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

Use of Piloted Simulation for Evaluation of Abrupt-Wing-Stall Characteristics

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A piloted simulation architecture is presented for evaluating uncommanded wing drop due to asymmetric abrupt wing stall for a given aircraft configuration. The architecture incorporates a newly proposed aerodynamic modeling technique that characterizes the wing drop motion as being triggered by aerodynamic stall, modeled by a nonzero basic rolling moment coefficient, and sustained by reduced or propelling roll, modeled via the roll damping derivative. The determination of such derivatives/coefficients from either analytical or experimental methods is not addressed, and the successful identification of such terms, on which any piloted simulation evaluation hinges, remains a topic of research. Models with varying nonzero basic rolling moment coefficients and varying roll damping were inserted into the aerodynamic model and then evaluated by a pilot familiar with wing drop. The pilot assessed the varying models, assigning handling qualities ratings to predeveloped tasks aimed at diagnosing the severity (or absence) of any wing stall characteristics. Tasks included wind-up turns and a closed-loop tracking task in which the pilot tracked a target while flying a drop-prone simulation. The pilot was able to distinguish between satisfactory and unsatisfactory aerodynamic configurations. Pilot ratings and comments, as determined by the lateral aerodynamic model, were generally consistent with the expected handling qualities from flight test.

Nomenclature

b	=	wing span, ft
C_L	=	lift coefficient
C_l	=	rolling moment coefficient
C_{l_0}	=	basic rolling moment coefficient
C_{l_p}	=	roll damping coefficient
M	=	Mach number
N_Z	=	load factor, g
p	=	roll rate, deg/s or rad/s
V	=	velocity, ft/s
α	=	angle of attack, deg or rad
β	=	angle of sideslip, deg or rad
δ	=	control surface deflection, deg
ϕ	=	angle of bank, deg

Introduction

ALTHOUGH not a new phenomenon,[1] uncommanded lateral motion attracted considerable publicity recently during F/A-18E/F developmental testing. Discovered during the first months of flight test, the elimination of wing drop required a multimonth investigative effort that included well in excess of 100 sorties. The problem was eventually solved through a combination of software and hardware updates, and the production E/F is free of any wing drop throughout its maneuvering envelope.

Though it is now realized that the wind-tunnel data provided hints as to the existence of the wing drop, those clues were not appreciated and not modeled in the simulation that was developed before first flight. During the campaign to fix the problem, no architecture could be conceived to model the phenomena for piloted simulation studies. Consequently, the most significant engineering challenge to the aircraft's development had to be solved without the aid of modeling and simulation. If a method to evaluate the effect of uncommanded lateral activity had been available before the commencement of flight-test efforts, the wing drop issue might have been discovered and resolved before first flight, or its resolution might have been less protracted and costly.

Although the use of simulation to assess aircraft flying qualities has been accepted for a number of years,[2] use of the simulator to evaluate the impact of abrupt wing stall on flying qualities is a relatively new concept. Given a sufficient mathematical model (the suggested structure of which is addressed in this paper), then it is suggested that fixed-base simulation with a pilot in the loop could be used to assess the impact of abrupt stall-induced motions on mission capability. Such a method could be used to filter potential candidate configurations before flight. Once a promising candidate has been determined, then flight test is warranted to validate the findings from the simulation.

This paper describes a candidate architecture for reproducing the uncommanded motion from the abrupt wing stall (AWS) phenomena in a piloted simulation. This investigation sought to address the use of fixed-base simulation by implementing a proposed mathematical model structure into simulation and comparing the characteristics with flight results. Although the architecture is very successful in imitating the wing drop, the methodology presumes the availability of requisite data to populate the model, presumably from either computational or experimental sources. The method does not yet provide for a means of confidently mapping such results to a high-fidelity simulation model.

