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Integrated Approach to Assessment of Transonic Abrupt Wing Stall for Advanced Aircraft

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Abrupt wing stall at transonic flight conditions can result in uncommanded rolling motions that have historically degraded flying qualities, compromised mission performance, and reduced safety of flight for a variety of aircraft. Recently, a U.S. government research program, the Abrupt Wing Stall Program, has advanced the state of the art in detection of abrupt wing stall through computational fluid dynamics, experimental aerodynamics, and flight dynamics. It is therefore essential that these tools be combined into an integrated approach that not only provides for the identification of abrupt wing stall, but also allows for the resulting flight characteristics to be assessed and the risks to the aircraft program be mitigated. The primary means of assessing the flying qualities impacts of transonic abrupt wing stall is through the construction of an aircraft math model that can accurately characterize the dynamic response to abrupt stall. The primary means of mitigating program risks is through the inclusion of free-to-roll wind-tunnel testing in the acquisition plan. Recommendations for assessing transonic abrupt wing stall are presented for the aircraft designer and for the program manager.

Nomenclature

$C_{l\,\mathrm{AWS}}$ = rolling moment caused by AWS
Cl_β = dihedral effect (1/deg)
Clo = basic rolling-moment coefficient
Clp = damping-in-roll
β = sideslip angle, deg

Introduction

ABRUPT wing stall (AWS) at transonic flight conditions has presented significant flight dynamics challenges in the development of several major aircraft programs.[1] For AWS-prone aircraft, small disturbances in the flowfield at the AWS flight condition can generate a sudden large imbalance in lift between wing panels, which creates an uncommanded roll. Depending on the lateral characteristics of the airplane, AWS can produce wing drop, wing rock, or a steady roll-off (also known as heavy wing), which can degrade flying qualities, compromise mission performance, and reduce safety of flight. Chambers and Hall[2] provide an excellent overview of the various aircraft that have experienced AWS.

This paper is concerned with the assessment of AWS for advanced aircraft. Advanced aircraft refer to platforms such as tactical aircraft that perform mission-related tasks at elevated load factors in the transonic flight regime. As such, these aircraft will typically be equipped with modern fly-by-wire control systems that are capable of augmenting the dynamic response of the bare airframe with judicious use of flight controls.

One example of an advanced aircraft that experienced AWS is the F/A-18E/F Super Hornet. In flight tests of the F/A-18E/F Super Hornet during the engineering and manufacturing development (EMD) phase of the program, pilots encountered wing drops at transonic flight conditions.[3] Flap schedules were reoptimized, and a porous fairing was added to the wingfold in order to eliminate the wing drops. In 1998, a panel of independent aerodynamics experts convened by the U.S. Department of Defense (DoD) concluded that the root cause of wing drop was not well understood.[4] In response, the DoD and NASA created the Abrupt Wing Stall Program—a five-year collaborative research effort between the U.S. Navy, NASA, the U.S. Air Force, and academia. Hall and Woodson provide a comprehensive overview of the AWS Program in Ref. 5.

The AWS Program has advanced the state of the art in aircraft design considerations, computational fluid dynamics (CFD), experimental aerodynamics, simulation, and flight dynamics. New design tools to assist in the identification of AWS characteristics have been developed. The likelihood of achieving a design free of unacceptable dynamics caused by AWS will be maximized through an integrated application of these tools. Program managers can reduce the risk that AWS poses to cost, schedule, and performance by integrating these new tools into their acquisition strategy.

Design Tools and Processes

A notional design process that the aircraft designer uses to meet flight dynamics requirements is displayed in Fig. 1. In developing the flight dynamics characteristics of an airplane design, the engineer will typically begin by acquiring stability and control data from analytical predictions, CFD calculations, and preliminary wind-tunnel tests. Dynamic wind-tunnel testing can be utilized to predict dynamic and spin characteristics of the configuration. These data are

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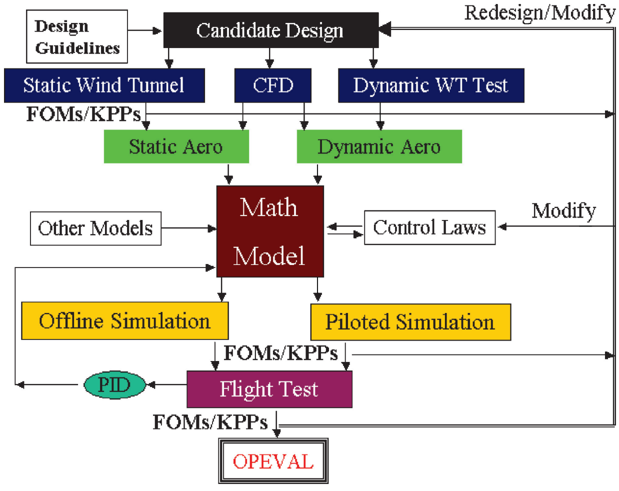

