F-15 EAGLE SPIN TESTS

"...OUTSTANDING HIGH ANGLE OF ATTACK CHARACTERISTICS…"

JACK ABERCROMBIE

9 DEC 2007

"...OUTSTANDING HIGH ANGLE OF ATTACK CHARACTERISTICS..."

"...the F-15A exhibited outstanding high angle of attack characteristics when compared to any other tactical jet fighters currently in the Air Force inventory. It proved capable of effective operation at angles of attack in excess of those attainable by previous Air Force fighters. These excellent characteristics should greatly enhance the capability of the F-15A to fulfill its primary mission of air superiority…."

Air Force Flight Test Center Report AFFTC-TR-75-32, January 1976

So now, after a decade of effort on the parts of many dedicated individuals, the United States had a fighter aircraft with high angle of attack capabilities superior to any in history. For the first time, the combat pilot would be able to control the skies without undo risk of losing the battle due to departures from controlled flight in the high angle of attack, "dog fight" environment.

Unlike the last chapter, there are no "villains" in this one. To the contrary, everyone associated with the F-15 high angle of attack, stall, and spin program did an exemplary job. But there are a few who should be singled out for their efforts.

First, the McDonnell Test Pilots:

Denny Behm—With the cards stacked against him, he unintentionally flew the first F-15 spin, but with a cool head, he brought the airplane home safely.

Jack Krings—Jack was the designated primary McDonnell spin test pilot enduring some 63 spin maneuvers out of the total of 115 performed during the formal Category I (Contractor Development) and Category II (Customer Development) tests. He holds the record for having made some 251 complete turns around the compass during upright spins as well as having experienced 12 ½ turns in a single spin!

The USAF Test Pilots:

Pete Winters, Lt. Col.—Pete flew several early Air Force participation spin flights as well as most of the Category II (USAF controlled testing) high angle of attack and spin test flights. Pete totaled some 40 spins.

Dave Peterson, Maj.—Dave was one of the F-15 "Streak Eagle" time-to-climb record-breaking pilots. He joined the high angle of attack program late but managed to fly several of the Category II spin flights.

John Hoffman, Lt. Col.—John was not involved in the original high angle of attack program, but he became very much involved some eight years later when we had a surprise event (which will be discussed in a later chapter).

The Flight Test Engineers, *Gary Trippensee* and (later) *Tom McDuffee* for McDonnell, *Don Wilson* for the Air Force; and subscale model test expert, *Jim Bowman,* of NASA Langley Research Center share a large part of the credit for a successful program. And we could not have gotten along without the McDonnell analytical experts, *Dick Thomas* and (later) *Pat Wider.*

But one individual deserves special mention—*Skip Hickey* of the F-15 SPO (see Pages 4 and 16). Skip had joined the SPO in 1968 with the task of establishing specification requirements for the F-15 flying qualities, including stall, spin susceptibility, and spin recovery. He, with the support of his supervisor, *Fred Rall,* had to battle his way "up stream" in the Air Force's Aeronautical Systems Division to have the requirements he defined accepted by the Air Force community. One of those requirements has already been discussed— "feet-on-the-floor" roll maneuvering utilizing only a mechanical control system (see Page 5). The other requirements pertinent to this chapter were for the airplane to have a low susceptibility to departure from controlled flight, low susceptibility to spinning, and, if a spin were to occur, the airplane could be easily recoverable.

My part in the high angle of attack, stall, and spin program was to digest the technical information generated by the experts; communicate analysis and test results to pilots, other engineers, and management; provide guidance to the flight test team through on-the-spot, cursory analysis of data; and help define appropriate control system modifications for the airplane. As it developed, I also became somewhat of a historian for the spin test program.

My historian credentials were based on the fact that I was the one engineer who was consistently most involved throughout the entire program. Of the 115 spins accomplished during the development testing, I monitored 85% of them in real-time in front of the telemetry data charts. In this capacity, I evaluated the data for accuracy, selected which data should go through the complete data reduction routine for transmittal to St. Louis, I participated en every pre-flight briefing and post-flight debriefing, I analyzed *every* spin, and I documented the events with both daily, informal reports as well as with weekly, formal ones.

In addition, I advised and kept track of the NASA activities on our behalf.

F8 FLT 145 9 Dec 74 — Krings — High α

Same as Flt 144

- ① Cont. Cycle
- ② TO
- ③ Phase
- ④ 35K, 180 kt, SB out, 30 unit, 360° Roll, Full δLAT, 2100/2200 #, CAS off
- ⑤ " " " " BB Roll " 2000/2150 CAS ON
- ⑥ " " " " " Full Pedal 1800/2200 "
- ⑦ " 30° αi, CAS off, SB in then out, 1750/2100
- ⑧ 45K, .9M WUT to 30° αi, SB in then out, CAS off – 55°/s r, 28° β w/SB
- ⑨ " X-cont/defeat ARI attempt, SB out, 1500/1700 – α decreased
- ⑩ " " " " " " 1100/1400 – "
- ⑪ " " " " " SB in, 600/900 – spin rmax = 85, αmax = 75. Neut Rec. — oscillatory, violent
- ⑫ " " " " " SB out – α decreased

(CAS ON — ⑨–⑫)

- ⑬ 35K, PA, SB out, CAS off, 1g stall attempt to control roll-off with stick. A/C started right yaw – left lat stick increased yaw rate. Cycled stick back & forth – wound up with stick slight fwd – Brought stick back and yaw rate increased – went to smooth, stdy left spin – αi ≈ 62°, r ≈ -55°/s. After ~2 turns, full lat didn't help – Gear up/flaps up – full lat control – 2 turns – no help; Brought SB in for 2-3 turns – no apparent effect. Pulled chute @ 22K, made 1 more turns. ~8 turns total.

F8 – Flt. 145 – Record 13 — 9 Dec 74

Spin Entry Conditions:

1G stall, PA configuration with speedbrake out, CAS off, 38K — Mk IV Mod C

While attempting to control roll-off with lateral stick, it was noted that yaw motion was aggravated by stick input. Right stick was applied at a nominal 30°/sec right yaw rate while AOA oscillated between 22° and 60° indicated. Yaw rate decreased to zero at which point, the lateral stick was neutralized. Yaw rate continued towards the left, building up to a nominal 60-70°/sec at a nominal AOA of 70°. Full anti-spin lateral control was applied about 12 seconds with no apparent effect. Gear and flaps were retracted while full lateral anti-spin stick was maintained. Lateral ratio changer was at near minimum authority after the gear was retracted for about one turn until the proper stick position for full authority was found. Full anti-spin control was maintained for another turn while the speedbrake was retracted – no apparent response. The spin chute was deployed at about 22000 feet (at which point, AOA may have been decreasing. Final data will be required to determine whether this was actually the case). About one turn was made after the chute blossomed with recovery occuring at 21000 feet.

Spin parameters were AOA 62°, yaw rate -55°/sec, very steady. A total of eight turns were made.

But probably most important, I maintained records. Although I considered all this as part of my job, I did it for the pure enjoyment as well. Although there were some nervous moments during the spin program, I regarded this part of my assignment as an exhilarating learning experience—not at all like the tense times described in the previous chapter.

MEMORANDUM
241-JMA-174
0035.41
16 December 1974

SUBJECT: F-15 Flight Test Activity – Aerodynamics (9 through 13 December 1974)

TO: H. H. Cole

CC: D. R. Barklage, V. W. Bender, C. E. Chisolm, L. E. Cooper, J. R. Hanson, P. Henry, J. E. Krings, S. Kuhlman, R. Luckey, W. C. Moody, D. E. Nash, K. G. Richter, M. K. Schwartz, E. I. Staley, G. A. Trippensee, D. Walker

J. W. Agnew, I. L. Burrows, H. F. Creel, C. P. Garrison, L. Guenther, D. B. Hamer, H. W. Hamm, B. P. Hoffman, A. L. Jarrett, J. T. Johnston, F. Laacke, J. F. Mello, C. W. Miller, C. H. Mongold, W. P. Murden, W. G. Nelson, R. A. Noyes, M. L. Ramey, R. D. Samuelson, D. L. Schock, E. R. Shields, D. J. Thompson, W. C. Trent, J. Warakomski, F-15 ECRF (1)

FROM: J. M. Abercrombie

1.0 F-8 HIGH ANGLE OF ATTACK CHARACTERISTICS

1.1 Spin Chute Recovery

A spin chute recovery was made at 22,000 feet in accordance with established procedures on flight 145. The following summarizes the significant events of the maneuver leading up to the spin, the spin characteristics, and the subsequent recovery:

- Departure in the PA configuration (production speedbrake with the 45° actuator) occurred at 26° angle of attack.
- Attempts to control the directional motion with the lateral stick merely aggravated the yaw excursions.
- Even with neutral lateral-directional control, the yaw rate and angle of attack continued to increase reaching a spin condition at 31,000 feet with the angle of attack peaking at 74° and the yaw rate peaking at -71° per second.
- Anti-spin lateral control reduced the angle of attack and yaw rate to a mildly oscillatory condition with a nominal angle of attack at 55° and -48° per second yaw rate. After a little more than 1 1/2 turns with anti-spin control maintained, recovery was not apparent. The pilot elected to clean up the aircraft, retracting the gear and flaps.
- Upon gear retraction, anti-spin control was effectively lost for about two turns (the lateral control authority reverted to the washed out, near minimum schedule) with attendant increases in angle of attack and yaw rate.
- During the next two turns, while still maintaining anti-spin lateral stick deflection, angle of attack decreased slightly to about 53°; and yaw rate stabilized at -52° per second (yaw rate remained at a constant level for about 5 1/2 seconds).
- At 22,000 feet, the controls were neutralized, and the spin chute was deployed (a ground rule established many months ago); and recovery occurred in one more turn.

241-JMA-174
0035.41
16 December 1974
Page 2

A total of eight turns were made with an altitude loss of about 10,000 feet (the altitude loss was very nearly in perfect agreement with estimates). Anti-spin lateral stick deflection was maintained for a total of 29 1/2 seconds or about 4 3/4 turns.

Whether the two turns during which yaw rate stabilized prior to spin chute deployment could be called a new spin mode is debatable. Although the angle of attack was decreasing slightly, there was no indication that the yaw rate was decreasing. The characteristics during this time were in close agreement with those observed very briefly on the NASA 13% as well as the 3/8 scale spin models for neutral lateral control. But even on the models, this characteristic was not identified as a separate mode, as it was never allowed to proceed beyond about two turns. Piloted simulation studies last spring revealed a similar characteristic; but at that time, the accuracy of the simulation was in question. Needless to say, analysis is proceeding.

1.2 Speedbrake Effects

Testing with the 45° speedbrake is completed. The wind tunnel predictions of degradation to stability about all axes at moderately high angle of attack was verified by the flight results. There is no question that an automatic speedbrake retraction device will be required in view of the PA configuration characteristics noted above as well as the characteristics observed with the clean aircraft (speedbrake extension in the neighborhood of 25° angle of attack causes immediate departure). The aircraft will be in layup all next week for installation of the auto-retraction device.

