JOURNAL OF AIRCRAFT
Vol. 42, No. 3, May–June 2005

Accomplishments of the Abrupt-Wing-Stall Program

Robert M. Hall*
NASA Langley Research Center, Hampton, Virginia 23681
Shawn H. Woodson†
U.S. Naval Air Systems Command, Patuxent River, Maryland 20670
and
Joseph R. Chambers‡
Ball Aerospace, Fairborn, Ohio 45324

The Abrupt-Wing-Stall (AWS) Program has addressed the problem of uncommanded lateral motions, such as wing drop and wing rock, at transonic speeds. The genesis of this program was the experience of the F/A-18E/F program in the late 1990s, when wing drop was discovered in the heart of the maneuver envelope for the preproduction aircraft. Although the F/A-18E/F problem was subsequently corrected by a leading-edge flap scheduling change and the addition of a porous door to the wing fold fairing, the AWS program was initiated as a national response to the lack of technology readiness at the time of the F/A-18E/F development program. The AWS program objectives were to define causal factors for the F/A-18E/F experience, to gain insights into the flow physics associated with wing drop, and to develop methods and analytical tools so that future programs could identify this type of problem before going to flight test. The major goals of the AWS Program, the status of the technology before the program began, the program objectives, the accomplishments, and the impacts are reviewed. Lessons learned are presented for the benefit of programs that must assess whether a future vehicle will have uncommanded lateral motions before going to flight test.

Nomenclature

C_L	=	lift coefficient
C_{WB}	=	wing-bending moment coefficient
c_l	=	sectional lift coefficient
M_∞	=	Mach number
α	=	angle of attack, deg

Introduction

THE Abrupt-Wing-Stall (AWS) Program has addressed the problem of uncommanded lateral motions, such as wing drop and wing rock, at transonic speeds with experimental, computational, and simulation tools. This coordinated, focused program has been a cooperative effort of government, industry, and academia.[1] The general objectives of the program are based on the technology shortcomings identified during the wing-drop experience of the preproduction F/A-18E/F aircraft.[2] The AWS program has extended its research scope beyond the preproduction F/A-18E to include three other aircraft, the AV-8B, the F/A-18C, and the F-16C. Additionally, the AWS program has employed computational fluid dynamics (CFD) to investigate all four configurations and, specifically, to understand why the preproduction F/A-18E had to overcome the wing drop challenge, whereas the F/A-18C did not. Additional efforts were invested in simulating wing drop with the F/A-18E simulation package.

The research objectives of the AWS program can be grouped into four major topic areas. The first area of research was to analyze the existing legacy data from the preproduction F/A-18E wing-drop resolution efforts and other historical programs. The F/A-18E wing-drop resolution effort, in particular, offered an abundant source of wind-tunnel data, CFD grids and results, and flight data for the wing-drop events. The second research area included efforts to generate new data to complement and extend the legacy data for the preproduction F/A-18E. These new data addressed the AWS program objectives of both understanding the flow physics involved in the abrupt stall on the early F/A-18E, as well as establishing a foundation for understanding other configurations. The third research area was that of developing new experimental wind-tunnel methods, developing figures of merit for wind tunnel and CFD, and improving the mathematical simulation tools. The key objectives were to have in place better methods and tools and to advance the state of the art so that a future program can satisfactorily predict whether its aircraft will experience transonic uncommanded lateral motions well before flight tests. The fourth, and last, topic area was to conduct an assessment of the developed methods and figures of merit. This assessment was to be conducted by static and dynamic wind-tunnel test techniques and CFD calculations for two configurations susceptible to wing drop, the pre-production F/A-18E and the AV-8B at extremess of its envelope, and for two configurations not susceptible to drop, the F/A-18C and the F-16C.

The paper will summarize the results from each of the four major research areas. The reader is referred to other AWS, or related, reports for a detailed overview of the research efforts to date.[3–22] Following the highlights of the research areas, lessons learned will be summarized and presented according to discipline: wind tunnel, computations, and simulation.

To obtain approval for releasing this paper to the public, quantitative information has been removed from most vertical scales as directed by guidelines from the Department of Defense.

Research Areas

Each major topic area will be organized by subsections, providing the state-of-the-art at the beginning of the AWS program, efforts undertaken, accomplishments, and impacts.

Legacy Data

State of the Art

In past generic studies and experiences with other specific aircraft programs, certain flow phenomena had been observed that were

Presented as Paper 2003-0927 at the AIAA 41st Aerospace Sciences Meeting, Reno, NV, 6–9 January 2003; received 18 July 2003; revision received 16 October 2003; accepted for publication 18 October 2003.

*Senior Research Engineer. Associate Fellow AIAA.
†Aerospace Engineer. Associate Fellow AIAA.
‡Senior Consultant, Systems Division.

believed to contribute to wing drop and wing rock. Specifically, these phenomena included loss of aerodynamic damping in roll for wings with abrupt stall characteristics, out-of-trim rolling moments at stall, unsteady shock-induced separation at high subsonic and transonic conditions, and dynamic vibrations of models during wind-tunnel tests. Unfortunately, these observations had not been focused into a coordinated effort to develop analysis procedures and figures of merit over a variety of aircraft platforms.

AWS Efforts

The first of two initial contractual efforts funded by the AWS program was to task Chambers and Hall[3] to survey past aircraft programs that experienced uncommanded lateral motions, such as wing drop, wing rock, or heavy wing, at transonic conditions. When the documented occurrences of uncommanded lateral motions were combined, it became clear that many of the high-performance aircraft programs over the past 50 years had experienced problems with lateral motions in the transonic speed regime. In virtually all cases, the degraded lateral behavior had not been predicted before actual flight tests in the aircraft development program. The second of the initial contracts was to task The Boeing Company to summarize and organize their wind-tunnel efforts to resolve the F/A-18E/F wing drop problem. In addition, AWS participants, with help from U.S. Naval Air Systems Command (NAVAIR) flight-test personnel, were also able to review flight-test information as well as flight videotapes.

