, autorotative rolling moments, nose slice, and pitch-up throughout the α range permits pilots to quickly discover the advantages of high α flight in the dogfight arena. Test and tactical group pilots developed ACM techniques that employed the high α capability by flying mock dogfights against modified A-4, slatted F-4, and F-106 aircraft. Since then the fleet, employing these techniques, has found that an F-14 can always get behind an opponent by performing a rolling scissor or some other maneuver at high α. In the meantime, the opponent may stall and spin, flame out, or attempt to break off the engagement and, therefore, invite a missile shot. Significantly, this scenario is taking place with the clean (unslatted) wing since the ACM configuration is not yet available to the fleet.

The superb dogfighting performance of the basic F-14 could not be convincingly demonstrated during the development phase since the air-to-air combat capability of an aircraft is very difficult to evaluate analytically or on a simulator. The key performance parameters traditionally employed to identify agility are sustained g and instantaneous g. The factors influencing these parameters are W/S, T/W, L/D, and maximum C_L. The optimum mix of these characteristics has been a controversial subject over the years, even when the aircraft being evaluated were limited to the traditional fighter maneuvering envelope, i.e., to some maximum usable C_L below stall. The ability of these factors to predict superiority, however, becomes severely limited when applied to an aircraft having a high α(i.e., 30–60 deg) maneuvering capability. For instance, as previously shown in Fig. 7, the steady-state lift is very high on the F-14 due to vortex lift and the automatic Mach-sweep programmer. For the unslatted wing, the maximum tracking C_L, as is always the case, falls below this value. Flight experince has shown, however, that F-14 pilots not only exceed the α for maximum tracking lift but also the angle for maximum steady-state lift and in so doing generate values of instantaneous g based on dynamic lift. This dynamic lift is appreciably higher than the maximum tracking lift.

An unrestricted α capability does more than allow the pilot to generate superior levels of instantaneous g. Pilots have found that by flying above $\alpha = 30$ deg they effectively convert the aircraft into a flying speed brake. In this α region, longitudinal stick inputs through a double bob weight feel system permit the pilot to precisely command pure speed changes of rather large magnitude. Also, when flying in this high α region, the pilot finds it extremely easy to command the attitude changes required to point the aircraft at the target as he falls in behind his adversary. Therefore, because of superior levels of instantaneous g and longitudinal deceleration, the F-14 pilot ends up behind his adversary. An aircraft having superior T/W can determine if and when it desires to engage in a dogfight. Without high α capability, however, the traditional advantage attributed to a high level of T/W is lost upon engagement.

Conclusions

The F-14 has demonstrated that a fighter aircraft can be designed to have no lift curve break or α limitation. This requires the configuration to be free of wing rock, autorotative rolling moment, nose slice, and pitch-up throughout the α range. In so doing, the maneuver flight envelope has been expanded beyond what has traditionally been considered possible. The value of high α agility in a dogfight has been convincingly demonstrated in flight. It has also been demonstrated that slats and an ARI system can further enhance this capability.

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