Fig. 1 Notional flight dynamics design process.

implemented into a simulation model, flight control laws are formulated, and the resulting flight characteristics are predicted via offline and piloted simulation. Throughout the design process, the predicted aerodynamic performance and flight dynamics of the candidate design are compared to contract requirements, figures of merit (FOM) developed from best practices, and key performance parameters (KPPs). KPPs are top-level program metrics used to assess overall program risk. Once an aircraft configuration that meets all of the requirements has been finalized, test articles are constructed and flight tested. Ideally, flight characteristics will show close agreement with those predicted through modeling and simulation. Once a significant amount of flight testing has been accomplished, flight characteristics must be adequate to pass an operational evaluation (OPEVAL).

For piloted aircraft, the pilot is the ultimate judge of the aircraft's handling qualities. During preproduction F/A-18E EMD flight testing of wing drop, a qualitative "green-yellow-red" rating system was employed to assess the severity of wing drop during wind-up turns.[3] Although this technique was satisfactory for flight tests, the designer and the program manager require a means to assess risk before flight test. Therefore, a significant development in the AWS Program occurred when Roesch and Randall derived a FOM that connected qualitative pilot assessments of wing drop in flight to quantitative values of the rms of roll rate and rms of roll acceleration.[6] This finding provides the designer with quantitative thresholds with which to evaluate the dynamic predictions from the math model.

Math Model Development

The key to assessing AWS before the first flight-test article is built is to develop an accurate math model that is capable of predicting nonlinear aircraft dynamics resulting from an aerodynamic bifurcation, a sudden change in flow topology that occurs when a critical value of a parameter is reached. In the context of this paper, "math model" refers to the empirical data that represent the aircraft, the number and type of terms used to implement these data into force and moment coefficients, and the assumptions made in the equations of motion. There are primarily two factors that determine the accuracy of the math model: first, the accuracy of the aerodynamic, mass, propulsion, actuator, and other data that are empirically obtained and implemented into the model; and second, the assumptions made in the equations of motion and associated coefficient build-up equations that determine the structure of the math model. Both of these factors will be discussed in detail. Because the objectionable dynamics as a result of AWS occur primarily in the lateral axis, rolling-moment characteristics will be emphasized. Furthermore, although an aerodynamic bifurcation can be accompanied by flow unsteadiness it is assumed that the flight dynamics impacts of AWS can be adequately represented using time-independent aerodynamic functions.

Static Aerodynamic Data

Aerodynamic data are obtained from analytical predictions, CFD studies, and experimental techniques. Although CFD holds much promise for future math model development, to date the vast majority of data implemented into aerodynamic databases are derived from the wind tunnel. Therefore, it is essential that planning for the transonic wind-tunnel testing includes careful evaluation near wing stall angles of attack (AoAs). In past aircraft programs, a common reaction to lateral asymmetries observed in the aerodynamic data near stall AoAs on a symmetric model with symmetric boundary conditions has been to ignore or dismiss the finding as "bad data." To remedy this misperception, Capone et al.,[7] provide guidelines for assessing AWS characteristics. These recommendations include measuring the variability of the balance signals, equipping the wind-tunnel model with wing bending gauges, and obtaining data in half-degree AoA increments near wing stall. Lamar and Hall[8] discuss guidelines on how to interpret these measurements. These conclusions are based on static data acquired by pitching the model to a specified incidence angle, pausing the model at this condition, and recording data. Several transonic wind tunnels utilize a continuous-sweep technique to improve test efficiency. In this technique, static data are acquired while the model is swept through a range of AoAs. If this technique is used, it is recommended that pitch-pause experimental runs be executed at the beginning of the test and the data compared to those acquired through continuous sweep at various sweep rates. The optimum sweep rate is then determined by comparison to the pitch-pause data. Nevertheless, the significance of the variability in balance signals acquired through continuous sweep is not known. Furthermore, flight experience has indicated that the severity of the uncommanded dynamics is inversely proportional to rate of change of AoA.[3] Therefore, a hybrid technique combining pitch-pause sequences near wing stall AoAs and the continuous sweep method at other AoAs might provide a significantly increased probability of detecting flow bifurcation.

Lamar and Hall[8] researched several candidate FOMs developed from static aerodynamic data that appear to provide necessary, but not sufficient, conditions for bifurcation. In addition to these FOMs, hysteresis in the force and moment data might be an indicator of aerodynamic bifurcation.[9] For this reason, it is important to perform run sequences including both increasing and decreasing angles of attack. Furthermore, sideslip surveys should be performed at small sideslip increments in both directions at AoAs where FOMs indicate the possibility of AWS. The presence of hysteresis in sideslip at an AoA flagged by another FOM is a clear indicator of a flow bifurcation.