Accomplishments

The task by Chambers and Hall[3] was important because it clarified the scope and breadth of the challenge that uncommanded lateral motions have been to a variety of aircraft with various leading-edge sweeps, airfoil sections, and other broad differences in planform (Fig. 1). This review[3] also highlighted the experiences from a number of development programs, F-4, F-5, F-111, F-14, British Gnat, and YF-17. An example from the F-4 history is given in Fig. 2, which illustrates the benefit, for that aircraft, of adding leading-edge slats to the wing. All three significant stages of increasingly undersirable flight characteristics, buffet onset, wing rock, and wing stall, are significantly delayed by the addition of the slats.

That the flow was unsteady over the F/A-18E wing in the angle-of-attack range near wing drop was apparent after reviewing the flight videotapes and talking with test flight personnel (Hall and Woodson). This important observation led the AWS Program to take unsteady pressure measurements during the wind-tunnel testing and explore unsteady computations.

Impact of Results

First, uncommanded transonic lateral motions, such as wing drop and wing rock, have been documented for a wide variety of aircraft planforms and airfoil sections.[3] In light of this experience, the characteristics of the preproduction F/A-18E/F were not unique by any means. Future high-performance aircraft programs should be alert for the possible existence of this problem early in design and development.

Second, unsteady, shock-induced separation had been observed in past programs; however, the AWS program focused on unsteadiness as a potentially important aspect of the abrupt stall process.

Fig. 1 Examples of high-performance aircraft that have had to deal with uncommanded lateral motions; see Chambers and Hall.[3]

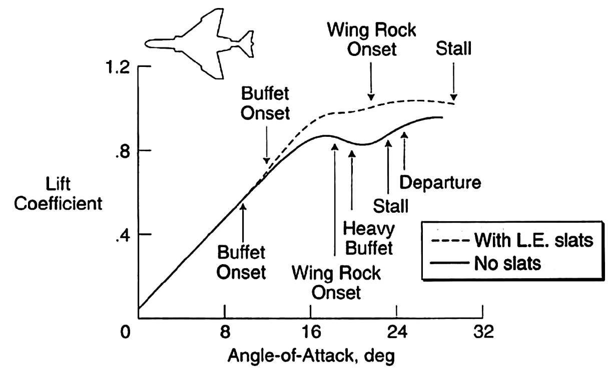


Fig. 2 Lift curve variation for basic F-4 and F-4 with leading-edge slats.

Developing Flow Understanding

State of the Art

Interpretations of the different aspects of the abrupt stall process had already surfaced during the wing-drop resolution effort for the preproduction F/A-18E/F. However, the fundamental abrupt stall process was not understood. For example, was the abruptness of the stall due to leading-edge separation or was it due to the shock-induced, boundary-layer separation migrating forward from the trailing edge? The importance of flow unsteadiness was another unknown.

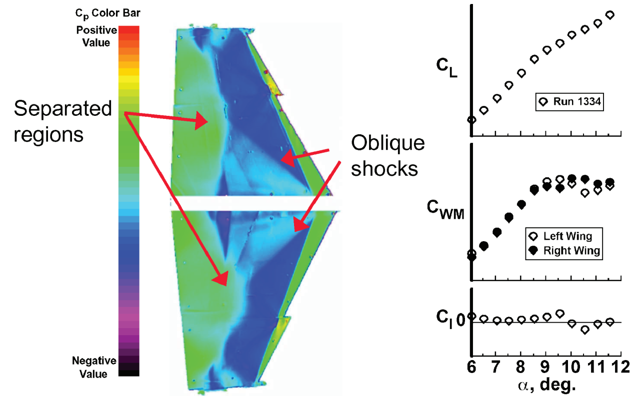
Another question involved which wing geometry differences between the F/A-18C and the F/A-18E were responsible for the increased sensitivity of the preproduction F/A-18E to wing drop, in contrast to the F/A-18C, which did not display that problem.

AWS Efforts

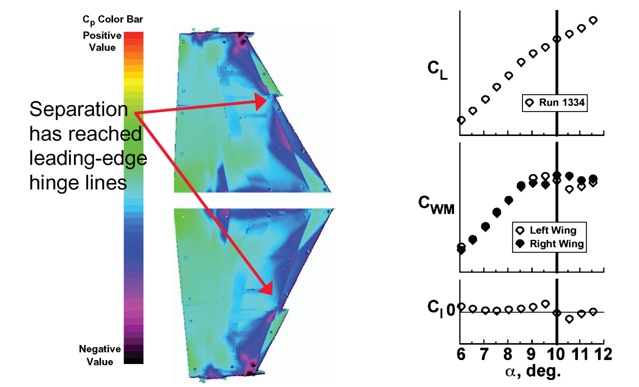
Fundamental understanding of physical phenomena associated with abrupt-wing-stall was one of the major objectives of the AWS program. Two major transonic wind-tunnel entries were dedicated to this effort and involved the use and interpretation of steady and unsteady pressure transducers, wing-root bending moments, and pressure-sensitive paint (PSP) images. An equally broad CFD effort was conducted in which three major codes were utilized: WIND,[5,14] TetrUSS,[8,9] and COBALT.[7] All three codes were used in the Reynolds-averaged Navier–Stokes, time-averaged mode, and one code, COBALT, was used in a time-accurate detached-eddy simulation (DES) mode. Both the wind-tunnel and CFD efforts were focused on determining the critical flow separation process leading to the abrupt stall. Another very informative study that yielded a large degree of understanding was an effort by Green and Ott,[14] who addressed the question of which of the wing geometric differences between the preproduction F/A-18E and the F/A-18C were most responsible for the increased sensitivity to abrupt stall displayed by the preproduction F/A-18E.