1.3 Negative Angle of Attack

The initial high negative angle of attack investigations were begun on flight 148. Stabilized negative 22-23° angle of attack were achieved as predicted from wind tunnel tests as well as with the 3/8 scale model.

2.0 TEWS POD/AFT LIMIT INVESTIGATION

F-1, flight 479, made the first flight for evaluation of the aft C.G. limit with two TEWS pods, four AIM-9E's, and four AIM-7F's. Data were obtained at C.G.'s ranging from 26.9 to 27.6 percent MAC. Thus far, characteristics have been satisfactory.

3.0 FOUR-G 360° RPO'S

F-4, flight 296, completed theCAS off, 4G 360° RPO TIS requirements. For the conditions investigated, although extremely uncomfortable (requiring considerable stick dumping to prevent excessive G spikes), safety of flight did not appear to be compromised.

4.0 STREAK EAGLE

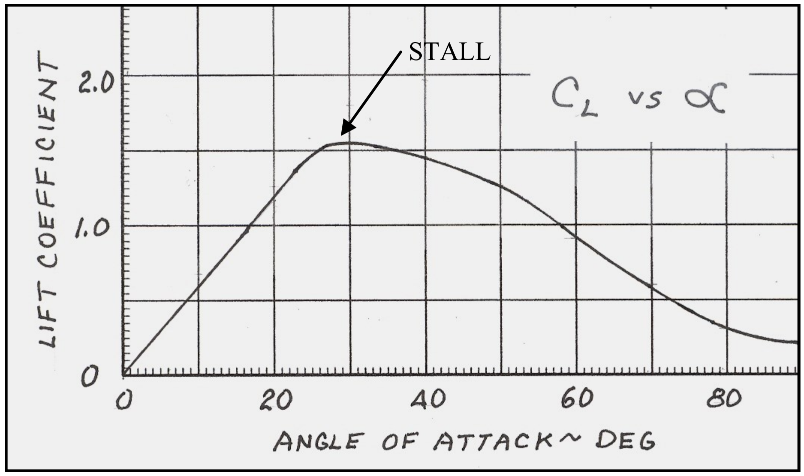
F-17 completed the Edwards portion of the Time-To-Climb activity with satisfactory results, achieving greater than 96,000 feet on flight 42.

Jack M. Abercrombie

J. M. Abercrombie – Project Aerodynamics Engineer – Dept. 241-EAFB-Sta. 72054

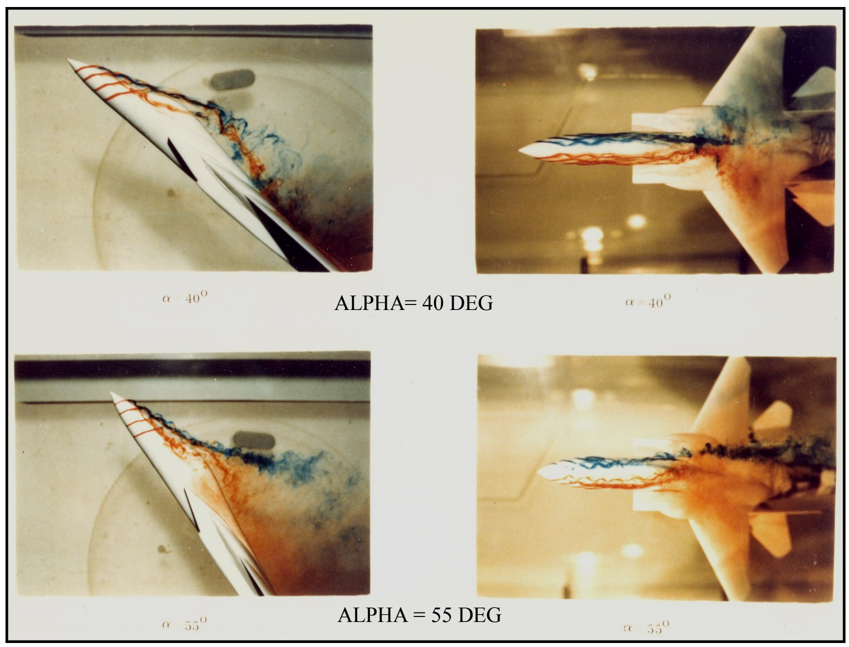
But I'm getting ahead of the story. A bit of background is necessary.

STALL AND SPIN



Wing *stall* was briefly discussed in the earlier chapter about wing tip shape, air-flow separation, and buffet. At the stall, any further increase to angle of attack will not produce any additional lift for the same airspeed, so the wing is said to be *stalled.* Any increase in angle of attack beyond that for stall, will result in a loss of lift. In other words, stall represents the most lift that can be generated.

Flight at the stall condition yields the lowest airspeed at which the airplane can be flown. The ideal landing is one made at the minimum speed—stalling with the landing gear just a few inches above the ground results in the shortest landing distance. Birds routinely make full-stall landings employing all their high lift devices (raptors have been observed to occasionally stall on take-off if the loading is excessive—in this case, stall is not good). The point is that stall, per se, is not a bad thing providing it occurs at the proper location in the sky and providing that there is some warning to the pilot (e.g., buffet) of approaching the stall, that the lift loss beyond the stall is not too abrupt, that the stall is fairly symmetrical on both wings, and providing that the airplane does not immediately depart into uncontrolled flight.



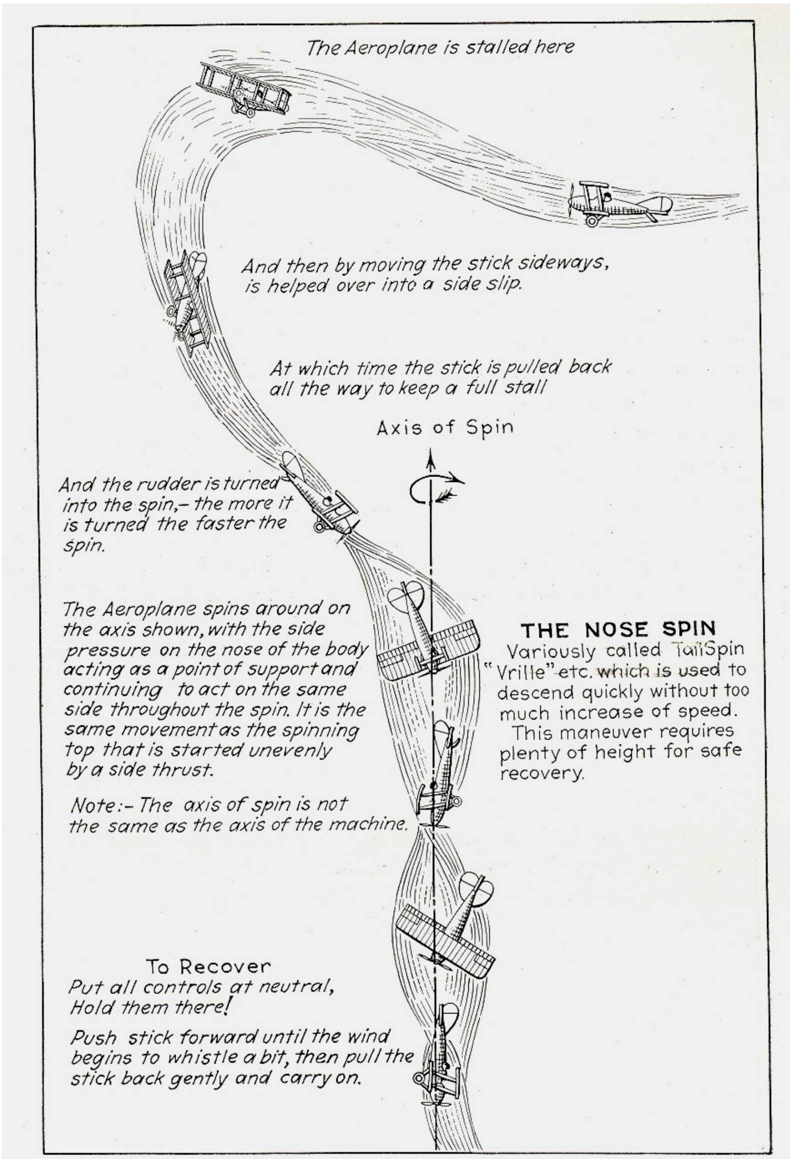
Any flight testing of a new airplane configuration must involve evaluation of stall characteristics including the impact of both slow and rapid approaches to the stall, the effect of mis-applied controls, post-stall aircraft motion, altitude lost during stall recovery, and so on—whatever is needed to ensure that the airplane is safe in the hands of a reasonably trained pilot.

Post-stall motion of an airplane can be very unpredictable, and occasionally, the gyrations can be violent. In some cases, a *spin* may be encountered. A spin is a stable auto-rotation about a vertical axis at angles of attack above the stall. In a spin, the aerodynamic forces and moments tend to take a back seat to those resulting from inertia (gyroscopic) effects because of the low forward airspeed involved and the massive air flow separation regions in which the aerodynamic surfaces are immersed.

An airplane may have multiple spin *modes* varying from smooth motion to extremely oscillatory; the airplane nose may be nearly level with the horizon with rapid rotation about the spin axis; or the nose may be pointing well below the horizon. A spin may be upright (erect) with the sky in the pilot's view, or it may be inverted with nothing but the earth in view. The spin axis may be through some point in the airplane or displaced some distance away.

The modal qualities are greatly influenced by the aerodynamic characteristics even though the aerodynamics are relatively weak at spin conditions. What may be surprising, the steady state spin rate is a strong function of the aerodynamic *pitching* moment; the aerodynamic *roll and yaw damping* impact the bank angle; and the angle of attack (or whether the nose is high or low) is a function of the aerodynamic *yawing moment stability derivatives.* As a consequence, in a spin, the airplane doesn't always respond "normally" to pilot control input.

The most obvious spin occurrences in nature are the spins used by the seeds of maple trees and other samaras for dispersal and subsequent species propagation. When they launch from the parent tree, the seed pair clusters split into two asymmetric winged configurations. The asymmetric configuration may be likened to an airplane with one wing so completely "stalled" that it produces near-zero lift—as for the missing wing of the seed pod. The remaining seed pod wing may be stalled across some of the inboard portion of its span. The falling seed quickly stabilizes at a very "nose high, flat spin" with a high rotation rate (about 1000 rpm) but at a slow descent rate thereby allowing the wind to carry it for some distance before ground contact.



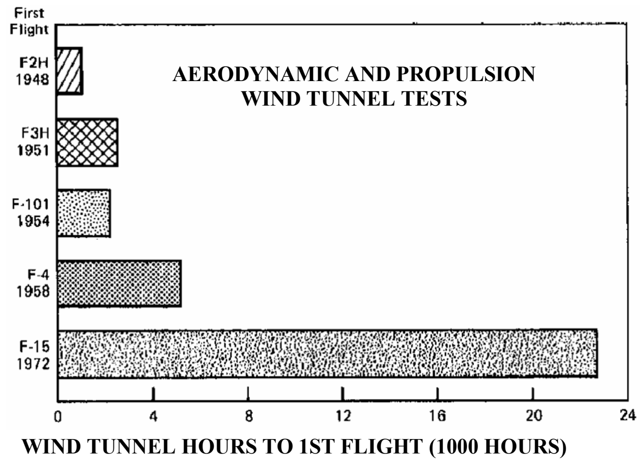
There was a time during World War I when some pilots advocated spinning the airplane as a tactical maneuver to escape a pursuer. Training manuals included instructions for entering a spin and recovering from one after the resulting desired altitude change. Note in the figure on the left that recovery was to be recognized when *"the wind begins to whistle a bit.."* However, the spin later came to be regarded as, at best, a nuisance, and at worst, a potential killer in some modern combat airplanes.