Static stability data should be obtained in such a way to maximize flexibility into math model implementation.[10] For example, traditional linear representations of the rolling-moment build-up equation might not capture nonlinear lateral stability characteristics near stall. Figure 2 shows a notional example of both linear and nonlinear rolling-moment trends with sideslip (dashed and solid lines, respectively). In the rolling-moment build-up equation at a

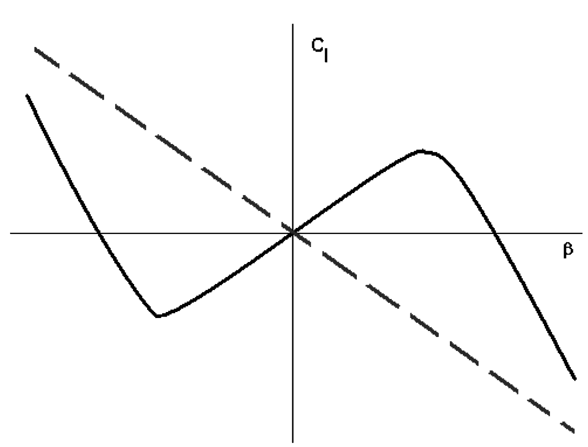

Fig. 2 Notional rolling-moment trends with sideslip.

specified Mach number as shown in Eq. (1), dihedral effect $C_{l\beta}$ is represented as a function of AoA only:

$$C_l(\alpha) = C_{l_o}(\alpha) + C_{l\beta}(\alpha)\beta + (b/2V)\left[C_{l_p}(\alpha)p\right] + \Sigma\Delta C_{l\,\text{controls}} \quad (1)$$

Although this aerodynamic model can accommodate the linear trends shown in Fig. 2, this model is not well suited for the nonlinear lateral stability trends. Thus, in order to obtain an accurate assessment of AWS it is essential that nonlinear stability trends be identified and that the buildup equations accommodate them. Therefore, stability characteristics must be evaluated over several values of sideslip, especially near wing stall.

Dynamic Aerodynamic Data

Dynamic stability derivatives are normally obtained at low-speed test conditions using forced oscillation testing. Although a transonic forced oscillation capability exists,[11] it has not been widely applied to advanced aircraft. Previous attempts (as early as the 1920s) to predict roll damping for high-aspect-ratio wings involved the integration of two-dimensional airfoil characteristics using strip theory. Although this approach was very successful in predicting dramatic reductions in damping encountered near and at stall, it is not applicable to the moderate- and low-aspect-ratio wings of many advanced aircraft, which exhibit powerful three-dimensional flow effects. Thus, values for transonic dynamic stability derivatives have frequently been determined from analytical methods or extrapolated from subsonic results.

Kokolios and Cook[12] indicate that damping-in-roll *Clp* is an important parameter in replicating adverse dynamics from AWS. Although the emerging sophistication of CFD methods for computation of unsteady aerodynamics offers exciting possibilities, the state of the art does not offer a validated computational method for predicting dynamic aerodynamic data. Therefore, the AWS Program has focused attention on empirical means of determining *Clp*.

Capone et al.[13] developed a transonic free-to-roll wind-tunnel test technique as part of the AWS Program. Owens et al.[14] present a method of estimating roll damping from free-to-roll time histories. Although forced oscillation techniques are generally regarded as a more controlled way to quantify *Clp*, free-to-roll testing provides a way to obtain estimates of *Clp* while providing the added benefit of a procedure that characterizes the severity of the lateral motions. Therefore, the free-to-roll technique has the advantage of providing estimates of *Clp* for the math model and offering risk reduction to the program manager.

Flight Controls

There are two basic ways of using flight controls to attempt to improve handling-qualities deficiencies caused by AWS: feedforward control and feedback control. Traven et al.[3] indicate that changes in feedforward controls led to the "80% solution" to wing drop on the F/A-18E. Specifically, the leading-edge flap (LEF) schedule was biased to higher angles than specified by the baseline control laws; changes to the LEF schedule are shown in Fig. 3, from Traven et al.[3] In the feedforward approach, data are analyzed using FOMs to determine a combination of control surfaces that will improve or eliminate AWS at specified conditions. This is sometimes referred to as "scheduling out" the bifurcation.

Therefore, it is recommended that multiple flap settings be examined and compared to FOMs. However, robustness to AWS is not the only factor that determines flap schedules. In fact, changes made to the flap schedules of the F/A-18E were only possible because margins existed to KPPs. As indicated in the Fig. 1 flowchart, any design trade made to improve AWS characteristics must be balanced with overall system performance requirements.