Accomplishments

Static and dynamic wind-tunnel results are reported by McMillin et al.,[4] Schuster and Byrd,[6] Lamar et al.,[10] and Owens et al.[12] PSP images taken by McMillin not only describe the surface pressures over the F/A-18E wing panels but also correlate well with measured forces and moments, see Fig. 3 for an example. The paper by McMillin contains many PSP images which document the variability of the surface flow state with angle of attack and with repeat data.



a) $\alpha = 6.1$ deg



b) $\alpha = 10.0$ deg

Fig. 3 PSP images from Langley 16-ft TT correlated well with asymmetries in balance forces and moments; baseline, flaps at 10/10/5 deg, and $M_\infty = 0.90$.

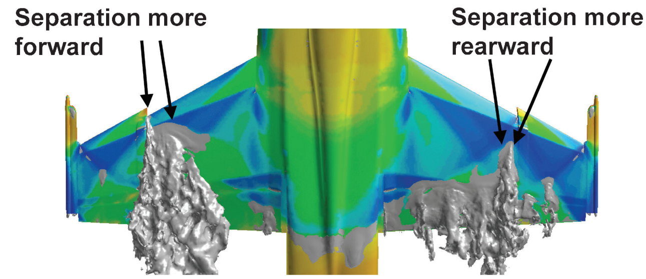


Fig. 4 Asymmetry in separation patterns between left and right wing panels, $M_\infty = 0.90$ and $\alpha = 9.0$ deg.

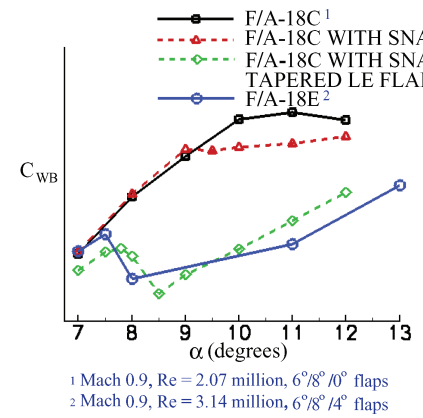


Fig. 5 Results of Green and Ott[14] showing impact on wing-root bending by modifications to the F/A-18C compared to preproduction F/A-18E.

With regard to measurements of flow unsteadiness, Schuster and Byrd[6] determined from pressure time histories the range of unsteady transonic shock movement and the magnitude of pressure fluctuations as a function of angle of attack. This work also served to provide crucial calibration of the unsteady computational work conducted by Forsythe and Woodson.[7] Additional unsteady information was captured by routing the signals from the wing-root bending gauges, accelerometers, balances, and pressures through rms instrumentation at the wind-tunnel facility.[4,10,16] These measures of unsteadiness, although not containing any frequency content, produced, with little effort, valuable insights into the levels of unsteadiness through the stall process.

The steady-state computational work highlighted the importance of the upwash being generated inboard of the leading-edge snag on the preproduction F/A-18E.[5] This upwash generated by the snag is strongest just inboard of the snag and makes that area along the leading edge most vulnerable to separation. Consequently, the snag appears to be a key feature driving the separation process over this wing. This vulnerability is also highlighted by unsteady COBALT DES solutions by Forsythe and Woodson.[7] Their animation of the flow near the notch of the snag illustrated two important observations. First, vorticity is being shed from the snag in the notch region. Second, the amount of vorticity shed and the entire shock system just downstream of that snag are unsteady and fluctuate near the abrupt stall conditions. An instant in time for one of their DES computations is shown in Fig. 4. Even though the oncoming flow is symmetric, asymmetries in separation patterns downstream of the snags develop between the left and right wing panels. The levels of rolling moment asymmetries predicted by Forsythe and Woodson are of the correct magnitude, based on flight values, and are the result of shock-induced separation being farther forward on one wing panel than on the other. The asymmetries appear without intentional intervention in the code and are attributed by Forsythe and Woodson to amplification in the unstable flow of asymmetries in the grid partitioning, ordering of the grid, machine roundoff, etc. In fact, they show that the separation over the wings is periodic. That is, the shock will first be forward on one wing panel but then will be forward on the other wing panel. These asymmetries found by Forsythe and Woodson can provide a trigger mechanism for the wing-drop process itself.

However, the addition of the snag was not the only geometric difference between the F/A-18E and the F/A-18C that significantly influenced the flow. Green and Ott[14] computed angles of attack at which abrupt stall was predicted to occur for the baseline F/A-18C wing and then repeated these same computations for the F/A-18C wing modified to incorporate the various geometric differences between the F/A-18C wing and the F/A-18E wing. They examined individually, and in selected combinations, the effects of adding the snag, reducing the local chord of the leading-edge flap, reducing leading-edge radius, increasing the thickness of the wing, and removing camber and twist. As reported by Green and Ott,[14] the addition of the leading-edge snag and the reduction of the local leading-edge flap chord associated with the F/A-18E leading edge were the primary factors influencing the increased sensitivity of the preproduction F/A-18E to abrupt stall. In addition, for the application of a snag as implemented by the F/A-18E, the lateral location of the minimal leading-edge flap local chord is just inboard of the snag and is at the position where the likelihood of flow separation about the flap is greatest because of the snag upwash.