This research effort was conducted as part of the National Abrupt Wing Stall Program, a joint initiative between the U.S. Navy, NASA, U.S. Air Force, and academia to advance the understanding of abrupt wing stall.[3]

Presented as Paper 2003-0924 at the AIAA 41st Aerospace Sciences Meeting and Exhibit, Reno, NV, 6–9 January 2003; received 7 August 2003; revision received 24 December 2003; accepted for publication 24 December 2003.

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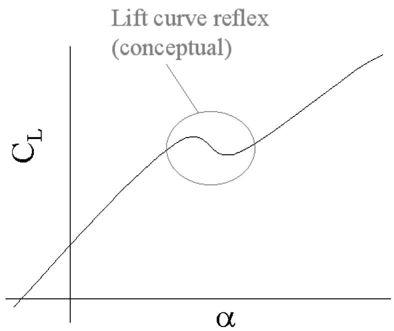

Fig. 1 Conceptual lift curve slope.

Mathematical Model Development

Formulation of a representative mathematical model constituted the first step in the use of the simulator to evaluate the effect of wing drop. A number of factors contribute to the complexity of attempting to model wing drop via simulation. Key among those factors is the unsteady nature of the abrupt stall.

Stall-induced wing drop is a complex aerodynamic phenomenon, whereby lift loss is caused by flow separating asymmetrically between the left and right wing. In addition to decreasing the amount of total lift, the imbalance in lift produces a rolling moment on the aircraft. Figure 1 shows a conceptual lift curve slope with a region of negative lift slope (reflex). The angle of attack (AOA) corresponding to the reflex in the lift curve coincides with the AOA for wing drop. To grasp this concept, picture a scenario where the aircraft AOA is slowly increasing, approaching the reflex region of the lift curve. Then as the aircraft enters the reflex region, imagine a small disturbance causing an imbalance of local AOA between left and right wing, leading to a lift imbalance (between left and right wing) and ensuing rolling motion. As the aircraft begins a rolling motion, the downgoing wing experiences a (kinematically induced) further increase in effective AOA, and inasmuch as it is in the reflex region, a corresponding further decrease in the lift on that wing (negative $\delta C_L/\delta\alpha$). Conversely, the upgoing wing experiences a further (kinematically induced) decrease in AOA, causing a further increase in lift (again, due to a negative $\delta C_L/\delta\alpha$). The net effect of the imbalanced lift is a significant rolling moment in the direction of the original small disturbance, a moment that is propelling rather than dissipative. In essence, this interprets the negative lift curve slope as negative roll damping, and the abruptness and severity of the induced rolling moment is proportional to the magnitude and steepness of the notch in the lift curve. Note that in AOA regions below and above the notch the lift curve slope is positive and that any lateral disturbances are met with positive roll damping.

The nonlinear and stochastic nature of the problem creates a challenging modeling problem. Consequently, significant research effort has been invested into modeling abrupt stall. One recent effort made use of indicial modeling to predict wing stall.[4] In another effort, Cook et al.[5] modified the lateral equation of motion in the AV-8B simulation to assess the impact of uncommanded lateral motions at transonic conditions.

The intent of the mathematical model was to model faithfully the lateral dynamics caused by the abrupt stall. Longitudinal effects, such as loss of lift due to stall, were not considered because these were considered negligible with respect to mission impact. A thorough description of the initial efforts to model the lateral effects due to abrupt stall were documented in an earlier paper,[6] where it was concluded that the use of an incremental model, consisting of an increment to the basic rolling moment coefficient, ΔC_{l_0}, and an increment to the roll damping, ΔC_{l_p}, were sufficient to model abrupt stall for use in piloted simulation assessment. The model is repeated here for reference:

$$\Delta C_l = \Delta C_{l_0}(\alpha) + \Delta C_{l_p}(\alpha)(pb/2V)$$

During the course of evaluating this model, two piloted simulation sessions were conducted at the U.S. Naval Air Warfare Center Aircraft Division Manned Flight Simulator (MFS) at Patuxent River, Maryland, in August 2001 and April 2002. The pilot for this investigation was quite familiar with the effects of abrupt stall, having served as the Navy Chief Test Pilot during the F/A-18E/F developmental flight-test program, as well as personally flying many of the wing drop diagnostic missions. For the initial session, unstable roll damping was modeled over an artificially large AOA range, approximately 7–13 deg (Fig. 2, mathematical model structure A). The large AOA range was purposely chosen to ensure that an abrupt roll upset was experienced. During that session, the pilot did experience wing drop, which was reported as being generally representative of that seen in flight during developmental testing. The simulation response was noted as lacking adequate sensitivity to AOA rate. Specifically, during flight test, wing drop was highly dependent upon AOA rate. A pilot might encounter a wing drop during a "slow" pull, but, for the same configuration, could pass through the same AOA–Mach region without seeing wing drop if the AOA onset rate was "fast." During the first simulation session, the pilot saw no such dependence on AOA rate. Instead, for a given mathematical model configuration, the pilot would always encounter a drop when passing through the targeted AOA region, regardless of AOA rate.

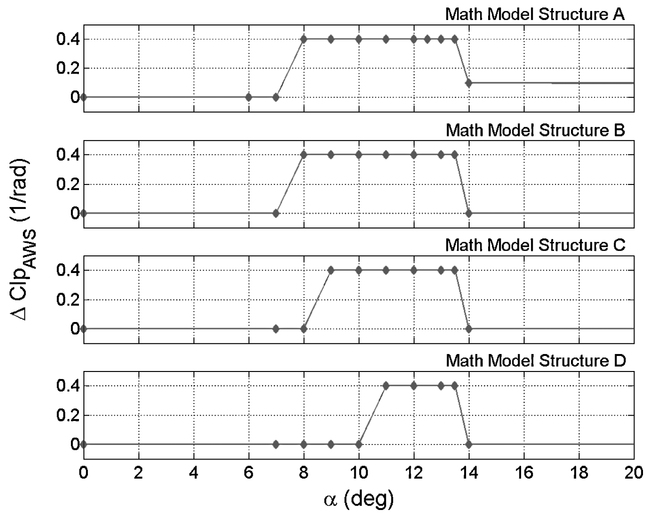

Fig. 2 Roll damping increment implementations.

Smaller ranges of AOA were investigated in the second simulation session, in hopes of introducing a sensitivity to AOA rate. The bottom three plots of Fig. 2 shows how the range of roll damping was modified, including a medium AOA range (approximately 9–13 deg, mathematical model structure C), and a narrowband (approximately 11–13 deg, mathematical model structure D) range. A wideband AOA range model, similar to the first session model, but slightly refined, was also included (mathematical model structure B) for comparison purposes. Pilot comments indicated that the narrowband (model structure D) range was successful, at least qualitatively, in capturing the AOA rate dependency of the abrupt stall phenomenon, as encountered during flight.

Piloted Simulation

Simulator and Aircrew

The MFS facility is the U.S. Navy's aircraft engineering simulator site. The facility consists of laboratories that provide the visual system and instructor operator stations: individual platform cockpits are then connected to the laboratory station (Fig. 3). The F/A-18E/F simulator consists of a two-seat cockpit with accompanying high-fidelity aerodynamic honed by four years of flight test, plus flight controls, gear, and other necessary models represented in FORTRAN code. Hardware-in-the-loop flight control boxes are also available for use in the simulations, but were not utilized for this investigation.

Table 1 Lateral activity rating criteria

Rating	Description
Green	Conditions are clean of any notable lateral activity, or lateral activity whose impact is inconsequential to the mission.
Yellow	Lateral activity whose magnitude or slow rates permits the pilot to compensate using a brief, small control input to either keep the aircraft trajectory from being perturbed or promptly correct; includes any wing drops that could promptly be countered by small lateral stick deflections.
Red	Lateral activity that shows an abruptness or magnitude such that mission performance would be clearly degraded at that specific flight condition; aircraft's trajectory positively affected; includes rolloffs that could not promptly be countered by small lateral stick deflections.

Fig. 3 Laboratory station with cockpit.