In contrast to the feedforward approach, a feedback control strategy involves programming flight controls to react to an uncommanded aerodynamic event. For example, it might be possible to arrest a wing drop caused by AWS with the automatic application of aileron. There are significant challenges with the feedback control approach. First of all, because AWS occurs so suddenly, the bandwidths of the sensors, actuators, and other items in the control path must be very high. Gains must be tuned to provide rapid disturbance rejection without sacrificing overall system stability. Nonlinear limitations such as actuator rate and position limits must be considered. Furthermore, because wing control surfaces tend to lose effectiveness near stall (e.g., Ref. 15) nonlinearities in control derivatives must be accommodated.

A preliminary study was conducted to examine the ability of high-gain and realistic feedback control schemes to compensate for an uncommanded roll acceleration disturbance. The control schemes utilized generic linearized lateral-directional dynamics for a combat airplane at transonic flight conditions, with neutral damping-in-roll. The uncommanded input was formulated as a roll acceleration impulse function that had amplitude and duration based on values estimated from flight-test data. Aileron and rudder actuator rate limits were varied from 25 to 200 deg/s. The dynamic responses were analyzed in the manner described by Roesch and Randall[6] and classified by the figure of merit developed from flight-test data.

The high-gain control scheme was tuned to approximate the behavior of an optimal control law with the objective of minimizing the time to zero roll rate. The purpose of this evaluation was to determine if sufficient control power and bandwidth existed to control the disturbance within an acceptable amount of time. Figure 4 shows that the approximate optimal control system is capable of providing adequate (below the green/yellow flight boundary) performance for actuator rate limits from 200 to 50 deg/s. Marginal (between the green and red flight boundaries) performance was obtained with the 25-deg/s actuator rate limit. The realistic control system was based on dynamic inversion architecture and designed to provide level 1 flying qualities, gain margins, and phase margins as established by MIL-F-1797A (Ref. 16). Figure 4 shows that these added considerations prevent the control system from yielding adequate responses to the roll acceleration inputs.

Therefore, although it might be theoretically possible to compensate for uncommanded dynamics as a result of AWS via feedback

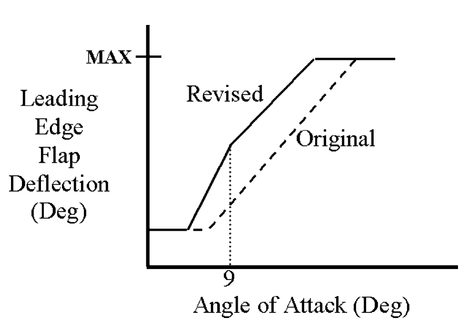

Fig. 3 Application of feedforward controls to improve flying qualities degraded by AWS (from Ref. 3).

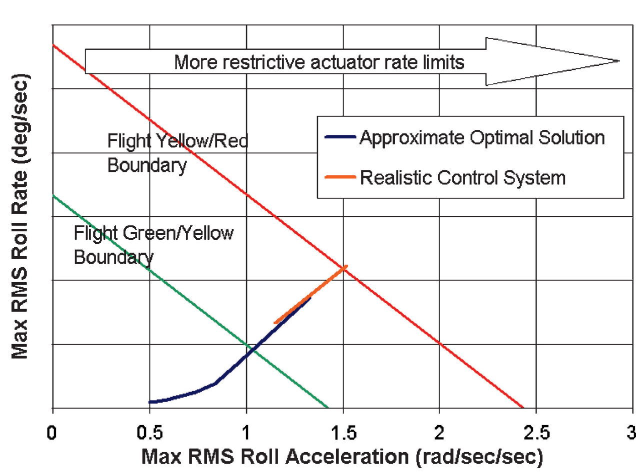

Fig. 4 Effect of rate limits on system response to the roll acceleration impulse for the approximate optimal and realistic control systems.

controls, considerations of other system requirements and physical limitations of system components will degrade the ability of the system to react to AWS. This finding, although preliminary, is consistent with F/A-18E/F program experience and should discourage reliance upon feedback controls as a primary means to compensate for AWS.

Math Model Structure

Cook et al. in Ref. 17 devised a model to simulate aperiodic rolling motions using data from the 9% F/A-18E free-to-roll experiment in the NASA Transonic Dynamics Tunnel (TDT), performed as part of the AWS Program. As shown in Fig. 5, at a pitch angle θ of 8 deg the model experiences two abrupt left-wing-down rolling motions, qualitatively similar in character to the wing drop dynamics observed in flight. The smaller magnitude motions in Fig. 5 that result from unsteady aerodynamic effects were not modeled.