Figure 5 summarizes the wing root bending moment, a figure of merit, for the various configurations assessed in Ref. 14. Whereas the aileron deflection is different between the F/A-18C, 0 deg, and F/A-18E, 4 deg, aileron deflections in flight test for the F/A-18E were found to have only a modest effect on the occurrence of wing drop and are not expected to significantly influence the comparisons in Fig. 5. As can be seen in Fig. 5, the slope of the wing-root bending moment for the F/A-18C is positive up until a value of α of about 11 deg. (When the slope of the bending moment curves becomes zero, it is expected that roll damping of the configuration can become neutrally stable or go unstable.) When a snag is added to the baseline F/A-18C configuration, the zero slope α drops

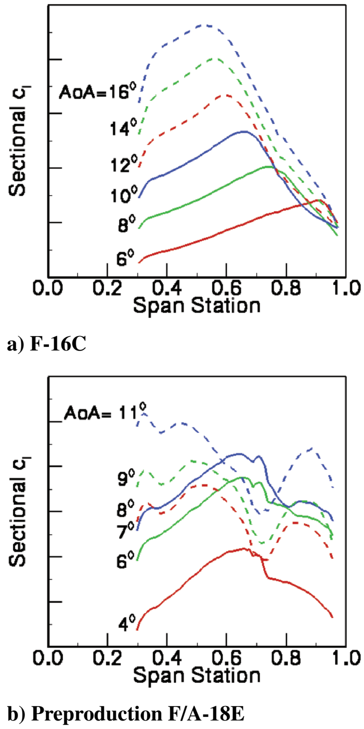


Fig. 6 Sectional lift distributions for two aircraft at $M_\infty = 0.80$.

down to 9 deg. Furthermore, when the tapered, or reduced chord, leading-edge flap is simulated in addition to the snag, the zero slope α becomes 7.75 deg. The same information for the preproduction F/A-18E is also shown and is quite similar to the F/A-18C with the snag and the tapered leading-edge flap. This observation, among others, led Green and Ott[14] to conclude that the snag and the tapered leading-edge flaps are the critical geometry differences that explain the sensitivity of the preproduction F/A-18E to wing drop.

Insights into design were also gained by conducting CFD computations on three other configurations, the AV-8B, the F/A-18C, and the F-16C.[8,9] In the research by Parikh and Chung[8] (Fig. 6), it is clear that there were significant differences in sectional lift distribution as a function of angle of attack between the preproduction F/A-18E and the F-16C, which is known not to exhibit wing drop. Whereas the sectional lift distribution for the F-16C generally shows a smooth progression of maximum sectional lift migrating inboard, the F/A-18E distribution is highly nonlinear with an obvious collapse in its lift distribution between the 0.6 and 0.8 span stations beginning at an angle of attack of 8 deg. Examining sectional lift distributions across the wing through the stall process using CFD codes can give a quick glance at how abrupt, or smooth, the stall process is and may form the basis for a design metric.

Impact of Results

First, new guidelines are provided for the density of experimental and CFD data required to describe the aircraft behavior through the potentially abrupt stall region. For example, it is not feasible to test with 2-deg increments in angle of attack and detect the abrupt character of the wing stall. Smaller increments, on the order of 0.5 deg, are needed in the wing stall angle-of-attack range.

Second, the findings involving the unsteady character of the experimental pressures as well as the unsteady nature of the COBALT DES solutions have important implications. The very presence of these shock oscillations may provide a trigger for the wing-drop motion.

Third, design insights are provided by morphing work by Green and Ott,[14] as well as other computational studies.[8,9,17]

Fourth, work by Green and Ott[14] provides a methodology to obtain the background information to make trades between the transonic maneuver capability and other mission requirements. With this approach, it is possible to assess quantitatively the impact on transonic maneuver limits of geometric modifications such as adding snags, reducing flap chord length, thickening wings, and removing camber and twist.

Developing Methods and Approaches

State of the Art

Before and during the F/A-18E resolution effort, transonic wind-tunnel test data lacked credibility with regard to predicting wing drop. This lack of credibility occurred when several modifications to the subscale models that appeared to show significant improvement during the tunnel testing proved to be disappointing when applied to the aircraft and evaluated by flight test. Computational tools had not been fully validated against wind-tunnel or flight data and also lacked metrics. In addition, the mathematical simulation of the F/A-18E did not have the capability to resolve relatively abrupt changes in aerodynamic properties. In general, the methods and approaches were not in place to assist the wing-drop resolution effort in a timely and reliable manner. Consequently, flight test, with its costs, limitations, and "cut and try" approach, was considered the definitive tool with which to evaluate modifications.

AWS Efforts

Significant effort was expended to explore thoroughly candidate figures of merit for both wind-tunnel experiments and CFD. The most desirable means of predicting uncommanded lateral activity would be during the usual static, or conventional, testing early in the development process. Consequently, much of the effort for experimental figures of merit involved examining the results of static wind-tunnel testing. All wind-tunnel entries performed by the AWS program were scrutinized on this basis.

However, it became clear from historical data[19,20] and from data being collected during the AWS experiments, that static figures of merit may not have sufficient reliability to predict activity confidently before going to flight test. Consequently, an effort began to adapt an existing dynamic testing technique allowing the model to be free-to-roll (FTR) about its body axis to assess dynamic stability. The FTR technique had been used for low-speed evaluations[21,22] but had not been used transonically in large tunnels. Furthermore, a different approach was used for the new transonic FTR rig,[11] which was to mount the rotating fixture in the support structure downstream of the model sting. This was in contrast to the usual low-speed approach, which replaced the model balance with a fixture within the model that permitted body-axis rotation. This new approach permitted testing with a typical metal model built for performance testing, its model balance, and its model sting. In addition, the approach permitted both static, or conventional, testing when the FTR feature was locked out with a bar and then immediate FTR evaluation by removing the locking bar if anything suspect was seen in the static testing results. As a result of this design, FTR testing could be concurrent with static testing, and there would be no need to build a special model or to schedule a dedicated wind-tunnel entry at a later date.[11]