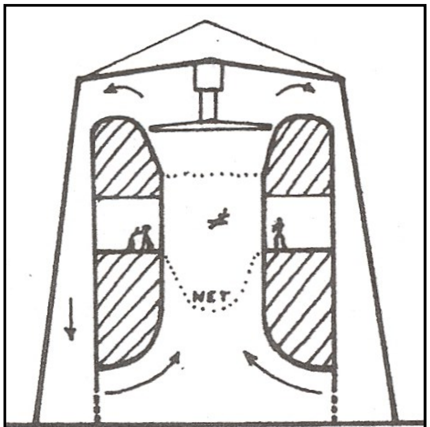
Now that the reader knows as much about stalls and spins as the writer, it's time to return to the F-15 story. The following may get a bit technical in spots; the reader will be warned so that the technical material can be skipped or pursued to further depths.

SUB-SCALE F-15 MODEL DEVELOPMENT TESTS

The F-15 development utilized the most extensive wind tunnel test program ever conducted for an aircraft. Aerodynamic and Propulsion testing alone accounted for nearly 23,000 wind tunnel occupancy-hours prior to first flight (that was about five times as many hours as had been utilized on the F-4 Phantom). This figure does not include the time for Loads, Store Separation, or Structural Dynamics testing. Wind tunnel tests continued during the flight test program as the configuration evolved or when additional information was required.

In addition to the Aerodynamics / Propulsion *force* and *moment* measuring wind tunnel tests before first flight, the program made extensive use of NASA Langley Research Center (LaRC) high angle of attack expertise in the testing of dynamically scaled free (or tethered) flight models in Langley facilities—a 1/30 Scale Spin Tunnel model (beginning in 1969), a 10% Scale Tethered Wind Tunnel model (early 1971), and a 13% Scale Helicopter-Drop, Remotely Piloted model (1972).





NASA 20 FT SPIN TUNNEL

The dynamically scaled model tests provided the best "real world" experience available without using the actual airplane.

<u>1/30 SCALE SPIN MODEL</u>**.** The 1/30 scale model had a wing span of about 17 inches and a weight of about 2 pounds, 14 ounces. Spin tests began in 1969 during the time that the three competitors' F-15 proposals were being prepared. The model test results were actually factored into the source selection process. The tests utilized the NASA Langley vertical wind tunnel (the wind blows upwards to simulate the relative motion of an airplane descending vertically) into which the small model is launched by hand with an initial spin as if throwing a "Frisbee." Often, the model will stabilize in a certain spin mode "hovering" in space supported by the vertical wind. High speed photography is used to determine the spin characteristics (attitude and spin rate). But more important, the models are outfitted with remotely activated controls and/or a recovery parachute to define spin recovery characteristics. Once recovery from the spin occurs (or not), the model is captured in a net and used again. The 1/30 Scale F-15 Spin model tests were most satisfying. It was concluded that:

> **"(1) The model has both a steady and an oscillatory spin mode requiring pro-spin controls to maintain each. There was a natural tendency to recover with neutral controls.**
> **(2) Recoveries were rapid and consistent, requiring about two turns from steady spins, and one turn from oscillatory spins with anti-spin controls…."**

<u>13% SCALE HELICOPTER-DROP MODEL</u>**.** The 13 % scale drop model was remotely piloted and was used to evaluate departure (from controlled flight) characteristics or spin susceptibility to aggravated control maneuvers as well as to verify recovery characteristics as determined by the "Frisbee" tests. This model, tested in early 1972, had a wing span of 5.55 feet and weighed about 145 pounds. The model was un-powered, so data had to be obtained during descent prior to initiating deployment of the recovery parachute.

Again, model test results were quite satisfactory. The model was very departure resistant. In order to enter a spin, it was necessary to apply stick and rudder controls in a certain sequence which later became to be known as the "**ARI Defeat**" scheme (more will be said later about this). The spin mode and recovery characteristics determined with the 1/30 scale spin model were verified.

10% SCALE, TETHERED WIND TUNNEL MODEL. In between the spin model tests, one office at NASA Langley (*not* the spin experts headed up by Jim Bowman) performed some wind tunnel testing of a remotely controlled, tethered, "free flight" model F-15 in early 1971. This office created quite a stir in that the NASA office thought they had discovered a serious problem beginning at 23 degrees angle of attack. The facility wrote a damning letter to the SPO (Skip Hickey) and to MCAIR (my colleague John Havey) noting that the "present F-15" exhibits "directional divergence at high angles of attack" and that "considerable documentation of aerodynamic characteristics must be undertaken." In other words, they wanted their (large) piece of the pie. Both Hickey and Havey were on temporary assignment to Langley during these tests to protect F-15 interests. At this time, I was filling a job on the Advanced F-15 (see Page 9), but was loaned back to the Project to help put out the fire. The NASA office had attributed the "problem" to a rarely occurring phenomenon called a "coupled roll-spiral" oscillation.

TECHNICAL STUFF

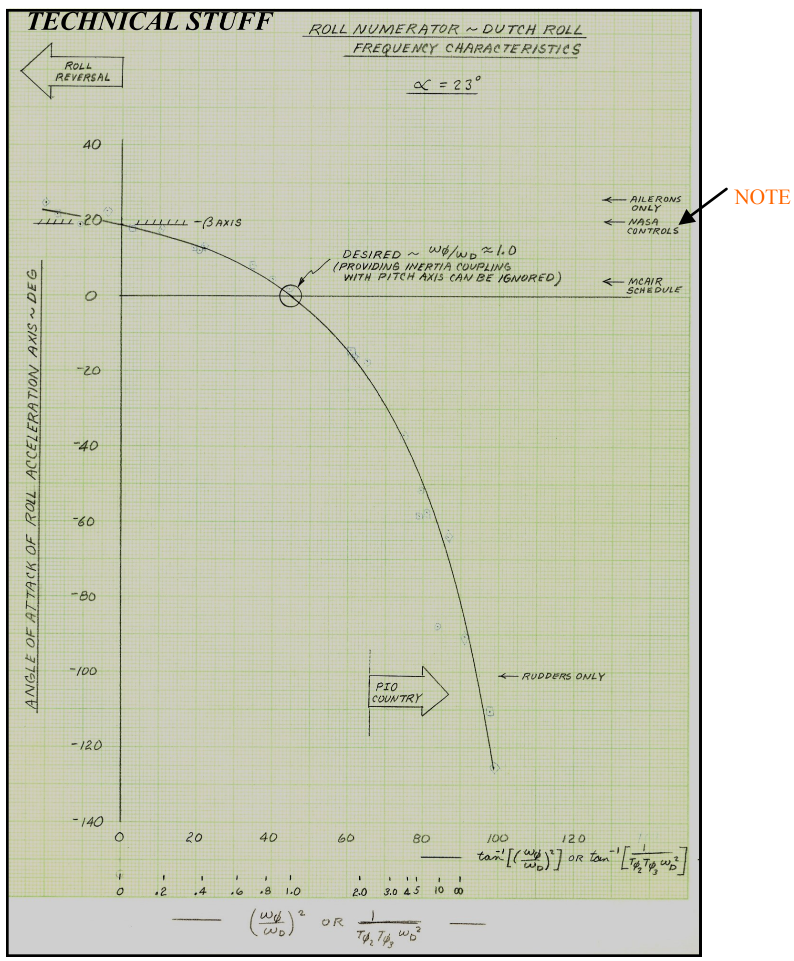
Every airplane exhibits three different oscillation modes—one in which a slow oscillation in altitude and speed occurs trading back and forth between potential and kinetic energy; one quick oscillation mode in which the airplane pitch attitude and angle of attack "vibrate" much like a spring-loaded, swinging saloon door; and one involving the roll and yaw axes in which a hunting occurs in bank angle, heading angle, and sideslip. Although these oscillations generally cause no problems, tracking tasks compromised by the latter two can be improved with use of automatic stability augmentation systems. A fourth mode is extremely rare—a very slow oscillation involving the roll and yaw axes, a "coupled roll-spiral" which is at a frequency very nearly impossible for a pilot to control.

In 1967, when NASA was heavily involved in "lifting body" technology (which ultimately led to the Space Shuttle), Test Pilot Bruce Peterson was nearly killed in the crash of the M2-F2 lifting body. It is widely believed that a "coupled roll-spiral" oscillation caused the spectacular crash. Peterson, although battered badly and losing one eye, had the distinction of having his crash shown in the 1973 movie, "The Six Million Dollar Man" as well as at the beginning of every program over and over again in the weekly television series of the same name.

My job back on the Project was to discount the NASA conclusions and find out the real reason for their loss of control with the "free flight" model. With the expertise of Engineer, Dick Thomas, it did not take long to conclude that the real problem was one caused by NASA themselves—they were using their own control system schedules for the blending of the aileron and rudder programmed as a function of the amount of lateral control stick applied. As a result, the model experienced "roll reversal"—control stick input in one direction resulted in rolling in the opposite direction! On the contrary, the aileron-rudder interconnect (ARI) schedule we, MCAIR, had developed nearly two years earlier worked quite well. The problem was not the dreaded roll-spiral coupling.

Needless to say, we got the NASA office off our backs.

The time spent stomping out this unnecessary fire was resented somewhat at the time, but, overall, the exercise didn't hurt us. It enabled us to more fully inform our management and the customer of the effort we had been devoting to high angle of attack maneuvering during the previous two years.



TECHNICAL STUFF

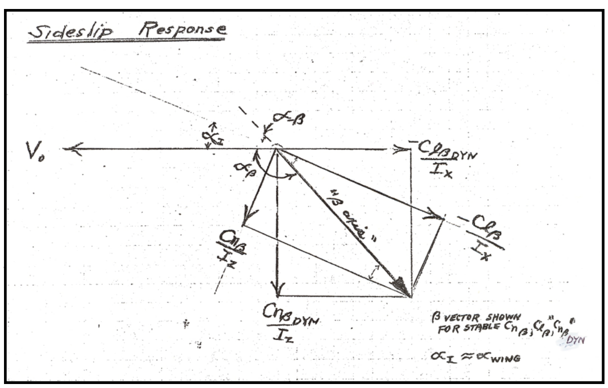
An esoteric but interesting and troublesome fact about sub-scale model testing—it is impossible to completely replicate the full size airplane characteristics with a sub-scale model. There happen to be eight relations to duplicate, but there are only seven variables. So, one has to be very choosy. Where air compressibility effects (shock waves and things) are most important, it's important to match Mach number (the ratio of airspeed to the speed of sound or, actually, the ratio of Inertia to Elastic forces). Where viscous skin friction predominates, a good match of Reynold's Number is important (the ratio of Inertia to Viscous forces). For the case of dynamic spin testing where Aerodynamic forces take a back seat , it's important to match Froude number (the ratio of Inertia to Gravitational forces)—named for father and son William and Robert Froude who developed the concept for testing ocean-going vessels during the 1870s.