Static rolling moment was measured as a function of roll angle during the nondynamic portion of the experiment. Parameter identification (PID) was performed using these data and the free-to-roll time histories to obtain estimates for damping in roll. This process identified the contributions to the total rolling-moment coefficient by static and dynamic rolling-moment components as a function of bank angle at constant values of theta, as shown in Eq. (2):

$$C_l(\phi) = C_{l_{\text{static}}}(\phi) + C_{l_{\text{dynamic}}}(\phi)(pb/2V) \qquad (2)$$

The resulting values of the basic rolling-moment coefficient *Clo* and *Clp* were compared to those in the F/A-18E six-degree-of-freedom simulation math model. Increments to *Clo* and *Clp* were developed as functions of bank angle. These trends are shown in Fig. 6.

Implementation of these coefficients into a one-degree-of-freedom simulation model in the form of Eq. (2) produced bank-angle trends similar to those observed in Fig. 5. Figure 7, from Ref. 17, displays the result from the simulation model with the two left-wing-down aperiodic motions observed in the experiment. The time histories show reasonable agreement, and this result provides impetus for extension to the full aircraft math model.

Similar model structures have been examined in two flight simulation studies that examine changes to the rolling-moment buildup equation to account for uncommanded lateral motions. Cook et al.[18]

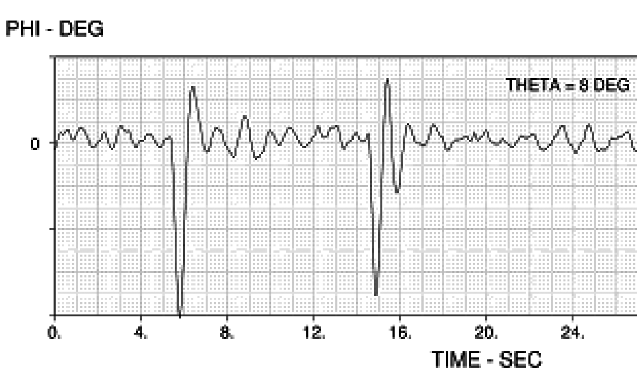

Fig. 5 Aperiodic roll-angle time history observed in F/A-18E free-to-roll testing, TDT run 2226 (from Ref. 17).

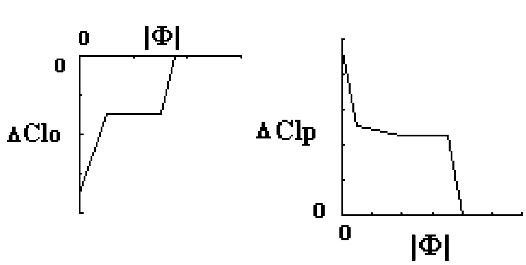

Fig. 6 Changes in *Clo* and *Clp* trends needed to model aperiodic lateral motions in free-to-roll time histories.

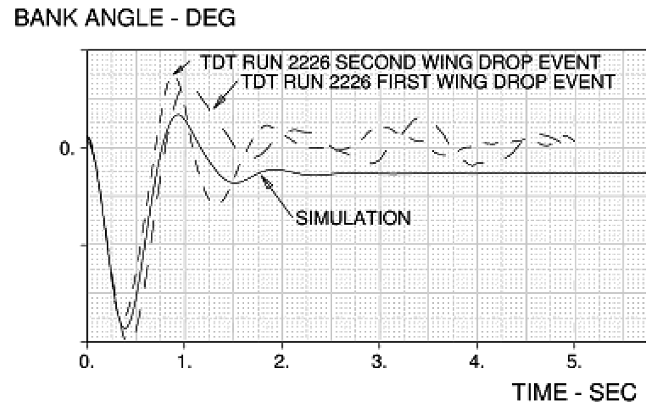

Fig. 7 Comparison of simulation results to aperiodic rolling motions observed in F/A-18E free-to-roll testing, TDT run 2226 (from Ref. 17).

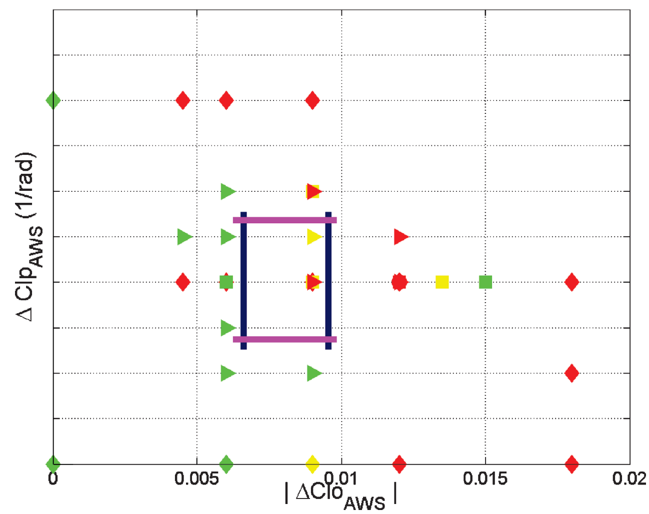

Fig. 8 Δ*Clp* and Δ*Clo* values used in the simulation experiments (from Ref. 19) with approximate empirical values for AWS-prone configurations.