The other major thrust of this specific research topic area within the AWS program was in the area of flight dynamics and simulation. As mentioned, the initial mathematical simulation of the F/A-18E was not designed to model abrupt nonlinear changes or asymmetries in aerodynamic coefficients because of the sparseness of the data input angles of attack. Furthermore, it was not understood what variables, or combination of variables, had to be modified to simulate the wing-drop events seen in flight. Once it was found that introducing spikes into the rolling moment and reductions in roll damping over a short range of angle of attack led to reasonable agreement with the flight data records, an additional objective of this effort was to determine if pilots in a fixed-based simulator could get enough visual cues to interpret the aerodynamic response as a wing drop.[15,18] As demonstrated by Kokolios and Cook,[15] the simulation studies found that pilots would indeed rate disturbances in the simulator in a manner comparable to the corresponding disturbances in flight test. That is, in Fig. 7, the flight-derived green and yellow boundaries are representative of the general splits in the simulation results between the green points, clean maneuvers, the yellow points, lateral

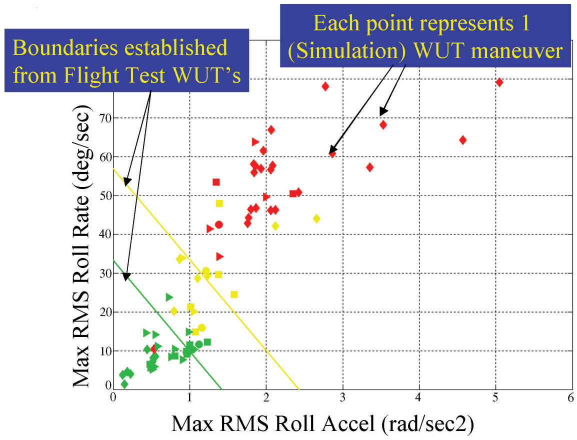


Fig. 7 Piloted simulation demonstrated to reproduce wing drop; wind-up turns (WUT) utilized.

motions that could be promptly countered by small lateral stick deflections, and the red points, where lateral activity was such that mission performance would be degraded.

Accomplishments

The effort expended to develop static figures of merit arrived at the same conclusion as the efforts of Boeing during the resolution effort with the preproduction F/A-18E: There is not one all-encompassing static figure of merit that is reliable for general configurations.[10]

On the other hand, the results with the FTR rig met or exceeded expectations.[12,16] As will be detailed under the next major topic, the FTR technique is considered a robust national asset and is recommended to resolve any abrupt stall questions identified during static testing.

Simulation modifications were also successful.[15] First, modifications to the simulation were developed that permitted the modeling of abrupt nonlinear events, such as wing drop. Second, it was found that the key input variables that are required to model adequately a wing drop are asymmetric rolling moments at zero sideslip and reductions in roll damping. Both of these variables can be measured during either static testing or determined by applying parameter identification techniques to the FTR data. Third, it was also demonstrated that fixed-base simulators could replicate a wing drop realistically, based on evaluations by pilots familiar with wing drop in flight.

Impact of Results

First, static, or conventional, wind-tunnel testing does not, based on AWS efforts, appear to predict reliably angles of attack at which uncommanded transonic lateral activity will occur in flight.

Second, based on the present four-configuration study, testing with a FTR rig will provide a robust indication of possible uncommanded lateral motions in flight. This capability should be used to evaluate all new configurations that maneuver at transonic conditions with highly separated wing flows.

Third, piloted simulation, when modified as developed during the AWS program, can replicate wing drop in a realistic manner. When the simulation databases are provided with values of roll asymmetries at zero sideslip and values of roll damping from FTR testing, simulation should be capable of evaluating the impact of those nonlinearities on mission performance before going to flight test.

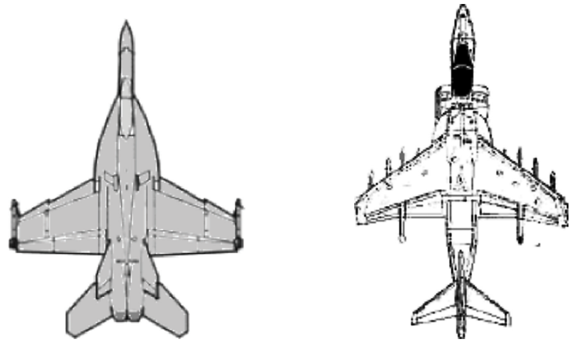
Assessment

State of the Art

Whereas other studies have addressed the problem of predicting abrupt stall for specific configurations, no other study has appeared to assess their figures of merit over a range of vehicles. Because much of the early AWS research involved the preproduction F/A-18E/F configuration, it was recognized that all of the derived AWS figures of merit, methods, and approaches would have to be

Table 1 Wing comparisons

Parameter	F/A-18E/F	AV-8B
Aspect ratio	3.5	4.0
Leading-edge sweep, deg	29.4	36
Airfoil	Uncambered	Supercritical
Leading-edge radius	Essentially sharp	Blunt
Thickness ratio,%	6.2–4.3%	10.5 average
Twist, deg	None	0–8
Dihedral, deg	−3.4	−10.3
Leading-edge snag	Yes	No
Leading-edge flap	Yes	No
Trailing-edge flap	Yes	Yes
ALEX/ARef, %	15	4



a) b)

Fig. 8 Wing drop occurs for wings with significant differences: a) F/A-18E/F and b) AV-8B.

assessed and validated for other configurations as well. Specifically, the goal was undertaken to validate these AWS efforts by testing another aircraft that exhibits wing drop, the AV-8B near the extremes of its flight envelope, and by testing two other aircraft that do not exhibit wing drop in flight, the F/A-18C and the F-16C. If any of the figures of merit or methods from the AWS program were going to have credibility, these figures of merit and methods would have to be effective for another configuration susceptible to wing drop and for those that are not.