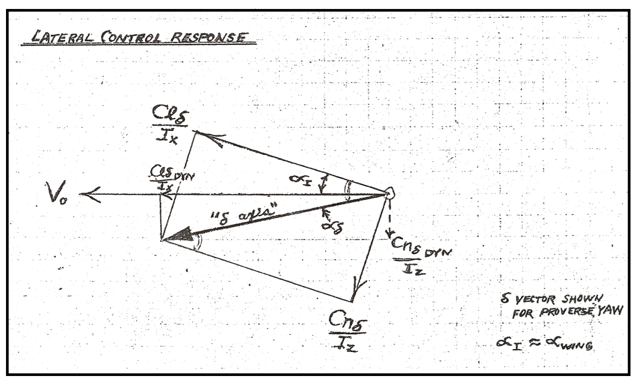
Consequently, there are certain rules for scaling a small spin model to match the characteristics of the real airplane: ***[Model Weight] = [Airplane Weight] x [Scale Factor]^3*** *if tested at the same altitude. So, the weight for a 10% (1/10) scale model should weigh 1/1000 that of the real airplane. A further adjustment would be required if tests were not performed at the same altitude.*

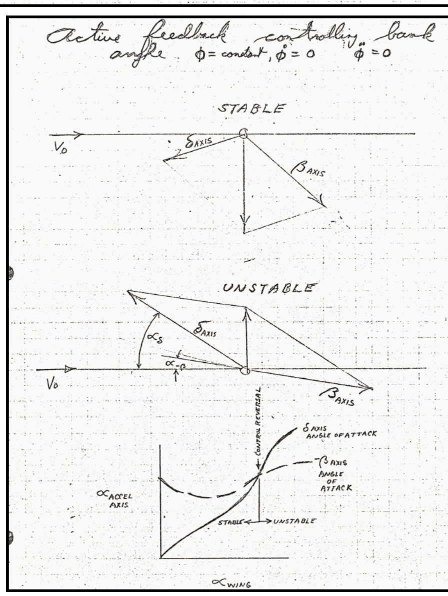
Further application of the rules would then result in the model spinning much faster than the real airplane. If ***Ω= spin rate= $(p^2 + q^2 + r^2)^{1/2}$*** *with* ***p,q,r*** *representing roll rate, pitch rate, and yaw rate, and with* ***λ*** *representing the scale factor, the real airplane spin rate would be represented with the equation,* ***$\Omega_{full\ scale} = \Omega_{model}\ (\lambda)^{1/2}$*** *. Thus, for the 1/10 scale example, a model spin rate of 300 degrees/second would represent the real airplane with a spin rate of 95 degrees/second*

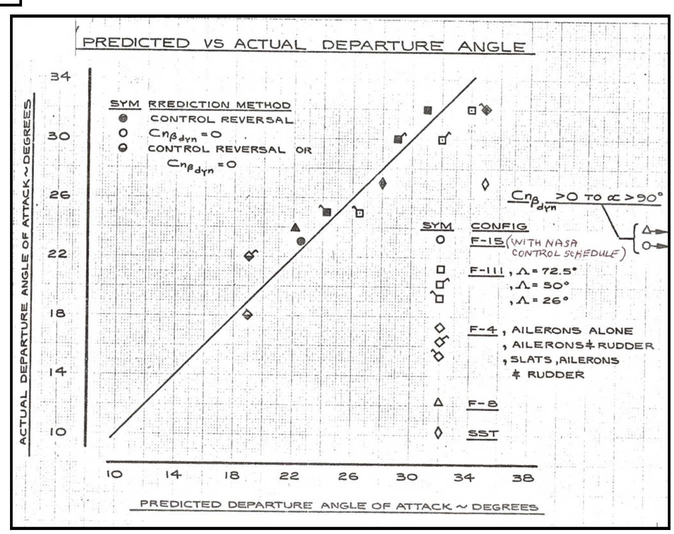
ANALYTICAL PROGRESS

The pace of high angle of attack analyses we had set during the proposal period never let up. We developed airplane departure prediction criteria which were new to the industry.

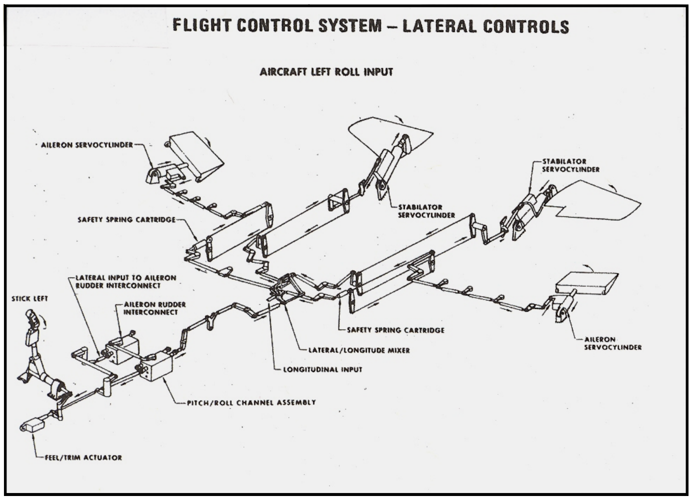


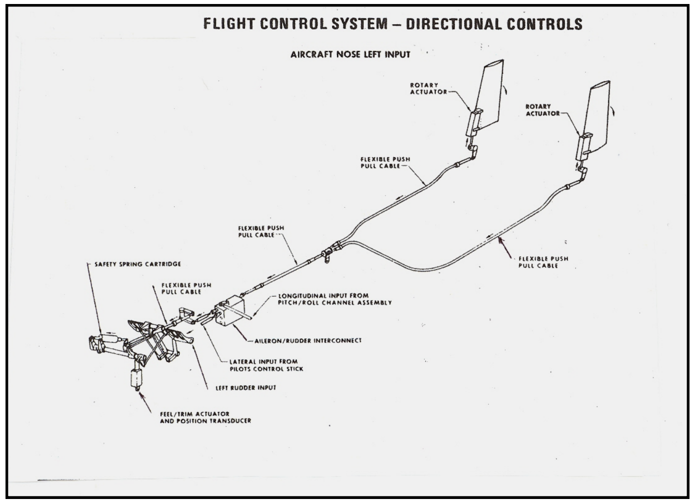


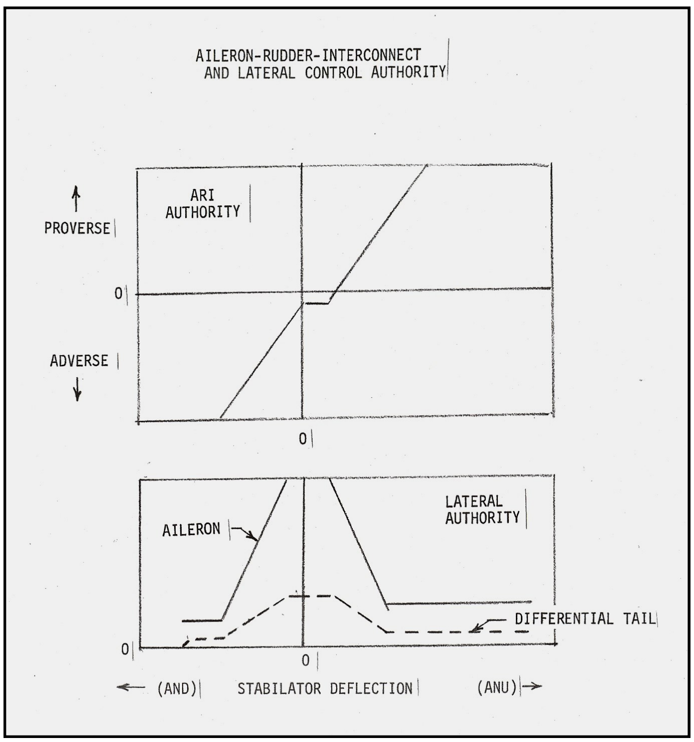


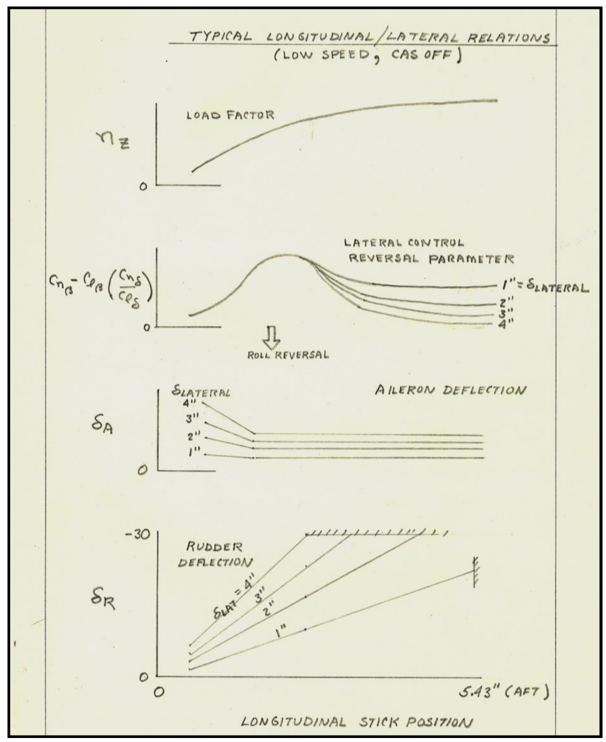


Using the results of NASA's spin model tests, we fine-tuned our aerodynamic data base. Our piloted simulations increased our confidence in the mechanical control scheme in allowing true "feet-on-the-floor" roll maneuvering at high angle of attack. The blending of lateral control authority with the commanded rudder deflection via the Aileron-Rudder Interconnect (ARI) was validated as a tremendous improvement over any other scheme ever flown.