added a $C_{l\,\text{AWS}}$ term to the rolling-moment buildup equation to simulate uncommanded lateral dynamics at transonic conditions, as shown in Eq. (3). Empirical data for $C_{l\,\text{AWS}}$ were not available, and values for $C_{l\,\text{AWS}}$ were extracted from flight data. In addition, a gain was applied to the aileron rolling-moment contribution in order to simulate the loss of aileron effectiveness at AWS conditions.

$$C_{l\,\text{total}} = C_{l_o} + C_{l\,\text{AWS}} + C_{l\beta}\beta + (pb/2V)\left(C_{l_p}\right) + K_{\text{ail}}\delta_{\text{ail}}\left(C_{l_{\delta_{\text{ail}}}}\right) + \Sigma\Delta C_{l\,\text{other}} \qquad (3)$$

Kokolios and Cook[12] added an incremental rolling-moment coefficient to the buildup equations. This incremental coefficient was composed of increments to *Clo*, the basic rolling-moment coefficient, and *Clp*, the damping in-roll as shown in Eq. (4):

$$\Delta C_l = \Delta C_{l_o}(\alpha) + \Delta C_{l_p}(\alpha)(pb/2V) \qquad (4)$$

Values for Δ*Clo* and Δ*Clp* were estimated from flight data, then varied parametrically and compared with pilot opinion and figures of merit. It was determined that this model structure was sufficient to simulate dynamics representative of the uncommanded motions resulting from AWS in a fixed-base simulation. The range of Δ*Clo* and Δ*Clp* values examined, along with the pilot's green-yellow-red qualitative assessment of the severity of the uncommanded dynamics, is reproduced from Kokolios et al.[19] in Fig. 8.

The blue vertical lines overlaid on Fig. 8 indicate an approximate range of the magnitudes of the time-averaged rolling-moment spikes that were measured during static wind-tunnel testing for similar AWS-prone configurations. The horizontal purple lines indicate an approximate range of ΔClp values that were determined through time-history matching and PID estimates of free-toroll and flight data for similar AWS-prone configurations. It is observed that if both of these values were known prior to flight tests piloted simulation would have successfully predicted marginal or unsatisfactory lateral dynamics as a result of AWS. Thus, determining these values before flight and integrating them into the simulation math model holds much promise for accurate prediction of the severity of wing drop. However, exact guidelines and procedures for implementing empirical data into the math model do not exist and remain a significant research challenge.

Tobak and Chapman[20] have proposed more complex model structures using superposition integrals especially designed to account for aerodynamic bifurcations. Several researchers (e.g., Refs. 21 and 22) have applied these models to bifurcation phenomena with varying degrees of success. These advanced model structures were not evaluated as part of the AWS Program, caused in part by the success of replicating the flight dynamics as a result of AWS with a more traditional modeling approach.

Simulation

Cook et al.[18] utilized offline simulation to assess the impact of uncommanded aperiodic lateral motions on the symmetric pull-up maneuver. A pilot model was constructed to correct for the uncommanded bank-angle change, and altitude loss as a result of the lateral motion was quantified. Offline results compared adequately to piloted results for the conditions evaluated.

Kokolios et al.[19] used piloted fixed-base simulation to evaluate the model in Eq. (4). Wind-up turns were simulated, and qualitative green-yellow-red pilot ratings were acquired. Excellent agreement was obtained between the qualitative ratings and the flight-derived figure of merit as shown in Fig. 9.

The impact of wing drop on closed-loop target tracking tasks was also evaluated in fixed-base simulation. The pilot assessed the workload associated with the task using the Cooper–Harper handling-qualities rating (HQR) scale.[23] The HQRs showed general agreement with the figure of merit derived from flight. Kokolios et al.[12] conclude that the math model used in fixed-base simulation was adequate to assess the severity of abrupt uncommanded lateral motions resulting from AWS.

Because the math model interpolates aerodynamic data between entries in look-up tables, a large number of breakpoints might be required at AoAs near wing stall in order to capture nonlinearities in force and moment coefficients. Furthermore, it must be emphasized that applying simplifying assumptions to the aerodynamic data, that is, "smoothing" the data, will compromise the accuracy of the math model and thus compromise the ability to assess AWS.