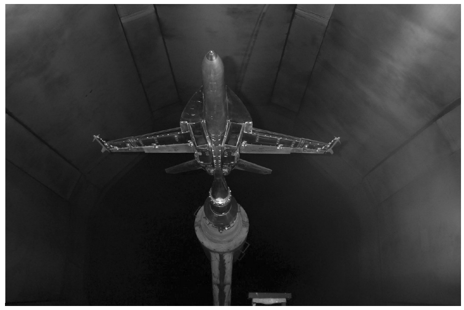
AWS Efforts

The approach taken by the AWS program was to evaluate all four aircraft by 1) performing CFD calculations at conditions representative of the FTR wind-tunnel test program and 2) conducting both static, or conventional, testing and FTR testing. As already stated, the two aircraft that were susceptible to wing drop were the preproduction F/A-18E and the AV-8B. Because these two configurations have very different wing characteristics (Fig. 8 and Table 1) there was reason to suspect that there could be differences in the flow mechanisms of wing drop and wing rock for these two aircraft. The two aircraft configurations that did not exhibit drop in flight, the F/A-18C and the F-16C, were considered a control group. The four models representing these aircraft are shown in Fig. 9 as they were tested in the Langley 16-ft Transonic Tunnel (TT).

The databases developed by computations and the wind tunnel were then utilized for a number of critical analyses. First, both sets of data were used to evaluate the accuracy of candidate static figures of merit.[8–10,16,17] Second, the experimental FTR data were evaluated by comparing to flight data for each of the configurations.[12,16] Third, the wind-tunnel data were also used to calibrate the static predictions of forces and moments for the CFD results.[8,9] The first two of these analyses were critical to establish a risk reduction approach for future aircraft.

Accomplishments

The assessment program was successful in reaching its objectives. With regard to static figures of merit, it is reported by Lamar et al.[10] that they are not robust predictors of lateral activity. For example, if



a) Pre-production F/A-18E

b) AV-8B

c) F/A-18C

d) F-16C

Fig. 9 Four aircraft evaluated by both static and FTR testing in the Langley 16-ft TT.

nonlinearities are present in the lift-curve slope, then lateral activity, such as wing drop, may occur at that angle of attack or at a higher angle of attack or not at all.[10] Of course, part of the difficulty with the static figures of merit is in determining thresholds magnitudes for significant slope changes in the respective parameters. The problem is that such thresholds are not obvious from the present work and may actually vary from configuration to configuration.

The agreement between the FTR predictions of lateral activity and what is known from flight-test experience is very good.[12,16] Whereas some development of metrics for this technique has been necessary, it seems that a metric based on both amplitude and rate[12] appears to be most indicative of lateral activity.

With the FTR technique established as a feasible testing technique at transonic speeds, it is now possible to define a procedure for predicting if a future vehicle will experience uncommanded lateral motions, such as wing drop, before going to flight. The procedure is outlined in Fig. 10. The steps are first to conduct static-wind tunnel experiments or time-averaged CFD computations. If alerts are raised in this first stage, such as lift-curve breaks, asymmetries in rolling moment, or peaks in rolling-moment unsteadiness with angle of attack, then it is necessary to evaluate the configuration with the FTR technique. (If the vehicle has to maneuver through wing stall, then FTR testing is strongly recommended regardless of static testing indications.) After FTR data are obtained and if issues remain, then assessments with piloted simulation are in order. The purpose of the piloted simulation would be to determine if what was seen in the tunnel would significantly impact the vehicle mission. If not, the potential problem can be dismissed. If, however, there is an impact on mission performance, then two typical approaches to explore are to 1) redefine the flap schedule to try to work around the conditions at which the lateral activity is predicted to occur or 2) attempt to upgrade the lateral control system with either faster sensors or faster actuators. If these efforts fail, then an aerodynamic configuration change will have to be explored.

The computational results were generally representative of the experimental data obtained for the F/A-18E, the F/A-18C, and the F-16C.[8,9] An exception to this was the calculations for the AV-8B.[9] The CFD solutions predicted wing stall several degrees below that measured in the wind tunnel. This discrepancy is believed, at least in part, to be caused by differences between the full aircraft geometry and the geometry modeled in the CFD calculations. Whereas the

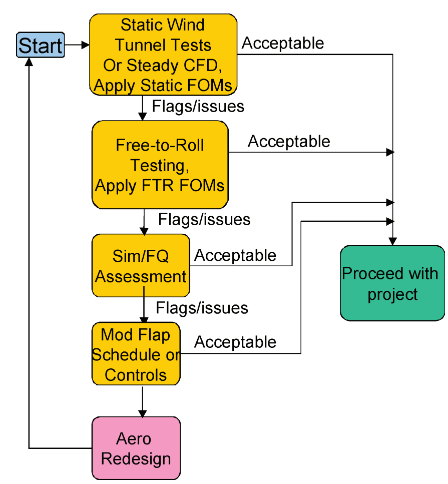


Fig. 10 Proposed risk reduction process for future vehicle programs.

AV-8B flies with one vortilon (similar to a leading-edge fence) and 11 vortex generators on each wing panel to delay wing panel stall, these geometric features were not represented in the CFD grid. In hindsight, it would seem logical that if those devices were tested and placed on the aircraft, they were there to delay separation. Consequently, it is believed that the premature stall found by the CFD solutions are a result of the lack of modeling of the vortilons and vortex generators.

Impact of Results

First, the most significant impact from the aircraft configuration assessment was the clarification of limitations involved with the static figures of merit (FOM) and the success of the FTR technique and its metrics. Within the limitations of having only evaluated four aircraft, the FTR technique appears to be a robust predictor of uncommanded lateral motions in flight.