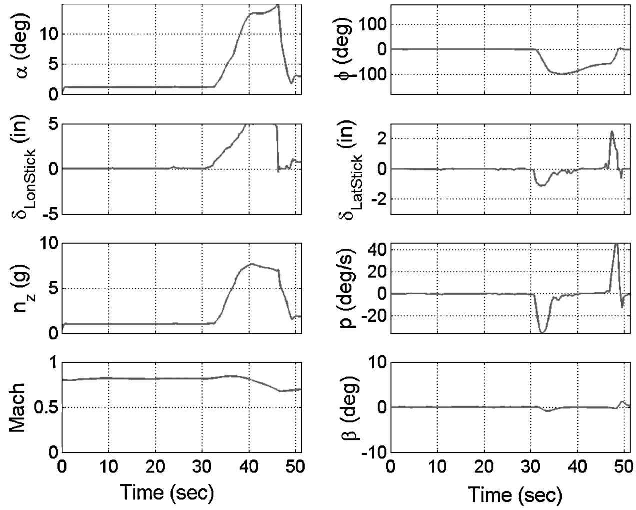

Fig. 4 Simulation time history of wind-up turn.

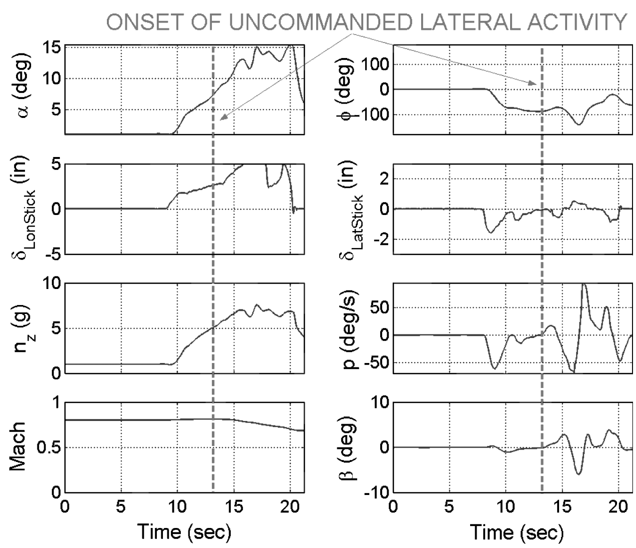

Fig. 5 Simulation WUT time history with uncommanded lateral activity.

Open-Loop Evaluation

During both simulation sessions, open-loop evaluations were conducted. These consisted of wind-up turns (WUT), a descending turn during which load factor and AOA are increased smoothly while holding Mach constant. The pilot was asked to assign a stoplight red–yellow–green rating for each maneuver flown, as was performed during developmental flight tests.[7] The rating criteria, as developed and used during developmental flight tests, are described in Table 1.

To validate the use of simulation for assessing abrupt stall, the stall model increments were adjusted via scale factors before each maneuver. The pilot was not informed as to how the model was adjusted before performing the maneuver. Simulated flight conditions were initialized at 15,000 ft, $0.8M$, the heart of the flight envelope in which wing drop was experienced. The pilot was asked to perform WUT maneuvers in a prescribed direction, left or right, and was asked to target 1 g/s load factor onset rate; the maneuver was complete upon reaching 7.5 g or AOA limit. The pilot was then asked to rate the maneuver according to the stoplight criteria defined earlier.

Figure 4 is a typical time history from a WUT maneuver flown in the simulator. The maneuver commenced at $0.8M$, 15,000 ft. The pilot banked the aircraft until reaching approximately 80-deg bank, then steadily increases AOA (and load factor Nz) by pulling back on the stick. Mach is maintained constant throughout the maneuver by increasing power and allowing for a slight descent. Figure 5 shows a similar time history, but one in which a wing drop is encountered. As the pilot increased AOA through approximately 13 deg, a wing drop occurred. Note the large spike in roll rate despite the pilot's attempt to maintain constant bank. This episode was consistent with the nature of abrupt stalls seen during flight test.