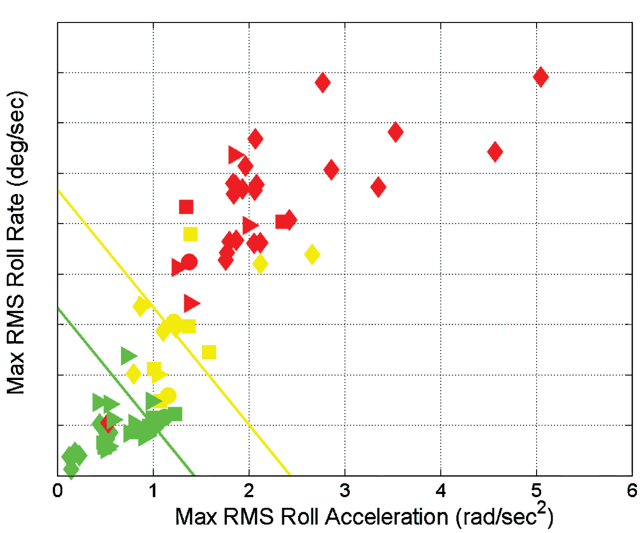

Fig. 9 Qualitative pilot ratings compared with the figure of merit derived from flight-test data (from Ref. 19).

Flight-Test Implications

Traven et al.[3] note that the ability to introduce flap biases during flight tests through flight control software provisions accelerated the discovery of the "80% solution." Owens et al.[14] reported that flap setting had a significant effect on the dynamics observed in the free-to-roll testing. Therefore, providing the capability to introduce flap biases into the flight control systems of test aircraft should be seriously considered.

The wind-up turn was the primary means of assessing wing drop during F/A-18E EMD. In the Ref. 19 simulation work, it was noted that closed-loop maneuvers such as target tracking were effective for assessing smaller levels of uncommanded motions. Therefore, transonic openloop and closed-loop maneuvers that transit AoA regions near stall must be included in the test and evaluation planning. To validate the aerodynamic model, maneuvers that excite the lateral axis of the airplane should be flown at transonic conditions at AoAs near stall. The resulting data can be analyzed using PID techniques, some of which were evaluated as a part of the AWS effort.

During the wind-up turn, the lateral axis was typically only excited in response to a wing drop of unknown magnitude and duration. This uncertainty presented significant challenges to the PID formulation. Several approaches were attempted; it was determined that a model in the form of Eq. (4) could be identified at AoAs near wing stall. The Integrated Data Evaluation and Analysis System (IDEAS)[24] software tool was used to extract values for ΔClo and ΔClp for two maneuvers as a "proof-of-concept" exercise. When the identified damping-in-roll increment was added to the *Clp* value in the aerodynamic model, the total aircraft *Clp* increased to a propelling value near the wing drop AoA. This result is consistent with that obtained from piloted fixed-base simulation. Because PID has the potential to identify deficiencies in the math model, provisions for parameter identification should be incorporated into the acquisition plan.

DoD Acquisition Considerations

Because of the potential cost, schedule, and performance impacts that AWS presents to an aircraft program, it is important for program management to understand how to manage this risk in conjunction with the acquisition policy. Although no longer mandatory for acquisition programs, the DoD 5000 Acquisition Model[25] presented in Fig. 10 provides a useful framework for discussing the acquisition process.

If the acquisition process is entered at milestone A, the likelihood of AWS impacting mission requirements must be considered. For instance, an aircraft designed primarily for reconnaissance might be limited such that AoAs near wing stall are barely obtainable at transonic conditions. In contrast, a fighter airplane is likely to encounter AoAs near wing stall at transonic conditions on a regular basis. The degree to which AoAs near stall are likely to be encountered will determine the degree to which AWS risks are considered in program risk management. Before milestone B, various configurations can be preliminarily screened for AWS based on wing geometry considerations. Green and Ott[26] provide examples of geometric features that can increase susceptibility to AWS.

These geometric considerations remain important as the systems development and demonstration (SDD) phase is entered at milestone B, but as the program acquires empirical aerodynamic data for the selected concept higher-fidelity AWS assessments can be made. As stated earlier, the key to providing an integrated approach to assess AWS is building an accurate math model capable of simulating nonlinear aerodynamic responses. Therefore, data for the math model should be generated via numerical studies and static wind-tunnel testing early in SDD in accordance with the guidelines put forth by Woodson et al.[27] and Capone et al.,[7] respectively. Once these data have been obtained, they must be expeditiously and carefully implemented into the math model. Until *Clp* values can be empirically obtained, conservative (neutral or unstable) values should be carried in the aerodynamic model at AoAs near stall.