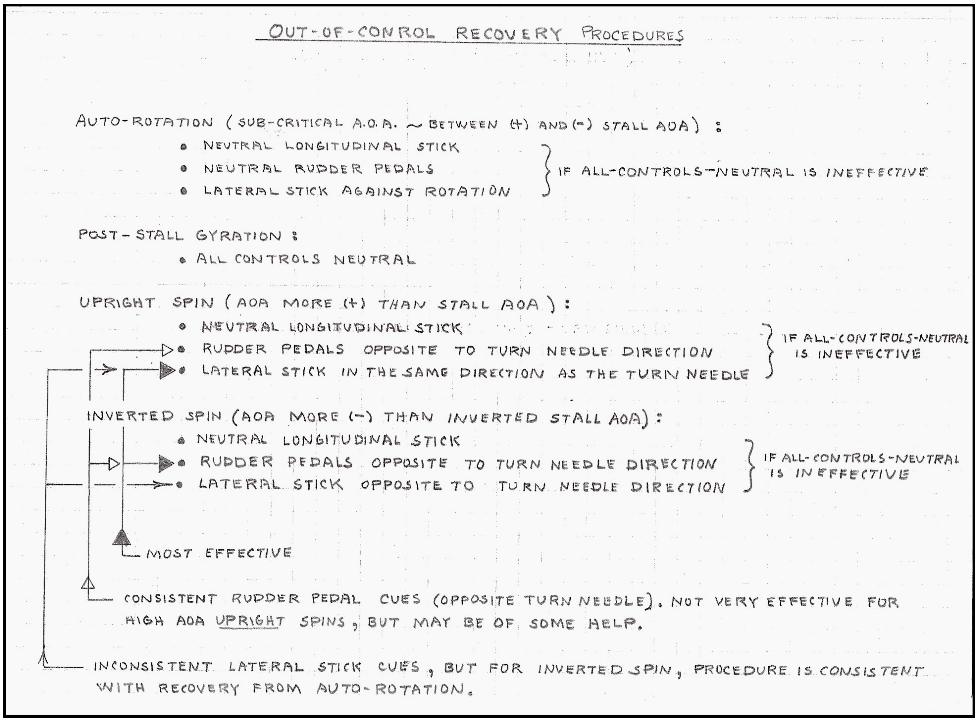


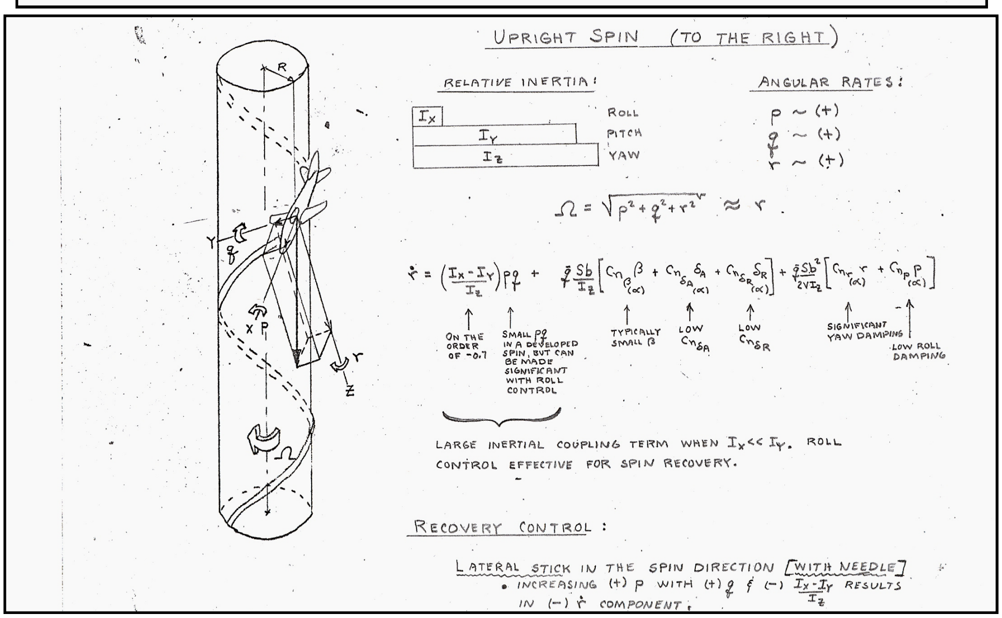
By the time of first flight in July 1972, we were confident that we could conduct a safe high angle of attack / stall / spin flight test program. Two upright, or erect, spin modes for the airplane had been identified. Although we did not have a data base or model experience to identify an inverted mode (upside down), we anticipated that there would be an inverted mode.

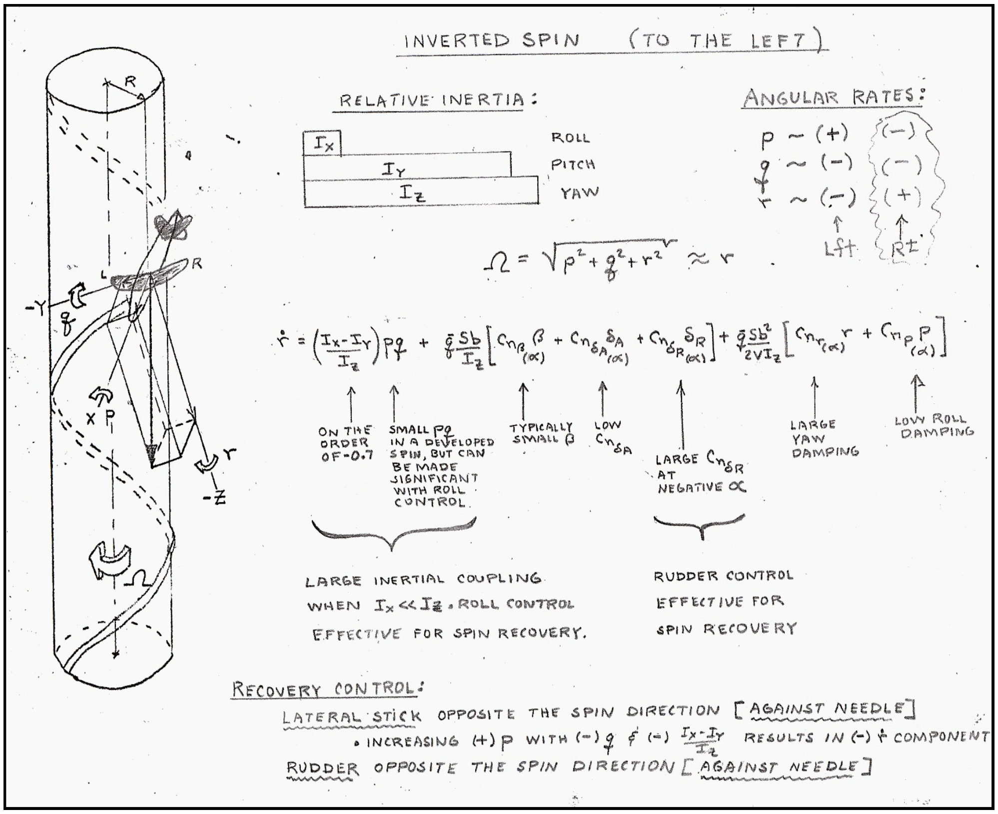
The primary upright spin mode was a steady "flat" spin anticipated to occur at angles of attack varying from about 65 to 82 degrees with a fast spin rate of about 100 to 170 degrees per second. The spin would be faster and flatter with increased amounts of pro-spin control deflection. At these angles of attack, the airplane nose would be pointing from eight to 35 degrees below the horizon. Our spin attempt simulations occasionally resulted in a second mode, an *oscillatory* spin whose angle of attack varied from about 50 to 80 degrees and with a nominal spin rate of about 80 degrees per second.

Of course fitting into a specific mode does not mean that the motion of every spin in that mode is identical—it merely means that there are significant similarities in the characteristic motion.

By this time, we were confident that we had defined the proper control system and could define the necessary pilot input to recover from a spin. The key requirement was for the pilot to recognize whether the aircraft was in an upright or an inverted spin and to scan the cockpit instruments to ascertain the spin direction (right or left) particularly for an inverted spin which can be quite disorienting.







HAZARDOUS FLIGHT TESTS

All flight testing has an element of risk associated with it. Trouble can arise from many sources—some as mundane as the use of the wrong fastener during assembly, a factory worker's tools left inside the airplane during assembly, or the use of the wrong polarity in an electrical component (wired backwards). All these and others have happened on more than one occasion—some with the subsequent loss of the aircraft. More sophisticated risks may involve undetected material flaws leading to premature failure of some critical component (tires, wind shields, engine turbine blades, etc.). The known risks which get the most attention are those associated with explorations of previously untried concepts or of areas that experience with similar test articles have shown to be of a high risk.

To address the last case, a test or series of tests are labeled in advance as "Hazardous Tests." This category receives a lot of deserved attention within both the engineering and program management disciplines. For the obvious concerns, seemingly countless scenarios are considered, safety reviews are held involving the appropriate Contractor and Customer personnel, contingency plans are formulated, and back-up equipment is incorporated in the event of mission-critical equipment failures.

High angle of attack / stall / spin tests fall into the "Hazardous Test" category for good reason. Since the beginning of the jet age, particularly for fighter aircraft, the airplane designer has been met with new challenges—configurations employing highly swept, thin wings and densely packed, "fuselage loaded" layouts. The previously unknown aerodynamic in the transonic speed regime was not fully understood (and is not completely comprehended to this day). To cope with the higher control surface air loads, the use of hydraulics to aid the pilot was necessary—this led to a loss of natural airplane "feel" to the pilot handling the controls; artificial feel systems had to be developed.

The growing pains of aircraft design during this time were many. The problems that early Air Force fighters had (and the Navy aircraft experienced similar characteristics) have been best summarized by Skip Hickey of the F-15 System Program Office. He wrote,

“In order to better understand the F-15 ‘Spin Story’ we should look back a few years to the mid 60s when most of our first-line combat fighter aircraft suffered from unacceptable flying qualities at high Angles of Attack (AOA). The tactical effectiveness of these aircraft was severely limited. Furthermore, the pilot’s main concern in a high maneuver environment was often aircraft departure and loss of control. ‘Pitch up’ characteristics of the F-101 and F-104 caused by loss of pitch stability resulted in the loss of many of these aircraft. The loss of directional stability at high AOA caused a yawing motion or ‘nose slice’ on F-4Cs and Ds. Adverse yawing motions or actual ‘roll reversals’ often occurred with the F-4 and F-100 during high AOA rapid rolling maneuvers. And finally, after a ‘departure’ from normal flight control, many of our fighter type aircraft (F-4, F-5, T-38, F-100, F-101, and F-104) developed certain spin modes which were unrecoverable.”

Even flight testing under controlled conditions and with what were considered to be adequate safeguards resulted in some unpleasant surprises. Dedicated high angle of attack test aircraft flown by highly skilled test pilots and supported by staffs of engineer experts were lost due to unrecoverable spin modes. McDonnell Aircraft test airplane losses included two versions of the F-4 “Phantom II” (both a Navy and an Air Force version), two versions of the F-101 “Voodoo” (a single-place F-101A piloted by future MCAIR President, Bill Ross), and a two-place F-101B), and an F3H “Demon..” *(Actually, the F3H wasn’t a total loss, but it certainly was an embarrassment. Spin tests were being conducted on the F3H. When the airplane refused to recover from an inverted spin, the emergency spin recovery parachute was deployed. After several more turns with no hint of recovery, the test pilot bailed out. Soon thereafter, for whatever reason, the airplane righted itself, flew for 150 miles until running out of fuel, and then landed perfectly <but wheels up> in a farmer’s field. There may have been more damage to the pilot’s pride than to the airplane.).* Pete Winters, our Air Force spin pilot had lost a General Dynamics F-111 during a spin test when it wouldn’t recover.

Understandably, there was concern on all fronts about the risk associated with the forthcoming stall and spin tests. Not only was the adequacy of the aerodynamic data base and the robustness of the flight control system questioned, but also the operability of the engine / inlet system had to be thoroughly addressed. (The engines were being developed concurrently with the airplane). Contingency plans in case of an otherwise unrecoverable spin called for the incorporation of a 32 1/2 foot diameter spin ‘chute fired by a mortar from a canister between the vertical tails of the high AOA test aircraft. In addition, an auxiliary power source or Emergency Power Unit (EPU) to operate hydraulic pumps and a battery pack for electrical power were incorporated in the event the engines quit and slowed down to a very low rotation speed.