Closed-Loop Evaluation

A closed-loop piloted evaluation was also conducted during both simulation sessions. Closed-loop tasking consisted of a gunsight tracking task. An S-turn flight profile was first flown by the pilot with the baseline (nonstalling) simulation. That trajectory was then saved to disc and rerun to drive the visual target for the remaining events. The pilot was then required to track the clean aircraft with the modified simulation that included the abrupt stall model. The target aircraft was positioned approximately 2000 ft ahead of the pursuing aircraft. The pilot was asked to evaluate the impact of the stall-modified configuration while attempting to maintain gunsight tracking on the lead aircraft.

Results

General

In general, the pilot found the abrupt stall characteristics of the simulation, updated with the incremental stall model (model structure D), qualitatively representative of what was encountered during developmental flight-test efforts for the F/A-18E/F. This held true for some model structures (see further discussion later) and increment values more than for others, but in general, the model structure led to flight characteristics that proved representative of what the pilot had observed in flight. For certain maneuvers, in which a particular character and level of lateral activity was encountered, the pilot was even able to relate the characteristics of the wing drop as being representative of a given developmental aircraft configuration (control law version and/or wing configuration), as flown during developmental testing.

Open-Loop Results

As described earlier, the abrupt stall model increments were scaled parametrically to induce various level of lateral activity during a given maneuver. The pilot was asked to rate each maneuver based on the lateral activity encountered. A summary of these ratings, as rated by the pilot during the WUT (open-loop) maneuvers is shown in Fig. 6. Results are shown that encompass data from both sessions and include the four mathematical model structures discussed earlier. The ratings are plotted against a figure of merit (FOM) developed from flight-test data.[8] The FOM plots the maximum root-mean-square roll rate value against the maximum rms roll acceleration experienced during the maneuver. Boundaries (as shown in Fig. 6) were ascribed to delineate between green and yellow ratings and between yellow and red ratings as determined during developmental flight test.

Figure 6 shows the same flight-test-derived boundaries merged with rated maneuvers flown during the simulation sessions. Given that the majority of ratings fall within or close to the bounds developed from flight-test data, it appears that the flight FOM is equally applicable for use in the fixed-base simulator. The implication is that the fixed-base simulator can reasonably be used as a tool for evaluating the effects of abrupt stall on a mission task.

The relationship between the incremental coefficient values and pilot ratings was also examined. Figure 7 shows this relationship. In general, the ratings were more likely to be in a red region as $|\Delta C_{l_0}|$ increased in magnitude and as ΔC_{l_p} increased, that is, less stable roll damping. As $|\Delta C_{l_0}|$ became sufficiently large (>0.01), red ratings were encountered even when the roll damping increment was zero. Similarly, as the incremental roll damping was increased (overall roll damping reduced), smaller levels of $|\Delta C_{l_0}|$ were required to trigger red ratings. In general, the distribution of ratings on the graph demonstrates that both nonzero C_{l_0} and unstable (or reduced) C_{l_0} contribute to reducing flying qualities to unacceptable levels during wing drop. However, more research is needed in this area to tie the ratings together with coefficient values.

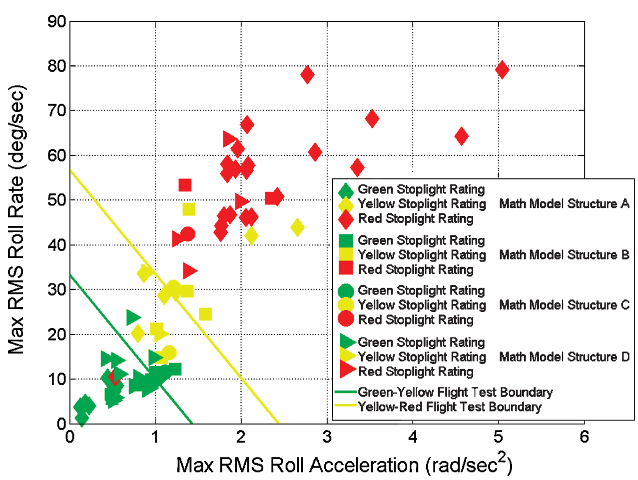

Fig. 6 Simulation WUT stoplight ratings vs flight-derived boundaries.