As soon as the math model is available, off-line and piloted simulation of open-loop and mission-representative tasks should be evaluated and compared against the figure of merit developed from flight[6] for various control law formulations. This figure of merit—a

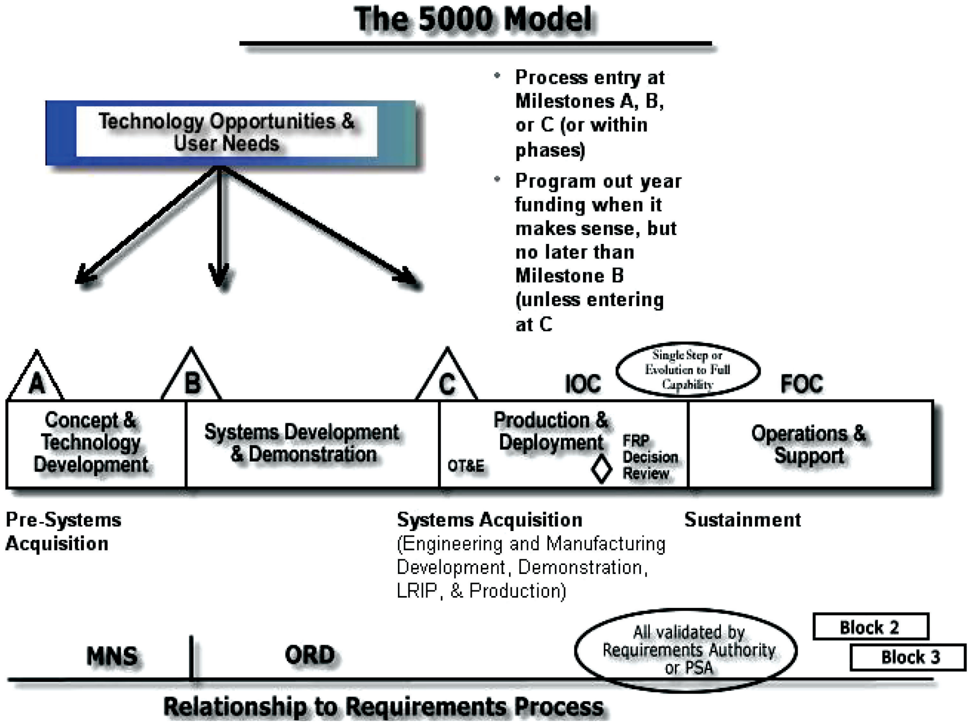

Fig. 10 DoD 5000 Defense Acquisition System Model (from Ref. 25).

cross plot of rms of roll rate and rms of roll acceleration shown in Figs. 4, 8, and 9—is the best tool available to the program manager to assess AWS-related risk. As indicated in this paper, this figure of merit correlates flight results with control system and piloted simulation results. Furthermore, this FOM integrates the effects of static aerodynamic data, dynamic aerodynamic data, flap schedules, feedback controls, and other models to provide a prediction of the dynamics that will be experienced in flight.

Should indications of unsatisfactory AWS characteristics be indicated by this figure of merit, the best tool that the program manager has available to mitigate this risk is free-to-roll wind-tunnel testing. Free-to-roll testing provides a means to assess both the static and dynamic aerodynamic characteristics of the aircraft, and the effect of feedforward controls on AWS can be ascertained. Furthermore, free-to-roll testing offers the designer the opportunity to assess the impact of proposed design modifications on AWS characteristics by comparison to free-to-roll figures of merit.[14] Therefore, it is recommended that the program manager include transonic free-to-roll testing in the acquisition plan for an advanced aircraft.

Conclusions

The key to assessing AWS is to integrate data from various elements of the design process into a math model that can simulate nonlinear aerodynamic responses that can result from AWS. Using the figure of merit developed from flight data, risk can be assessed through analysis of offline and piloted simulation results. Unsatisfactory risk levels can be mitigated by using the free-to-roll wind-tunnel technique.

Specifically, the following actions are recommended to implement an integrated approach to assess transonic AWS:

1) Conduct CFD studies, static wind-tunnel tests, dynamic wind-tunnel tests, and figure-of-merit analyses in a manner consistent with recommendations from the Abrupt Wing Stall (AWS) Program [e.g., analyze wing bending moment, obtain data at fine angle-of-attack (AoA) increments near stall, quantify flow unsteadiness, etc.].

2) Obtain data for multiple flap settings in order to use feedforward control to mitigate AWS characteristics.

3) Evaluate hysteresis characteristics of force and moment data in AoA and sideslip.

4) Do not rely on feedback control as a primary means to mitigate uncommanded dynamics resulting from AWS.

5) Until empirical data are available, assume *Clp* is neutral or unstable at AoAs near wing stall.

6) Include free-to-roll testing in the system acquisition plan.

7) Determine the optimal math model structure that can accommodate nonlinear data with finer breakpoints, so that nonlinear dynamic responses can be accurately simulated.

8) Incorporate all nonlinearities in the aerodynamic data into simulation aerodynamic model.

9) Employ off-line and piloted simulation to assess open-loop and closed-loop tasks.

10) Include transonic open-loop and closed-loop maneuvers that transit AoA regions near stall in flight-test and evaluation planning.

11) Perform flight-test maneuvers that excite the lateral axis of the airplane at transonic conditions at AoAs near stall so that parameter identification can be employed to update the math model.

12) Integrate the capability to introduce flap biases into the flight control system of test aircraft.

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