Second, a recommended procedure to determine if a future flight vehicle has the potential for lateral motions, before going to flight, has been defined.

Lessons Learned

This section will group the lessons learned into the three categories of wind tunnel, computations, and simulation.

Wind Tunnel

First, during conventional, static wind-tunnel testing, it is necessary to be conscious of warning signs, such as severe model dynamics, that are a signal that the flow may be changing topologies. If flow topologies are changing abruptly, then lateral activity is a possibility. Other key indicators are asymmetries in rolling moment, peaks in rolling moment unsteadiness, and lift-curve nonlinearities. However, despite examples of correlation of the named indicators for specific configurations, the AWS efforts demonstrate that, in general, static FOMs are inadequate for predicting uncommanded lateral motions in flight.[10] On the other hand, FTR testing and evaluation appears to be a reliable prediction of what will happen in flight for the present four aircraft study.[12]

Second, during static and dynamic testing, it is necessary to increase the density of data acquired near the wing stall or topology change. It is suggested that the increment in angle of attack be 0.5 deg, or less. If increments are larger than this value, then the abrupt changes in lift slope or rolling moment may be missed.[4]

Third, it is important to test a model with a sufficient number of leading-edge flap settings to be able to simulate the aircraft flying on automatic flap schedule throughout the region of lateral activity.

Fourth, because of the inherent unsteadiness associated with abrupt-wing-stall, it is important to take repeat data for critical conditions or angle-of-attack sweeps. As found by McMillin et al.,[4] differences in the onset of lift-curve breaks and in the magnitudes and trends of rolling moment asymmetries can occur over the duration of a wind-tunnel entry.

Fifth, the most cost-effective instrumentation addition for an abrupt-wing-stall wind-tunnel test is to add wing-root-bending gauges on both wing panels.[10]

Sixth, the PSP method results in useful flow images but is time intensive.[4]

Last, any FOM must be successfully applied to a number of aircraft configurations before being considered reliable and validated.

Computations

First, unsteady CFD calculations for the F/A-18E showed that DES provides a credible means of calculating the unsteady effects associated with abrupt wing panel stall. The simulations were roughly 10 times more expensive than steady calculations. Although expensive, they are possible today and could become more routine as processor speeds increase. DES calculations on a full aircraft showed that shock oscillations on each wing panel can be out of phase and thereby provide the initial impetus for a wing drop event.[7]

Second, whereas greater flow physics are captured by the unsteady DES calculations, the static calculations still appear to yield sufficient information to predict the wing stall region.[17]

Third, the need for fine increments in angle of attack holds true for computations as it does for wind-tunnel testing. Increments at least as fine as 0.5 deg are needed to describe the stall break appropriately.[14]

Fourth, turbulence models have an impact, as does grid density. Changes in configuration should be accompanied by some attempt at code calibration with wind-tunnel force and moment information as well as either oil-flow images or PSP images, if available.

Fifth, frequency of shock oscillations and the magnitude of rolling-moment asymmetry were shown, for the F/A-18E, to be independent of whether the calculation was done on a half-plane grid or on a grid with both left and right wing panels.[7]

Sixth, to describe the stall progression process, it is necessary to employ higher-order CFD codes with a Navier–Stokes level of technology.[8]

Last, if the aircraft under consideration will have fences or vortex generators, then those devices must be modeled for CFD.[9]

Simulation

First, it is clear that asymmetries in the wind-tunnel data can not be ignored when building the aerodynamic database for the mathematic simulation of a high-performance aircraft at transonic speeds. Specifically, rolling-moment asymmetries at zero values of sideslip are a good example of what is typically, but arbitrarily, changed to zero before being placed in the simulation. Whereas it is possible to have rolling-moment offsets due to tunnel swirl or model asymmetries, these would be expected to be relatively constant over the angle-of-attack range and can be eliminated. The asymmetries that are important to retain for the simulation description are those that depend sharply on angle of attack and are resulting from asymmetric wing stall. It is also possible to estimate values of roll damping from the FTR testing. These data are also essential to proper modeling of a configuration in simulation.[15]

Second, increments in angle of attack are an issue for simulation as well as for the tunnel and CFD. Here the need is for sufficiently fine angle-of-attack increments in the simulation so that a nonlinear change over a degree or two can be modeled. This is necessary to capture sharp discontinuities in rolling moment at zero values of sideslip and roll damping as the aircraft passes through abrupt stall.[15]

Third, having a flight FOM, such as that of Roesch and Randall,[13] is an absolute necessity for being able to evaluate the potential impacts of the nonlinearities seen during the experiment.

Summary

At the beginning of the AWS program, the F/A-18E/F program had just resolved an unexpected wing-drop problem with the preproduction F/A-18E by the modification of its leading-edge flap schedule and the addition of the porous wing fold fairing door. The usefulness of transonic wind-tunnel testing and conducting viscous CFD solutions was limited during the preproduction F/A-18E resolution process. FOMs, or metrics, had not been established for conventional wind-tunnel testing or for CFD.