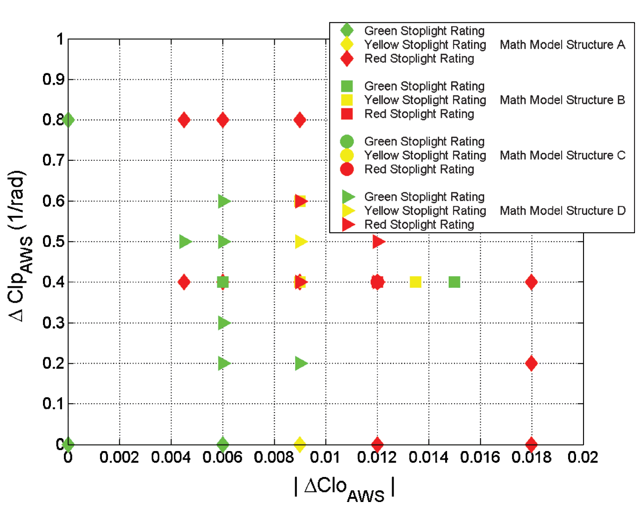

Fig. 7 Correlation between C_{l_0}, C_{l_p}, and pilot ratings.

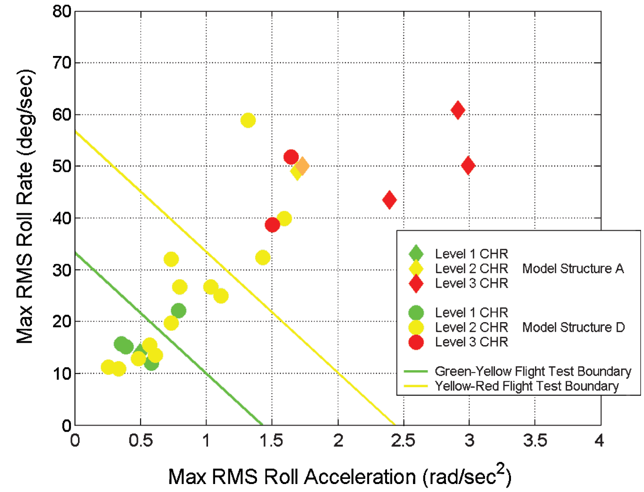

Fig. 8 Simulation target tracking ratings vs flight-derived boundaries.

Closed-Loop Results

Figure 8 summarizes the closed-loop evaluation points flown during the investigation. Cooper–Harper[9] handling qualities ratings (HQR) were assigned for each attempted maneuver, consisting of a tracking task during an S-turn maneuver. These ratings, shown as level 1 (HQR 1, 2, or 3), level 2 (HQR 4, 5, or 6), and level 3 (HQR 7 or greater), are plotted against the flight-test-derived boundaries discussed earlier in the open-loop results discussion. As for the open-loop maneuvers, various levels of lateral activity were induced by varying scale factors on the incremental wing stall terms in the mathematical model.

In general, the HQR levels assigned by the pilot during the closed-loop tasks correlated fairly well with the red–yellow–green flight-test-derived boundaries extracted from open-loop maneuvers. That is, level 1 ratings tended to have lateral activity rms values that were below the green–yellow boundary, level 2 ratings generally fell within or near the green–yellow and yellow–red boundary, and level 3 ratings were associated only with those maneuvers that experienced lateral activity greater than that defined by the yellow–red boundary.

The pilot was able to assess quickly the impact of the lateral activity on the mission-related task. In one case, the maneuver rating dropped from a level 1 (HQR-3) to a level 3 (HQR-7) when an abrupt stall was encountered. At other times, the task was abandoned due to inability to continue tracking.