ANOTHER SUBSCALE MODEL TEST

NASA Dryden Flight Research Center (DFRC) at Edwards AFB came on the scene much later than their counterparts at Langley with a subscale model of the F-15. The model was of 3/8 scale with a wing span of 16 feet and a weight of 1800 pounds). In addition to my other chores (such as dealing with the last chapter’s supersonic directional control problems at the time), I was designated to be the MCAIR contact with NASA Dryden.

Dryden Flight Research Center ECN-3804 Photographed 1973
F-15 Remotely Piloted Research Vehicle mounted under the wing of NASA's B-52. NASA photo

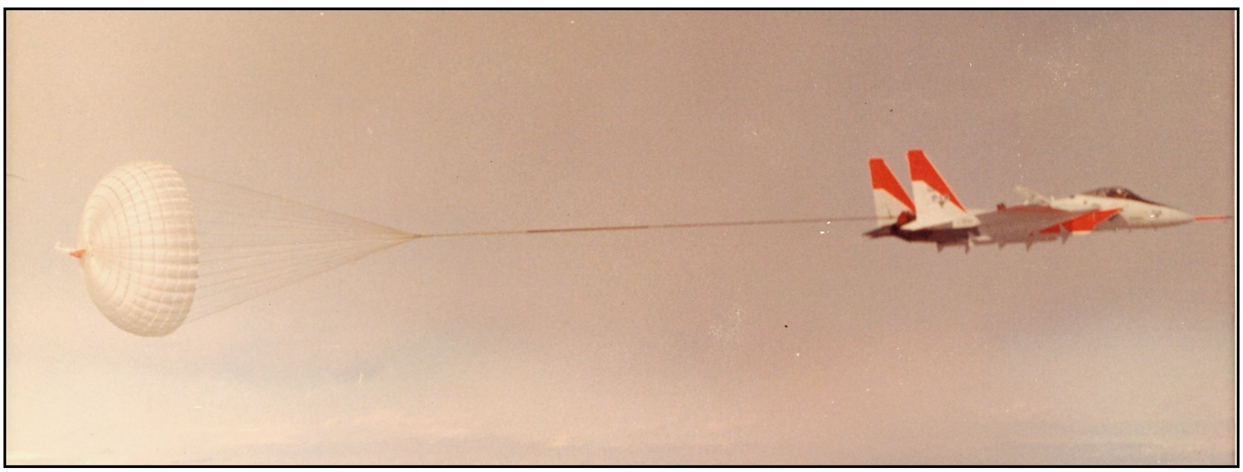
One month prior to the beginning of the full-scale high AOA program, NASA made the first flight of the 3/8 scale Remotely Piloted Vehicle (RPV)—12 Oct 1973. The model was launched from a B-52 (the same airplane that had launched the X-15 research airplane and other NASA research vehicles). Launch conditions (typical for the remainder of the program) were 45,000 feet altitude at 175 knots calibrated airspeed. The first drop was primarily a check-flight up to about 26 degrees AOA, but some engineering data were obtained with the use of their “derivative extraction” algorithms, a technology in its infancy at the time.   The RPV descended to about 15,000 feet in about 10 minutes at which point, a parachute was deployed, and a helicopter from Pt. Magu snatched it at about 10,000 feet and delivered it to the NASA ramp.

The RPV pilot, Einar Enevoldson, sat at a ground-based simulator in front of an instrument panel with telemetered flight data and a TV screen with a view out the front of the model's "cockpit."   I attended the debriefing for the first flight and was amazed at the size of the crowd. The event appeared to be more momentous to NASA than was the first flight of the real airplane to us at MCAIR!

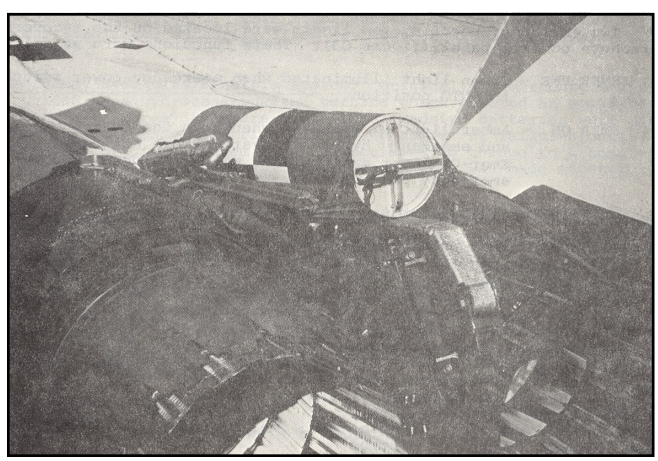
The second 3/8 scale model flight occurred on 8 Nov 1973. I had previously bet a martini with one of the NASA engineers that the model would *not* depart from controlled flight during the planned test. The NASA experts were adamant that the model would depart at 29 degrees AOA. I was late for the post-flight debriefing—as I entered the theater, I overheard Bruce Peterson (the pilot discussed on Page 49, now wearing an eye-patch) remark, "I'm keeping one eye out for Abercrombie!" Needless to say, I had won my bet; the model was very well behaved during the test; and the NASA experts were very favorably impressed with our control system and its control of the model.

RISK REDUCTION VERIFICATION

Continuing this narrative somewhat chronologically, while NASA continued flying the model, we got further along with the real airplane with its planned high AOA program, but it wasn't until January 1974 that we began to check out the operation of one of the safety devices—the emergency spin recovery parachute. The first deployment at a rather benign flight condition was successful.   And then, we had a series of flights to make cer-



tain the presence of the parachute canister / boom installation between the two vertical tails would not adversely affect the airplane flying qualities.



The Emergency Power Unit (EPU) burned hydrazine rocket fuel to provide power for driving the airplane hydraulic pumps in the event of a dual-engine flame-out with subsequent loss of engine RPM. (A small battery pack was provided for necessary systems electrical power). The EPU became available in mid-April 1974. Ground and flight tests of the unit continued for a seven week period. However, on 7 Jun 74, the EPU tests came to a screeching halt. The system developed a leak while in flight. The pilot, Pete Winters made an emergency lake-bed landing and immediately evacuated from the cockpit whose rear section was floating in hydrazine!

The hydrazine leak was a serious matter—hydrazine is highly flammable, very corrosive and toxic, and can do terrible things to the lungs. Although hydrazine fuel had been used in the successful space capsule programs (and is now standard equipment in the later F-16 ***single engine*** airplane), the risk of continuing to employ it on the already high risk, high AOA F-15 program was considered too great. On 13 Jun 74, the powers-that-be decided to stop work on the high AOA program until the test airplane could be out-fitted with a battery pack large enough to drive the hydraulic pumps. Consequently, the hydrazine EPU was dropped from the picture. (These decisions were well beyond my pay grade and level of expertise).

The EPU set-back added fuel to the fire in ongoing discussions about ***not*** conducting a full-blown spin program. Momentum was building both at MCAIR and within some portions of the Air Force to do all that was necessary to evaluate stall and departure characteristics using "reasonable" amounts of aggravated control inputs (well beyond what would normally be encountered in operational use) but not to risk deliberate spins. The philosophy of emphasizing "spin avoidance" in the test program rather than demonstrating "spin recovery" was becoming very popular.

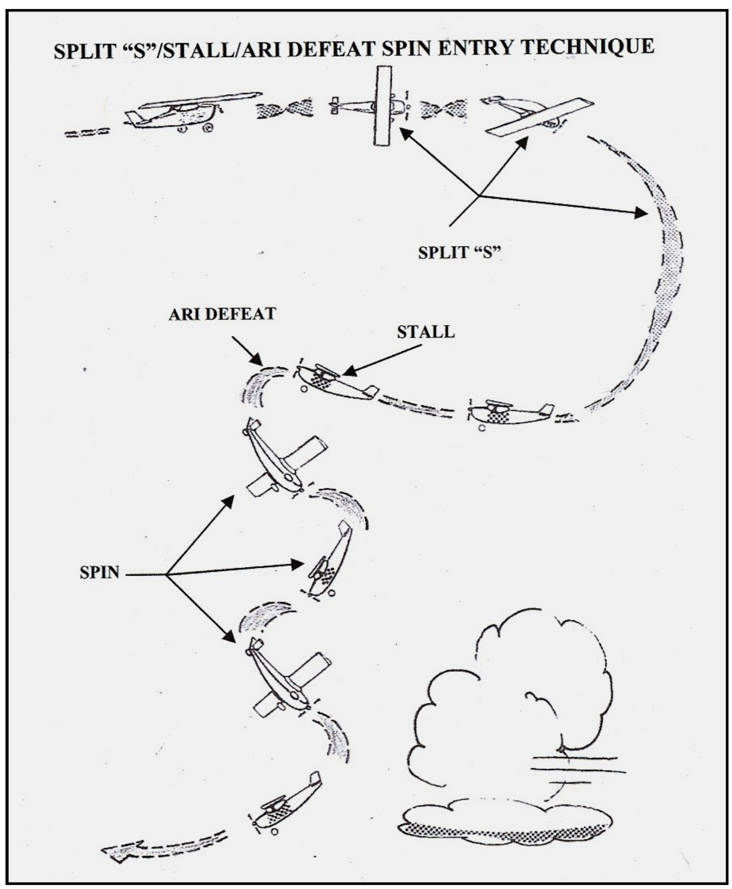
ANOTHER MARTINI BET

Back in February 1974, MCAIR Test Pilot, Denny Behm, flying the NASA Dryden simulator found a good way to make the mathematical model of the airplane spin using a procedure similar to that used with the NASA 13% scale Drop Model—manipulating the controls to defeat the blending of the rudder and lateral controls functions of the control system. Recall the Aileron-Rudder Interconnect (ARI) discussion earlier. At certain flight conditions, by pulling the stick all the way aft to achieve a stall angle of attack, putting in roll control in one direction while cross-controlling the rudders in the opposite direction, then dumping the stick forward so that maximum cross-control deflections existed while the airplane was still at high AOA, occasionally a spin would develop. But the maneuver had to be entered at a high kinetic energy condition, and the controls manipulation timing had to be "just right." This technique was referred to as the "ARI Defeat" maneuver.

NASA DFRC plans for the fifth drop of the 3/8 scale RPV on 6 Mar 74 included the "ARI Defeat" maneuver to be performed at essentially a level flight, low energy condition. I won another martini bet from my Edwards supervisor, Hank Rechtien—the model did ***not*** spin.

Finally, on the seventh RPV flight on 21 Jun 74, a spin was induced by using the "ARI Defeat" technique but from a ***high energy, split "S"*** maneuver rather than from a one-g condition. (There were no martini bets on the outcome of this attempt, as all agreed a spin was most likely). The spin mode was the smooth, flat one which had a spin rate of about –195 deg/sec (corresponding to –120 deg/sec when reduced to the scale of the real airplane). Recovery control input broke the spin in about 3 1/2 turns.

The 3/8 scale model spin was met with a brief flurry of interest by the technical and pilot communities, but what really stirred up some excitement was an event only four days later with the real airplane—F-15#1.