With the progress that the AWS program has demonstrated, it is now possible to assess experimentally the propensity of a vehicle to have uncommanded lateral activity as soon as a wind-tunnel model can be tested. A major contribution of the AWS program is the development of a transonic FTR technique, which allows the wind-tunnel model to rotate freely about its body axis as it reacts to asymmetric wing panel stall and to the presence or absence of roll damping. The FTR technique appears to be a robust means of predicting uncommanded lateral motions, whereas FOMs for conventional, or static, testing have been demonstrated to be unreliable.[10,12,16]

The AWS program studied the transonic flow about the F/A-18E with a variety of computations and with a variety of transonic wind-tunnel instrumentation approaches. It was found that the role of the leading-edge snag in the transonic separation process was critical, based on both experimental PSP data and from computations using both Reynolds-averaged Navier–Stokes and DES levels of technology. Whereas general wing separation is migrating forward from the trailing edge as angle of attack increases, separation generated just inboard of the snag appears to be the key link to the abrupt stall of the wing panel.[4,7,17]

The computational efforts of the AWS program resulted in many additional insights. First, by the modification of a F/A-18C with the different wing geometry attributes of the F/A-18E, Green and Ott demonstrated that the reduced leading-edge flap chord of the F/A-18E was contributing to an earlier separation process.[14] Second, differences were seen between the low-speed and transonic character of abrupt stall. The high-speed character from both the F/A-18E and the AV-8B shows separation beginning in the midwing region, whereas the low-speed separation pattern for the AV-8B was more outboard.[5,7–9] Third, based on comparisons of the sectional lift distributions as a function of angle of attack for both the F/A-18E and the F-16C, a smooth progression of sectional lift through wing stall would seem to be an important design guideline.[8,14]

Other AWS progress occurred in the area of simulation. A procedure was demonstrated that permits modeling, by fixed-based piloted simulation, of potential mission impacts of the AWS activity measured in wind-tunnel testing before going to flight. This can alert a program several years in advance of when the program would have historically detected such a problem in flight test.

References

[1] Hall, R., and Woodson, S., "Introduction to the Abrupt Wing Stall Program," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 425–435.

[2] Harris, R., "Blue Ribbon Panel II Report," *Inside the Navy*, Vol. 11, No. 10, 16 March 1998, pp. 5, 6.

[3] Chambers, J., and Hall, R., "Historical Review of Uncommanded Lateral–Directional Motions at Transonic Conditions," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 436–447.

[4] McMillin, S. N., Hall, R. M., and Lamar, J. E., "Transonic Experimental Observations of Abrupt Wing Stall on an F/A-18E Model," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 586–599.

[5] Woodson, S. H., Green, B. E., Chung, J. J., Grove, D. V., Parikh, P. C., and Forsythe, J. R., "Understanding Abrupt Wing Stall with Computational Fluid Dynamics," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 578–585.

[6] Schuster, D., and Byrd, J., "Transonic Unsteady Aerodynamics of the F/A-18E Under Conditions Promoting Abrupt Wing Stall," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 485–492.

[7] Forsythe, J. R., and Woodson, S. H., "Unsteady Computations of Abrupt Wing Stall Using Detached-Eddy Simulation," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 606–616.

[8] Parikh, P., and Chung, J., "Computational Study of the Abrupt-Wing-Stall Characteristics of F/A-18E and F-16C," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 600–605.

[9] Chung, J., and Parikh, P., "A Computational Study of the Abrupt Wing Stall (AWS) Characteristics for Various Fighter Jets: Part II, AV-8B and F/A-18C," AIAA Paper 2003-0747, Jan. 2003.

[10] Lamar, J., Capone, F., and Hall, R., "AWS Figure of Merit (FOM) Developed Parameters from Static, Transonic Model Tests," AIAA Paper 2003-0745, Jan. 2003.

[11] Capone, F., Owens, D., and Hall, R., "Development of a Transonic Free-To-Roll Test Capability," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 456–463.

[12] Owens, D., Capone, F., Hall, R., Brandon, J., and Cunningham, K., "Free-To-Roll Analysis of Abrupt Wing Stall on Military Aircraft at Transonic Speeds," AIAA Paper 2003-0750, Jan. 2003.

[13] Roesch, M. T., and Randall, B. E., "Flight-Test Assessment of Lateral Activity," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 634–640.

[14] Green, B. E., and Ott, J. D., "F/A-18C to E Wing Morphing Study for the Abrupt-Wing-Stall Program," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 617–626.

[15] Kokolios, A., Cook, S. P., and Niewoehner, R. J., "Use of Piloted Simulation for Evaluation of Abrupt-Wing-Stall Characteristics," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 641–645.

[16] Capone, F. J., Hall, R. M., Owens, D. B., Lamar, J. E., and McMillin, S. N., "Review and Recommended Experimental Procedures for Evaluation of Abrupt-Wing-Stall Characteristics," *Journal of Aircraft*, Vol. 41, No. 3, 2004, pp. 448–455.

[17] Woodson, S. H., Green, B. E., Chung, J. J., Grove, D. V., Parikh, P. C., and Forsythe, J. R., "Recommendations for Computational-Fluid-Dynamics Procedures for Predicting Abrupt Wing Stall," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 627–633.

[18] Cook, S. P., Kokolios, A., Page, A., Chambers, J., Niewoehner, R., Owens, D. B., and Roesch, M., "Integrated Approach to Assessment of Transonic Abrupt Wing Stall for Advanced Aircraft," *Journal of Aircraft*, Vol. 42, No. 3, 2005, pp. 646–652.

[19] Ross, A. Jean, "Flying Aeroplanes in Buffet," *Aeronautical Journal*, Vol. 81, Oct. 1977, pp. 427–436.

[20] Bore, C. L., "Post-Stall Aerodynamics of the Harrier GR1," *Fluid Dynamics of Aircraft Stalling*, CP-102, Paper 19, AGARD.

[21] Nguyen, L., Yip, L., and Chambers, J., "Self-Induced Wing Rock of Slender Delta Wings," AIAA Paper 81-1883, Aug. 1981.

[22] Grafton, S., and Libbey, C., "Dynamic Stability Derivatives of a Twin-Jet Fighter Model for Angles of Attack from –10 deg to 110 deg," NASA TN-D-6091, Jan. 1971.