A number of maneuvers that were rated level 2 by the pilot fall below the green boundary. Pilot comments from these maneuvers indicate that the pilot rated these as level 2 maneuvers due to the challenge of the tracking task, not due to lateral activity. Overall, further investigation is warranted to evaluate how the levels of lateral activity correspond with pilot rating for the closed-loop task.

Discussion

The described trials demonstrated the viability of imitating, for the purpose of piloted simulation, the dynamic behavior of an airplane exhibiting AWS. The methodology presented, however, does not yet pose a viable diagnostic for determining what airplanes or configurations might be sensitive to AWS. The mathematical model depends on rolling damping and rolling moment increments added to the basic aerodynamic model. For the purpose of this experiment, those increments were determined heuristically, adjusting their magnitude until the desired dynamic response was observed. This is still short of an ability to predict or model AWS behavior before the flight of a new vehicle. Work remaining includes development of a process for mapping wind-tunnel results to the simulation without a priori knowledge of the airplane's flight characteristics.

The mathematical model, therefore, requires development of the following information:

1) Adequate wind-tunnel testing must be carried out to allow for sufficient modeling of terms included in the incremental model. This would include appropriate static wind-tunnel testing to capture any nonzero basic rolling moment coefficient. Testing around suspected abrupt stall conditions may need to be executed at smaller increments of AOA than is usually performed, for example every $^1/_2$ deg instead of every 4 deg. Also forced oscillation and/or a free-to-roll test effort may need to be conducted at and near a suspected abrupt stall condition, to allow for extraction of roll damping characteristics.[10] Parameter identification techniques will likely need to be applied to be able to extract representative values of the roll damping.

2) Appropriate modeling of roll damping must encompass the range of flight condition at which the nonzero basic rolling moment coefficient occurs. In the mathematical model representation, the nonzero basic rolling moment coefficient acts as the trigger that initializes the rolling moment. It embodies the effect of the asymmetric abrupt stall, caused by the rapid separation of flow over one wing while the flow over the other remains attached. The combined effect of basic rolling moment coefficient and roll damping then determines the severity of the wing drop. Weak roll damping might not provide enough damping to counter the rolloff motion, and objectionable lateral activity may ensue. If the roll damping is unstable, then the initial rolloff motion will be sustained, causing the wing drop to be severe enough to interfere with the mission task.

Conclusions

The use of piloted simulation to assess the impact of abrupt stall on mission capability has been demonstrated. With use of a fixed-base, high-fidelity simulator modified with an abrupt stall mathematical model, the impact of abrupt stall on mission task capability was assessed. Results of open-loop tasks validated the use of simulation by showing that pilot ratings from the simulator were consistent with rating boundaries developed from developmental flight testing. Closed-loop tasks confirmed the utility of the simulation in that the pilot was able to assess clearly the impact of lateral activity on a mission-related task.

The investigation confirmed that the proposed model structure faithfully modeled the effects of abrupt stall and was effective for simulator evaluation of mission tasks. This model consisted of both a nonzero basic rolling moment coefficient term and a reduced or unstable roll damping term, with reduced or unstable values occurring at the flight condition at which the basic rolling moment coefficient increment is nonzero. The range of AOA over which the unstable roll damping is programmed may be quite small.

Future programs with concern for abrupt stall may wish to direct test efforts to ensure adequate preflight data are gathered. Such data could then be used to construct a sufficient mathematical model for assessing the impact of abrupt stall on flying qualities in the simulator.

Acknowledgments

The authors wish to acknowledge the support of the Office of Naval Research and Program Management Activity (PMA)-265, the F/A-18 program office, for providing resources in support of this research. The authors also wish to acknowledge The Boeing Company and the National Abrupt Wing Stall Program for additional resources. Finally, the authors wish to acknowledge the U.S. Naval Air Warfare Center Aircraft Division Manned Flight simulator staff in accomplishing the simulations sessions. Particular thanks go to Stephen Naylor and Tammy Hallihan for their dedicated efforts in facilitating these sessions.

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