"...THERE'S BETA TAKING OFF—AND—AROUND WE GO…"

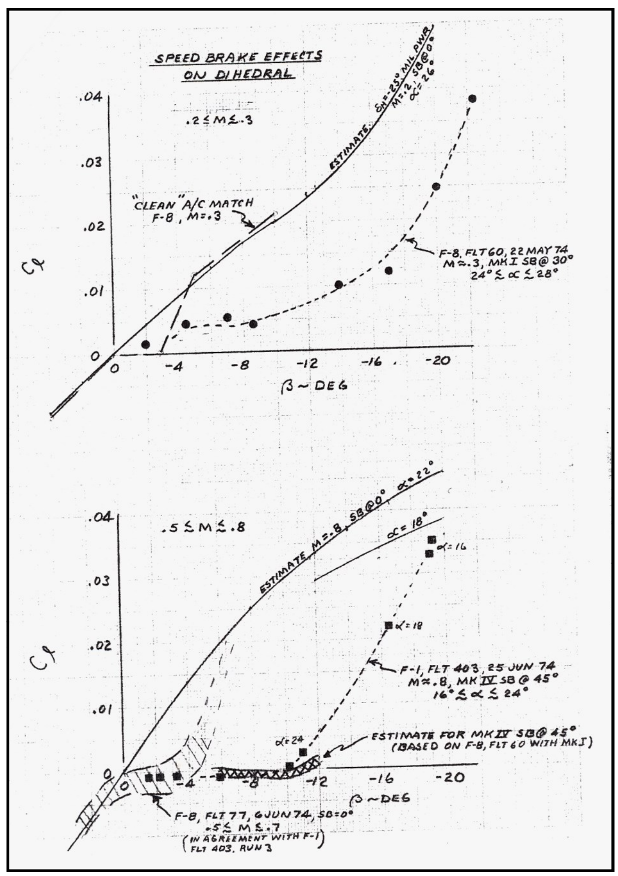
The real airplane test program took a turn, so to speak, in the afternoon of 25 Jun 74 on a test flight whose purpose was to demonstrate the adequacy of the speedbrake to do its job of decelerating the airplane. At the time, F-15#1 was the only airplane configured with the larger Mark IV Mod C speedbrake which had been defined for the production airplane (see Page 32), so it was the one chosen to fulfill the test requirement. The test plan called for a decelerating wind-up-turn (a maneuver which combines pulling g's while in a banked turn) at idle engine power beginning at M=1.2 at 40,000 feet with simultaneous extension of the speedbrake.

All was routine until the airplane suddenly departed to the right (the nose sliced in a right yaw without any control input) at about 20 degrees AOA, M=0.81 and began to roll. In the radio transmission words of the test pilot, Denny Behm,

> **"There's Beta taking off—and—around we go, and we're in a —un-commanded roll situation. Son of a bitch!...[**46 seconds later] **Breathing again! O.K., I think I've got a heartbeat—I just felt it...Holy ****!..."**

In my words (somewhat technical), written late that evening,

> **"...the right yaw departure began. Normal corrective action of stick forward and left (briefly) was applied with no significant effect on angle of attack and none on roll rate...About two** [compass] **turns were experienced before the spin actually developed...Following about two more oscillatory turns with a probable angle of attack oscillating about 70 degrees** [beyond F#1 instrumentation limit], **full anti-spin lateral control (right stick) was applied. Sub-critical** [below stall] **angles of attack ...were reached within two turns…"**



There were other factors contributing to the excitement: the LH engine stagnated during the departure followed soon after by the RH engine. Shut-down of both engines because of high turbine temperature resulted in loss of telemetry for about 15 seconds during the recovery. Re-start was slow but uneventful. The airplane was fully recovered with both engines operating at 15K feet.

Although we had observed briefly on earlier flights that the speedbrake (either the small, pre-production or the larger Mark IV Mod C) could contribute significantly to departure susceptibility, there had not been sufficient time to completely evaluate the repercussions.

But I had seen enough—I immediately recommended that we automatically preclude speedbrake deflection at the higher angles of attack. The recommendation was subsequently adopted some time later.

Another anomaly was noted—the mechanical ARI was not engaged at the time when it could have been helpful. The ARI was designed to be inoperative supersonically and to be operative only at subsonic speeds. During the deceleration from M>1 to M<1, the mechanism hadn't had time to re-engage. My recommendation written that evening to design the system with a quicker ARI turn-on feature when decelerating through Mach 1.0 was also incorporated into production.

But most important, when the test data system were re-interrogated using a different data format, it was discovered that there was considerable Left-Right wing fuel asymmetry due to a faulty fuel system design. The airplane was about 1250 pounds left wing heavy, which was equivalent to a 10,000 ft-lb moment. Apparently, as we later learned, this was nothing new—the airplane had a history of fuel asymmetry. Several of us both at Edwards and in St. Louis share the blame for not observing the situation and raising a red flag. Communication between the fuel system designers, the flight test and flying qualities engineers, and the pilots could have been better had any of us realized the importance of the situation.

In any event, the combination of the speedbrake-induced lateral instability and the wing fuel asymmetry caused the spin. The inoperative ARI, if it had it been operating per the design charts, could have ameliorated the departure problem. But the cards were stacked—there was no way a spin could have been avoided under the circumstances.

In addition to those lessons learned, we learned something else—**We would now have a spin program!** Unfortunately, because of the EPU decision made less than two weeks before, we didn't have a high AOA test airplane!

To recap the 13 days in June 1974 which changed the program so significantly:

- 13 June—Work stopped on the hydrazine EPU for the high AOA test airplane F#8 to await a battery EPU.
- 21 June—NASA DFRC spun the 3/8 scale F-15 model.
- 25 June—F-15#1 made an inadvertent spin.

THE STALL / DEPARTURE / SPIN PROGRAM RESUMES

For the next three months while awaiting the new battery pack EPU, NASA DFRC made six more flights of the 3/8 scale model. Although their effort contributed nothing to the F-15 design, the model test results gave us more confidence in the correctness of our design.

We used this time to "lobby" for control system modifications to retract the speedbrake above a certain angle of attack and to enable a quick turn-on of the ARI, and the fuel system designers worked to gain a better understanding of the cause of the fuel imbalance problem.

Finally, in late September '74, the new EPU was ready, and the high AOA program resumed with another check of the emergency spin 'chute. Alas, the 'chute streamered, and we were down for another three weeks while the installation was re-designed. At last, on 29 Oct 74, Jack Krings in F-15#8, Flight 122, after *nine* attempts using the "ARI Defeat" technique, managed to spin the airplane and recover successfully. The next 22 flights documented the effects of the speedbrake and lateral fuel asymmetry. In addition, aggravated control inputs during gross maneuvers were evaluated. But only with deliberate spin attempts and/or large fuel asymmetries were spins accomplished. In these 22 flights, 10 spins were made. Both the predicted oscillatory mode as well as the smooth, high rate mode were experienced. In all cases, recovery was rapid upon application of recovery controls.

THE "ONE MORE TURN" MODE

We had some excitement on 9 Dec 74 (F-15#8, Flight 145) when a spin was encountered which didn't appear to go by the rules. My report of 16 December summarizes the event.

> A spin chute recovery was made at 22,000 feet in accordance with established procedures on flight 145. The following summarizes the significant events of the maneuver leading up to the spin, the spin characteristics, and the subsequent recovery:
>
> - Departure in the PA configuration (production speedbrake with the 45° actuator) occurred at 26° angle of attack.
> - Attempts to control the directional motion with the lateral stick merely aggravated the yaw excursions.

- Even with neutral lateral-directional control, the yaw rate and angle of attack continued to increase reaching a spin condition at 31,000 feet with the angle of attack peaking at 74° and the yaw rate peaking at –71° per second.
- Anti-spin lateral control reduced the angle of attack and yaw rate to a mildly oscillatory condition with a nominal angle of attack at 55° and –48° per second yaw rate. After a little more than 1 1/2 turns with anti-spin control maintained, recovery was not apparent. The pilot elected to clean up the aircraft, retracting the gear and flaps.
- Upon gear retraction, anti-spin control authority was effectively lost for about two turns (the lateral control authority reverted to the washed out, near minimum schedule) with attendant increases in angle of attack and yaw rate.
- During the next two turns, while still maintaining anti-spin lateral stick deflection, angle of attack decreased slightly to about 53°; and yaw rate stabilized at –52° per second. (Yaw rate remained at a constant level for about 5 1/2 seconds).
- At 22,000 feet, the controls were neutralized, and the spin chute was deployed (a ground rule established many months ago); and recovery occurred in one more turn.

A total of eight turns were made with an altitude loss of about 10,000 feet (the altitude loss was very nearly in perfect agreement with estimates). Anti-spin lateral stick deflection was maintained for a total of 29 1/2 seconds or about 4 3/4 turns.

Whether the two turns during which yaw rate stabilized prior to spin chute deployment could be called a new spin mode is debatable. Although the angle of attack was decreasing slightly, there was no indication that the yaw rate was decreasing. The characteristics during this time were in close agreement with those observed very briefly on the NASA 13% as well as the 3/8 scale spin models for neutral lateral control. But even on the models, this characteristic was not identified as a separate mode, as it was never allowed to proceed beyond about two turns. Piloted simulation studies last spring revealed a similar characteristic, but at that time, the accuracy of the simulation was in question. Needless to say, analysis is proceeding.

Although this spin lasted for almost 30 seconds through eight turns total and had never before occurred with the full-scale airplane, it could not be ***positively*** identified by the experts as a ***new*** mode. There were some of us, however, who had suspicions.

Subsequent St. Louis simulations during the next few weeks with updated aerodynamics suggested that had recovery controls been maintained for just ***one more turn*** (rather than popping the 'chute), the airplane would have recovered. We'll never know.

This spin became known (perhaps derisively) as the ***"One More Turn Mode."***

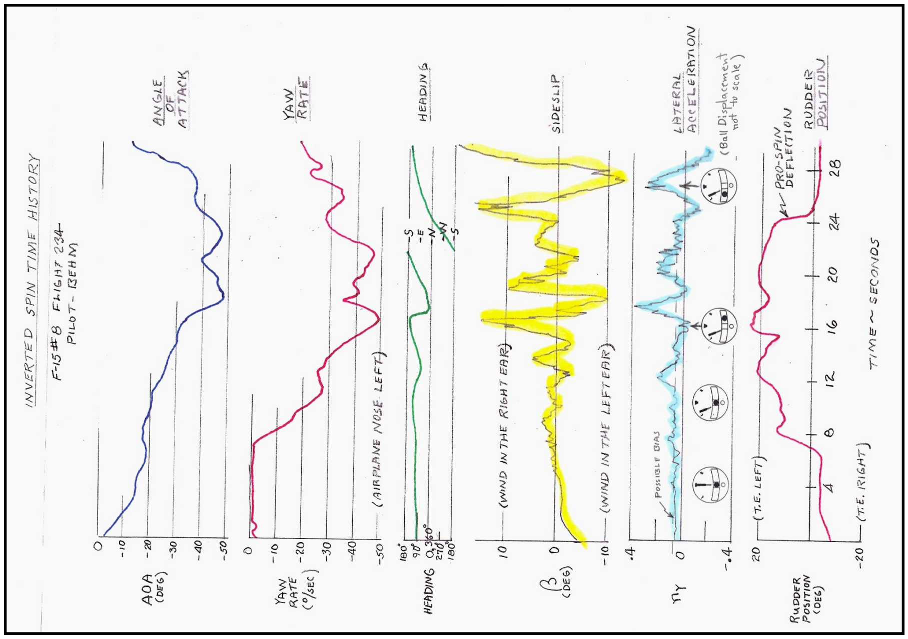
THE TRIVIAL INVERTED SPIN

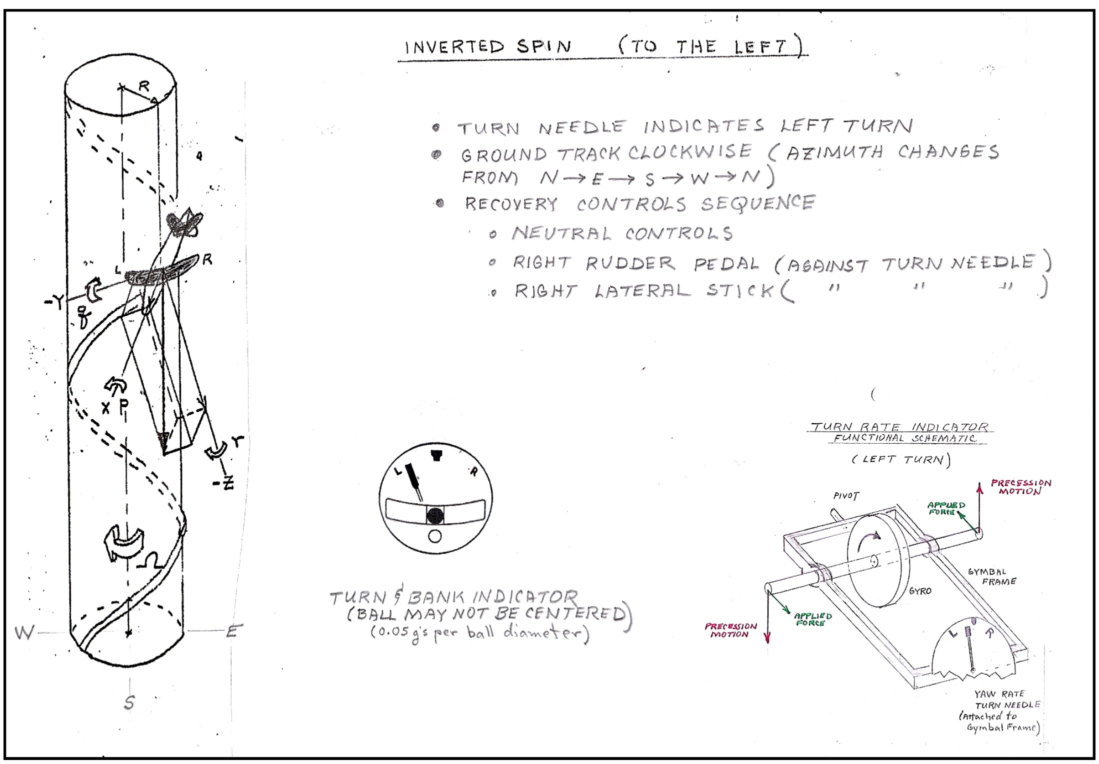
We had no data base for large negative angles of attack. Nor had NASA exercised the small models in inverted spins. Thus, we had no real handle on how the airplane would behave in this regime. Fortunately, in October 1974, NASA's 3/8 scale model did some inverted spin work with satisfactory results. Consequently, we (or at least I) had no qualms about inverted spins for the real airplane which commenced in March 1975.

I recently took some good-natured FLAK for referring to the F-15 *inverted* spin mode as "trivial." In fact, from my perspective as an engineer sitting behind a desk with a slide rule, a time-history of an inverted spin, and a copy of the six-degree-of-freedom equations of motion, the F-15 inverted spin *was* trivial. It was easy to get into—roll the airplane upside down, push the stick into either the right or left forward corner, and hold it there a few seconds. The spin motion was mild (as spins go) with yaw rates of about 36 to 50 deg/sec with angles of attack of tack of about –40 to –50 degrees. And recovery was rapid—let go of the stick (or move it back to the normal centered position), and the airplane self-recovered. However, there *were* occasional engine stalls during the spin as well as unpleasant airplane gyrations during recovery.

Test Pilot Jack Krings had this to say about the inverted spin, **"...the inverted spins...are terrible. You have to do a lot of inverted spins before you get anywhere knowing which way you are going. You are not too sure which way the airplane is turning in a inverted spin because the world is not really working the way it should."**

Indeed, a few months ago, I revisited the issue by trying to visualize the view from the cockpit of the airplane performing an inverted spin. I found that the task can twist one's mind out of shape, particularly when on the outside looking in. In the process, I made some enhancements to the sketch of Page 54 with some gyroscopic information. It may not help the reader much in trying to visualize the inverted spin, but it helped me some 30+ years after first becoming involved with the issue.



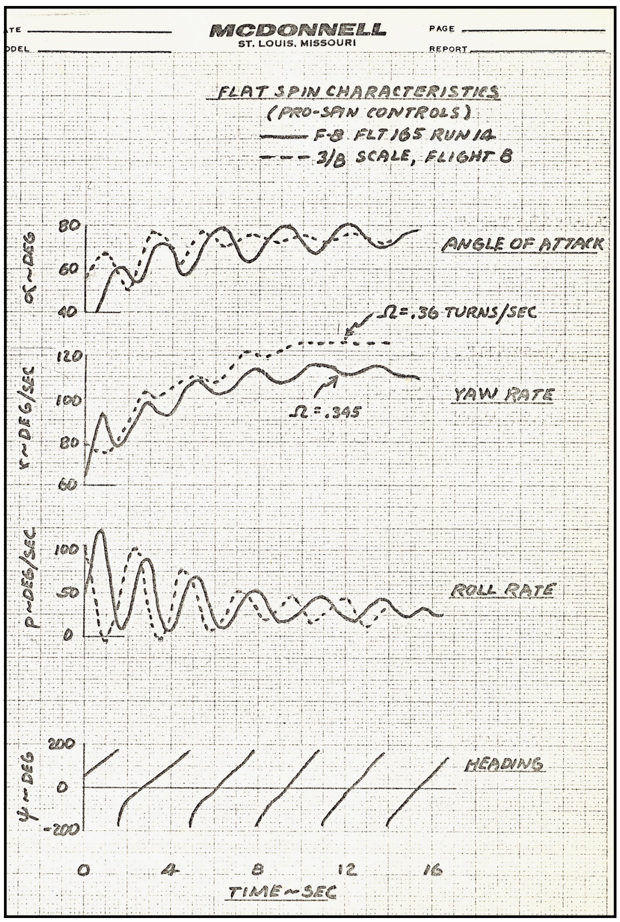


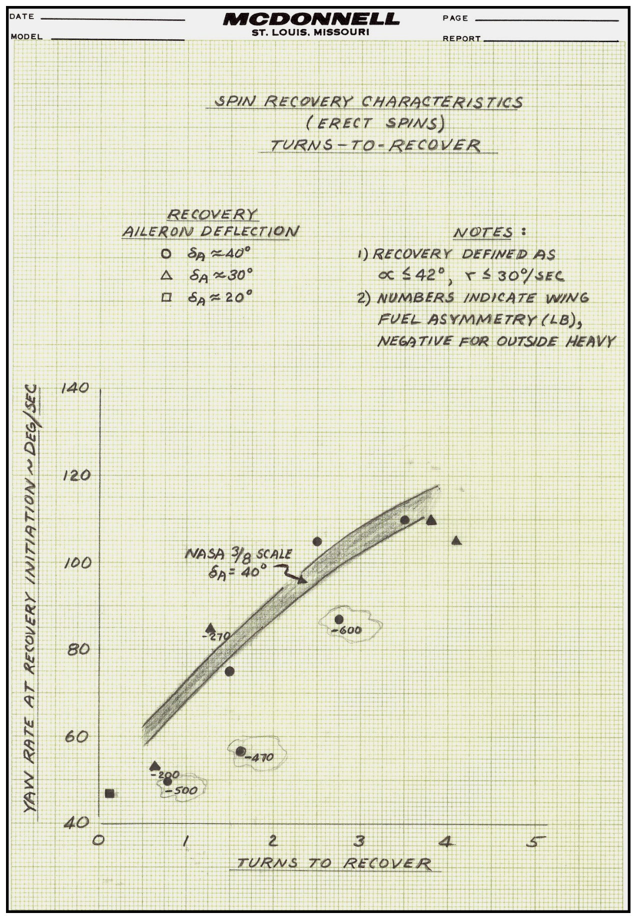
COMPLETION OF THE SPIN TEST PROGRAM

Prior to the first inverted spin of 25 Feb 75, we had accomplished 19 spins total (including the inadvertent spin with F-15#1). During the remaining six months of the program, another 97 spins were made (for a total of 116) from a total of about 200 deliberate spin attempts. With enough practice, the spin pilots were able to reach spin conditions using techniques other that the Split-S entry, but always had to use a version of the "ARI Defeat" technique for the laterally symmetric airplane.

We evaluated the effects of asymmetrical external store loadings (up to 10,000 ft-lb) on departure susceptibility, spin, and spin recovery—a first for fighter aircraft.

During this last six month period, NASA DFRC continued tests with the 3/8 scale model. The comparisons of model characteristics with those of the real airplane were remarkable. The last flight of the model was





Flight No. 16 in mid-January 1975. The model (actually the second physical model after the first was destroyed in a landing mishap) was severely damaged on ground impact during an attempted desert landing without the parachute and didn't fly again until after the real airplane testing was completed.

The flight test results enabled us to define some minor, but significant, control system modifications and warning cues which were eventually incorporated into production. These included speedbrake retraction at 15.5 degrees AOA, full authority lateral control for spin recovery above a 60 deg/sec yaw rate, a 30 deg/sec yaw rate warning tone. In addition, we recommended incorporation of a fuel asymmetry warning cue for the pilot. The missile launch sequence was modified as a consequence of the asymmetric loading effects we encountered.

The F-15 Stall / Departure / Spin program was arguably the most successful in history. We didn't lose an airplane. For the first time for any spin program, we were able to systematically determine the effects of large amounts of lateral asymmetry, and we demonstrated the value of sub-scale model tests in full-scale airplane development.

Category II testing ended with the last high AOA flight of F-15#8 on 30 Jul 75. The successful conclusion of the test marked the first time in the history of jet fighter aircraft that all development flight tests were accomplished without losing a test airplane. That record still stands today.

With the end of Category I and II development tests, my work at the Flight Test Center was complete. It was time to return to St. Louis operations. After a final farewell party, we packed up most of our belongings (everything except son, Dave, and his possessions which included his motorcycle and the '64 Corvair once owned by my dad. Dave would stay to finish his senior year.

There will be more F-15 adventures in a later chapter..

Jack Abercrombie
9 December 2007